Securing IP Mobility Management for Vehicular Ad Hoc Networks

by

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

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Abstract

The proliferation of Intelligent Transportation Systems (ITSs) applications, such as Internet access and Infotainment, highlights the requirements for improving the underlying mobility management protocols for Vehicular Ad Hoc Networks (VANETs). Mobility management protocols in VANETs are envisioned to support mobile nodes (MNs), *i.e.*, vehicles, with seamless communications, in which service continuity is guaranteed while vehicles are roaming through different RoadSide Units (RSUs) with heterogeneous wireless technologies.

Due to its standardization and widely deployment, IP mobility (also called Mobile IP (MIP)) is the most popular mobility management protocol used for mobile networks including VANETs. In addition, because of the diversity of possible applications, the Internet Engineering Task Force (IETF) issues many MIP's standardizations, such as MIPv6 and NEMO for global mobility, and Proxy MIP (PMIPv6) for localized mobility. However, many challenges have been posed for integrating IP mobility with VANETs, including the vehicle's high speeds, multi-hop communications, scalability, and efficiency. From a security perspective, we observe three main challenges: 1) each vehicle's anonymity and location privacy , 2) authenticating vehicles in multi-hop communications, and 3) physical-layer location privacy.

In transmitting mobile IPv6 binding update signaling messages, the mobile node's Home Address (HoA) and Care-of Address (CoA) are transmitted as plain-text, hence they can be revealed by other network entities and attackers. The mobile node's HoA and CoA represent its identity and its current location, respectively, therefore revealing an MN's HoA means breaking its anonymity while revealing an MN's CoA means breaking its location privacy. On one hand, some existing anonymity and location privacy schemes require intensive computations, which means they cannot be used in such time-restricted seamless communications. On the other hand, some schemes only achieve seamless communication through low anonymity and location privacy levels. Therefore, the trade-off between the network performance, on one side, and the MN's anonymity and location privacy, on the other side, makes preservation of privacy a challenging issue. In addition, for PMIPv6 to provide IP mobility in an infrastructure-connected multi-hop VANET, an MN uses a relay node (RN) for communicating with its Mobile Access Gateway (MAG). Therefore, a mutual authentication between the MN and RN is required to thwart authentication attacks early in such scenarios. Furthermore, for a NEMO-based VANET infrastructure, which is used in public hotspots installed inside moving vehicles, protecting physical-layer location privacy is a prerequisite for achieving privacy in upper-layers such as the IP-layer.

Due to the open nature of the wireless environment, a physical-layer attacker can easily localize users by employing signals transmitted from these users.

In this dissertation, we address those security challenges by proposing three security schemes to be employed for different mobility management scenarios in VANETs, namely, the MIPv6, PMIPv6, and Network Mobility (NEMO) protocols.

First, for MIPv6 protocol and based on the onion routing and anonymizer, we propose an anonymous and location privacy-preserving scheme (ALPP) that involves two complementary sub-schemes: anonymous home binding update (AHBU) and anonymous return routability (ARR). In addition, anonymous mutual authentication and key establishment schemes have been proposed, to authenticate a mobile node to its foreign gateway and create a shared key between them. Unlike existing schemes, ALPP alleviates the tradeoff between the networking performance and the achieved privacy level. Combining onion routing and the anonymizer in the ALPP scheme increases the achieved location privacy level, in which no entity in the network except the mobile node itself can identify this node's location. Using the entropy model, we show that ALPP achieves a higher degree of anonymity than that achieved by the mix-based scheme. Compared to existing schemes, the AHBU and ARR sub-schemes achieve smaller computation overheads and thwart both internal and external adversaries. Simulation results demonstrate that our sub-schemes have low control-packets routing delays, and are suitable for seamless communications.

Second, for the multi-hop authentication problem in PMIPv6-based VANET, we propose EM^3A, a novel mutual authentication scheme that guarantees the authenticity of both MN and RN. EM^3A thwarts authentication attacks, including Denial of service (DoS), collusion, impersonation, replay, and man-in-the-middle attacks. EM^3A works in conjunction with a proposed scheme for key establishment based on symmetric polynomials, to generate a shared secret key between an MN and an RN. This scheme achieves lower revocation overhead than that achieved by existing symmetric polynomial-based schemes. For a PMIP domain with n points of attachment and a symmetric polynomial of degree t, our scheme achieves $t \times 2^n$-secrecy, whereas the existing symmetric polynomial-based authentication schemes achieve only t-secrecy. Computation and communication overhead analysis as well as simulation results show that EM^3A achieves low authentication delay and is suitable for seamless multi-hop IP communications. Furthermore, we present a case study of a multi-hop authentication PMIP (MA-PMIP) implemented in vehicular networks. EM^3A represents the multi-hop authentication in MA-PMIP to mutually authenticate the roaming vehicle and its relay vehicle. Compared to other authentication schemes, we show that our MA-PMIP protocol with EM^3A achieves 99.6% and 96.8% reductions in authentication delay and communication overhead, respectively.

Finally, we consider the physical-layer location privacy attacks in the NEMO-based VANETs scenario, such as would be presented by a public hotspot installed inside a moving vehicle. We modify the obfuscation, *i.e.*, concealment, and power variability ideas and propose a new physical-layer location privacy scheme, the fake point-cluster based scheme, to prevent attackers from localizing users inside NEMO-based VANET hotspots. Involving the fake point and cluster based sub-schemes, the proposed scheme can: 1) confuse the attackers by increasing the estimation errors of their Received Signal Strength (RSSs) measurements, and 2) prevent attackers' monitoring devices from detecting the user's transmitted signals. We show that our scheme not only achieves higher location privacy, but also increases the overall network performance. Employing correctness, accuracy, and certainty as three different metrics, we analytically measure the location privacy achieved by our proposed scheme. In addition, using extensive simulations, we demonstrate that the fake point-cluster based scheme can be practically implemented in high-speed VANETs' scenarios.

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Dedication

To the soul of my dear father, I will never forget you for the rest of my life

To my beloved mother, my prayer to GOD is always to make you happy

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List of Abbreviations

AAA	Authentication, Authorization, and Accounting server
AP	Access point
AR	Access router
BU	binding update
C2C-CC	Car-to-Car Communication Consortium
CN	Correspondent node
CoA	Care of address
DAD	Duplicate Address Detection
DHCP	Dynamic host control protocol
DNS	Domain name server
DoS	Denial of service attack
FMIPv6	Fast MIPv6
FG	Foreign gateway
HA	Home Agent
HoA	Home address
HIP	host identity protocol
HMIPv6	Hierarchial MIPv6
IETF	Internet engineering task force
IP	Internet protocol
ITS	Intelligent transportation system
LMA	Local mobile anchor
MAG	Mobile access gateway
MIPv6	Mobile IPv6
MN	Mobile node

MNN	Mobile network node
MNP	Mobile network prefix
MR	Mobile Router
NEMO	Network mobility
MANET	Mobile ad hoc network
OBU	On-board unit
PMIPv6	Proxy MIPv6
RA	Router advertisement.
RN	Relay node
RS	Router solicitation
RSS	Received signal strength
RSSI	RSS identifier
RSU	Roadside unit
V2V	Vehicle-to-vehicle
V2I	Vehicle-to-infrastructure
V2V2I	Vehicle-to-vehicle-to-infrastructure
VANET	Vehicular ad hoc network
V2G	Vehicle-to-grid
VANET	Vehicular ad hoc network

Chapter 1

Introduction

In recent years, both academic and industry have shown significant interest in the field of mobility management for vehicular networks achieving seamless communications for mobile nodes (MNs), *i.e.*, vehicles [4]. Mobility management protocols, such as Mobile IPv6 (MIPv6) and the NEtwork MObility (NEMO) protocols, have been proposed by many consortia as well as standards organizations, including the Car-to-Car Communications Consortium (C2C-CC) [5] and the Internet Engineering Task Force (IETF). In addition, industry integrates these mobility management protocols with Vehicular Ad Hoc Networks (VANETs) [6] to support Intelligent Transportation Systems (ITSs) applications, including Internet access, real-time traffic information, video streaming, and infotainment. However, integrating mobility management with VANET as a kind of not only mobile, but also heterogeneous networks [7], poses challenges - vehicles change their points of attachments frequently, which causes the network topology to be changed abruptly.

The security and privacy preservations have been considered as important challenges in this mobility management-VANETs integration. Spending at least two hours per day in vehicles, passengers prefer using the ITS applications, however, most of them are concerned about their privacy when using these applications. Current mobility management standards, namely Mobile IP (MIP) and its updates, rely on the IPSec protocol, which supports authentication and data privacy and security services in a limited way. For example, the industry reports the lack of wide adoption of the MIPv6 protocol due to the problems with interoperability in IPSec implementations. In addition, implementing IPSec with VANETs increases the vehicle's handover delay, which in turn prevents seamless communications for real-time applications.

1.1 IP Mobility Management for Vehicular Networks

The first trend to support nodes' mobility was through the MIP protocols, due to their standardizations and widely deployment. However, security, resource overhead, and scalability have been reported as MIP's shortcomings, due to the dual role of the IP address as a mobile node's identity and location. Therefore, IETF issues many MIP updates, such as Proxy MIPv6 (PMIPv6) and Hierarchial MIPv6 (HMIPv6), to ameliorate MIP's problems [8].

In addition, many alternatives such as locator/ID separation protocol (LISP) [9], Host Identity Protocol (HIP) [10], and Mobility and Multihoming Supporting Identifier Locator Split Architecture (MILSA) [11], have been proposed. The main idea is to separate the MN's identity and location, in order to achieve better network performance than that achieved with the dual-role MIP standards. LISP (as well as Virtual ID [12]) allows the MN to communicate with a mapping server that maintains an identifier-locator mapping in order to get the locator of the correspondent node's identifier. In addition, HIP introduces a cryptographic-based public key to represent the MN's identity, while the IP address is used only as a locator. The domain name server (DNS) maintains the binding between the MNs' identities and locators, hence, another network delay is added because the DNS is a single point of failure and overload. Relying on changing the MN's stack, the MILSA [11] separates the MN's identifier, represented by a Hierarchial URI-like Identifier (HUI), and its locator, represented by the IP address. The HUI is used by the transport layer, and its mapping to the IP address is performed by a mapping sub-layer into the network layer.

IP mobility management for VANETs involves location management used to track the vehicle's location and to enable packet reception, and handover management used to support seamless handover. In this kind of handovers, also called seamless communications, the vehicle's connection to the infrastructure is kept active while the vehicle moves and changes its point of attachment. More specifically, the seamless handover [13, 14] is a vertical handover process in which vehicles are roaming along heterogeneous access networks, such as IEEE 802.11p, WiMaX, and WiFi. When using this time-restricted handover process, both mobile node and service provider have some benefits, including low cost, wide coverage, and high bandwidth. Therefore, many ITS applications such as infotainment and video-streaming download empoly the seamless handover, supported by the MIP protocols, to increase networking performance.

1.1.1 Mobile Applications in VANETs

In Vehicular Ad hoc Networks (VANET), a vehicle that is equipped with an On-Board Unit (OBU) communicates with other vehicles via a Vehicle-to-Vehicle (V2V) domain, and communicates with a Roadside Unit (RSU) via a vehicle-to-Infrastructure (V2I) domain. V2V and V2I communication domains are mainly for safety VANET applications, such as road accident notifications and weather warnings. In addition, non-safety VANET applications, such as service infotainment and Internet access, have recently received a great deal of attention. Seamless mobile applications in VENETs are presented as follows:

- **Video streaming**

  Downloading video files, anywhere anytime, is one of the most important features for wireless video applications. However, wireless video applications face some performance problems [15] due to the lossy nature of the wireless channel, which increases the transmission error rate. There are two types of wireless video applications: real-time interactive applications such as video conferences, and video streaming applications such as live multimedia files. The solution to decrease the error rate is to apply an error concealment technique in order to hide the error. Passengers can download multimedia files via RSUs to vehicles driving through. In addition, live news or football matches can also be watched.

- **Online gaming**

  Passengers sitting in different vehicles can enjoy playing online games on the roads.

- **Wireless VoIP**

  Voice communication is one of the most important applications in wireless networks. However, voice over IP (VoIP) on a wireless requires interoperability between the circuit-switched GSM network and the H.323 IP network. Compared to the traditional VoIP in GSM, the VoIP on wireless [15] costs more and requires more functions, because it requires dynamic reservation of the network's resources for the path from the sender to the receiver. This dynamicity is a result of the user mobility. Moreover, VoIP on wireless also requires more advanced encoding algorithms to support the voice traffic on the IP networks. More specifically, wireless VoIP is an open research area due to the trade-off between the interoperability requirements and the high level of performance that is required with real-time voice communications.

- **Wireless file systems**

The main requirement in a wireless file system is that the wireless file transmission should not be disconnected while the mobile device moves among different wireless networks. In other words, the availability of the file system is a challenge due to the mobility of the wireless devices. Moreover, when attempting to download videos, mobile devices may encounter a problem connecting to the server. To solve this problem, disconnected and weakly connected operations can be used [15].

- **Location dependent applications**

  There are three types of mobile location applications [15]: 1) in-vehicle mobile location applications, 2) personal mobile location applications, and 3) government mobile location applications. The in-vehicle mobile location applications are high-mobility applications in vehicular Ad hoc networks. Emergency service and stolen car location services are examples of those applications. Moreover, the personal mobile location services (e. g., personal location tracking) are low mobility applications. The government location mobile applications (e. g., road pricing system) are applications that are presented by governments.

1.2 Research Challenges

Securing mobility management protocols for VANETs is a challenging process due to the unique characteristics of VANETs that conflict with the IP mobility, and hence prevent using traditional security algorithms. As a kind of mobile network, the mobility management-based VANET's security requirements are described herein:

1. **Authentication:** Each mobile node, *i.e.*, vehicle, must be able to authenticate itself to both its home agent and the correspondent node communicating with it. Moreover, the mobile node requires the ability to authenticate the source of its received data. The mutual authentication requirement protects mobile IPv6 users from impersonation and masking attacks.

2. **Communication privacy:** Communication among the mobile node, the home agent, and the correspondent node should be confidential, and an intermediate eavesdropper should not learn the content of the transmitted data.

3. **Message integrity:** Active attacks should be prevented by message integrity mechanisms, by which the mobile node guarantees that the received data is not modified during transmission.

4. **Anonymity and location privacy:** The mobile node must guarantee its anonymity in the network. The anonymity of a network is the ability to hide a specific item among a group of similar items, and location privacy is the ability to prevent tracking a user's mobility. Anonymity and location privacy prevent a traffic analysis attacks from learning the identity or the location of the mobile node.

5. **Payment protocol:** The roaming mobile nodes always use the foreign networks' resources, therefore a payment protocol is required to charge the mobile node. The payment protocol must be secure in protecting the location privacy of the mobile node; moreover, the mobile node must authenticate the network operator before paying for the service.

6. **Revocable privacy vs. perfect privacy:** Although perfect privacy is required to ensure a high level of security, revocable privacy is also needed in any case where the mobile node disputes payment. In revocable privacy techniques, there must be at least one entity in the network that can revoke the privacy of the mobile node at any time.

1.2.1 Mobility Management Challenges

When integrating IP mobility with VANETs, the following challenges occur [16]:

Seamless mobility with high speed VANETs

Due to the high speeds of vehicles and hence the increase of number of handovers, applying seamless mobility in VANETs becomes more challenging. Fast handover is required to decrease the delay in ITS applications, so the accessability and service continuity are guaranteed regardless of the vehicle's location and the wireless technology. PMIPv6 and NEMO protocols are the most suitable mobility protocols for the ITS in VANETs, while the MIPv6 protocol encounters high signaling overhead. New adaptations in the MIPv6 protocol have been standardized, such as FMIPv6 and HMIPv6, with the goal of decreasing the handover delay by early detection of the vehicle's roaming. In addition, the PMIPv6 protocol decreases the overhead by introducing local mobility that serves the MN's roaming inside one PMIP domain. However, the signaling overhead increases when the MN moves through multiple domains. Furthermore, the NEMO protocol has been used in many ITS projects, such as C2C-CC, in which the Mobile Router (MR) performs the signaling operations on behalf of the Mobile Network Nodes (MNNs) that only implement IPv6 without any mobility functions. However, the problem of nested NEMO [17], in which signals from nested MRs travel through all parent MR's home agents, increases the seamless communication delay.

IPv6-based multi-hop VANETs

In early research, the focus was to support IP mobility for VANET where there is a direct connection between the vehicle and the RSU , *i.e.,* a one-hop connection [18, 19]. However, with the proliferation of Vehicle-to-Vehicle-to-Infrastructure (V2V2I) communications, the need for the multi-hop VANETs increases. New challenges in applying IP mobility are described below [20]:

- The operations and performance of IP in the current 802.11p/WAVE VANET standard has not been identified clearly yet.
- IP mobility support for the multi-hop environment adds complexity to VANET scenarios with a short duration multi-hop connections, given the high-speed VANETs.
- Asymmetric links are difficult to be implemented in V2V2I communications.
- The intermediate vehicle has a lack of motivation to forward generated data to other vehicles.
- Heterogeneity in vehicular networks is not only in wireless technology, but also in type of equipments and applications.

Scalability and efficiency

Vehicular networks could be very large in size, where thousands of vehicles may communicate together. In addition, the frequent changes of the point of attachment for each vehicle coupled with the vehicle high speeds, affect the VANET topology, therefore the IP mobility protocol needs to be scalable and efficient in signalling overhead during handover, in order to support service continuity and seamless communications for vehicles.

1.2.2 Security Challenges

Vehicle's anonymity and location privacy

Previous studies have attempted to secure the mobility signaling in mobile networks by focusing on the authentication and integrity problems only [21–24]. Moreover, much recent research work has been done on anonymity and location privacy problems [25–27]. As mentioned in [28, 29], location privacy threats vary from a simple interference with personal activities and habits, to a more dangerous physical attack after identifying a person and his favorite locations.

In transmitting mobile IPv6 binding update messages, both the mobile node's HoA and CoA are transmitted as plain-text, hence they can be revealed by network entities and attackers. The mobile node's HoA and CoA represent its identity and its current location respectively. Therefore, revealing an MN's HoA means breaking its anonymity and revealing an MN's CoA means breaking its location privacy. On one hand, some existing anonymity and location privacy schemes [30–33] require intensive computations, hence, they cannot be used in the time-restricted seamless handovers occurring in mobile networks such as VANETs. On the other hand, some other schemes [34, 35] achieve low anonymity and location privacy levels. Therefore, the trade-off between the network performance on one side and the MN's anonymity and location privacy on the other side makes privacy preserving a challenging issue.

Authenticating vehicles in multi-hop communications

In order to support seamless communications, an adaptation for IP mobility management protocol, such as Proxy Mobile IPv6 (PMIP), has been proposed in [36] to provide IP mobility support in an infrastructure-connected multi-hop vehicular network. In such a multi-hop PMIP network, an MN uses a Relay Node (RN) for communicating with its Mobile Access Gateway (MAG) (i.e., the point of attachment to the infrastructure). The existing authentication schemes that can authenticate this MN to its MAG , use the RN to only forward the authentication credentials between MN and MAG. However, an extra mutual authentication, between MN and RN, is required to thwart authentication attacks early.

Without that authentication, the mobile node may initiate a denial of service (DoS) attack toward the MAG, or the RN may initiate a fraud attack to mislead the MN. In mobile environments, DoS and fraud attacks can cause service disruptions and financial losses, due to resources' exhaustion and high end-to-end delay [37]. The difficulty of generating a security association between MN and RN, which are arbitrary nodes and have not met each other before, makes proposing an authentication-preserving scheme a challenge. Moreover, if public-key authentication schemes are employed for this MN-RN authentication, they would require a large delay that cannot be tolerated by seamless vehicular communications.

Physical-layer location privacy attacks

In addition to the location privacy mechanisms implemented in the network layer in order to protect MNs while roaming among different networks, we observe that other mechanisms are required to thwart lower-layers location privacy attackers, such as triangulation attackers, that localize the senders from the strength of their transmitted signals. Triangulation attackers can be found when applying NEMO protocol to support public hotspots inside moving vehicles.

Two benefits can be acquired when integrating the NEMO protocol With VANET: commercial and performance. Commercially, the cost of achieving the mobility function in NEMO-based VANET decreases, because the passengers' devices do not need to implement the NEMO protocol. The OBU is the only entity that implements NEMO protocol, because it works as the hotspot's Mobile Router (MR) and manages the mobility of the whole network as one unit. In addition, the network performance increases because NEMO-based VANET achieves a lower message routing delay for each user than that achieved when using a host mobility protocol like MIPv6. Therefore, unlike the MIPv6 protocol, NEMO-based VANETs can be used for supporting real-time applications such as video streaming download. Despite the aforementioned benefits, preserving user location privacy in such a public mobile hotspot for NEMO-based VANET is a challenge.

Specific to the NEMO-based VANETs hotspots, controlling information leakage at the physical-layer is important to ensure user's location privacy in wireless LANs, even with applying confidentiality to the data-link layer [38]. Due to the open nature of the wireless environment, a physical-layer attacker can easily localize users from the strength of their transmitted signals. Being supported with isotropic antennas, which emit signals in all directions, users' mobile devices in hotspots cannot hide their transmitted signals from physical-layer attackers. In addition, with the recently extensive researches that have been done to increase the accuracy of positioning systems used to localize mobile devices in location-based services, physical-layer location privacy attacks become more difficult to mitigate because they exploit these high-accuracy positioning systems to localize the victims. Using cheap equipment such as a Received Signal Strength Indicator (RSSI), the attacker can easily localize the sender by only acquiring its transmitted wireless signals even if an IP-layer security scheme is implemented [39]. Furthermore, existing physical-layer location privacy schemes are limited to power variability [40] that uses different power levels in transmitting packets, obfuscation [41] that confuses attackers by replacing real location information with fake, and adding noise [42] that decreases the accuracy of sender's localization to noise ratio.

Those schemes are not appropriate for NEMO-based VANET hotspots. Power variability schemes have been proven as weak solutions, because attackers can easily reveal the original signals' powers. In addition, existing obfuscation schemes disguise the exact user's location by returning to the attacker an expanded area in which the user is located. However, in NEMO-based VANET hotspots, location privacy attackers can get the exact users' locations instead of an obfuscated area with the help of the high-accuracy positioning schemes. Furthermore, adding noise to transmitted signals decreases the overall network performance.

1.3 Thesis Motivations and Contributions

Securing mobility management for VANETs is an important research area to get the benefits of the ITS applications. Despite the studies that have been done to improve VANETs' performance and seamless communications through different mobility management protocols, the security issue for such mobile networks is still an open research area. Therefore, in this dissertation, we address the security challenges that are mentioned in Section 1.2.2 by proposing three security schemes to be employed for different mobility management scenarios in VANETs, namely, MIPv6, PMIPv6, and Network Mobility (NEMO) protocols. The thesis contributions are described as follows:

1. For MIPv6 protocol, we propose an anonymous and location privacy preserving scheme (ALPP) [43] that consists of two complementary sub-schemes: anonymous home binding update (AHBU) and anonymous return routability (ARR). In addition, anonymous mutual authentication and key establishment schemes have been proposed to work in conjunction with ALPP to authenticate a mobile node to its foreign gateway and create a shared key between them. ALPP adds anonymity and location privacy services to mobile IPv6 signaling to achieve mobile senders and receivers privacy. Unlike existing schemes, ALPP alleviates the trade-off between the networking performance and the achieved privacy level. Combining onion routing and the anonymizer in the ALPP scheme increases the achieved location privacy level, in which no entity in the network except the mobile node itself can identify this node's location. Using the entropy model, we show that ALPP achieves a higher degree of anonymity than that achieved by the mix-based scheme. Compared to existing schemes, both AHBU and ARR sub-schemes require less computation overhead, and thwart both internal and external adversaries. Simulation results demonstrate that our schemes have low control-packet routing delays, and are suitable for the seamless handover.

2. For the multi-hop authentication problem in PMIPv6, we propose EM^3A [21], a novel mutual authentication scheme that guarantees the authenticity of both MN and RN. EM^3A thwarts authentication attacks, including DoS, colluding, impersonating, replay, and man-in-the-middle attacks. EM^3A works in conjunction with a proposed scheme for key establishment, based on symmetric polynomials, to generate a shared

secret key between MN and RN. This scheme achieves lower revocation overhead than that achieved by existing symmetric polynomial-based schemes. For a PMIP domain with n points of attachment and a symmetric polynomial of degree t, our scheme achieves $t \times 2^n-$secrecy, whereas the existing symmetric polynomial-based authentication schemes achieve only $t-$secrecy. Computation and communication overhead analysis as well as simulation results show that EM^3A achieves low authentication delay and is suitable for seamless multi-hop IP communications.

3. For physical-layer location privacy attacks in NEMO-based VANETs, we modify the obfuscation, *i.e.*, concealment, and power variability ideas and propose a new physical-layer location privacy scheme, the fake point-cluster based scheme, to prevent attackers from localizing users inside NEMO-based VANET hotspots. The proposed scheme involves fake point and cluster based sub-schemes, and its goal is to confuse the attackers by increasing the estimation errors of their RSS measurements, and to prevent attackers' monitoring devices from detecting the sender's transmitted signals. Using the correctness, accuracy, and certainty metrics, we show that the fake point-cluster based scheme achieves high location privacy in the MNN. In addition, our extensive simulations show that the fake point-cluster based scheme can be implemented in reality, due to the high possibility of having many MNNs select the same fake points and hence increasing the attacker's confusion. Compared to the fake point sub-scheme, our proposed scheme achieves 23% and 37% decreases in the average sender's power and the MNN-AP route path length, respectively.

1.4 Thesis Outlines

This thesis is organized as follows. Chapter 2 reviews the three mobility management protocols that will be used in our proposed security schemes: MIPv6, PMIPv6, and NEMO protocol. In addition, the vehicular IP address configuration methods are explained in this chapter. The first proposed security scheme, ALPP, is introduced in Chapter 3. In Chapter 4 , we present our EM^3A scheme as well as a case study, which is the MA-PMIP protocol for IP services provision in asymmetric vehicular networks. The fake point-cluster based scheme is proposed in Chapter 5 to thwart the physical layer location privacy attackers in NEMO-based VANETs. Finally, Chapter 6 gives the conclusions of this research and outlines our future work.

Chapter 2

Background and Related Work

Due to their wide deployment, Intelligent Transportation Systems (ITSs) receive a great deal of attention from many organizations, such as the Institute of Electrical and Electronic Engineers (IEEE), International Standard Organization (ISO), and the European car industry. Therefore, sharing the same frequency band of 5.9 GHz, many VANETs protocol stacks - such as IEEE Wireless Access in Vehicular Environment (WAVE), ISO CALIM, and Car to Car Communication Consortium (C2C-CC) - have been recently proposed [1] for ITSs. For example, Figure 2.1 shows the C2C-CC architecture that is used for the ETSI ITS. As depicted in the figure, the IPv6 protocol is a common factor for all VANET architectures including the C2C-CC, because of its wide use by vehicular applications.

With the goal of supporting vehicles with Internet applications and communications, the integration of the MIP and VANET is performed through three functionalities: 1) vehicular IP address configuration , 2) IP mobility mechanisms, and 3) forwarding IP packets among vehicular networks. The first functionality, vehicular IP address configuration, supports a vehicle with a unique and permanent IP address, which the vehicle uses inside its home network. The second functionality, IP mobility mechanism, manages the mobility of the auto-configured vehicle while roaming across many networks, and keeps its connectivity to the Internet. Finally, the third functionality, forwarding IP datagrams, helps the vehicle in forwarding its IP packets through vehicle routing schemes. In this thesis, we focus on the second functionality, IP mobility, however in this chapter we briefly review the IP auto-configuration addresses to vehicles because it is a prerequisite not only for IP mobility, but also for address-based routing protocols in VANETs.

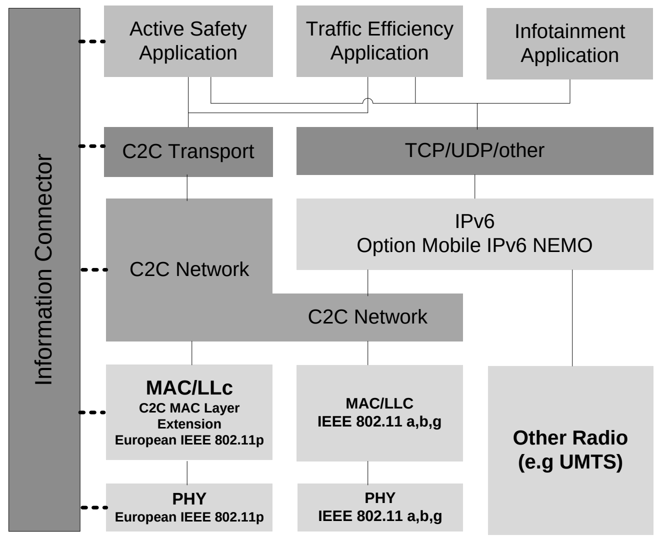


Figure 2.1: Car to Car Communication Consortium (C2C-CC) [1]

2.1 Vehicular IP Address Configurations

Due to the challenges of the VANET multi-hop nature and the lack of multicast communications, traditional IP stateless and stateful auto-configuration schemes cannot be used to assign unique IP addresses to vehicles. In addition, auto-configuration IP addresses schemes for Mobile Ad hoc Networks (MANETs) add high configuration delays and hence are not suitable to be used in VANETs [44]. Therefore, the configuration of IP address in VANETs is a key research issue. For the Internet-based VANETs applications such as ITS, the key requirements for IPv6 address configuration schemes can be mentioned as follows [45]:

1. Configure a globally valid address.
2. Present low complexity.
3. Decrease signaling overhead.
4. Suitable for movement detection
5. Provide gateway selection for the vehicle in the case where multiple RSUs are reachable

6. Executed in a fully-distributed fashion to prevent single point of failure (Security)
7. Provide authentication and integrity of the signalling messages (Security)
8. Protect the privacy of the vehicles (Security)

Existing IP address configuration schemes for VANETs are classified into centralized, distributed, and geographical based schemes. Both centralized and distributed schemes rely on the Dynamic Host Configuration Protocol (DHCP), while the geographical based scheme relies on the vehicles' geographic locations.

2.1.1 Distributed IPv6 Vehicular Configuration

The Vehicular Address Configuration (VAC) [46] is the first distributed IPv6 vehicular configuration scheme that depends on the VANET topology and the DHCP enhancement. Instead of having a DHCP server for the whole network, VAC creates a leader chain among the communicating vehicles. Each leader works as a DHCP server to support vehicles in its coverage area with an IP address. The number of vehicles under a leader's coverage area is determined by a SCOPE, that is a number of hops defined by each leader. An ordinary vehicle may become a leader if the number of hops to its leader is larger than a max-threshold of the leader's SCOPE, and a leader may change to an ordinary vehicle if many leaders are located near to each other. VAC supports unique IP addresses within a defined SCOPE, however, there will be a need for a Duplicate Address Detection (DAD) scheme to detect any vehicles that have the same IP address.

Having the same idea as the VAC scheme, the Cluster-based Addressing Scheme in VANET (CAVET) [47] divides the VANET into clusters in order to guarantee the scalability of the networks with the high mobility of the vehicles. CAVET is proposed mainly for the ad hoc structure in VANET (V2V communications), in which cluster heads are responsible for propagating vehicles' packets. In addition, the Regional-based Auto-Configuration Protocol Association with Coding Architecture for VANETs (RAPACA) [2] is used for V2I communications, therefore, it is used along with the CAVET protocol to support V2V2I communications in VANETs. RAPACA divides the region into clusters, with a unique code for each area, and designs a new IPv6 distribution scheme, in which the 16 bits of the host IP present the vehicle's home network and the last 16 bits of the network prefix present the cluster ID (CID), as depicted in Figure 2.2. The vehicle home network part guarantees the uniqueness of the IP address, therefore, the DAD is no longer needed and the signaling delay decreases. However, a scalability problem occurs because the length of

0-63 Network Prefix		64-127 Host ID	
Site Network	CID	Home ID	Host ID
48 bits	16 bits	16 bits	48 bits

Figure 2.2: IPv6 distribution structure. [2]

the host identity decreases to 48 bits, and hence a maximum of 2^{48} vehicles can be assigned with IP addresses inside each cluster.

Considering the above IPv6 address configuration requirements, the distributed IPv6 vehicular configuration schemes solve the single point of failure in the VANET as well as present low complexity schemes, but they still have some drawbacks. The distributed schemes require modifications in the IP stack of the node. Additionally, the signaling overhead increases with the need for DAD schemes, and in general there is no global IP address assigned with distributed configurations. Leaders and cluster headers are normal vehicles in the VANET, therefore, they need to sacrifice their resources in serving other nodes.

2.1.2 Centralized IPv6 Vehicular Configurations

The centralized Address Configuration (CAC) protocol [48] uses a centralized DHCP to support vehicles in urban areas with unique global IP addresses. The RSUs distributed along the road work as access points (APs) to relay the address request from the vehicle to the DHCP server. Centralized schemes are more complex than distributed schemes, as they rely on a single point of failure, the DHCP server. However, the signaling delay is much lower than that in the distributed.

2.1.3 Geographical-based IPv6 Vehicular Configurations

Unlike both centralized and distributed schemes, which are stateful configurations, the geographical based schemes are stateless auto-configurations. The Geographically Scoped Stateless Address Configuration (GeoSAC) [45] adapts the existing IPv6 Stateless Address

Auto-configuration (SLAAC) scheme by extending the IPv6 link to a specific geographical area controlled by a point of attachment (AP). GeoSAC is used in many ITS architectures such as the C2C-CC depicted in Figure 2.1, where a sub-IP layer called C2C NET is added to resolve the VANET multi-hop nature with the IPv6 multicast transmission. The C2C Net performs the following functions:

1. Supports multi-hop distribution by employing geographic routing, manages ad-hoc routing, and presents a flat network topology to the IPv6 layer.

2. Configures IP broadcast domain, fixedly or on a per-packet basis, according to the geographic parameters.

3. Defines a multicast link to represent a part of the VANET created by all nodes within a certain geographical area.

Based on the C2C Net sub-layer, each point of attachment periodically sends IPv6 Router Advertisement (RA) messages that contain an IPv6 prefix to all nodes located within a well-defined geographical area. When receiving the RA messages, the node's C2C Net applies geographic filtering and forwards the messages to other vehicles in its geographical area. Consequently, a multi-hop path is created between the vehicles. In addition, each node creates its IPv6 address by appending its network identifier, derived from its MAC address, to the received IPv6 prefix. Finally the mobile node applies a DAD scheme to ensure the uniqueness of its derived IPv6 address.

2.2 IP Mobility Management

Having the same goal of supporting global Internet connectivity for ITS applications, mobility management protocols [49] can be classified into host-based and network-based mobility. In host-based mobility management protocols, such as Mobile IPv6 (MIPv6) [27], the mobile node manages its own mobility, whereas in network-based mobility protocols, such as Proxy MIPv6 (PMIPv6) [21], the mobility of an MN is managed by network entities, such as ARs, without involving the MN. In addition, the network mobility protocol, also called NEMO [50], is an extension of the MIPv6 protocol to manage the mobility of the moving network as one unit.

In this thesis, the security considerations for MIPv6, PMIPv6, and NEMO in VANETs are presented, therefore, the following sub-sections recall the three mobility management schemes and their existing security schemes.

2.2.1 Mobile IPv6

In roaming across "all-IP" networks that employ the IPv6 protocol, as shown in Figure 2.3, each mobile node (MN) has two different IP addresses: a home address (HoA) and a care of address (CoA). The HoA is the original MN's address that is configured by the MN's home agent (HA), which is a router located in the MN's home network. The CoA is acquired from a Foreign Gateway (FG), which is a router located in the visited network.

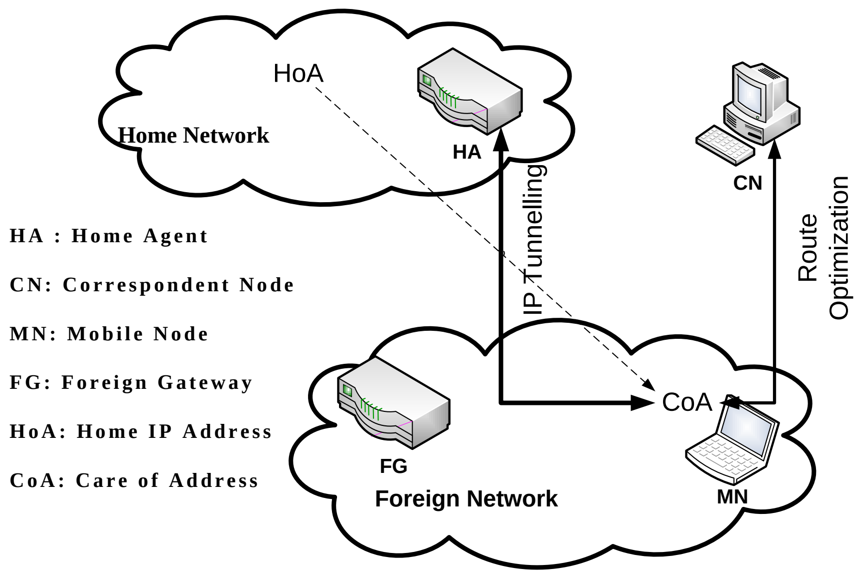


Figure 2.3: Roaming among mobile IPv6 heterogeneous networks.

When moving out from its home network to a foreign network, an MN uses the mobile IPv6 control messages, home binding update, and return routability messages, to perform the seamless handover process. The home binding update control messages are sent to the MN's home agent, while the return routability control messages are sent to the MN's correspondents, which are called Correspondent Nodes (CNs). By sending these control messages, an MN informs both its HA and its CNs about its current location, which is represented by its CoA. Therefore, the roaming MN can receive any subsequent messages, destined for its HoA, at this CoA. Both HA and CN create bindings between the MN's home address and CoA, and then transmit any subsequent messages to this CoA instead of to the MN's HoA.

Due to the MIPv6 highly handover latency, the IETF proposes other MIP variants such as the Hierarchial MIPv6 (HMIPv6) [51] and Fast MIPv6 (FMIPv6) [52] to decrease delays and increase network performance. HMIPv6 decreases the round trip time delay in MIPv6 by choosing a Mobile Anchor Point (MAP), close to the MN, to work as the MN's HA. In addition to its CoA, known as Regional CoA (RCoA), the MN acquires another address called On-link CoA (LCoA) from the MAP that controls the MN's area. Furthermore, this LCoA address changes as the MN moves to a new MAP's domain. Instead of sending frequent BU messages to its far-off HA, the MN sends local BUs to the MAP in order to bind its LCoA with its RCoA. In addition, the MN sends a BU message to its HA to bind its HoA and RCoA. The BU messages to MAP are transmitted frequently, whereas there is no need to send those messages to the MN's HAAs as long as the MN is located in the same MAP domain.

Furthermore, FMIPv6 creates a tunnel between an MN's previous AR (PAR) and new AR (NAR). This tunnel is used to transmit MNs' messages from PAR to NAR during the handover time, and it is disconnected after the MN fully moves to the new subnet. When the MN detects its link-layer movement to a new subnet, it sends a router solicitation proxy message to its PAR asking for the identification of the new subnet, and then sends a fast BU message to its PAR, after creating a new CoA (NCoA) based on the new subnet identification. The PAR sends a handover initiate (HI) message to the NAR in order to create a tunnel between PAR and NAR. To reply to the HI message, the NAR first carries a DAD mechanism for the NCoA to guarantee its uniqueness.

2.2.2 Proxy Mobile IPv6

Proxy Mobile IPv6 (PMIPv6) [3] is a network-based mobility management protocol, in which the network itself manages the MN's mobility. The PMIPv6 is also a localized protocol, because the MN moves within the local mobility domain (LMD) without changing its IP address. The LMD contains one or more Local Mobility Anchors (LMAs) that work as an MNs' home agents, and a group of Mobile Access Gateways (MAGs) that send the mobility signals to LMAs on behalf of MNs. When the MN enters the LMD, it sends a Router Solicitation (RS) to its directly attached MAG, which in turn sends a proxy binding update (PBU) message to the LMA. After authorizing the MN, the LMA creates a tunnel with the MAG and sends a Proxy Binding Acknowledgement (PBA) message containing the MN's Network Prefix(es) (NPs) to the MAG, which in turn forwards the PBA to the MN by sending a router advertisement message. Using the NPs, the MN creates its IP address, and then uses a DAD scheme to guarantee the uniqueness of its configured IP address. Therefore, the MN can move among different MAGs inside the LMD using its configured address and without detecting its movements, which are detected by the attached MAGs and stored at the LMA in its cache memory. Figure 2.4 shows the PMIPv6 operations.

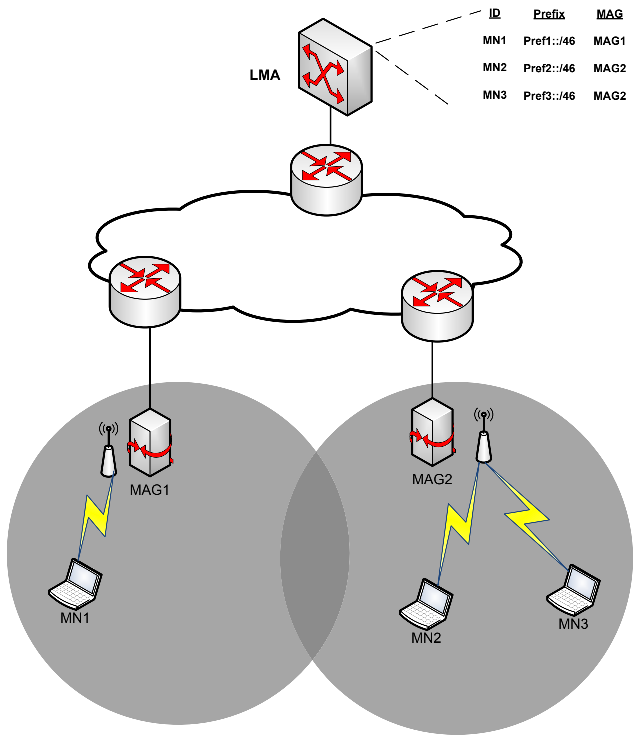


Figure 2.4: Proxy Mobile IPv6 [3]

2.2.3 Network Mobility

The NEMO basic support (NEMO BS) protocol [53] is the standard protocol to manage mobility in the entire moving network. As an extension of the mobile IP protocol [54, 55], NEMO BS employs mobile IP's basic functionalities, such as the home binding updates; however, these functionalities are performed by the Mobile Router (MR) rather than the Mobile Network Nodes (MNNs), which only implement the basic IP protocol without being aware of the entire network mobility.

Initially, to create its network, the MR announces its responsibility for managing the mobility of the entire network by periodically broadcasting its Mobile Network Prefixes (MNPs), acquired from the MR's home network. To join the network, each MNN selects a distinct MNP to be its address in the moving network. When moving out from its home network, the MR acquires a new Care of Address (CoA) from the Foreign Agent (FA), located in the foreign network, and sends home binding update messages to its Home Agent (HA) to bind its Home Address (HoA) with its new CoA. Two modes for the binding update messages are defined: explicit and implicit. The former attaches the MR's MNPs to the transmitted binding update messages, while the latter does not attach them because a dynamic routing protocol is running, between the MR and its HA, which facilitates the HA's ability to identify the MR's MNPs. Accordingly, the whole network's movement is controlled by this MR. The HA stores a binding cache and an extra prefix table to store the MR's HoA with CoA and MNPs, respectively. Finally, a tunnel between MR's CoA and HA is created; therefore, messages transmitted between MNNs and Correspondent Nodes (CNs) are sent first to the HA, as illustrated in Figure 2.5.

Supporting the MNNs with the required mobility, NEMO BS has some benefits over the MIP protocol, such as reducing signaling overhead and mobility costs. NEMO BS is designed to support a single-hop mobile network, in which a direct communication between an MR and the Internet access router is formed. Therefore, to support Vehicle-to-Vehicle-to-Infrastructure (V2V2I), in which the vehicle communicates with the RSU through multi-hop access, the integration of NEMO with VANET, namely NEMO-based VANET, has two roles: 1) supporting session continuity and global Internet access via NEMO BS, and 2) supporting multi-hop communication via V2V2I routing schemes such as georouting [56, 57].

To integrate NEMO BS with VANET, two approaches have been defined [58, 59]: MANET-centric and NEMO-centric. In the MANET-centric approach, V2V2I multi-hop communications are supported by implementing a NEMO BS protocol that is run on top of a MANET routing protocol. The advantage of this approach is the separation of the MANET routing from the NEMO BS, as depicted in the protocol stack shown in Figure 2.6. On the other hand, the NEMO-centric approach supports multi-hop communications by implementing at least one NEMO mobile routing scheme in the vehicles that form the V2V2I path between the MR in the mobile network and the infrastructure. In addition to working as an MR, each OBU, in the intermediate V2V2I communication path, works also as a relay for the MNNs. MANET routing protocols can be used in the NEMO-centric approach to optimize the routing paths resulting from the NEMO BS protocol. Figure 2.7 shows the protocol stack for the NEMO-centric approach, which is more appropriate for nested NEMO and hierarchical structured networks, whereas the MANET-centric approach is more suitable for our scenario, wherein the ad-hoc structure is implemented in multi-hop communication. Table 2.1 compares the two approaches.

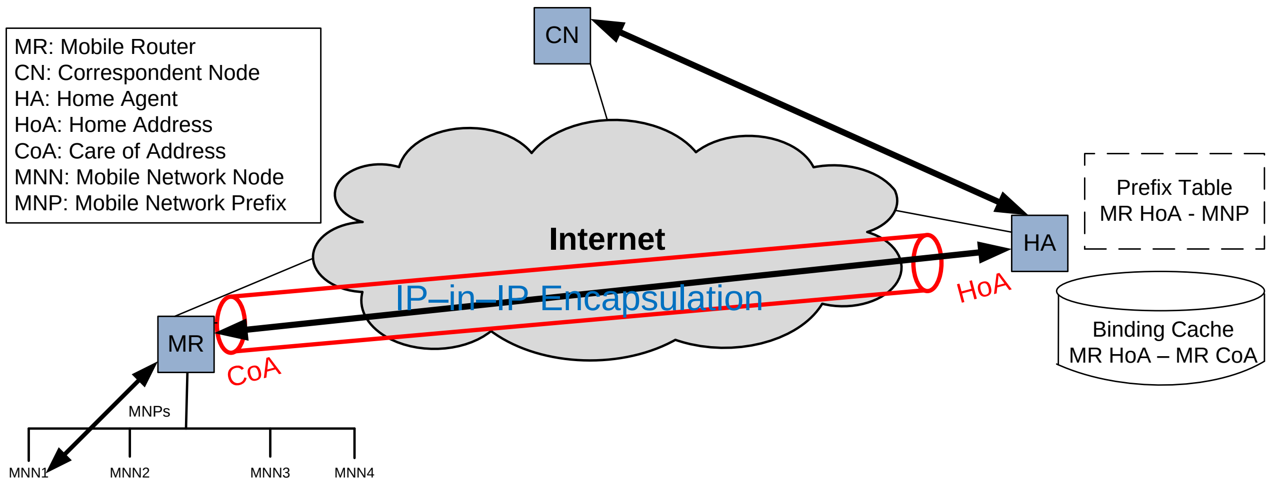


Figure 2.5: NEMO-based VANET.

Table 2.1: MANET-Centric and NEMO-Centric Comparison.

MANET-Centric	NEMO-Centric
Less mobility cost	high cost
Simple V2V2I implementation	Complex implementation
Self MNP delegation of OBU/MR	Hierarchical MNP delegation
Less signaling overhead	High signaling
Ad-hoc domain	Infrastructure domain
Georouting protocols can be used for multihop communications	Hierarchical topology can not use georouting protocols

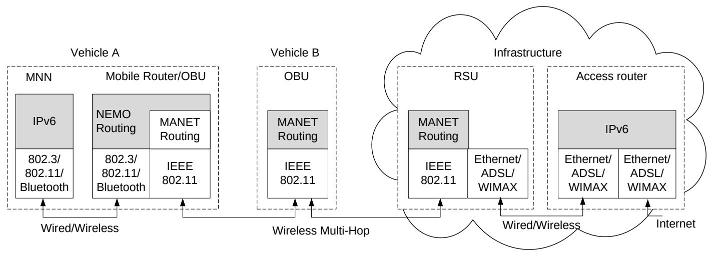


Figure 2.6: MANET-Centric approach.

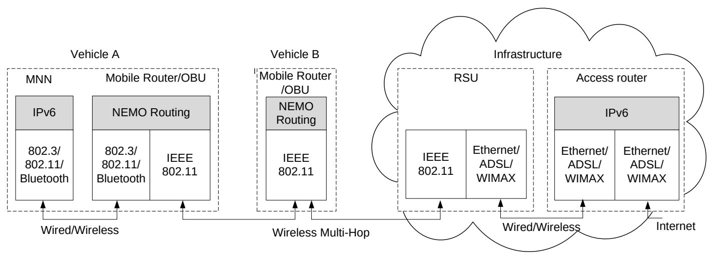


Figure 2.7: NEMO-Centric approach.

2.2.4 Securing IP Mobility for VANETs

MIPV6 protocol defines both the IPSec protocol and the return routability procedure to protect the MN's communications to the HA and CNs, respectively. The IPSec protocol is an internet protocol which was implemented originally to support wired network with confidentiality and authentication security services. With the introduction of mobility, the Internet Engineering Task Force (IETF) has updated the IPSec to support the Internet mobility protocols [60]. The IPSec protocol consists of two protocols: Encapsulating Security Payload (ESP) protocol, and Authentication Header (AH) protocol. Moreover, the IPSec is implemented in two different modes: the transport mode and the tunnel mode. The IPSec protocol is used by the mobile IPv6 protocol to secure the signalling data transmitted between the mobile node and the home agent. Due to its static policy configuratons, the IPSec protocol alone cannot support the mobile IPv6 protocol with the required security mechanisms. However, the mobile IPv6 protocol requires changing the policy as a consequence of the mobility feature. Therefore, the return routability procedure is added in order to achieve both security and privacy of the mobile node.

The goals of the return routability procedure are to authenticate the mobile node to the correspondent node and to construct a shared key between them. As depicted in Figure 2.8, this procedure consists of four transmitted messages transferred between the two parties, namely an MN and CN.

1. Home Test Init (HoTI) Message: This message is sent by the roaming mobile node to the correspondent node through the home agent using the IP tunneling (1a in the figure). It contains a random number generated by the mobile node called home init cookie. It is protected using the IPSec ESP protocol in the tunnel mode. The inner source address of this message is the mobile node's home address, the inner destination address is the correspondent-node's address, the outer source address is the mobile node's care of address, and the outer destination address is the home agent's address.

2. Care of-Test Init (CoTI) Message: This message is sent by the mobile node directly to the correspondent node and it contains another random number called care-of Init Cookie (1b in the figure). It does not contain any security mechanism to protect the transmitted data.

3. Home Test Message: This message is sent by the correspondent node to the mobile node, through the mobile node's home agent, using IP tunneling (2a in the figure). The inner source address of this message is the correspondent node's address, the inner destination address is the mobile node's home address, the outer source address is the mobile node's home agent, and the outer destination address is the mobile node's CoA. It contains three values used to construct a secret key between the mobile node and the correspondent node. The first value, the home init cookie, is the same random value, which the mobile node sends in the home test init message. The second value, the home keygen token, is a secret value generated using the HMAC-SHA1 algorithm as follows:

$$Homekeygentoken = First(64, HMAC - SHA1(K_{cn}, (HoA|nonce|0))) \qquad (2.1)$$

   Where K_{cn} is a 20-octet secret key and nonce is 64-bit secret value. Both K_{cn} and the nonce are known only by the correspondent node. The home keygen token is the first 64 bits of the HMAC-SHA1 function, which takes the concatenation of the mobile node's home address (HoA), the secret nonce, and a zero-octet as inputs and uses the K_{cn} as the secret key of the function. The third value, the home nonce index, is sent instead of sending the nonce itself as it is a secret value and cannot be sent to the mobile node.

4. Care of test (CoT) message: This message is sent by the correspondent node directly to the mobile node without going through the home agent (2a in the figure). The

source address of this message is the correspondent node's address and the destination address is the mobile node's CoA. It contains three different values: care of init cookie, care of keygen token, and care of nonce index. The care of init cookie is the same value which the mobile node sends to the correspondent node in the care of test init message. The care of keygen token is another secret value generated as follows:

$$Careofkeygentoken = First(64, HMAC - SHA1(K_{CN}, (CoA|nonce|1))) \quad (2.2)$$

The care of keygen token value is generated similarly to the home keygen token generation, except that the care of address is used instead of the home address and one-octet is appended instead of zero-octet.

Using both the home keygen and the care of keygen tokens, the MN and the CN construct a temporary shared key, called a binding management key, K_{bm}. This shared key is used to secure the binding update messages transmitted between the MN and the correspondent node. The binding management key is constructed as follows:

$$K_{bm} = SHA1(homekeygentoken|care - ofkeygentoken) \quad (2.3)$$

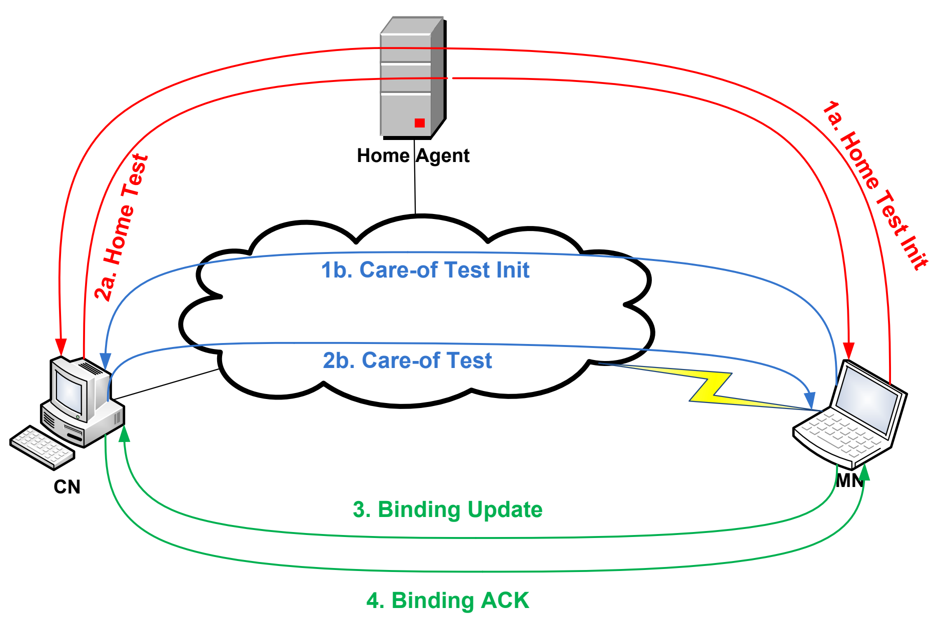


Figure 2.8: Return Routability Procedure

Securing PMIPv6

In the PMIPv6 protocol, the IPSec secures the communication between the LMA and MAGs, however, there are no standard security schemes defined for the communications between an MN and MAGs. To authenticate an MN that roams to the PMIPv6 domain, the Internet Authentication, Authorization, and Accounting (AAA) servers are used with the help of the LMA and MAGs that forward the MN's credentials to the AAA servers. However, due to the large delay, this method of communications between MN and AAA is not suitable for such a localized mobility protocol , PMIPv6, whose goal is to decrease the transmission delay in seamless communications. In [61], a localized authentication and billing scheme that is based on the hash-chain value is proposed to locally authenticate the roaming MN in PMIPv6 domain. The seed of the hash-chain is created by a key agreement scheme, between the MN and the AAA server, which delegates the authentication to the LMA in order to create the hash-chain for the MN. Having a dual goal, the employment of a hash-chain decreases the communication distance between the MAGs and AAA, as well as creats an electronic currency to be used by the MNs.

Securing NEMO BS

Among the mobility management protocols, the NEMO BS protocol is more suitable for VANET's ITS applications. Therefore, many security considerations have been proposed to protect users when the NEMO protocol is employed. Using the AAA servers deployed in each subnet along the Internet, and the Foreign AAA (FAAA) server, the scheme in [62] employs the PANA protocol [63] to authenticate the MR to its Home AAA (HAAA) when roaming to a visited network. This authentication scheme is implemented before the MR sends the BU message to its HA, hence, it requires 300s to perform the authentication, which is not suitable for the seamless communications in ITSs. Therefore, in [64], the MR can be authenticated by the FAAA server rather than the HAAA server to decrease the authentication time. A cost function is calculated to decide whether to use FAAA or the HAAA. In addition, the LMAM scheme [65] is an authentication scheme proposed for the MR in VANETs to locally authenticate itself to the FAAA. In this scheme, the FAAA server authenticates the MR by this MR's MAC address and without referring to the MR's HAAA. Due to the need for storing all MRs' MAC addresses, this scheme can only be used in small networks, and it does not work for Internet-based VANET's applications.

Although it is not standardized yet, the NEMO route optimization security has been greatly discussed. In [66], a route optimization scheme that is based on certificated nodes has been proposed to be employed in NEMO-based networks. In the proposed scheme, public-key certificates are used by the MRs and correspondent routers (CRs) to mutually authenticate each other as well as authenticate the MNPs. Assuming a pre-assigned public key infrastructure (PKI), the proposed scheme uses a trusted third party to construct the PKs and the certificates for all uses.

Furthermore, in [67], a new secure NEMO route optimization, called SeNERO, has been proposed to overcome the high latency problem that is found in traditional route optimization schemes. Under the assumption of the ease of construction of a PKI in aeronautical systems, SeNERO constructs a mutual authentication as well as a direct path between an MR and a CR. It is assumed that there is a hierarchical certificate authority system, in which every router, including MR and CR, uses to prove its authenticity. The MR attaches to its outgoing messages a certificate chain, which includes the MR's certificates starting from it and ending at the trusted root Certificate Authority (CA). SeNERO achieves two levels of authentications, initial and subsequent authentications. In the initial authentication, both the MR and CR share a secret key , K_s, which is constructed by CR on the MR's demand. Afterwards, both MR and CR exchange their certificate path protected by the K_c and their signatures to prove their authenticity and their ownership for the MNPs. In the subsequent authentication, which is performed after an MR's handover occurs, the CR creates a new K_s for the roaming MR and uses the key to protect the transmitted BU and BA messages. Unlike the initial authentication, both certificate and signature operations are not performed in subsequent authentication.

Although it seems to achieve a high level of security by using public key operations, SeNERO suffers from a security problem: transmitting the shared key in clear form without encrypting it. The attacker can easily eavesdrop the transmitted key and break the system. Moreover, the scheme is based on a certificate chain that relates the MR to the root CA without considering the mobility feature of the MR. When the MR moves to a new network, the certificate chain needs to be changed to adapt to the MR's new location. In addition, due to using digital signature, SeNERO faces a problem of large handover delays, in which the delays reach $100s$ for each authentication level.

Chapter 3

ALPP: Anonymous and Location Privacy Preserving Scheme for Mobile IPv6 Heterogeneous Networks

3.1 Introduction

A mobile node's anonymity and location privacy is among the security challenges that occur in MIPv6-based mobile networks. The contributions of this chapter are twofold. First, based on the onion routing [68] and anonymizer [69], we propose an anonymous and location privacy preserving (ALPP) scheme that consists of two complementary sub-schemes: anonymous home binding update (AHBU) and anonymous return routability (ARR). Those sub-schemes efficiently add anonymity and location privacy services to mobile IPv6 home binding update and return routability control messages, respectively, to achieve mobile senders' and receivers' privacy. In other words, AHBU is used to send anonymous home binding update messages to the MN's HA, while ARR is used to send anonymous return routability messages to the MN's CN. Using the onion routing, we repeatedly encrypt the transmitted messages at each hop to protect them from traffic analysis adversaries. In addition, we adapt the traditional anonymizer, which is a fixed proxy used to hide the MN's location, by changing this anonymizer at each time the MN roams to a foreign network. Our adaptation for the anonymizer solves the single point of failure problem that occurs with the traditional anonymizer. Second, based on the certificate-less public key cryptography [70], we propose anonymous authentication and key establishment schemes to work in conjunction with the ALPP scheme. The authentication scheme is used to authenticate an MN to its FG while preserving the MN's anonymity. The challenge of proposing such a scheme is the difficulty of constructing a mutual trust between arbitrary nodes, which have not met each other before. The key establishment scheme is used to generate a shared key between an MN and its FG. Using the certificate-less public key cryptography helps in decreasing the computation overhead of the proposed schemes.

Unlike existing anonymity and location privacy preserving schemes, the ALPP scheme alleviates the trade-off between the network performance and the achieved privacy level. We show that AHBU and ARR sub-schemes achieve a high level of location privacy, where no entity in the network can reveal an MN's locations except the MN itself. Moreover, using the entropy model, we show that our proposed scheme achieves a higher degree of anonymity than that achieved by the mix-based scheme with one mix server. Additionally, extensive simulation results demonstrate that our sub-schemes have low routing delays and can thus be used during time-restricted seamless communications for mobile networks.

The remainder of the chapter is organized as follows. Section 3.2 recalls the certificate-less public key cryptography. Section 3.3 reviews the related work. The system models are presented in Section 3.4. The proposed scheme, ALPP, is presented in Section 3.5. The privacy and security analysis are given in Section 3.6, while Section 3.7 presents the performance evaluation and simulation results. Finally, the chapter summary is given in Section 3.8.

3.2 Preliminaries

3.2.1 CERTIFICATE-LESS PUBLIC KEY CRYPTOGRAPHY

A trusted key generator center (KGC) uses a security parameter, K, and runs a setup algorithm to produce two keys, (s, $Param$). The master key, s, is selected randomly from $\mathbb{Z}_q^*$, and is kept secret at the KGC. The public $Param = \langle \mathbb{G}_1, \mathbb{G}_2, e, n, P, P_0, H_1, H_2 \rangle$ is transmitted to all network's users. $\mathbb{G}_1$ and $\mathbb{G}_2$ are cyclic groups of a large prime order, q, $\hat{e} : \mathbb{G}_1 \times \mathbb{G}_1 \rightarrow \mathbb{G}_2$ is a bilinear pairing function on elliptic curves [71], n is the bit-length of the plaintext, P is $\mathbb{G}_1$'s generator, $P_0 = s \times P$, and $H_1 : \{0,1\}^* \rightarrow \mathbb{G}_1^*$ and $H_2 : \mathbb{G}_2 \rightarrow \{0,1\}^n$ are two hashing functions.

Upon receiving a request from a user A with identity ID_A, the KGC creates A's partial private key, $D_A = s \times \mathbf{Q}_A$, where $\mathbf{Q}_A = H_1(ID_A)$. The KGC securely transmits the partial private key, D_A to A . The D_A is used by A to create its public-private key pair, (P_A, S_A), as follows:

$$\begin{aligned} &x_A \in_R \mathbb{Z}_q^* \\ &S_A = x_A \times D_A \\ &X_A = x_A \times P \\ &Y_A = x_A \times P_0 = x_A \times s \times P \\ &P_A = \langle X_A, Y_A \rangle \end{aligned} \tag{3.1}$$

This cryptography is called certificate-less public key cryptography (CL-PKC) [70] because unlike traditional public key infrastructure, a user A does not need a certificate from a trusted certificate authority. Therefore, the CL-PKC saves the computation overheads needed for certificate distribution and verification. Algorithm 1 presents the certificate-less encryption of a message m that is transmitted to a user A. Notice that the sender uses only A's identity (ID_A) and public key (P_A) to produce a ciphertext, c. In Section 3.6.2, we prove that if either A's identity or public key is changed by an adversary, then the encryption operation will result a failure operation ($\perp$) or an incorrect ciphertext. Moreover, to decrypt this ciphertext, $c = \langle u, v \rangle$, A performs only one pairing function to get the message, $m = v \oplus H_2(\hat{e}(S_A, u))$.

Algorithm 1: CL-PK Encryption

Input: m, ID_A,and P_A
Output: Ciphertext c

if $\hat{e}(X_A, P_0) \neq \hat{e}(Y_A, P)$ **then**
    $c = \perp$
else
    $\mathbf{Q}_A = H_1(ID_A) \in \mathbb{G}_1^*$
    $r \in_R \mathbb{Z}_q^*$
    $c = \langle rP, m \oplus H_2(\hat{e}(\mathbf{Q}_A, Y_A)^r) \rangle$
end

In this chapter, we used CL-PKC to generate a shared key between two users, A and B. A sends its public key along with a random value T_A to B, which in turn replies with its public key P_B and another random number, T_B. $T_A = aP$ and $T_B = bP$, where a and b are randomly chosen by A and B respectively. Using this transmitted information, both

A and B create two keys: K_A is generated by A, and K_B is generated by B, as follows:

$$K_A = \hat{e}(\mathbf{Q}_B, Y_B)^a.\hat{e}(S_A, T_B) \tag{3.2}$$

$$K_B = \hat{e}(\mathbf{Q}_A, Y_A)^b.\hat{e}(S_B, T_A) \tag{3.3}$$

Using the pairing function's properties, it can be showed that both keys are identical as follows:

$$\begin{aligned} K_A &= \hat{e}(\mathbf{Q}_B, Y_B)^a.\hat{e}(S_A, T_B) \\ &= \hat{e}(\mathbf{Q}_B, x_B sP)^a.\hat{e}(x_A s\mathbf{Q}_A, bP) \\ &= \hat{e}(x_B s\mathbf{Q}_B, aP).\hat{e}(\mathbf{Q}_A, x_A sP)^b \\ &= \hat{e}(S_B, T_A).\hat{e}(\mathbf{Q}_A, Y_A)^b \\ &= K_B \end{aligned} \tag{3.4}$$

3.3 Related Work

Previous anonymity and location privacy schemes in mobile IPv6 networks are based on Chaum's mix [72] which introduces the idea of the mix-network. A mix-network is a group of servers, called mix servers, that decrypt incoming messages and then retransmit them to the destinations in a different order rather than their incoming order. The goal of this mixing is to hide the sender's identity and locations. The idea of mix-network is employed in schemes called cascaded overlay mix-network-based location privacy schemes [68,73,74]. Another Chaum's mix-based scheme, called anonymizer, is proposed in [69], which is based on a single trusted proxy that is used to hide user's identity and location information from a CN.

Based on the anonymizer [69], a scheme with eight different levels of anonymity and location privacy is proposed in [75]. This scheme introduces a new entity, called Information Translating Proxy (ITP), which works as an anonymizer in a mobile IPv6 network. Each mobile node shares a secret key with the ITP, and uses this key to encrypt the home binding update messages at the time of roaming. Instead of sending the binding update messages directly to the mobile node's home agent, the mobile node sends them to the ITP which removes the mobile node's identity information and then forwards these messages to the home agent. Although it presents a practical solution for location privacy, this scheme is susceptible to a single point of failure, because it uses a single trusted anonymizer for all mobile nodes. In our proposed scheme, ALPP, we use the idea of anonymizer, solving the single point of failure problem by changing the anonymizer as the MN moves among visited networks.

In [76], an anonymity scheme is introduced which is based on generating groups of pseudonyms and sharing them between the communicating parties. However, this scheme requires a precise synchronization, in such a way that both the sender and the receiver must use the same pseudonym at the same time. In the case of weak synchronization, a collision at the receiver side may happen. Furthermore, a pseudo HoA is randomly generated in [77] to replace the real HoA. Although this pseudo identity achieves the MN's privacy, it may cause a repudiation attack if the MN is a malicious one. A privacy tag is introduced in [78] to hide the MN's HoA from the correspondent node during transmitting the binding update messages from MN to its CN. This privacy tag is a function of the MN's HoA and it prevents the CN from knowing about the MN's roaming.

Because the mobile IP address represents both an MN's identity and location, mobile IP-based networks have location privacy problems. Therefore, in [12], a virtual ID is used to represent MN's identity and hence separate this identity from MN's location. Therefore, extra servers are needed to map virtual IDs to MNs' current locations. However, this scheme causes a triangle routing problem, because messages sent from the CN are transmitted to the MN's HA before reaching the intended MN. In [79], a name space is used to represent the MN's identity and a new layer, Host Identity Protocol (HIP), is added to the TCP/IP protocol stack. Supporting mobility and multi-homing is the main goal for the HIP, additionally it provides MN's location privacy service. We argue that HIP protocol is computationally expensive. To initiate a communication between two entities, initiator and responder, HIP uses the entities' public keys for both identification and sharing a secret key between these entities. In addition, the responder transmits a puzzle to the initiator in order to authenticate it, which takes CPU processing time from the initiator to solve the puzzle. By definition, the client puzzle is a difficult problem that requires amount of computations and/or storage to be solved at client side. Therefore, the HIP protocol cannot be used with seamless communications.

Furthermore, a mix-based location privacy scheme is proposed in [33] to achieve anonymity and location privacy for mobile IPv6 binding update control messages. A network of mix servers controlled by a mix center is deployed, and uses (k, n) ElGamal threshold mechanism to decrypt the binding update messages received from the roaming mobile node. This scheme uses the mix-network [72] to hide the MN's location and a pseudo identity to hide the MN's real identity. However, the mix center identifies the mobile node's home address, care of address, home agent, and foreign gateway. Therefore, the mix center can easily violate the mobile node's privacy. Unlike our proposed scheme, the mix-based scheme cannot be used for the time-restricted seamless communications, because it has high routing-delays, especially with a large number of mix servers.

In [34], the Internet Engineering Task Force (IETF) group defines the location privacy problem in the mobile IPv6 networks. The problem definition is divided into two main parts: disclosing the care of address to the correspondent node, and revealing the home address to an eavesdropper. Furthermore, the IETF group published experimental solutions in [35] to solve only the second part of the problem. Those solutions do not address the first part of the location privacy problem, i.e., unveiling the CoA to the correspondent node. Specifically, two schemes are proposed in [35]. The first scheme uses the encrypted home address (EHoA) to conceal the home address from the adversary, while the second uses pseudo identity (PHoA) to hide the home address from the correspondent node. However, EHoA and PHoA schemes achieve only the mobile node's anonymity, and assume that MN's location privacy is implicitly achieved. In our proposed scheme, in addition to the problems defined in [34], we solve two more privacy problems: disclosing the CoA to the HA, and revealing the HoA to the FG. In Section 3.6, we show that our proposed sub-schemes, AHBU and ARR, achieve higher anonymity and location privacy levels than those achieved by EHoA and PHoA schemes.

3.4 SYSTEM MODELS

3.4.1 Network Model

Our network model, as shown in Figure 3.1, consists of a group of heterogeneous networks, such as VANETs with IEEE 802.11p, WiMaX, and WiFi as heterogeneous access networks, that use the mobile IPv6 protocol as a mobility management protocol. The mobile IPv6 protocol supports the mobile users with mobility services; therefore, mobile users can receive their communication messages while they are roaming to foreign networks. Each network of these heterogeneous networks consists of a number of MNs, such as vehicles, and a set of gateways, such as the Road side units (RSUs) inside VANETs. Each gateway has three functions: 1) to work as a HA for MNs that are originally located in its network; 2) to work as a foreign gateway (FG) for the visitor MNs; and 3) to work as an intermediate foreign gateway (IFG) for MNs that are neither visitors nor originally located in this gateway's network. Each MN defines its HA, located in its home network, and its FG, located in its current visited network. Moreover, the MN also defines a list of all IFGs, which consists of all gateways that are located in all networks except gateways that are located in both MN's home network and currently visited network.

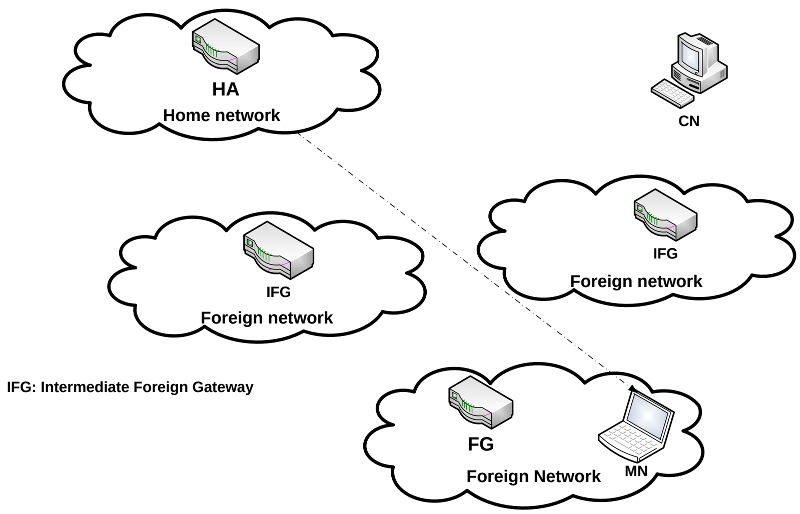


Figure 3.1: MIPv6 network model.

Using the IPsec Internet key-exchange protocol [80], each MN maintains a secret key, K_{MN-HA}, that is shared permanently between the MN and its HA. When roaming to a foreign network, the MN sends mobile IPv6 binding update control messages to both its home agent and its CN to inform them about MN's current location. Therefore, any subsequent data messages can be directed to the MN's current location (MN's CoA) instead of sending them to its home address. Originally, the roaming MN sends home binding update messages to its HA, and it sends return routability messages to its CN. In our model, we add anonymity and location privacy to these control messages in order to ensure senders' and receivers' privacy. Therefore, the roaming MN sends anonymous home binding update and anonymous return routability messages instead. Figure 3.2 depicts the control messages that will be used in our proposed scheme. Note that the original BU and BA messages use ESP protocol in transport mode; however, in our case we use ESP protocol in tunnel mode.

3.4.2 Threat and Trust Models

Two kinds of adversaries are defined: external and internal. The external adversary is a passive traffic analysis attacker, analyzing the transmitted packets to deduce useful information about the identities and the locations of the senders. The external adversary investigates the time of each transmitted packet, compares the received and the transmitted

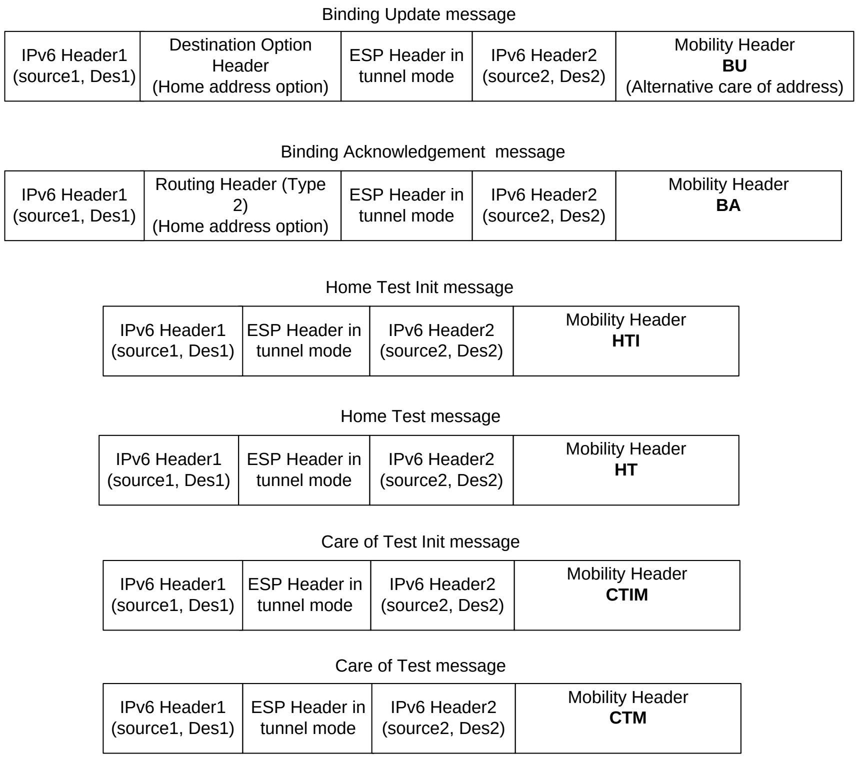


Figure 3.2: Mobile IPv6 control messages.

packets at each hop, and tracks the packet to know its destination.

The internal adversary is a network entity that intentionally observes MNs' identities and locations. In our model, we consider the HAs, FGs, and CNs entities as internal adversaries. These entities may misuse the observed MNs' privacy information and take malicious actions toward these MNs. Therefore, HAs, FGs, and CNs are prevented from learning MNs' private information. However, these entities need to learn an MN's locations because they help in the MN's mobility management process. To illustrate this contradiction, consider for instance a home binding update message that is sent from an MN to its HA. The receiver HA needs to know the MN's identity and current location, and stores this information in the HA's binding cache. Therefore, the HA can forward any subsequent messages destined for the MN's HoA to the current MN's CoA. However, at the same time the HA may maliciously use the MN's information to violate MN's location privacy. To solve this contradiction, we let the internal adversaries learn only part of the mobile nodes' private information. This part is adequate to perform the MN's mobility management process without violating MN's privacy. HAs and CNs are allowed to know mobile nodes' HoAs, however they are unable to learn MNs' care of addresses and foreign gateways. Moreover, the foreign gateway is allowed to know the mobile node's CoAs, and it should not know the MNs' home addresses. All in all, each internal adversary learns a different part of MN's privacy information. Therefore, internal adversaries may collude with each other to know the whole MN's private information.

We propose a revocable privacy scheme in which one entity, the HA, can reveal the MNs privacy at the time of dispute when the MN repudiates the service. Therefore, we consider the HA as a non-colluder with other entities in the network. Moreover, we consider all other entities, including the FGs, IFGs, and CNs, to be untrusted entities, and they may collude with each other to reveal the mobile node's private information. In addition, there is a trusted third party that generates a group key (K_{group}) for the entire networks. The created K_{group} is securely distributed in some way to all legitimate users in the system.

3.5 Anonymous and Location Privacy Preserving (ALPP) Scheme

In this section, we propose the anonymous and location privacy preserving scheme (ALPP), which is used by an MN when roaming from its home network to another foreign network. This time period is called seamless handover time, where the MN needs to continue its connectivity while roaming across heterogeneous networks. To preserve MN's anonymity and location privacy in this time-restricted seamless handover, ALPP performs three stages: the setup, AHBU, and ARR. We consider AHBU and ARR as two sub-schemes, because any one of them can be independently implemented in the network.

3.5.1 Setup

This stage takes place when an MN roams to a foreign network and comes under an FG's coverage. Based on CL-PKC, this FG works as a KGC for the CL-PKC and periodically transmits its identity and its public $Param = \langle \mathbb{G}_1, \mathbb{G}_2, \hat{e}, n, P, P_0, H_1, H_2 \rangle$ to the network's users. The goal of the setup stage is twofold: 1) to mutually authenticate the MN and FG while keeping MN's anonymity; and 2) to establish a shared secret key between those two nodes. The exchanged messages shown in Figure 3.3 illustrates the mutual authentication as well as the key establishment schemes.

The challenge of the mutual authentication scheme is the difficulty to establish a trust between two arbitrary nodes, MN and FG, which have not met each other before. The following steps summarize the setup stage, where the first three steps achieve the anonymous mutual authentication scheme, and the last step achieves the key establishment scheme.

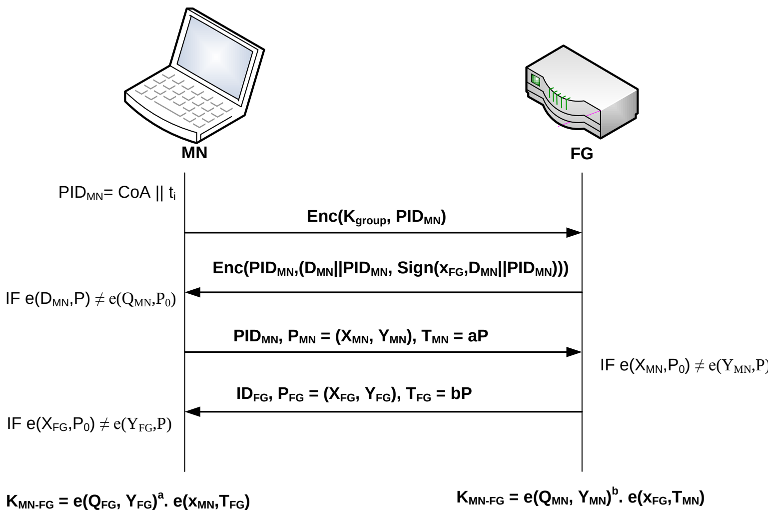


Figure 3.3: Setup stage.

1. The roaming MN creates a pseudo identity, PID_{MN}, by concatenating its acquired CoA and a time stamp, i. e., $PID_{MN} = CoA \| t_i$. Furthermore, the MN encrypts the PID_{MN} using the group key, K_{group}, and sends the encrypted message to the FG as follows:

$$FG \leftarrow MN : Enc(K_{group}, PID_{MN})$$

   By sending this message, the FG guarantees that the MN is a legitimate user. Recall that K_{group} is a secret key shared among all users in the system. The source address of this message is PID_{MN} and the destination address is the FG's address.

2. After authenticating the MN as a legitimate user, the FG creates the MN's partial private key, $D_{MN} = s \times \mathbf{Q}_{MN}$, where s and $\mathbf{Q}_{MN}$ are defined in Section 3.2.1. Furthermore, the FG signs the D_{MN} along with the PID_{MN} and then sends them to the MN after encrypting the whole message using the mobile node's pseudo identity, PID_{MN}, as follows:

$$Enc(PID_{MN}, (D_{MN} \| PID_{MN}, Sign(S_{FG}, D_{MN} \| PID_{MN})) \quad (3.5)$$

Note that the MN creates different PID_{MN} at each foreign network. The PID_{MN} involves the CoA, which is related to the FG. Therefore, when the MN communicates with a different FG, its CoA changes and accordingly the PID_{MN} will be changed. This property increases the MN's anonymity level.

3. The MN verifies the FG's signature in the received message and then checks the correctness of the received partial private key, D_{MN}, using the following condition:

$$IF \hat{e}(D_{MN}, P) \neq \hat{e}(Q_{MN}, P_0), wrong D_{MN}$$

After successful verification, the MN generates its public and private keys, P_{MN} and S_{MN}, using the received partial private key, D_{MN}. When the MN changes its PID_{MN}, the computed public-private key pair will be changed accordingly.

4. The roaming MN uses the generated public-private key pair to generate a secret key K_{MN-FG} shared with its FG as illustrated in Algorithm 2:

Algorithm 2: MN-FG shared key establishment

Input: PID_{MN}, P_{MN}, P_{FG}
Output: Shared secret key, K_{MN-FG}
$FG \leftarrow MN$: $PID_{MN}, P_{MN} = (X_{MN}, Y_{MN}), T_{MN} = aP$
if $\hat{e}(X_{MN}, P_0) \neq \hat{e}(Y_{MN}, P)$ **then**
    Return illegal MN
else
    $MN \leftarrow FG$:
    $P_{FG} = (X_{FG}, Y_{FG}), T_{FG} = bP$
    if $\hat{e}(X_{FG}, P_0) \neq \hat{e}(Y_{FG}, P)$ **then**
        Return illegal FG
    else
        at MN: $K_{MN-FG} = \hat{e}(\mathbf{Q}_{FG}, Y_{FG})^a.\hat{e}(S_{MN}, T_{FG})$
        at FG: $K_{MN-FG} = \hat{e}(\mathbf{Q}_{MN}, Y_{MN})^b.\hat{e}(S_{FG}, T_{MN})$
    end
end

Note that in the above steps, both MN and FG authenticate each other. The foreign gateway authenticates the mobile node by both the group key, K_{group}, and the pairing function, $\hat{e}$. In addition, the mobile node authenticates the foreign gateway by verifying

FG's signature, and checking the correctness of the partial private key that is created by this foreign gateway.

3.5.2 Anonymous Home Binding Update Sub-Scheme

The goal of the anonymous home binding update sub-scheme (AHBU) is to add the anonymity and location privacy services to the home binding update control messages. The AHBU sub-scheme involves two main stages: the binding update, and the binding acknowledgement. In the remainder of the paper, we consider that the mobile node's HoA and CoA represent its identity and its current location respectively.

Anonymous Binding Update

In this stage, the roaming MN uses the created shared secret key, K_{MN-FG}, to send anonymous binding update messages to its home agent, located in this MN's home network. As shown in Figure 3.5, the home binding update steps can be summarized as follows:

1. The roaming MN chooses an intermediate foreign gateway, call it home intermediate foreign gateway (HIFG), from the IFGs list. This HIFG is chosen to be any one of the gateways that are located on the shortest path between the MN's current location and MN home-agent's address. To choose this HIFG, the MN first asks its attached FG to broadcast a route request message to request the shortest routing path to its home agent's address. After receiving the route reply message that contains the shortest path, the MN then randomly chooses one gateway from the gateways on the shortest path to be the HIFG. As illustrated later, the MN uses this HIFG as an anonymizer to hide its location from its HA.

2. The mobile node creates an updated version of a binding update (BU) message and encrypts it using the default security protocol, IPsec protocol. The original BU message contains the mobile node's home address, HoA_{MN}, and its current location, CoA_{MN}. However, the updated BU message contains the HoA_{MN} encrypted by the MN-HA shared secret key, K_{MN-HA}, as well as the following additional fields:

    - Source address: Enc(K_{MN-FG}, PID_{MN})
    - Destination address: FG 's address
    - Enc(P_{HIFG}, HA's address)

- HIFG's address

Note that the source address looks like a wrong IPv6 address format; however, thanks to the setup stage that enables the FG to identify the CoA_{MN}. According to the the setup stage, the FG stores a binding between the encrypted address, Enc(K_{MN-FG}, PID_{MN}), and COA_{MN} as shown in Table 3.1. Figure 3.4 shows an encrypted BU message when it is transmitted from the MN.

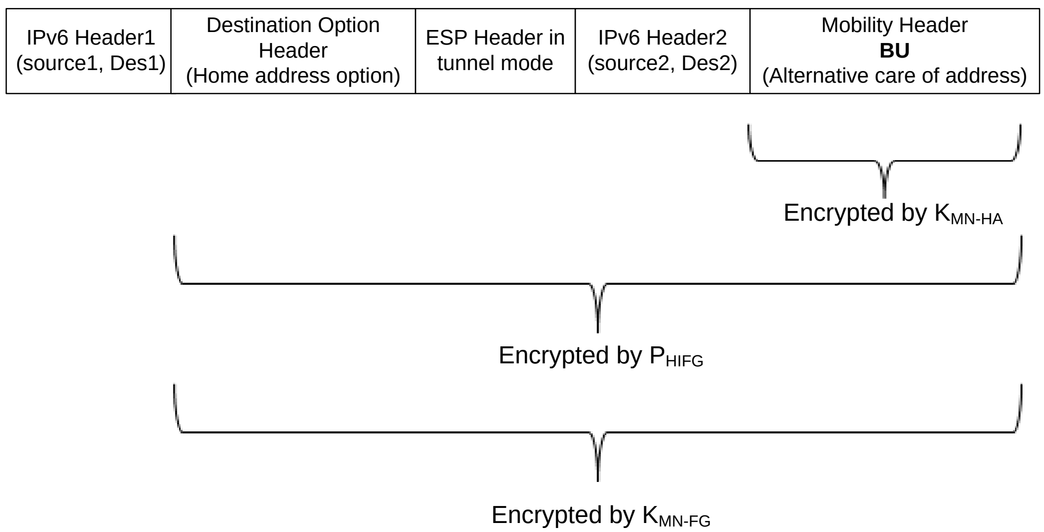


Figure 3.4: Encrypted binding update message.

Using the idea of onion routing, the MN then repeatedly encrypts this binding update message using three different keys: 1) the MN's shared key with its home agent, K_{MN-HA}; 2) the HIFG's public key, P_{HIFG}; and 3) the MN's shared key with the foreign gateway, K_{MN-FG}. The MN then sends this encrypted BU message to its FG.

3. The foreign gateway decrypts the received BU message using its shared key with the MN, K_{MN-FG}, and then sends the decrypted message to the HIFG after adapting the following fields:

   - Source address: FG's address
   - Destination address: HIFG's address
   - Enc(K_{MN-FG}, PID_{MN})

- Enc(P_{HIFG} ,HA's address)

4. The HIFG stores a binding between the encrypted care of address, Enc(K_{MN-FG}, PID_{MN}), and the FG's address. Note that PID_{MN} is a concatenation of MN's CoA and a time stamp t_i. Therefore, for any subsequent messages destined to the encrypted PID_{MN}, the HIFG forwards them to the FG instead. The HIFG also decrypts the encrypted home agent, Enc(P_{HIFG} ,HA's address), to identify the HA's address and then forwards the BU message to this HA. When the home agent receives the BU message, it contains the following fields:
   - Source address: HIFG's address
   - Destination address: HA address
   - Encrypted CoA, Enc(K_{MN-FG}, PID_{MN}).
   - HoA destination option (HoAD): Enc(K_{MN-HA}, HoA_{MN})
5. The home agent can identify the intended MN from the received HoAD, Enc(K_{MN-HA}, HoA_{MN}). This is because we consider that each HA stores the HoAs of MNs that are under its coverage as well as HoADs. Afterwards, the HA stores a binding between this MN's home address and the encrypted CoA that represents MN's current location. In this binding, the HA cannot identify the MN's current location because it is an encrypted version of the MN's CoA, Enc(K_{MN-FG}, $CoA_{MN}||t_i$). Therefore, the HA stores the HIFG's address as a proxy to reach this encrypted address. Consequently, the HA forwards any subsequent messages destined for the roaming MN or to the encrypted CoA to this HIFG's address.

Anonymous Home Binding Acknowledgement

After receiving a BU message, the MN's home agent replies by a binding acknowledgment message that is transmitted to the MN. The goal of this message is to inform the MN that the HA creates a binging between the MN's home address and MN's current location. Therefore, the home binding acknowledgement messages complete the mobility management process. As shown in Figure 3.5, the steps to perform anonymous home binding acknowledgement are as follows:

1. The home agent creates a home binding Acknowledgement (HBA) message, encrypted by the HIFG's public key, and sends it to the HIFG after adding the following fields:

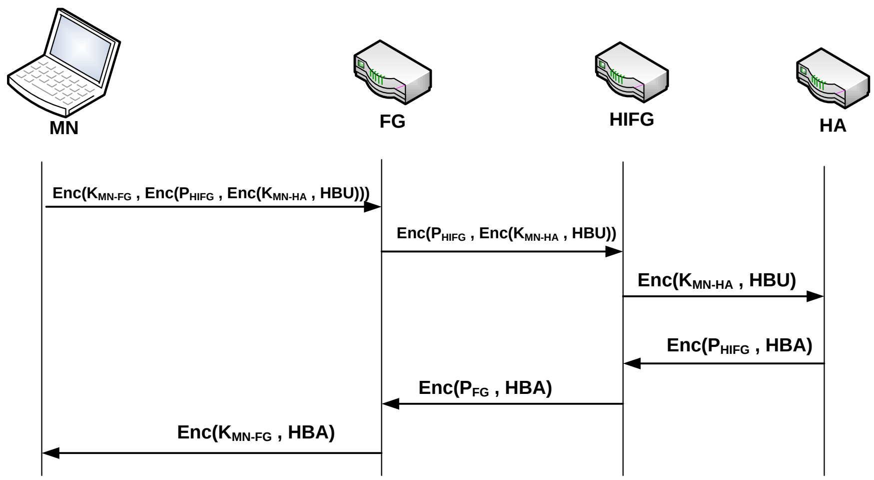


Figure 3.5: Anonymous home binding update scheme.

- Source address: HA's address
- Destination address: HIFG's address
- Enc(K_{MN-FG}, PID_{MN})

2. When receiving the HBA message, the HIFG checks its cache memory to identify the corresponding proxy that is attached with the encrypted address, Enc(K_{MN-FG}, PID_{MN}). This proxy is the MN's FG; therefore, the HIFG sends the HBA to that FG after encrypting it using the FG's public key and adapting the following fields:

   - Source address: HIFG's address
   - Destination address: FG's address
   - Enc(K_{MN-FG}, PID_{MN})

3. The foreign gateway decrypts the received Enc(K_{MN-FG}, PID_{MN}) and then forwards the HBA message to the intended mobile node's care of address.

Table 3.1 shows a summary of stored bindings at each network entity.

Table 3.1: Network Bindings

Entity	Binding(s)
FG	$PID_{MN} \rightarrow CoA_{MN}$,
	$Enc(K_{MN-FG}, PID_{MN}) \rightarrow CoA_{MN}$
HIFG/CIFG	$Enc(K_{MN-FG}, PID_{MN}) \rightarrow$ FG's address
HA	$HoA_{MN} \rightarrow Enc(K_{MN-FG}, PID_{MN})$,
	$Enc(K_{MN-FG}, PID_{MN}) \rightarrow$ HIFG's address
CN	$HoA_{MN} \rightarrow Enc(K_{MN-FG}, PID_{MN})$,
	$Enc(K_{MN-FG}, PID_{MN}) \rightarrow$ CIFG's address

3.5.3 Anonymous Return Routability Sub-Scheme

In mobile IPv4 networking, a roaming mobile node communicates with a CN using the reverse tunneling routing method. In this routing, the MN's CoA represents its current location and the CN doesn't identify this location. Therefore, instead of sending messages directly to the MN's CoA, the CN transmits these messages to the MN's HA, which eventually forwards the messages to the the MN's CoA. This indirectness in routing achieves mobile node's location privacy since the CN doesn't realize the mobile node's movement. However, the reverse tunneling increases the communication routing delay, and it may lead to a triangle routing problem. The worst case of the triangle routing problem occurs when both MN and CN are roaming to the same foreign network. In this case, the CN sends the messages to the MN's HA in home network, which in turn forwards the messages again to the same foreign network. This reverse tunneling routing cannot be used with the seamless communications because it increases the handover time and eventually causes a service interruption.

To solve the triangle routing problem, the mobile IPv6 introduces the route optimization routing method. In this routing, the CN identifies the MN's CoA; Therefore, the CN uses the shortest routing path to send messages to the roaming MN. This path is created using the return routability procedure, which is a group of four messages that is exchanged between the mobile node and the correspondent node. Home Test Init, Care of Test Init, Home Test, and Care of Test are the four messages of the return routability procedure. After successful transmission of these messages, the CN creates a binding between the MN's home address and current location, the MN's CoA, so the CN can directly transmit any subsequent messages to the MN's new location. This direct routing method decreases the routing delay; however, it breaks an MN's location privacy. By monitoring the return routability transmitted messages, the CN as well as an eavesdropper can reveal the MN's anonymity and location privacy.

In this section, the anonymous return routability (ARR) sub-scheme is proposed to add anonymity and location privacy services to the return routability procedure. In the Home

Test Init (HTIM) and Home Test (HTM) messages, the mobile node and the correspondent node communicate through the mobile node's home agent (reverse tunneling) to transmit the home-keygen token. Therefore, the AHBU sub-scheme illustrated in Section 3.5.2 can be used to add the MN's privacy for these two messages. HTIM and HTM messages are transmitted from MN to the HA then to the CN. They are similar to BU/BA message because they are also transmitted from MN to HA, so we consider HTIM and HTM messages as BU and BA messages from the transmitted path perspective. Although the messages' formats are different, we can use the same HIFG to transmit HTIM and HTM from MN to HA. Moreover, in the Care of Test Init message (CTIM) and Care of Test message (CTM), the care-of-keygen token is generated through the direct communication between the mobile node and the correspondent node. Therefore, the ARR sub-scheme is proposed to ensure MN's and CN's anonymity and location privacy for both CTIM and CTM messages transmissions. In the following subsections, two scenarios for the correspondent nodes will be presented: one for a fixed node, and one for a roaming node. In the former scenario, the correspondent node may be a fixed node or a mobile node that is located in its home network at the time of communication with an MN. In the latter scenario, the correspondent node is a mobile node which roams to a foreign network.

Fixed Correspondent Node Scenario

In this scenario, we consider that the MN's and the fixed-CN's home addresses are known to each other, However, to achieve location privacy, the MN's current location, CoA_{MN}, is kept unknown to the correspondent node. The ARR sub-scheme consists of two transmitted messages: Care of Test Init, and Care of Test messages. As shown in Figure 3.6, the CTIM is transmitted from the MN to the CN. The MN first selects an IFG, which we will call correspondent IFG, CIFG. The CIFG is chosen from among those on the shortest path between the MN and CN. The MN then repeatedly encrypts the message using three different keys: 1) the public key of the CN's home agent, P_{HACN}; 2) the CIFG's public key, P_{CIFG}; and 3) the MN's shared key with its foreign gateway, K_{MN-FG}. The MN then sends the encrypted message to the FG in the foreign network, which in turn forwards the message to the CIFG, and then the message is forwarded to the CN's HA. Finally the CN's HA forwards the message to the intended CN.

When receiving the care of test message, the CN creates a binding between the MN's home address and an encrypted version of the MN's current address, $\mathrm{Enc}(K_{MN-FG},PID_{MN})$. Furthermore, the CN also stores the address of CIFG as a proxy to reach this encrypted address, $\mathrm{Enc}(K_{MN-FG},\mathrm{PID}_{MN})$.

The CN then transmits a CTM message to the MN as an acknowledgement for the

Care of Test init message. The CN first encrypts the CTM using its shared key with its HA, $K_{HACN-CN}$, and transmits the encrypted message to its home agent. The CN's home agent then encrypts the message with CIFG's public key before transmitting it to the CIFG, which in turn encrypts and transmits the message to the MN's FG. Finally, the MN's FG encrypts the CTM using the shared key with that MN, K_{MN-FG}, and then transmits the encrypted CTM to the MN.

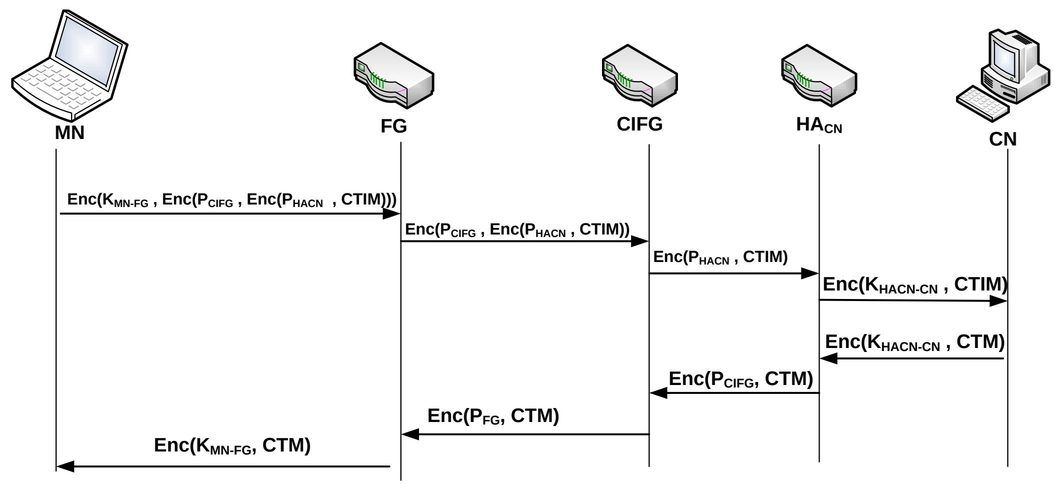


Figure 3.6: Anonymous return routability, fixed CN.

Mobile Correspondent Node scenario

The mobile CN scenario is more difficult than the fixed CN scenario because in this scenario, both the MN and the CN move to two foreign networks. The goal of the ARR sub-scheme here is to achieve MN's and CN's location privacy, which requires hiding the two nodes' current locations from each other. Considering an MN as a mobile sender and a CN as a mobile receiver, we here achieve anonymity and location privacy for both mobile senders and mobile receivers.

We consider that both MN's and CN's home addresses are known to each other. As a mobile node, the CN implements the AHBU scheme, introduced in Section 3.5.2, to achieve its anonymity and location privacy towards its home network. To implement the ARR sub-scheme, as shown in Figure 3.7, the MN sends a CTIM to the correspondent node. First, the CTIM message is sent to the CN's home agent, which discovers that the CN is currently

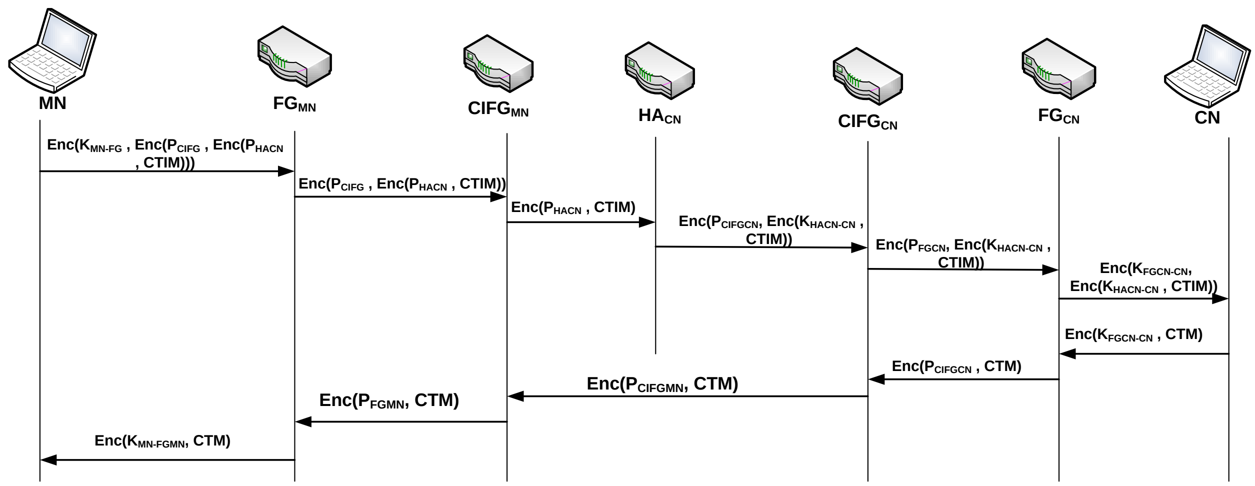


Figure 3.7: Anonymous return routability, mobile CN.

roaming on a foreign network. Therefore, the CN's home agent forwards the message to the CN's CIFG, $CIFG_{CN}$, which in turn transmits the CTIM to the roaming CN.

Going the other way, when the CN sends the CTM to the MN, it is sent directly to the MN's CIFG, $CIFG_{MN}$. The CTM message is not transmitted to the CN's HA because $CIFG_{CN}$ already knows the $CIFG_{MN}$'s address, and thus does not need to ask CN's HA about the $CIFG_{MN}$'s address. Therefore, the length of the CTM routing path is shorter than the length of the CTIM routing path, so the CTM routing path is used for data transmission between a roaming MN and a CN.

The worst case is when the CN and the MN move to the same foreign network. In this case, the two nodes select either the same or different FGs. If both nodes choose the same FG, then only this FG realizes that they are in the same network. Therefore, the FG delivers the messages between the MN and CN without forwarding them to the corresponding CIFGs. If the two nodes choose two different FGs in the same foreign networks, the MN-CN routing path goes through the corresponding CIFGs and this leads to high routing delay.

3.6 Privacy and Security Analysis

3.6.1 Privacy Analysis

In our network, the mobile node's HoA and CoA represent its identity and its current location respectively. Therefore, violating an MN's HoA means breaking its anonymity, and violating an MN's CoA means breaking its location privacy.

As in [81], we use the entropy model to measure the degree of anonymity for both our proposed scheme and the mix-based scheme [33]. The degree of anonymity, d, can be measured by the following equation:

$$d = 1 - \frac{H_M - H(X)}{H_M} = \frac{H(X)}{H_M} \tag{3.6}$$

H(X) is the entropy of the network, which measures the amount of information that an attacker knows about the identity of message's sender. H_M is the maximum entropy of the network. Therefore, the degree of anonymity for ALPP scheme can be measured as follows:

$$\begin{aligned} H(X) &= \sum_{i=0}^{n} [p_i \log \frac{1}{p_i}] = \log n \\ H_M &= \sum_{i=0}^{L.n} [p_i \log \frac{1}{p_i}] = \log(L.n) \\ d &= \frac{\log n}{\log(L.n)} \end{aligned} \tag{3.7}$$

where p_i is the probability that a node i is the sender of a message, n is the number of nodes in the home network, and L is the number of networks in the system.

Similarly, the degree of anonymity for the mix-based scheme can be computed as follows:

$$d = \begin{cases} \frac{\log m}{\log(L.n)} & K = 1, \\ \frac{\log(K.m)}{\log(L.n)} & K > 1. \end{cases}$$

where K is the number of mix servers, L is the number of networks in the system, and m is the number of messages that are mixed together at each mix server. The number of mixed messages is an indicator for the number of senders, because in the mix-based scheme, each sender sends one message at a time to the mix server. Therefore, m also represents number of senders in the network.

Figure 3.8 shows the degree of anonymity for our scheme at different values of L and for the mix-based scheme with one mix server ($K = 1$). ALPP's degree of anonymity increases as the number of nodes in the home network increases, but it decreases as the number of networks in the system increases. On the other hand, the degree of anonymity for the mix-based scheme increases as the number of senders increases. For the mix-based scheme, we fix the number of users in one network to be 1000 users. Therefore, for $L = 10$, the total number of users is 10000.

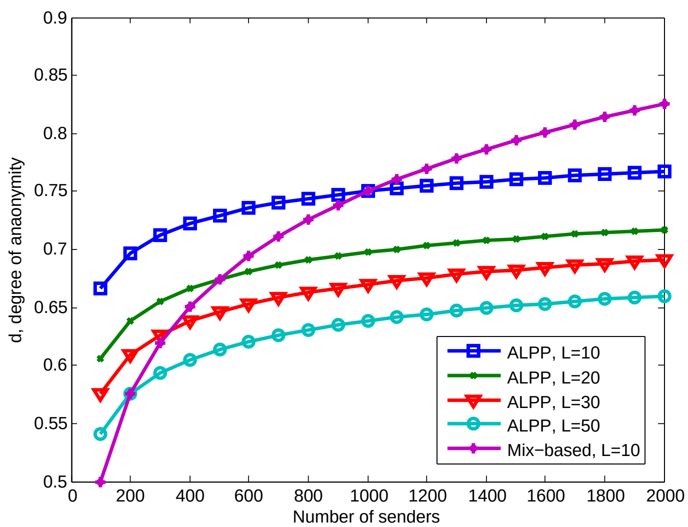


Figure 3.8: Degree of anonymity.

Compared to our proposed scheme, ALPP, the mix-based scheme with one mix server achieves a lower level of anonymity when number of senders is below 1000. Increasing the number of senders in the mix-based scheme causes a high delay, as will be shown later. Moreover, increasing the number of mix servers leads to increasing the level of anonymity, but also increases the network delay. This trade-off prevents the mix-based scheme from being used for seamless communications, which require low routing delay to achieve service continuity.

To illustrate the impact of delays on the mix-based scheme, Figure 3.9 shows the delay of the scheme multiplied by the achieved degree of anonymity. Assuming $2ms$ for the mix server to send and receive a message, the mix-based scheme with one mix server requires around 1.2sec to serve 1000 senders. This delay increases to around 5sec as the number of mix servers increases. To achieve higher anonymity using one mix server, the number of senders, m, that send messages to this mix server should be increased. For one mix server, m ranges from zero to the total number of users in the system $(L.n)$. However, the network delay increases as m increases, because the mix server needs to wait until receiving all messages from all senders, then mixes and retransmits them. Alternatively, the anonymity level can be increased when the number of mix servers, K, increases. In this case, the number of senders, m, is limited to $0 \leq m \leq \frac{L.n}{K}$. However, the network delay also increases when the number of mix servers increases, because these mix servers work sequentially with each other. As a conclusion, in the mix-based scheme, there is a trade-off between the achieved anonymity level and the network delays.

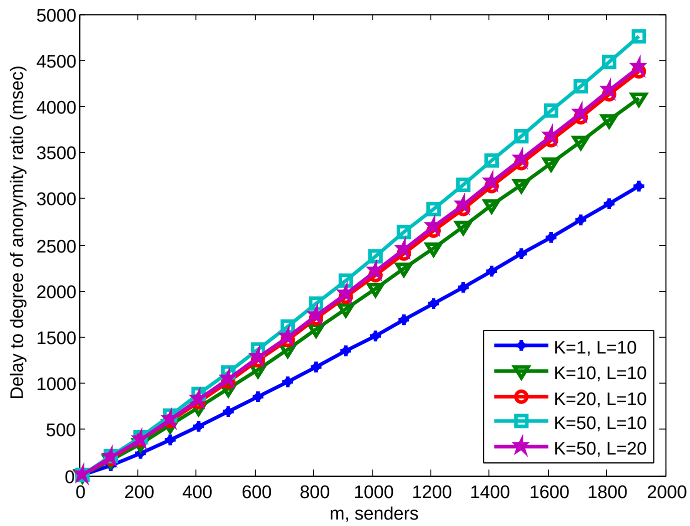


Figure 3.9: Mix-based delay to degree of anonymity ratio.

On the other hand, Figure 3.10 shows the delay of the ALPP scheme multiplied by its degree of anonymity. Compared to the mix-based scheme, our scheme has a delay of 1.5ms to serve 1000 users, which is 99% less than the mix-based scheme's delay.

The proposed ALPP scheme ensures sender's and receiver's location privacy by hiding their care of addresses from both the home agent and correspondent node. In our network, the care of address and the foreign gateway represent a node's location information. The mobile node's home agent cannot determine the mobile node's care of address, because it receives an encrypted address, Enc(K_{MN-FG},PID_{MN}), instead of a plain-text address. Moreover, the home agent does not communicate directly with the foreign gateway, they

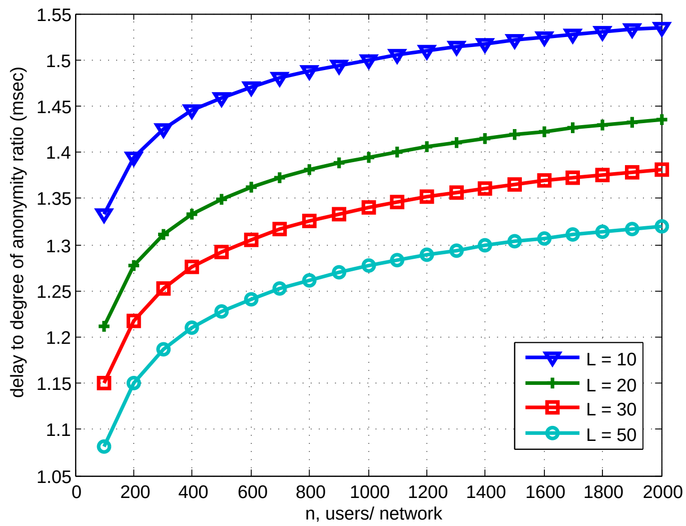


Figure 3.10: ALPP's delay to degree of anonymity ratio.

communicate through a proxy, IFG. Therefore, the home agent cannot identify the MN's FG.

Table 3.2 shows the mobile node's information that each entity in the network can acquire. In the table, the header column represents network entities, the header row represents MN's information, K means that the network entity knows the information part, and U means that the information is unknown to the network entity. As shown in the table, no network entity except the MN itself can identify this node's location, CoA. Two columns in the table represent MN's location information, the CoA and FG columns. The CoA column show that no entity knows the MN's CoA except this MN and its FG. Although the FG identify the MN's location, it does not identify this MN because the MN communicates with the FG by means of a pseudo identity instead of its real identity. In addition, the FG column shows that the MN, FG, and IFG know MN's FG. The IFG only specifies MN's FG, but it does not identify the MN itself.

3.6.2 Security Analysis

The security of the ALPP scheme is based on the security of the proposed key establishment scheme that is illustrated in Algorithm 2. Moreover, the security of the key establishment scheme is based on the hardness of the elliptic curve discrete logarithm problem (ECDLP).

Table 3.2: Mobile Node's Information Knowledge.

	HoA	CoA	HA	FG	CN	IFG
MN	K	K	K	K	K	K
HA	K	U	K	U	K	K
FG	U	K	K	K	U	K
IFG	U	U	K	K	K	K
CN	K	U	K	U	K	K
Adversary	U	U	U	U	U	K

In [82] it is proved that ECDLP can be solved in at least sub-exponential time. ECDLP is a hard problem since no polynomial time algorithm can solve it.

Definition 1. *The Elliptic Curve Discrete Logarithm Problem (ECDLP):*

Given P and xP as two points on elliptic curve E, find x where $x \in \mathbb{Z}_q^*$.

Theorem 1. *In Algorithm 2, under the assumption that an attacker knows the MN's private key, S_{MN}, the attacker is still unable to create the shared key K_{MN-FG}.*

Proof. To create a valid K_{MN-FG}, the attacker needs to compute the following pairing functions:

$$K_{MN-FG} = \hat{e}(\mathbf{Q}_{FG}, Y_{FG})^a . \hat{e}(S_{MN}, T_{FG})$$

Since the attacker knows S_{MN}, it easily computes $\hat{e}(S_{MN}, T_{FG})$. However, to compute $\hat{e}(\mathbf{Q}_{FG}, Y_{FG})^a$, the attacker needs to know the value of a. But the attacker knows only P and $T_{MN} = aP$. Thus this problem is equivalent to ECDLP. Since ECDLP is a hard problem, the attacker cannot create a valid K_{MN-FG} in a polynomial time. □

The Traffic Analysis Attack

The traffic analysis attacker attempts to capture a group of the transmitted packets and analyze them in order to learn the identity and the location of the mobile node. The identity of the mobile node, which is represented by its home address, is transmitted in an encrypted form. Therefore, the traffic analysis attacker cannot learn the true identity of the mobile node. Moreover, we use onion routing to prevent the attacker from correlating the input and output messages at a specific hop. For example, the binding update messages that are transmitted from an MN are repeatedly encrypted by three different keys: the shared key with the home agent, the intermediate foreign gateway's public key, and the shared key with the foreign gateway. When the foreign gateway receives these messages, it decrypts them using the shared key with the mobile node, and then retransmits the decrypted messages to the IFG. These decrypted messages are indeed messages encrypted by the remaining two keys. Therefore, at each hop, the messages are decrypted by one key then retransmitted to the next hop. Consequently, the attacker cannot identify the mobile node's movements.

The Collusion Attack

The collusion attack may be triggered among the foreign gateways, the intermediate foreign gateways, or the correspondent nodes. When our proposed schemes are used, a collusion attacker gains no information about the mobile node's identity and locations.

If the foreign gateways collude with each other, they would not learn the identity of the mobile node. In the setup stage, the mobile node uses a pseudo identity, $PID_{MN} = CoA \| t_i$, to identify itself to the FG. The MN's CoA, which is used to create the PID_{MN}, changes as the mobile node chooses different foreign gateways; hence MN's PID_{MN} also changes. Therefore, each foreign gateway identifies only one PID_{MN} of the MN's pseudo identities. It is thus not possible for the FGs to link all the care of addresses to the same MN.

Moreover, the collusion of the intermediate foreign gateways reveals nothing about MN's privacy, because they do not directly communicate with this MN. In our network, IFGs only communicate directly with the home agent and the foreign gateway. The IFG receives an MN's encrypted CoA, which represents the MN's location. Again when it roams among different foreign networks, the MN acquires different care of addresses and encrypts them by different keys. Therefore, if IFGs collude, they cannot link all encrypted CoAs to the same MN. Collusion among the FGs and the IFGs can reveal the mobile node's home agent, but this knowledge of the mobile node's home agent does not break the MN's privacy, because we argue that there are at least two nodes in the home network. Therefore, the probability of identifying the mobile node is:

$$P(MN) = \frac{1}{n}, n \geqslant 2 \tag{3.8}$$

where n is the number of nodes in the home network. Thus, with a large number of nodes located in the MN's home network, the probability of identifying the MN after identifying its network is negligible.

The Replay Attack

In the setup stage, an attacker may send a previously transmitted pseudo identity to the foreign gateway in order to deceive the foreign gateway and learn the MN's partial private key, D_{MN}. In our proposed schemes, the MN's pseudo identity, $PID_{MN} = CoA\|t_i$, is created by concatenating MN's CoA with the time stamp. The time stamp prevents the attacker from repeating transmission of previous messages. However, any legitimate user who knows the group key can decrypt the message, change the time stamp, and then resend the message again. From Theorem 1, we prove that even if a legitimate user succeeds in learning the MN's secret key, this user is still unable to create a valid shared key, K_{MN-FG}.

The MITM Attack

A man-in-the-middle (MITM) attacker may change either MN's identity, PID_{MN}, or public key, P_{MN}, to create a fake session with the FG. We prove by Theorem 2 that if either PID_{MN} or P_{MN} is changed in the middle of transmission, then the key generation algorithm returns "illegal MN".

Theorem 2. *If either PID_{MN} or $P_{MN} = (X_{MN}, Y_{MN})$ is changed by an attacker, then Algorithm 2 returns "illegal MN".*

Proof. **Case 1: If PID_{MN} is changed to $PI\grave{D}_{MN}$,then from Theorem 1, the attacker cannot create $K_{MN-FG} = \hat{e}(\mathbf{Q}_{FG}, Y_{FG})^a.\hat{e}(S_{MN}, T_{FG})$ because the attacker does not know the values of a and S_{MN}. Thus the attacker is an illegal MN.**

Case 2: If P_{MN} is changed to $\grave{P}_{MN} = (\grave{X}_{MN}, \grave{Y}_{MN})$, then the condition at line 2 of Algorithm 2 is satisfied. This means $\hat{e}(\grave{X}_{MN}, P_0) \neq \hat{e}(\grave{Y}_{MN}, P)$, and Algorithm 2 returns "illegal MN". □

In addition, an MITM attacker may send a fake partial private key, D_{MN}, to the MN in the setup stage. This case also happens if the FG is a malicious node and wants to mislead the MN. The result of this attack leads to an interruption of the MN's IP session. In our proposed schemes, however, the MN authenticates the FG by verifying its signature as illustrated in the setup stage- further, the MN also checks the correctness of the partial private key that is received from the FG, using the following condition:

$$IF \hat{e}(D_{MN}, P) \neq \hat{e}(\mathbf{Q}_{MN}, P_0), wrong D_{MN}$$

We can show that for a correct D_{MN}, the two pairing functions are identical, as follows:

$$\begin{aligned}\hat{e}(D_{MN}, P) &= \hat{e}(s \times \mathbf{Q}_{MN}, P) \\ &= \hat{e}(\mathbf{Q}_{MN}, s \times P) \\ &= \hat{e}(\mathbf{Q}_{MN}, P_0)\end{aligned} \tag{3.9}$$

3.7 Performance Evaluation

3.7.1 Computation and Communication Overhead

Tables 3.3 and 3.4 show the computation and communication overheads of the proposed sub-schemes, AHBU and ARR, compared to those of the mix-based scheme [33] with one mix server, and the EHoA and PHoA schemes [35]. In addition, we use Crypto++ benchmarks [83] to measure the computation time at the mobile node's side, as shown in Figure 3.11. We use the ElGamal encryption mechanism for public key encryption operations, and the AES scheme for symmetric encryptions. According to Crypto++ benchmarks, the modulus and exponent sizes used for ElGamal encryption are 2048 and 226 bits, respectively. Therefore, in the tables, T_{ELG} represents the time needed for ElGamal encryption operation, T_{Sym} represents the time needed for AES encryption or decryption, T_{pid} and T_{prf} represent the time needed to construct a pseudonym and to generate a random number, and $T_{EHOA-reg}$ and $T_{PHOA-reg}$ represent time needed for registering the encrypted and the pseudo home addresses. For computation overhead, $B_{Signalling}$ represents bytes needed to send the control information, while $B_{EHoA-reg}$ and $B_{PHoA-reg}$ represent bytes needed to send a PHoA and EHoA registration messages.

Table 3.3: AHBU Computation and Communication Overheads.

	Computation	Communication
Mix-Based	$3T_{ElG} + 2T_{Sym}$ $+ 2T_{prf} + T_{pid}$	$B_{signaling}$
AHBU	$T_{ElG} + 3T_{sym}$	$B_{signaling}$

In Table 3.3, our AHBU's computation overhead is smaller than the mix-based scheme's overhead by 66%. The mix-based scheme requires three public key encryption operations while the AHBU scheme requires only one public key operation.

Table 3.4 shows that the ARR sub-scheme is the second least time-consuming after the mix-based. In EHoA and PHoA schemes, an MN needs first to register the encrypted home address and pseudo home address before using them. Considering 5ms for one Round Trip Time (RTT) between the MN and its home agent, the computation overheads of EHoA and PHoA schemes are much higher than that of the ARR sub-scheme. ARR's computation overhead is smaller than the overhead of EHoA and PHoA by 79% and 89%, respectively. Figure 3.11 shows the time consumption for the ALPP scheme compared to other schemes.

The measured AHBU and ARR computation overheads do not include the time required for the setup stage, T_{setup}, because this time is only needed once per MN's stay on a given foreign network. If an MN sends many home binding update messages from the same foreign network, then only one T_{setup} is required. The setup time can be measured as follow:

$$T_{setup} = 2T_{Sym} + T_{verification} + 3T_{pairing} \tag{3.10}$$

Considering the AES scheme for T_{sym}, and the RSA scheme for signature verification time, $T_{verification}$, the estimated time needed for T_{setup}, is around 120 ms. To measure the pairing time, $T_{pairing}$, we consider a 2.93 GHz processor with the Tate pairing in [83] and get 6.83 ms for each pairing function. Following the Crypto++ benchmarks, the used Elliptic Curve field size is GF(2^n) where operations are implemented using trinomial basis. We also use 17 as the RSA scheme public exponent.

Table 3.4: ARR Computation and Communication Overhead.

	Computation	Communication
Mix-Based	$3T_{sym} + T_{Hash} + 2T_{pid}$	$B_{Signaling}$
EHOA	$3T_{sym} + T_{EHoA-reg}$	$B_{EHoA-reg}$
PHOA	$T_{Pid} + 2T_{PHoA-reg}$	$B_{PHoA-reg}$
ARR	$2T_{sym} + 2T_{ElG}$	$B_{Signaling}$

3.7.2 Power Consumption

Aiming to compute the energy consumed at MN, we follow the energy costs of cryptographic algorithms that are proposed in [84] for two different PDAs, a Compaq iPAQ3970 and an HP Hx2790. As shown in Figure 3.12, compared to the Mix-based scheme, the AHBU sub-scheme has the lowest energy consumption for both PDA types. AHBU achieves energy reductions of 65.66% and 66% when using Compaq iPAQ3970 and HP Hx2790, respectively. This is due to using only one public key operation, while the mix-based scheme uses three.

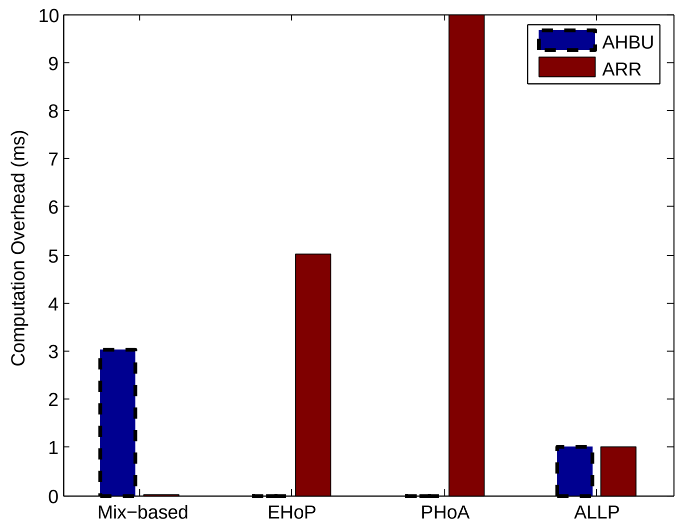


Figure 3.11: ALPP Computation Overhead

According to [84], one public key scheme requires 40.87mJ and 25.87.17mJ to encrypt a message in iPQ3970 and Hx2790, respectively.

3.7.3 Simulation Results

Based on the anonymizer scheme [69], we have proposed a new method of routing in which the transmitted binding update message is sent to an intermediate node, IFG, instead of sending it to the receiver directly. The selected home intermediate foreign gateway works as an anonymizer. Unlike the traditional anonymizer, which is a fixed proxy that serves all nodes and can easily break mobile nodes' privacy, our anonymizer changes with each mobile node and it cannot reveal the privacy information.

We develop a simulator to compare the effect of the updated routing method used by both AHBU and ARR sub-schemes with that of the original routing method, which does not ensure privacy for any MN.

Two kinds of mobile nodes are defined in our simulator. The first type, called the successful node, is the node that succeeds in finding an intermediate foreign gateway on the shortest path between the communicating parties. The second type, called the failed node, is the node that moves to a neighbor network, so the shortest path length is only one hop, from HA to FG. Therefore, the failed node cannot find an intermediate gateway on the shortest path.

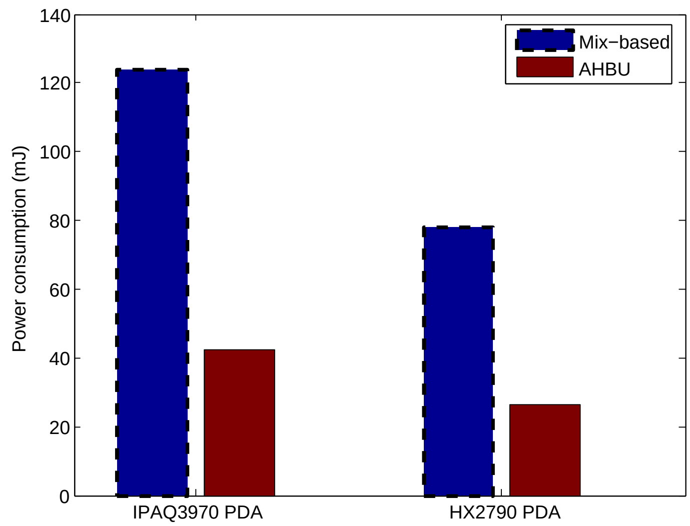


Figure 3.12: AHBU Power Consumption

Table 3.5: MIPv6 Networking Simulation Parameters.

Parameter	Value
System size	$5500m \times 5500m$
Network numbers in system	36
Network size	$1000m \times 1000m$
Number of nodes per system	1000 - 36000 nodes
Overlapping area	$100m$
Distribution of nodes	Uniform
Mobility model	Random Waypoint model
Nodes maximum speed range	2 m/sec - 20 m/sec
Nodes minimum speed	0 m/sec
Number of HA per network	one

We consider 351 simulation runs, where the number of nodes in the system increases from 1000 nodes in the first run, to 36000 nodes in the last. We consider a large number of nodes in order to check the scalability of our proposed scheme. At each run, the maximum node speed ranges from 2 m/sec to 20 m/sec. The time interval between each run is 10 minutes. We use the Bellman-Ford routing algorithm for message routing among gateways. Table 3.5 shows the full simulation parameters.

Figure 3.13 shows the routing delays of the proposed sub-schemes, compared with the

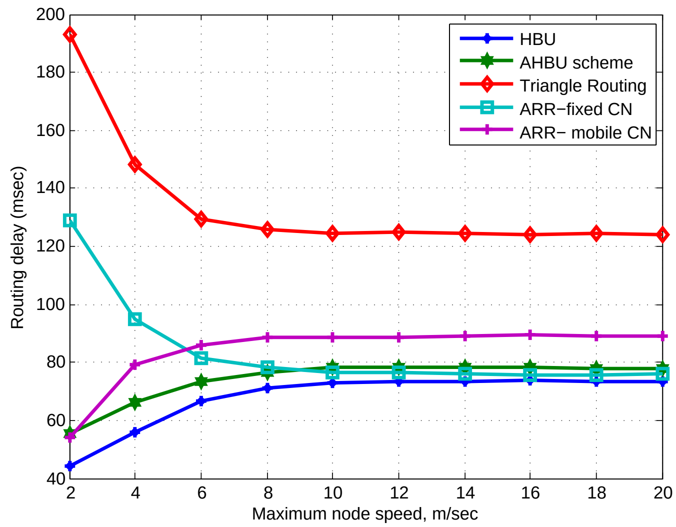


Figure 3.13: Routing delay at different mobility speeds.

home binding update (HBU) scheme and the triangle routing that is used by the mobile IPv4 protocol. HBU and triangle routing schemes are used as lower and upper references, respectively. In this figure, we measure the routing delay for a highly dense networking, 36000 nodes density.

As shown in the figure, the proposed sub-schemes (AHBU, ARR sub-scheme with fixed CN scenario, and ARR sub-scheme with mobile CN scenario), have very similar routing delays to that of the HBU. The HBU scheme does not apply any anonymity or location privacy services. This result indicates the ability of using our proposed schemes with scalable networks and real-time applications in which the routing delay is an important factor. The reported difference in the routing delays between our proposed schemes and the HBU results from the failed nodes. In our simulation, the failed nodes do not apply our updated routing method, since there is no IFG on the shortest path. An alternative solution is that the failed nodes can select any IFG at an adjacent network. In this case, routing delay values may depend on the network traffic, because the adjacent network is not located on the shortest path between the two communicating parties.

We also notice that the routing delay of the triangle routing method is larger than our schemes' delays. The triangle routing method ensures an MN's location privacy, but its high delay prevents its use for seamless communications. Our sub-schemes' routing delays are smaller than the triangle routing delay by an average of 32%.

Figure 3.14 shows the network routing delay for different network capacities at high node mobility, 20 m/sec. It can be seen that the number of nodes in the network does not have a significant impact on the routing delay, but the nodes' mobility speed has a large impact on this delay. Compared to the HBU scheme, our proposed sub-schemes, the AHBU, ARR-fixed CN, and ARR-mobile CN schemes, increase the routing delays by 2.7%, 4%, and 20% respectively. On the other hand, compared to the triangle routing scheme, our sub-schemes decrease the routing delays by 42%, 43%, and 30% respectively.

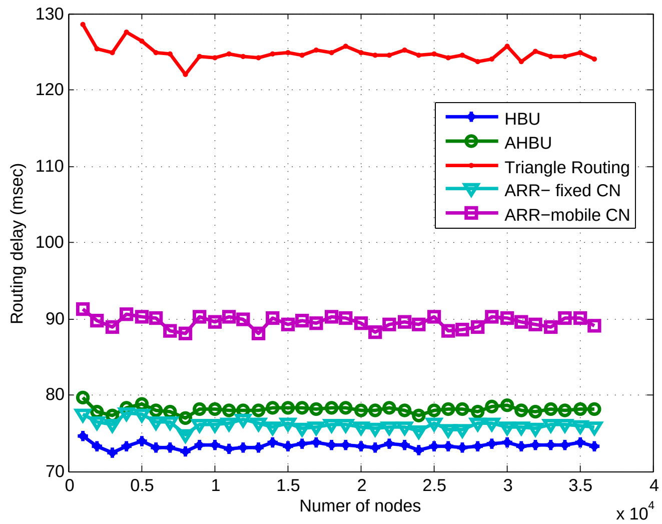


Figure 3.14: Routing Delay with different network capacity.

Figure 3.15 shows the number of successful and failed nodes with a 36000-node system and at different node speeds. It can be seen that the number of failed and successful nodes depends on the speed of the node. With mobility speeds below 8 m/sec, the number of the successful nodes increases as the nodes' speeds increase. However, with mobility speeds above 8m/sec, the numbers of successful and failed nodes are fixed. This result confirms that our schemes are more appropriate to be used in high mobility environments.

Additionally, we obtain the 95% confidence intervals (CIs) for both the successful nodes numbers' and the average routing delay. Table 3.6 shows the CIs with different system densities and mobility speeds, in which we consider low density as 1000 nodes and high density as 36000 nodes. Similarly, we consider low mobility as 2 m/sec and high mobility as 20 m/sec.

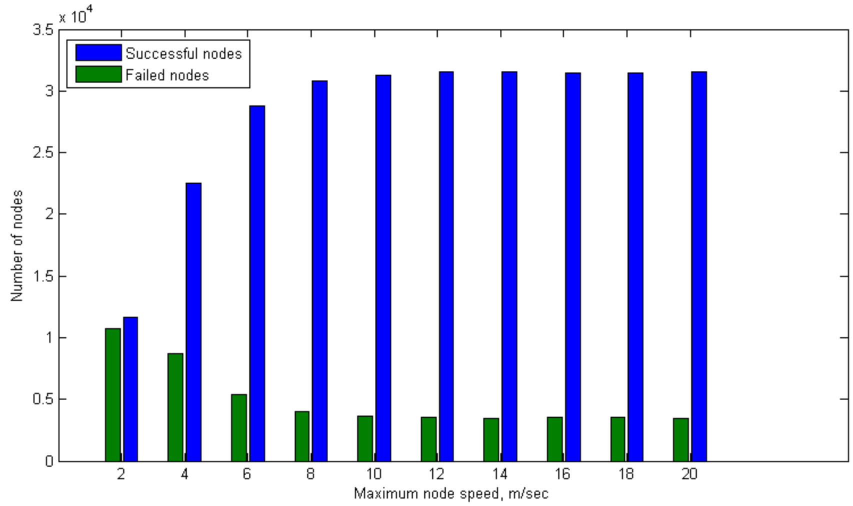


Figure 3.15: successful and failed nodes at mobility speeds.

3.8 Summary

In this chapter, based on the onion routing, anonymizer, and certificate-less public key cryptography, we have proposed an anonymous and location privacy preserving scheme (ALPP) to be employed in MIPv6 control signalling for heterogeneous networks. In addition, we have introduced a mutual authentication scheme as well as a key establishment scheme to be used among mobile nodes and foreign gateways in visiting networks.

The ALPP scheme involves two complementary sub-schemes, anonymous home binding update (AHBU) and anonymous return routability (ARR). The AHBU and ARR sub-schemes are employed to ensure anonymity and location privacy for a roaming mobile node that sends an MIPv6 home binding update and return routability messages to their home agent and correspondent node, respectively. In addition, the ARR sub-scheme can be used for both a fixed correspondent node that is located in its home network, and a roaming correspondent node that moves out from its home network. The challenge in the roaming correspondent node's case is to support anonymity and location privacy for a two moving nodes. The idea of both AHBU and ARR sub-schemes relies on introducing an intermediate entity, called the Intermediate Foreign Gateway (IFG), into the scenarios of sending the HBU and RR control messages. The IFG allows the roaming mobile node to hide its identity from its foreign gateway and hide its current location from its home agent and correspondent node. Therefore, both MN's anonymity and location privacy are

Table 3.6: 95% Confidence Interval of AHBU sub-scheme.

successful nodes				
Density	Mobility	mean	st.dev	CI
low	low	868	44.26	[781, 955]
low	high	876	10.55	[855.7, 897.1]
high	low	31273	1516.7	[28300, 34246]
high	high	31465	112.88	[31244, 31686]
Average Delay				
Density	Mobility	mean	st.dev	CI
low	low	73.22	1.58	[70.12, 76.32]
low	high	73.81	0.99	[71.86, 75.76]
high	low	73.63	1.32	[71.04, 76.22]
high	high	73.36	0.18	[73, 73.72]

achieved.

By the help of using the onion routing idea, we repeatedly encrypt the messages sent from the mobile node and change the mobile node identity, location, and encryption keys for each layer of encryption. In addition, the idea of the anonymizer is adapted to have a different anonymizer, *i.e.,* IFG, each time the mobile node sends a message. Therefore, the IFGs cannot collude to reveal the MN's identity and locations. Furthermore, we have proposed a mutual authentication and key establishment schemes between the roaming mobile node and its foreign gateway. The difficulty of creating a security association between those two arbitrary nodes, the mobile node and its foreign gateway, makes it a challenge to build trust between them. Using the certificate-less public key cryptography, we present an efficient and secure authentication scheme between such arbitrary nodes. The proposed authentication scheme allows the two parties to authenticate each other without constructing a public key infrastructure in the network. In addition, after this mutual authentication, the mobile node and the foreign gateway establish a shared key between them to be used in subsequent communications.

To analyze the privacy achieved by our proposed scheme, we use the entropy model to compare the degree of anonymity of both our scheme and the mix-based scheme. The degree of anonymity reflects the information known by the attacker about the mobile node identity. With a large number of senders in our system, the degree of anonymity in our scheme ends up between 60% and 85%, whereas the mix-based scheme encounters a high delay while increasing the degree of anonymity. Regarding the location privacy, we prove that when implementing the ALPP scheme, no network entity except the mobile node itself can identify this node's location, which is represented by the mobile node's care-of address.

In our security analysis, we prove that when using our proposed key establishment scheme, and under the assumption that the attacker knows the mobile node's private key, the attacker still is unable to create the shared key between the mobile node and the foreign gateway. In addition, we also prove that if either the mobile node identity or its public key is changed by an attacker, our proposed key establishment can detect this forgery. Therefore, based on these proofs, we show that the ALPP scheme thwarts traffic analysis, collusion, replay, and man-in-the middle attacks.

To evaluate the performance, we measure the computation and communication overheads as well as the power consumption of our proposed scheme, compared to previous anonymity and location privacy schemes. In addition, using extensive simulations, we show that our proposed sub-schemes decrease the routing delays by 42% for the AHBU sub-scheme, 43% for ARR-fixed correspondent node, and 30% for ARR-mobile node, compared to the triangle routing scheme.

As a privacy protocol, the ALPP scheme maintains the balance between network performance and the privacy level, especially with the mobile node's high speed mobility that is required for mobile networks such as vehicular networks. However, using the MIPv6 as the underlying mobility management protocol, which suffers a high delay in certain scenarios, our proposed scheme cannot increase network performance. Therefore, applying our proposed scheme for different mobility management protocols, such as the network mobility protocol, NEMO, gives much better performance improvement.

Chapter 4

EM^3A: Efficient Mutual Multi-hop Mobile Authentication Scheme for PMIP Networks

4.1 Introduction

An important requirement for current mobile wireless networks, such as VANETs, is that they be able to provide ubiquitous and seamless IP communications in a secure way. Moreover, these networks are envisioned to support multi-hop communications, in which intermediate nodes help to relay packets between two peers in the network. Therefore, in infrastructure-connected multi-hop mobile networks, the connection from the mobile node (MN) to the point of attachment may traverse multiple hops (Figure 4.1).

The reasons for relaying packets in infrastructure-connected mobile networks are twofold: 1) direct connection to the infrastructure may not always be available, thus, by using relayed communications, the network coverage can be extended, and its throughput and capacity can also be increased [85]; and 2) Relay Nodes (RNs) may benefit from offering their services as temporary relays; different cooperation incentive schemes have shown that it is in the best interest of each node to participate in multi-hop packet forwarding and earn credits that reward them per forwarded packets [86].

In this chapter, we propose an efficient mutual authentication scheme for multi-hop-enabled PMIP networks, EM^3A, which thwarts authentication attacks, including DoS, colluding, impersonating, replay, and man-in-the-middle (MITM) attacks. We also offer a

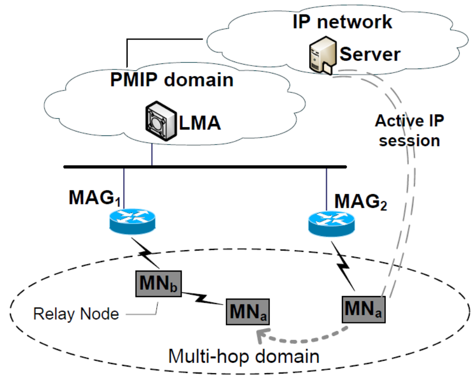


Figure 4.1: Infrastructure-connected multi-hop mobile network. MN_a is roaming to a relayed communication through relay node MN_b

case study of applying our proposed scheme in a novel Multi-hop Authenticated Proxy Mobile IP (MA-PMIP) Scheme for Asymmetric VANET [87]. EM^3A thwarts authentication attacks when handovers occur through the Infrastructure-to-Vehicle-to-Vehicle (I2V2V) communications, while achieving reduced overhead. In addition, we present a key establishment scheme based on symmetric polynomials [88–90], which generates a shared secret key between MN and RN. Compared to existing authentication schemes, our proposed scheme achieves higher secrecy as well as lower computation and communication overheads. For a domain with n MAGs, our scheme achieves $t \times 2^n-$secrecy, whereas existing symmetric polynomial-based authentication schemes achieve only $t-$secrecy. Extensive simulation is performed to show that our scheme can be used with seamless handover, since it results in low authentication delay. In addition, the proposed key establishment scheme achieves lower revocation overhead than that achieved by existing symmetric polynomial-based schemes.

The remainder of the chapter is organized as follows. Section 4.2 reviews the related work. Section 4.3 describes our system models, including network, threat, and trust models, and a review of symmetric polynomials. The proposed scheme is introduced in Section 4.4. The security analysis and performance evaluation are presented in Sections 4.5 and 4.6, respectively. The MA-PMIP scheme is offered in Section 4.7 as a case study. Finally, the summary is presented in Section 4.8.

4.2 Related Work

For the problem of security and authentication schemes for multi-hop wireless networks [91], previous works have mainly focused on two different approaches: 1) end-to-end authentication, which employs a relay node (RN) to only forward the authentication credentials between mobile node and the infrastructure; and 2) hop-by-hop authentication, which implements authentication algorithms between each pair of hops. Following the first approach, in [92] the MN uses a trusted delegation entity and its public key certificate to authenticate itself to the foreign gateway. On the other hand, the scheme in [93] uses both a symmetric key for authenticating an MN to its home network, and a public key for mutual authentication between home network and foreign network. However, the expensive computation involved with public key operations tends to increase the end-to-end delay.

Conversely, a symmetric key-based authentication scheme for multi-hop Mobile IP is proposed in [94]. In that work, an MN authenticates itself to its home authentication server (HAAA) using the extensible authentication protocol [95]. After a successful authentication, the HAAA derives a group of keys to be used by the MN, including a shared master key, extensible master key, and foreign MIP key. Despite the low computation and communication overheads, the symmetric key-based schemes cannot achieve as strong levels of authentication as those achieved by public key-based schemes. This is because the sharing of the secret key between the two peers increases the chances for adversaries to identify the shared key. Instead, public key-based schemes create a unique secret key for each user; hence, it is more difficult for adversaries to identify the keys.

Following the second approach, a mutual authentication that depends on both secret splitting and self-certified schemes is proposed in [96]. However, both schemes are prone to DoS attacks. Another scheme for hop-by-hop authentication, called Alpha, is presented in [97]. In Alpha, the MN signs the messages using a hash chain element as the key for signing, and then delays the key disclosure until receiving an acknowledgement from the intermediate node. Although Alpha protects the network from insider attacks, it suffers from a high end-to-end delay. A hybrid approach, the adaptive message authentication scheme (AMA), is proposed in [98]. AMA adapts the strength of the security checks depending on the security conditions of the network at the moment of packet forwarding. AMA works under the assumption that the entire network cannot be attacked at the same time. In some spots, the adversary attacks all the transmitted messages, while in other spots there is no attack at all. Consequently, AMA proposes two different modes: a relaxed mode, to be used as default mode, and a check-all mode, which is used when attacking is discovered.

Different from the aforementioned authentication schemes, in this chapter we propose a light-weight mutual authentication scheme, EM^3A, to be employed between the mobile node and the relay, which mitigates the high delay that is introduced by previous hop-by-hop schemes. This then means that the proposed scheme can be used with seamless handover operations in multi-hop VANET during the I2V2V communications, as illustrated in Section 4.7.

4.3 System Model

4.3.1 Network and Communication Model

Consider an infrastructure-connected multi-hop mobile network such as that depicted in Figure 4.1. The IP mobility support in MNs is provided by means of an adapted version of PMIP for multi-hop domains [36]. The only modification we introduce to [36] is the strict requirement for the MN to first connect directly to a MAG in order to obtain a valid IP prefix in the domain. Once an MN joins the domain for the first time, it sends Router Solicitation(RS) messages, which are employed by the MAG as a hint for detecting the new connection. After the PMIP signalling has been completed, the MAG announces the IP prefix in a unicast RA message delivered to the MN over the one-hop connection. After that, the MN may eventually divert to use an RN to reach the fixed network. We also assume that, after authenticating them, legitimate nodes in the PMIP domain faithfully follow the routing protocol when they are selected to provide their relay services for another MN in their surroundings.

The multi-hop communications that are studied in our system model are those occurring between MN and RN, when the MN intends to maintain a connection to the infrastructure. Applications of multi-hop mobile networks have been largely studied not only for vehicular communications networks, but also for wireless personal area networks [99], and wireless local area networks [100].

4.3.2 Threat and Trust Models

We consider both internal and external adversaries. Internal adversaries are legitimate users who exploit their legitimacy to harm other users. Thus, having the same capabilities as the legitimate users, internal adversaries have authorized credentials that can be used in the PMIP domain. Two types of internal adversaries are defined: impersonation and colluder. The former impersonates another MN's identity and sends neighbor discovery messages, such as Router Solicitation, through the relay node. The latter colludes with other domain users using their authorized credentials in order to identify the shared secret key between two legitimate users.

In the case of external adversaries, these are unauthorized users who aim at identifying the secret key and breaking the authentication scheme. These adversaries have high-quality monitoring devices so they can eavesdrop on messages transmitted between an MN and an RN. Moreover, they can inject their own messages and delete other authorized user's transmitted messages as well. We consider replay, MITM, and DoS attacks as external adversaries. The goal of the MITM and replay attacks is to identify a shared key between two legitimate users, while the goal of the DoS attack is to exhaust the system resources following a kind of irrational attack. DoS attackers can also be considered as internal adversaries when the attacker is one of the legitimate nodes.

In our model, we consider the LMA and all MAGs in the domain to be trusted entities. An MN trusts its first attached MAG in such a way that this MAG does not reveal the MN's evaluated domain polynomial, which is used by the MN to create shared keys with relay nodes. In addition, the MN trusts the LMA that maintains the secret domain polynomial, which can be used to reveal the shared keys for all nodes in the network.

4.3.3 Symmetric Polynomials

A symmetric polynomial is defined as any polynomial of two or more variables that achieves the interchangeability property, i.e., $f(x, y) = f(y, x)$. Such a type of mathematical function is often used by key establishment schemes to generate a shared secret key between two entities. A polynomial distributor, such as the access router, securely generates a symmetric polynomial and evaluates this polynomial with each of its users' identities. For example, given two users identities 1 and 2, and the symmetric polynomial $f(x, y) = x^2y^2 + xy + 10$, the resultant evaluation functions are $f(1, y) = y^2 + y + 10$ and $f(2, y) = 4y^2 + 2y + 10$, respectively. Then, the polynomial distributor keeps the original polynomial secured, and sends the evaluated polynomials to each user in a secure way. Afterwards, the two users can share a secret key between them by calculating the evaluation function for each other. Continuing with the previous example, if user 1 evaluates its function $f(1, y)$ for user 2, it obtains $f(1, 2) = 16$. In the same way, if user 2 evaluates the function $f(2, y)$ for user 1, it obtains $f(2, 1) = 16$. Therefore, both users share a secret key, 16, without transmitting any additional messages to each other.

New decentralized key generation schemes are proposed in [89], [90] to generate a shared secret key between two arbitrary MNs that are located in two heterogeneous networks.

These schemes achieve $t-$secrecy level, where t represents the degree of the generated polynomial. A scheme with $t-$secrecy property can be broken if $t+1$ users collude to reveal the secret polynomial. Moreover, for only one MN's revocation, the decentralized schemes require changing the entire system's keys, which leads to a high communication overhead. Later in section 4.6, we show how EM^3A reduces the revocation overhead, and increases the achieved secrecy level.

4.4 Efficient Mutual Multi-hop Mobile Authentication Scheme (EM^3A)

EM^3A consists of three main phases: a key establishment phase, for establishing and distributing keys; a mobile node registration phase, for MN's first attachment to the PMIP domain; and an authentication phase, for mutually authenticating the MN and RN.

4.4.1 Key Establishment Phase

Considering a unique identity for each MAG, the LMA maintains a list of those identities and distributes them to all legitimate users in the PMIP domain. The MAGs list's size depends on the number of MAGs in the domain. For n MAGs, each legitimate MN requires $(n \times \log n)$ bits to store this list. We argue that such storage space can be adequately found in mobile networks, such as vehicular networks. The LMA is also authorized to replace the identity of any MAG with another unique identity (this is specially useful for the management of MN's revocation, as it will be illustrated in Section 4.4.4).

Each MAG in the domain generates a four-variable symmetric polynomial $f(w, x, y, z)$, which we call the network polynomial, and then sends this polynomial to the LMA in its domain. After collecting all network polynomials, $f_i(w, x, y, z), i = 1, 2, ...n$, from every MAGs $(MAG_1, MAG_2, ..., MAG_n)$, the LMA computes the domain polynomial, $F(w, x, y, z)$, as follows:

$$F(w, x, y, z) = \sum_{i \in_R n}^{l} f_i(w, x, y, z), 2 \leq l \leq n \tag{4.1}$$

where n is the number of MAGs in the domain. The LMA randomly chooses and sums l network polynomials from the received n polynomials in order to construct the domain polynomial. The reason for not summing all the network polynomials is twofold: increasing the secrecy of the scheme from $t-$secrecy to $t \times 2^n-$secrecy, and decreasing the revocation overhead at the time of MN's revocation. After constructing the domain polynomial $F(w, x, y, z)$, the LMA evaluates it for each MAGs identity, ID_{MAG}, individually. The LMA then securely sends to each MAG its corresponding evaluated polynomial. Later on, the evaluated polynomials, $F(ID_{MAGi}, x, y, z)$, with $i = 1, 2, ..., n$, are used to generate shared secret keys among arbitrary nodes in the domain.

4.4.2 MN Registration Phase

When an MN first joins the PMIP domain, it authenticates itself to the MAG to which it is directly connected. This initial authentication may be done using any existing authentication schemes, such as RSA. After guaranteeing the MN's credentials, the first-attached MAG securely replies by evaluating its domain polynomial, $F(ID_{MAG}, x, y, z)$, using the MN's identity, to obtain $F(ID_{MAG}, ID_{MN}, y, z)$. Afterwards, the LMA also sends the list of current MAGs's identities to the MN.

The MN stores the received list along with the identity of its first-attached MAG (ID_{FMAG}). As a result, a mobile node a can establish a shared secret key with another mobile node b in the same PMIP domain, by evaluating its received polynomial, $F(ID_{FMAGa}, ID_a, y, z)$, to obtain $F(ID_{FMAGa}, ID_a, ID_{FMAGb}, ID_b)$. Similarly, b evaluates its received polynomial, $F(ID_{FMAGb}, ID_b, y, z)$, to obtain $F(ID_{FMAGb}, ID_b, ID_{FMAGa}, ID_a)$. Since the domain polynomial, F, is a symmetric polynomial, the two evaluated polynomials result in the same value and they represent the shared secret key between mobile nodes a and b, K_{a-b}.

4.4.3 Authentication Phase

Figure 4.2 illustrates the MN-RN authentication phase. When an MN roams to a relayed connection, the neighbor discovery messages for movement detection in the multi-hop-enabled PMIP scheme must go through an RN. The goal of the authentication phase is to support mutual authentication between the roaming MN and the RN. After a successful authentication phase, the RN ensures that the MN is a legitimate user, and the MN ensures that the RN is a legitimate relay. The authentication phase is composed of the three stages described as below.

MN initialization:

The MN sends a Router Solicitation (RS) or Neighbor Solicitation message that includes its identity and its first attached MAG's identity, $ID_{FMAG-MN}$. Therefore, the intended RN checks its stored MAGs list to see if $ID_{FMAG-MN}$ is currently a valid identity. If there is no identity equals to $ID_{FMAG-MN}$, the RN rejects the MN and assumes it is a revoked or malicious node. Otherwise, if $ID_{FMAG-MN}$ is a valid identity, the RN continues with the next step to check the MN's authenticity.

Challenge generation:

By using the MN's identity and $ID_{FMAG-MN}$, the RN generates the shared key K_{MN-RN} as described in the registration phase. The RN then constructs a challenge message, which includes its own identity, ID_{RN}, the MN's identity, a random number $Nonce_{RN}$, and a time stamp t_{RN}. Finally, the RN encrypts the challenge message using the shared key, K_{MN-RN}, and sends it, along with ID_{RN} and its first attached MAG's identity, $ID_{FMAG-RN}$, to the MN.

Response generation:

After receiving the challenge message, the MN checks $ID_{FMAG-RN}$ using its stored MAGs' identities list. When guaranteeing that $ID_{FMAG-RN}$ is a valid identity, the MN reconstructs the shared key, by using the RN's identity and $ID_{FMAG-RN}$, and then decrypts the received challenge message. The MN accepts the RN as a legitimate relay if the RN's decrypted identity is the same as the identity received with the challenge message, i.e., ID_{RN}. The MN then constructs a reply message, which includes RN's identity, $Nonce_{RN}$, t_{RN}, a new random number $Nonce_{MN}$, and a time stamp t_{MN}. The MN encrypts the reply message using the shared key, and sends it to the RN, which decrypts the message and accepts the MN as legitimate user if the decrypted $Nonce_{RN}$ equals to the original random number that the RN sent in the challenge message.

Once the authentication phase is completed, the neighbor discovery messages are properly forwarded toward the MAG, which allows for the multi-hop-enabled PMIP to continue its operation as described in [36] and maintain seamless communications. In Figure 4.2, Enc(K, M) represents an encryption operation of a message M using a key K. In addition, the Router-Solicitation, Challenge, and Reply are the three messages transmitted between the MN and the RN.

4.4.4 Mobile Node Revocation

To achieve backward secrecy, EM^3A should guarantee that a revoked MN does not use any of its previous shared keys to deceive the RN. When an MN is revoked, the LMA replaces this MN's first-attached MAG's identity, $ID_{FMAG-MN}$, with another unique identity,

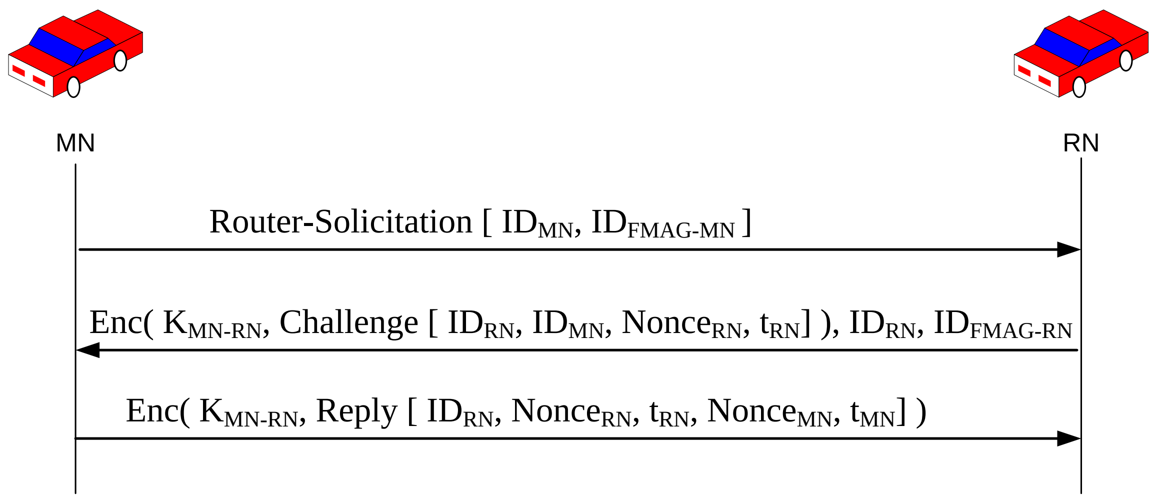


Figure 4.2: EM^3A authentication phase.

ID_{NFMAG}, and sends the new identity to all legitimate nodes in the domain. Subsequently, each legitimate node updates its stored MAGs list by replacing the old identity with the new one. The LMA also sends a message to each MAG in the domain, which includes a list of the mobile nodes that have ID_{NFMAG} as their first-attached MAG's identity, along with an evaluated polynomial, $F(ID_{NFMAG}, x, y, z)$, for the FMAG's new identity. Afterwards, the MAGs send the evaluated polynomial for those MNs that are in the received list and under MAGs' coverage areas. Eventually, each mobile node, in the MNs list, receives a new evaluated polynomial, $F(ID_{NMAG}, ID_{MN}, y, z)$, for both its identity and the new first-attached MAG's identity. Therefore, instead of changing the entire domain keys, only the MNs that share the same $ID_{FMAG-MN}$ need to change their evaluated polynomials and keys.

Figure 4.3 shows an example of the revocation operation. Consider a revoked MN_4 with a first-attached MAG as MAG_3. Three main messages are transmitted. The LMA first changes the MAG_3 identity to MAG_{03} and then broadcasts the new identity to all MNs in the domain. The second message transmitted from the LMA to all MAGs and it includes the new evaluated polynomial with the new identity, $F(ID_{MAG03}, x, y, z)$, along with the MNs that share the MAG_3 as their first-attached MAG. in the Figure, MN_2, MN_5, and MN_{10} are those intended nodes. Note that the nodes sharing the first-attached

MAG may not be located under the same MAG's control, therefore the LMA sends the second message to all MAGs. Finally, the last message is transmitted from the MAGs to those intended nodes, MN_2, MN_5, and MN_{10}.

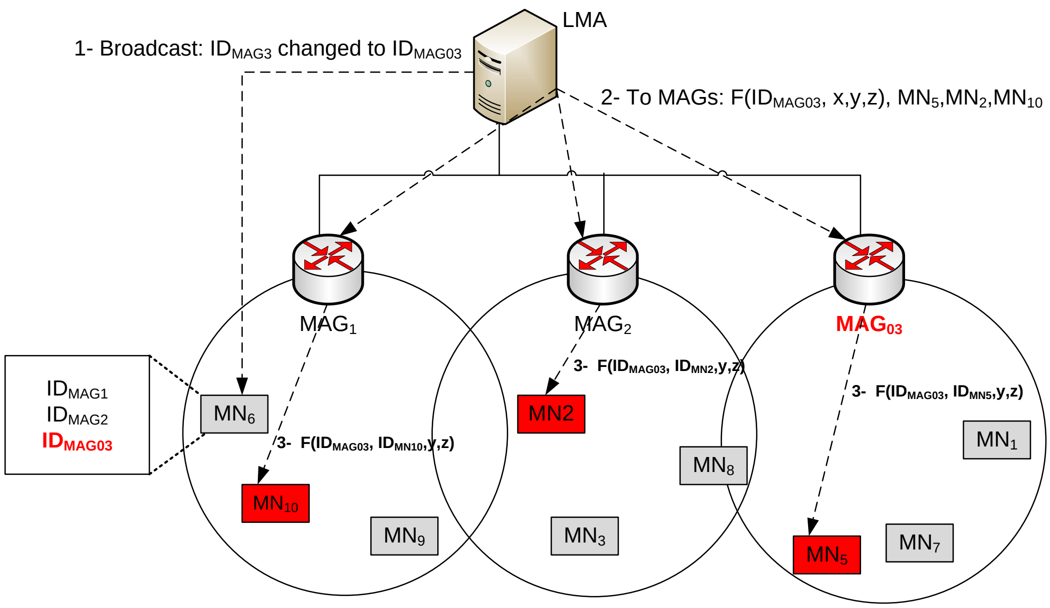


Figure 4.3: EM^3A MN Revocation.

4.5 Security Analysis

The security of our proposed scheme is based on the secrecy level of the key establishment phase proposed in Section 4.4.1. Therefore, in the following subsections we compute the security level of EM^3A scheme, and show that it thwarts both the internal and external adversaries defined in Section 4.3.2.

4.5.1 Internal Adversaries

The proposed EM^3A authentication scheme thwarts impersonation attacks by using a shared secret key, which is only known by the two communicating entities. To illustrate this, consider an adversary A, which aims at impersonating an MN in order to join a new MAG through an RN, and illegally benefit from the domain services. First, A sends an RS message and attaches the MN's identity, ID_{MN}. The RN replies with a challenge message, which is encrypted by the shared key K_{MN-RN}. In order to pass the authentication check, A needs to decrypt the challenge message and identify the RN's random number, $Nonce_{RN}$, which is included in the encrypted challenge message. However, A cannot reconstruct the shared key by using only the identities of the MN and RN. In addition to the identities, the adversary needs to know one of the evaluated polynomials, $F(FMAG_{MN}, ID_{MN}, y, z)$ or $F(FMAG_{RN}, ID_{RN}, y, z)$. Since the evaluated polynomials are secret, it is impossible for an impersonation adversary to break EM^3A.

Moreover, EM^3A mitigates the impact of a collusion attack by increasing the secrecy of the proposed key establishment scheme. Generally, a $t-$degree symmetric polynomial allows for a $t-$secrecy scheme, which means that $t+1$ colluders are needed to identify the secret polynomial and reconstruct the whole system's keys. However, in EM^3A, the domain polynomial is constructed as in (4.1), where the LMA randomly selects a group of the network polynomials to calculate the domain polynomial. Considering the following theorem, we show that at least $t \times 2^n + 1$ colluders must collude to break our authentication scheme.

Theorem 3. *The proposed key establishment in EM^3A scheme achieves $t \times 2^n$ secrecy level.*

Proof. If we consider the secrecy of each network polynomial as t, then the secrecy s of the domain polynomial can be computed as follows:

$$\begin{aligned} s &= \sum_{k=2}^{n} \binom{n}{k} \times t \\ &= t \times \sum_{k=0}^{n} \binom{n}{k} - [\binom{n}{0} + \binom{n}{1}] \\ &= t \times [2^n - (1+n)] \\ &\simeq t \times 2^n \end{aligned} \tag{4.2}$$

where n is the number of MAGs in the domain and t is the degree of network polynomials. Since the secrecy increases from t to $t \times 2^n$, the number of colluders that can break the scheme also increases from $t+1$ to $(t \times 2^n) + 1$. □

To show the significance of increasing the secrecy level, consider a PMIP domain with 10 MAGs and a symmetric polynomial of degree 10. On one hand, in traditional symmetric polynomial based key establishment schemes, only 11 colluders $(t+1)$ can break the system by revealing the used secret polynomial. On the other hand, in our scheme, EM^3A, the number of colluders increases to be 1001 $((t \times 2^n) + 1)$, which is 10-doubles of the original colluders. Consequently, as a way to impede the colluder attacks in our scheme, t is chosen to be a large number, and n should be preferably large.

4.5.2 External Adversaries

Similar to impersonation attacks, DoS attackers may trigger forged RS messages in order to exhaust the RN and MAG resources. Without EM^3A, the RN forwards all RS messages to the MAG and facilitates the DoS attack. However, using EM^3A, a DoS adversary A should know a valid shared key, K_{MN_i-RN}, in order for the RN to forward the RS message. Since A is an external adversary, it cannot construct any key, even if it knows the identity of a legitimate MN. On the other hand, A may repeat one of the RS messages that have been previously transmitted by a legitimated user, in order to trigger a replay attack. However, EM^3A thwarts this attack by adding both time-stamps and random nonces for each transmitted message between the MN and the RN. Finally, A may trigger an MITM attack in order to impersonate an MN or an RN. However, given that both the challenge and reply messages are encrypted, A cannot replace the MN or RN identities. Once more, A would need to know the shared key first in order to perform such attack.

4.6 Performance Evaluation

4.6.1 Computation and Communication Overheads

In this section, we evaluate the EM^3A scheme compared to previous multi-hop authentication schemes. Tables 4.1 and 4.2 show the computation and communication overheads for EM^3A comparisons. T represents the required time for an operation and B represents the transmitted bytes. Our scheme has the smallest computation overhead among other schemes, because EM^3A requires only two symmetric-key encryption operations ($2 \times T_c$). Both the AMA [98] and GMSP [93] require time for signing and verifying signatures (T_s, T_v), hence their computation overheads are higher than that in EM^3A. Like our proposed scheme, the multi-hop MIP scheme [94] consumes little time in computation; however, it requires high communication overhead to exchange a large number of keys. Moreover, ALPHA [97] requires an extra time ($T_{disclose}$) to delay the disclosure of the secret key. We employ Crypto++ benchmark [83] to compare the cost of each scheme. We use AES and RSA 1024 symmetric and public key operations respectively, in order to calculate the computation time required by the different schemes. The Round Trip Time (RTT) considered between vehicle and relay node is 5ms.

Table 4.1: EM^3A Computation Overhead.

Scheme	Computation overhead	Time(ms)
AMA [98]	$T_s + T_v \times Pr_{check}$	2.55
GMSP [93]	$T_s + T_v + T_c$	2.60
Multi-hop MIP [94]	$T_c + T_{EAP}$	.0194
ALPHA [97]	$T_c + T_{disclose}$	7.5094
EM^3A	$2 \times T_c$	.0194

Considering the communication overhead perspective, we observe that AMA, GMSP, and multi-hop MIP require transmission of a sender certificate in each transmitted message. Instead, the EM^3A scheme exchanges the list of MAGs only once at the key establishment phase, and the challenge/response messages ($B_{CHL-RESP}$) during handovers. The average length of the X.509 certificate is 3500 bytes, while the list of MAGs has a length of $n \log_2 n$ bits, where n is the number of MAGs in the PMIP domain. Therefore, in order for EM^3A to have a higher communication overhead than that in the other schemes, it would have to satisfy the condition $n \log_2 n \geq 28000 bits \times m$, where m is the number of transmitted messages in the certificate-based schemes. Consequently, n should be at least $236.64\sqrt{m}$ to satisfy such a condition. However, since n is a fixed value, and m increases over time with the length of active sessions, n becomes much smaller than m with time. Therefore, the condition cannot be satisfied and EM^3A's communication overhead is clearly lower when compared with the certificate-based schemes. Even when a lightweight certificate is used instead of the X.509 certificate, the EM^3A communication overhead is still lower than those with certificate-based schemes where certificates need to be appended to each message transmitted to different relay in the network. Note that ALPHA [97] results in the smallest communication overhead, but it suffers from a $T_{disclose}$ delay in the computation overhead, which is required before disclosing the secret key.

4.6.2 Simulation Results

We evaluate the impact of EM^3A in the overall performance of the network when an MN experiences handovers that involve the use of RNs. Experiments were conducted through

Table 4.2: EM^3A Communication Overhead.

Scheme	Communication Overhead
AMA [98]	B_{cert}
GMSP [93]	B_{cert}
Multi-hop MIP [94]	$B_{EAP} + B_{key-exchange}$
ALPHA [97]	$B_{ACK} + B_{disclose}$
EM^3A	$B_{FMAGs-list}$

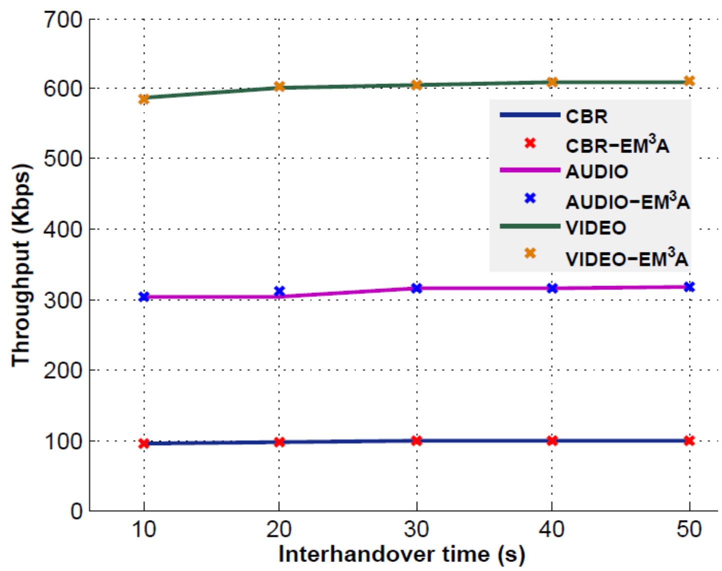
simulations using OMNET++ tool. The RTT between LMA and MAGs is fixed to 10ms. A server for the downloading of data traffic is located in an external network, so that RTT between server and LMA is 20ms. The MN is moving at different speeds that cause the frequency of handovers to vary from one every 10s to one every 50s (i.e., highly dynamic and slow changing scenarios). We consider the worst-case scenario in which every time the MN handovers to a new MAG, it first connects to an RN, so that EM^3A authentication is required before the exchange of neighbor discovery packets and PMIP signalling may happen. Other details of the simulation parameters are provided in Table 4.3.

Table 4.3: PMIPv6 Network Simulation Parameters.

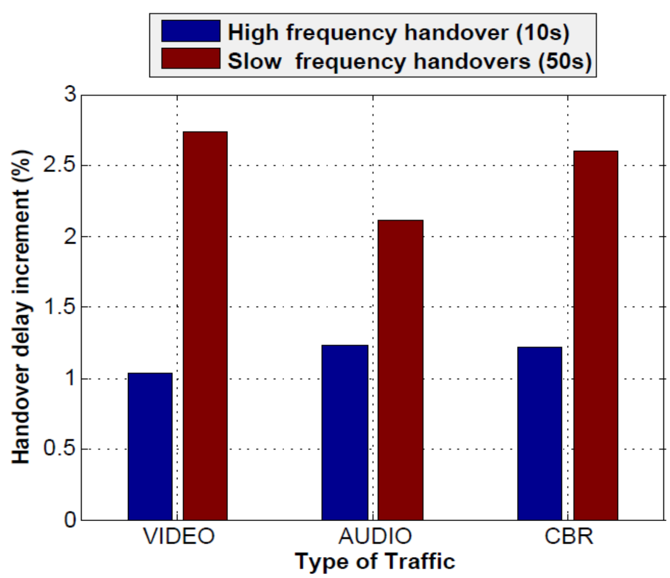
PHY Layer	2.4GHz, 5.5Mbps, 100mW Tx power, -110dBm sensitivity
MAC Layer	802.11 ad hoc mode, 150m radio range
Traffic type/rates	UDP / VBR video (mean 600Kbps),
	VBR audio (mean 320Kbps), CBR best effort 100Kbps
Session time	∼3min

Figure 4.4(a) shows the average throughput obtained for the multi-hop-enabled PMIP, when the EM^3A scheme is de-activated and activated respectively. It can be observed that the authentication scheme does not impact communications negatively, and that the achieved performance is almost equivalent to that achieved when no authentication has been activated. Thanks to the registration phase, which is executed when every node first joins the PMIP domain. At the moment of handover, EM^3A requires only one RTT between MN and RN before allowing for the continuation of normal handover signalling (i.e., the forwarding of RS from MN to MAG, the PMIP signalling between MAG and LMA, and the router advertisement message sent back to MN). The downside of such registration phase is the overhead and storage required for sending and maintaining the list of current identities for all the MAGs in the domain.

To better illustrate the impact of EM^3A, we provide the details for the handover delay

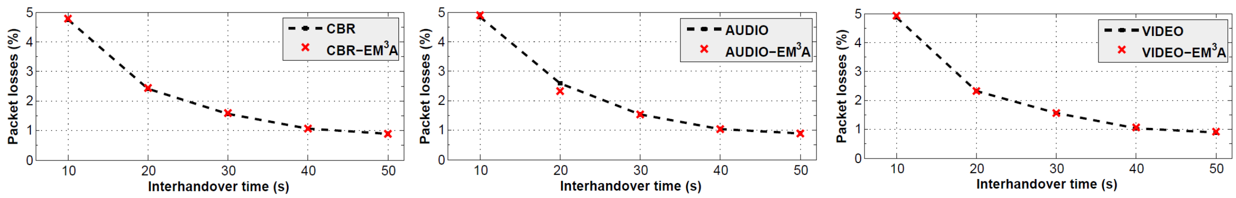


(a) Average throughput.



(b) Handover delay increase.

Figure 4.4: Comparison of performance between EM^3A and non-secure multi-hop-enabled PMIP.



(a) Packet losses for CBR traffic. (b) Packet losses for VBR audio traffic. (c) Packet losses for VBR video traffic.

Figure 4.5: Average packet losses obtained by EM^3A compared to non-secure multi-hop-enabled PMIP.

obtained during highly dynamic and slowly-changing scenarios in Figure 4.4(b). When the EM^3A has been activated , the delay increases by ∼1.1% and ∼ 2.5% in each scenario. Consequently, the low computation overhead of the symmetric key encryption/decryption operations makes the authentication process a light-weight mechanism for securely using multi-hop communications in PMIP domains.

Figure 4.5 illustrates the performance of the network in terms of packet losses for real time (audio and video) and best effort traffic. In general, the employment of the authentication scheme does not present a major impact compared to non-secure multi-hop PMIP. In the most demanding scenario, where handovers occur every 10s, a low 0.03% average increment among the three types of traffic results from the delay caused by the processing of EM^3A traffic. In the case of medium-to-slow changing scenarios, packet losses remain as low as 1%, and EM^3A accounts only for a 0.01% increment.

4.7 Case Study: MA-PMIP for Asymmetric VANET

Multi-hop Authenticated PMIP (MA-PMIP) for Asymmetric VANETs [87] is a new proposed scheme in which we demonstrate that multi-hop paths are useful tools for improving the performance of infotainment applications and Internet access in vehicular environments. Moreover, different from previous works that assume symmetric links among all wireless devices, we handle asymmetric links, and demonstrate that multi-hop communications are key for avoiding service breakage in the asymmetric VANET. In addition, and most importantly, we implement our efficient and mutual authentication scheme, EM^3A, and deal with the proposed MA-PMIP scheme to thwart authentication attacks when handovers occur through I2V2V communications.

The aforementioned contributions comprise the design goals of our Multi-hop Authenticated Proxy Mobile IP (MA-PMIP) scheme, which to the best of our knowledge, is the first to combine a predictive IP mobility scheme designed for multi-hop asymmetric VANET, with the security issues of employing I2V2V communications. In the following subsections, we first explain the network model for the MA-PMIP, then we briefly explain the handover operation through I2V2V communications in MA-PMIP, and finally we evaluate the computation overhead of our authentication scheme when implemented with MA-PMIP comparing to other previous schemes. For more detail about the novel MA-PMIP scheme, the reader is referred to [87].

4.7.1 MA-PMIP Network Model

We consider a vehicular communications network such as the one shown in Figure 4.6. Connections to the infrastructure are enabled by means of road-side Access Routers (ARs), each one in charge of a different wireless access network. Vehicles are equipped with wireless interfaces, as well as GPS systems that feed a location service from which the location of vehicles is obtained. Beacon messages are employed by vehicles to inform about their location, direction, speed, acceleration, and traffic events to their neighbors.

The ARs employ a higher transmission power than the one employed by vehicles. Therefore, we consider the presence of asymmetric links in the VANET. The delivery of packets is assisted by a geographic routing protocol. To serve this protocol, a location server stores the location of vehicles, and is available for providing updated responses to queries made by the nodes' geo-networking layer. In order to forward packets within the multi-hop VANET, a virtual link between AR and vehicle is created [56]. That means that a georouting header is appended to each packet, where the location and geo-identifier of the recipient are indicated. In this way, the geo-routing layer is in charge of the hop-by-hop forwarding through multi-hop paths, with no need of processing the IP headers at the intermediate vehicles.

The ARs service areas are well-defined by the network operator. A well-defined area means that messages from ARs to the VANET are only forwarded within a certain geographic region [45]. Each AR announces its services in geocast beacon messages with the flag AccessRouter activated. The beacons are forwarded through multi-hop paths as long as the hops are located inside the coordinates indicated by the geocast packet header. In this way, vehicles in the connected VANET can extract information from the geocast header, such as AR's location, AR's geo-identifier, and the service area limiting coordinates. We assume the infrastructure is a planned network with non-overlapping and consecutive service areas. Note that, although service areas are consecutive, some locations within them are not reachable through one-hop connections. This may be caused by weak channel conditions, and by the asymmetric links between ARs and vehicles.

To ensure the proper operation of the geo-routing protocol and MA-PMIP, it is required to maintain state information at the entities exchanging IP packets. The following are the required data structures:

Neighbors Table: stores information about the neighboring nodes. The table indicates a link type unidirectional or bidirectional for each neighbor. A node detects the bidirectional links in the following way: incoming links are verified when beacon messages are received from neighbors (i.e., this node can hear its neighbors); outward links are verified by checking the neighbors' locations and the node's transmission power, in order to calculate if such neighbors are inside the radio range (i.e., the neighbors can hear this node).

Default gateway table: stores information about the AR in the current service area. It contains the AR's geo-identifier and the service area coordinates. If the destination of a packet is an external node, the geographic routing forwards the packet toward the default gateway indicated in this table. Then, the AR routes the packet to its final destination.

We only consider IP-based applications accessed from the VANET. Such applications are hosted in external networks that may be private (for dedicated content), or public, such as the Internet. Since we have selected PMIP for handling the IP mobility in the network, all the ARs are assumed to belong to a single PMIP domain. The AR and MAG are co-located in our model. Therefore, the terms AR and MAG are used interchangeably in the following sections.

Unlike [45], in our scheme the AR does not send Router Advertisement (RA) messages announcing the IP prefix to vehicles in the service area. Instead, when a vehicle joins the network for the first time, individual IP prefixes are allocated through PMIP. It is required by MA-PMIP to obtain this initial IP configuration only when a one-hop connection exists between vehicle and MAG, so that authentication material is securely exchanged for future handovers of the vehicle over multi-hop paths. Note that a one-hop connection between two nodes is only established when a bidirectional link exists between them.

4.7.2 MA-PMIP Handover Operation

The signalling of MA-PMIP for initial IP configuration follows the standard PMIP. Once the vehicle joins the domain for the first time, it sends Router Solicitation(RS) messages, which are employed by the MAG as a hint for detecting the new connection. After the

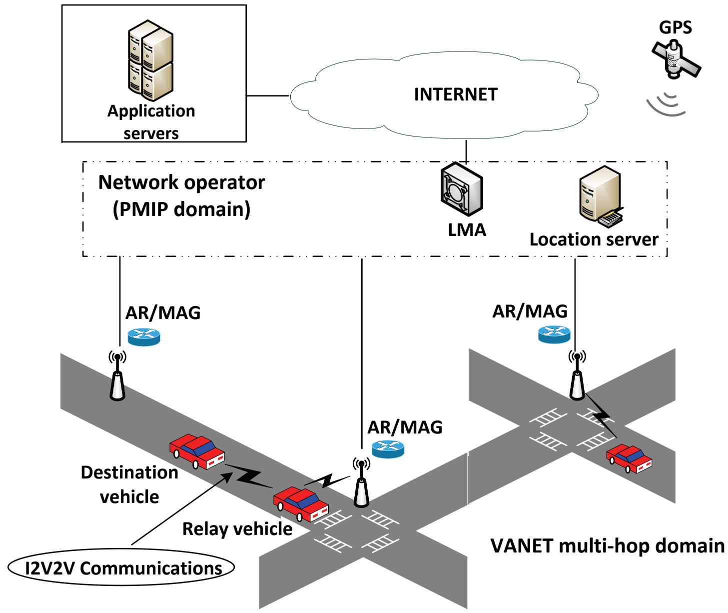


Figure 4.6: MA-PMIP network model.

PMIP signalling has been completed, the MAG announces the IP prefix in a unicast RA message delivered to the vehicle over the one-hop connection.

Figure 4.7 shows the basic MA-PMIP signalling employed when a vehicle experiences a handover through a relay. The movement detection could be triggered by any of the following events: 1) the vehicle has started receiving AR geocast messages with a geo-identifier different from the one registered in the default gateway table; or 2) the vehicle has detected its current location falls outside the service area of the registered AR. If the vehicle loses one-hop connection toward the MAG, but is still inside the registered service area, then no IP mobility signalling is required and packets are forwarded by means of the geo-routing protocol.

After movement detection, the RS message is an indicator for others (i.e., relay vehicle and MAG) of the vehicle's intention to re-establish a connection in the PMIP domain. Thus, an authentication is required to ensure that both mobile router and relay are legitimate and are not performing any of the attacks described in Section 4.3.2. Therefore, we apply our proposed EM^3A scheme explained in Section 4.4 to implement the authentication required in MA-PMIP. Once the nodes are authenticated, the RS packet is forwarded until it reaches the MAG, and the PMIP signalling is completed in order to maintain the IP assignment at the vehicles new location. To take advantage of the location information in VANET, we propose a prediction mechanism that enables a timely handover procedure. It consists of an estimation of the time at which the vehicle will move to a new service area.

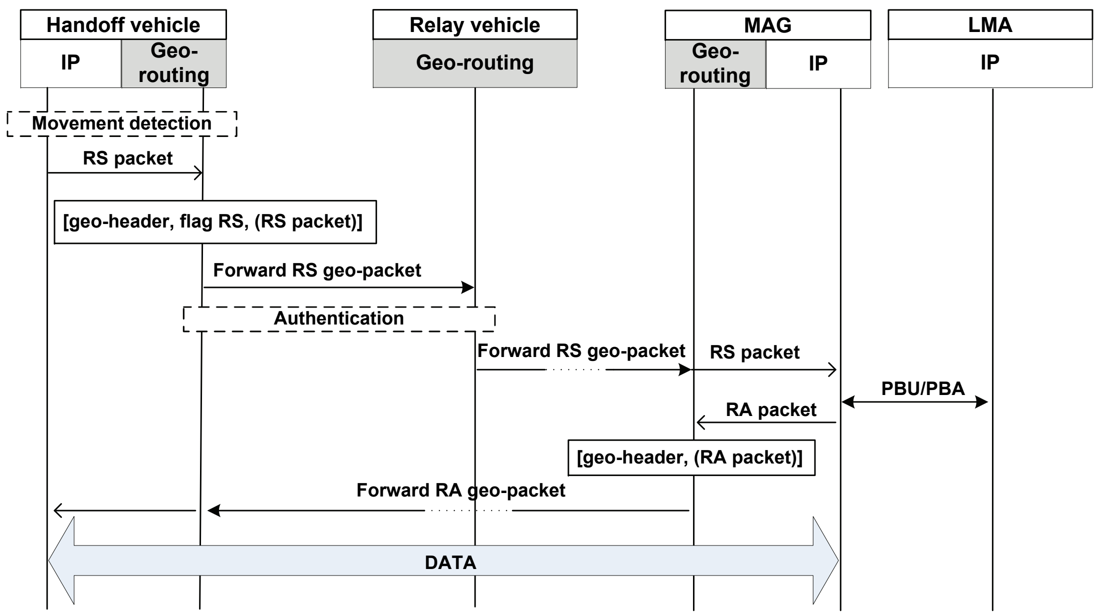


Figure 4.7: MA-PMIP handover through I2V2V communications.

4.7.3 Authentication Evaluations

To measure and compare the impact of the MA-PMIP authentication mechanism, we have integrated an implementation of AMA [98], with a simplified version of a multi-hop PMIP scheme (i.e., MA-PMIP with our proposed authentication mechanism disabled).

Figure 4.8 shows the authentication delay when the vehicle moves at different average speeds. Figure 4.9 depicts the comparison in terms of authentication overhead to payload ratio. As shown in both figures, MA-PMIP not only requires smaller delay and communication overhead than Multi-hop PMIP & AMA, but also has almost fixed impact for different speeds. On the other hand, Multi-hop PMIP & AMA have authentication delay and communication overheads that increase almost linearly with speed. Compared with Multihop PMIP & AMA, MA-PMIP achieves 99.6% and 96.8% reductions in authentication delay and communication overhead, respectively. The reason for these reductions is the high computation and communication efficiency achieved by our proposed authentication scheme. Therefore, unlike Multi-hop PMIP & AMA, MA-PMIP can be used with seamless mobile applications, such as VoIP and video streaming. Figure 4.10 shows a comparison between our proposed authentication scheme. Therefore, unlike Multi-hop PMIP & AMA, MA-PMIP can be used with seamless mobile applications, such as VoIP and video streaming.

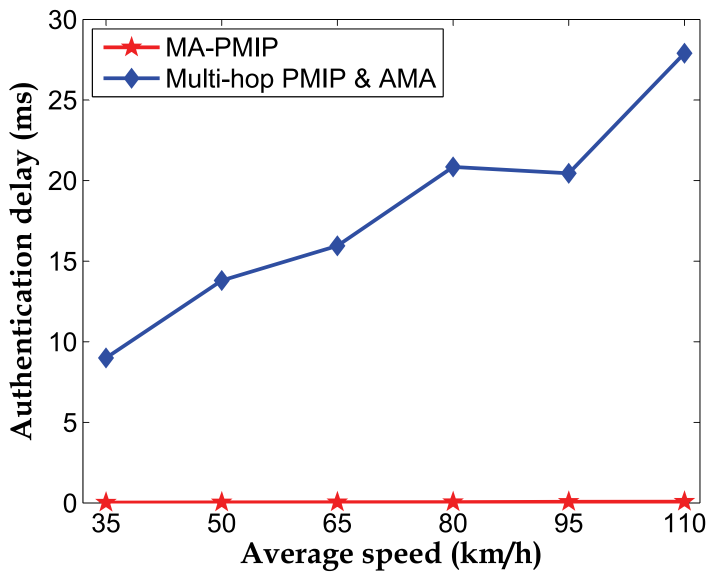


Figure 4.8: MA-PMIP authentication delay

4.8 Summary

In this chapter, an efficient authentication scheme, EM^3A, has been proposed to be employed between a mobile node and a relay node in a multi-hop-enabled PMIP domain. With EM^3A, both the mobile node and relay node guarantee the legitimacy of each other, and construct a shared key using a novel proposed symmetric polynomial-based key establishment scheme.

The multi-hop communications that are studied in our system model are those occurring between MN and RN, when the MN intends to maintain a connection to the infrastructure. In such a multi-hop communication, both MN and RN relate to the same PMIP

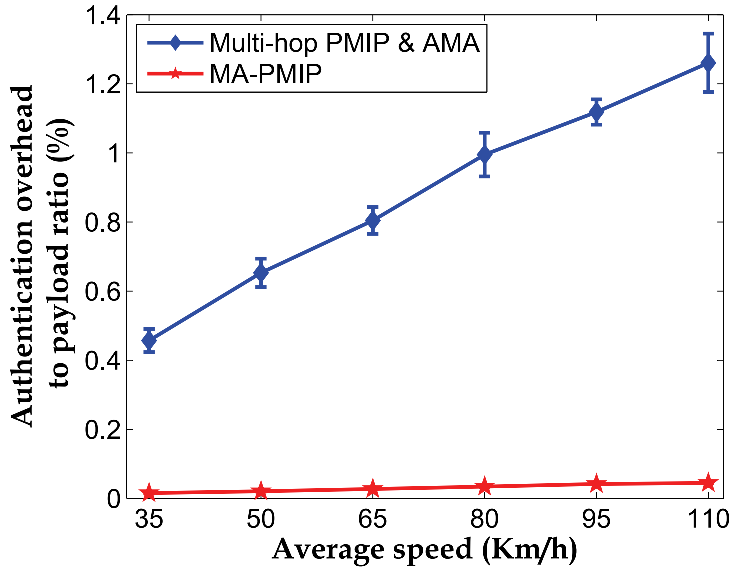


Figure 4.9: MA-PMIP communication overhead.

domain while there is no pre-security association between them. Therefor, we employ the symmetric polynomials to generate a shared key between those arbitrary nodes. Unlike previous symmetric polynomial schemes that are used to generate a shared key between two arbitrary nodes, our proposed scheme increases the secrecy level achieved in the key establishment from t-secrecy to $t \times 2^n$-secrecy. This results in hardening against collusion attacks, which requires at least $t \times 2^n + 1$ colluders rather than just $t + 1$ to reveal the shared key and break the secure system.

Furthermore, we have mitigated the problem of mobile node's revocation by proposing new security steps that also achieve mobile node backward secrecy. Compared to the traditional revocation that changes all system keys, our revocation changes only the keys of the mobile nodes sharing the same first attached mobile access gateway (MAG). However, the trade-off is to store an MAG's list of identities in each authenticated mobile node.

From a security analysis perspective, we show that EM^3A thwarts internal adversaries, including impersonation and collusion attacks, and external authentication adversaries, including replay, MITM, and DoS attacks. In addition, we show that our proposed scheme achieves a higher secrecy level than that achieved by other symmetric polynomial authentication schemes, and lower computation and communication overheads than those achieved by multi-hop authentication schemes. By means of simulations, we have shown that EM^3A

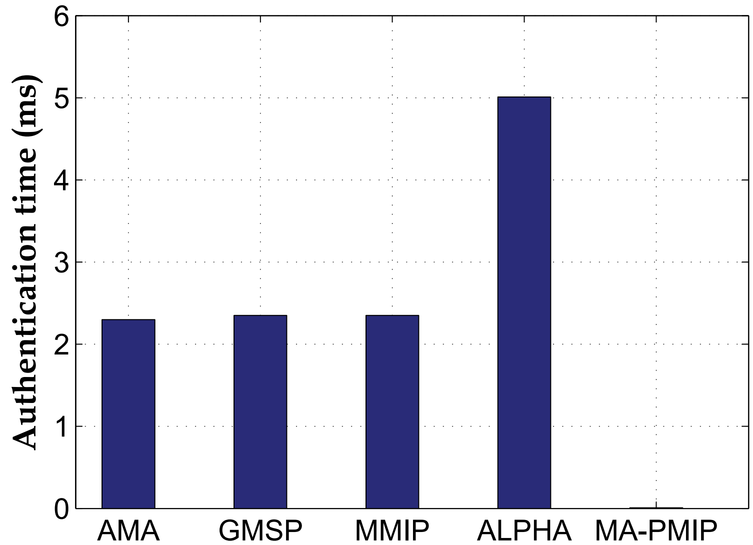


Figure 4.10: Comparison of computation time

results in a low delay and allows for seamless communications, even in highly mobile/highly traffic-demanding scenarios.

To show the impact of our proposed scheme, we present a case study implemented in vehicular networks, which is a proposed authentication multi-hop PMIP scheme, MA-PMIP. We have implemented the EM^3A in the multi-hop communication of the proposed MA-PMIP scheme. Compared to the AMA-PMIP that employed another authentication scheme (AMA), our MA-PMIP protocol with EM^3A achieves 99.6% and 96.8% reductions in authentication delay and communication overhead, respectively.

Although it offers high network-performance when employed with multi-hop vehicular networks, PMIP is not as popular a protocol for ITS as is the NEMO protocol. Therefore, in the next chapter we consider a new security problem that occurs in mobile public hotspots in NEMO-based VANETs.

Chapter 5

A Physical-layer Location Privacy-Preserving Scheme for Mobile Public Hotspots in a NEMO-based VANET

5.1 Introduction

As an extension of MIPv6, NEMO protocol works appropriately for a scenario such as the one depicted in Figure 5.1, where a Wi-Fi hotspot is deployed in a large van (bus, train, plane) and called a NEMO-based VANET [7, 58, 101, 102]. In such networks, the OBU inside a vehicle also works as a Mobile Router (MR) to support a group of Mobile Network Nodes (MNNs) located inside the vehicle with required communications.

In this chapter, we modify the ideas of obfuscation and power variability to propose a strong physical-layer location privacy scheme, the fake point-cluster based scheme, that can be used in public hotspots for NEMO-based VANET. To the best of our knowledge, the fake point-cluster based scheme is the first to apply obfuscation, *i.e.,* concealing, to a user's location by an exact location rather than a wide area. Unlike existing obfuscation schemes, which are employed in the current Location Based Service (LBS), our proposed scheme thwarts such a physical-layer attacker who tries to exploit the high-accuracy positioning schemes to define the sender's exact location. In addition, unlike current power variability schemes, our scheme changes the signal's power with respect to a specific reference point

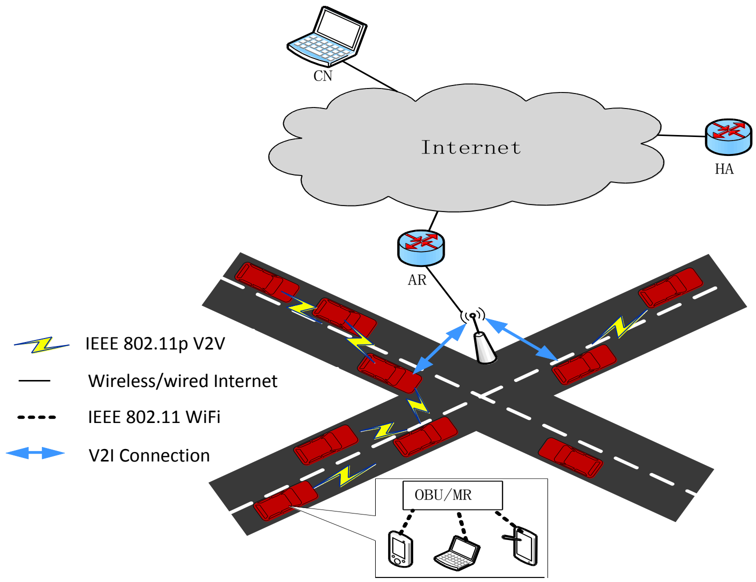


Figure 5.1: NEMO-based VANET.

that we call a fake point, therefore, it is difficult to mitigate the impact of the power variabilities.

The fake point-cluster based scheme combines two independent sub-schemes: fake point and cluster based. The idea of the fake point sub-scheme is that each sender selects and considers a random point inside the hotspot, called fake point, when calculating the packet transmission power. Therefore, when many senders select the same fake point, the attacker's received signals strengths measured for different senders will be equalized. Hence, the attacker is confused and the sender's location privacy is protected because the attacker calculates the sender's location wrongly. In addition, the cluster-based sub-scheme prevents some of the attacker's monitoring devices from detecting the sender's signals, hence, decreasing the accuracy of the attacker's positioning system.

To analyze our location privacy scheme, we use three different metrics: correctness, accuracy, and certainty. We conclude that the probability of an attacker localizing a sender, when the fake point sub-scheme is employed, decreases as the ratio of the number of attacker's monitoring devices and the number of defined spatial grid points in the network increases, because the possibility that the selected fake point is an attacker's monitoring device's location increases leaving the attacker confused. However, since the number of spatial grid points is always much larger than the number of attacker's monitoring devices, the probability of localizing the sender by an attacker is quite large. Therefore, we combine the proposed cluster based sub-scheme with the fake point sub-scheme to decrease this probability. In addition, using extensive simulations, we show that our fake point-cluster based scheme achieves 23% and 37% decreases in the average sender's power and the MNN-AP routing path length, respectively, over the fake point sub-scheme because in the fake point-cluster based scheme, the MNN selects a nearer fake point located in the neighbor cluster.

The remainder of the chapter is organized as follows. Section 5.2 discusses the wireless position estimation systems as the preliminaries. Section 5.3 reviews the related work. The system model and threat model are presented in Section 5.4. The proposed fake point-cluster based scheme is introduced in Section 5.5. The security analysis and the performance evaluation are introduced in Sections 5.6 and 5.7, respectively. Finally, the chapter summary is presented in Section 5.8.

5.2 Preliminaries

5.2.1 Wireless Position Estimation

Our threat model relates to a physical-layer attacker who exploits positioning systems in order to reveal a sender's physical location from the received signal strength (RSS). Therefore, the wireless positioning systems [103] are illustrated in more detail, in order to more deeply understand the attacker's strategy. In this sub-section, the two steps of the wireless position estimation process, distance measurement and location estimation, are described in detail.

The goal is to accurately estimate the mobile user's location inside a wireless network, such as Wi-Fi or a cellular network, when the user transmits signals. Starting with the distance measurement step, the mobile user's signal parameters are measured and the distances to the sender are estimated at certain reference points distributed across the network. Received signal strength (RSS), time of arrival (ToA), time difference of arrival (TDoA), and angle of arrival (AoA) are examples of the signal parameters. From the attacker's perspective, the RSS parameter is the best to use because unlike other signal parameter, RSS measuring requires only inexpensive equipment [103]. Therefore, in this sub-section, we focus on RSS-based estimation, in which each reference point at distance d from the mobile user measures the received signal power, $\bar{p}(d)$, as follows:

$$\bar{P}(d) = P_0 - 10n \log(d/d_0) \tag{5.1}$$

where P_0 is the received signal power to a known location that is located at distance d_0 from the reference point, and n is the path loss exponent, which depends on the propagation model of the signal in the wireless environment. In addition to the path-loss, the received power signal is also affected by both the shadowing and the fast fading (mutipath). In practice, with a long time interval of the signal observation, the effect of the multipath is excluded. Therefore, the received power is modeled to include the path-loss modeled in (5.1), and the shadowing modeled as a zero mean Gaussian random variable with a variance σ^2. The RSS measurement can be modeled as follows:

$$P(d) \sim N(\bar{P}(d), \sigma^2) \tag{5.2}$$

After measuring the RSS at a reference point i located in (x_i,y_i), the estimated distance, $f_i(x, y)$ to the sender is measured as follows:

$$f_i(x, y) = \sqrt{(x - x_i)^2 + (y - y_i)^2} \tag{5.3}$$

In the second step, location estimation, two techniques for location estimation are defined: 1) mapping (fingerprinting); and 2) geometric and statistical. The mapping techniques rely on an off-line training phase in which a database of different RSS estimations and their correspondent senders' locations is created. Depending on the training phase, a mapping method is used to match a new measured RSS value to entities in the database. In our NEMO-based hotspot, we assume that attackers cannot perform the training phase. Still alternatively, the geometric and statistical techniques can be used. In geometric techniques, the position of the mobile node (MN) can be estimated as the intersection of position circles obtained from RSS measurements that are estimated at different reference points. Since each RSS forms a circle, at least three reference points are needed to define the intersection point. This process is called triangulation, depicted in Figure 5.2. In addition, using the statistical techniques, the location of the MN can be defined as follows:

$$Z = f(x, y) + \eta \tag{5.4}$$

where $Z = [Z_1, Z_2, ..., Z_N]^T$, $f(x, y) = [f_1(x, y), f_2(x, y), ...f_N(x, y)]^T$, and $\eta = (\eta_1, \eta_2, ..., \eta_N)^T$ are the parameters collected from each reference point i as follows:

$$Z_i = f_i(x, y) + \eta_i, i = 1, 2, ...N \tag{5.5}$$

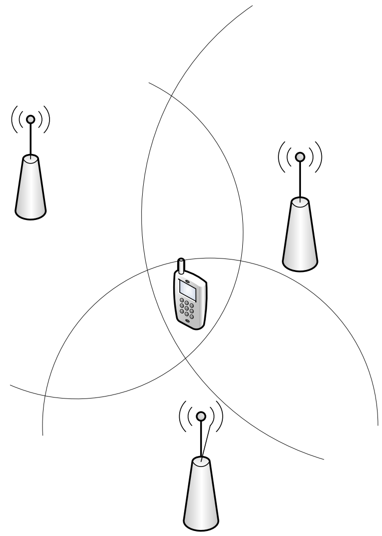


Figure 5.2: Attack triangulation on MNN

where N is the number of reference points, and $f_i(x, y)$ is the distance that a reference point i estimates for the sender location (x, y) by using the measured RSS value as in (5.3), and η_i is the estimation error at this reference point.

After collecting the estimated distances from all reference points, a general estimation $\theta = [x, y]^T$ of an MN's location is calculated. Based on knowledge of the probability density function (pdf) of the estimation error, η, parametric or non-parametric techniques can be used. Non-parametric techniques such as fingerprinting are employed if the error's pdf is not defined, while parametric techniques such as Bayesian and maximum likelihood (ML) estimators are used when the error's pdf is known. The Bayesian approach is used in the presence of a prior pdf on θ, $\pi(\theta)$ in order to minimize the cost function of estimating θ by using either the minimum mean square error, $\hat{\theta}_{MMSE}$, or the maximizing posterior estimations, $\hat{\theta}_{MAP}$ as follows:

$$\hat{\theta}_{MMSE} = E\{\theta \mid Z\} \tag{5.6}$$

$$\hat{\theta}_{MAP} = \arg\max_{\theta} P(Z \mid \theta)\pi(\theta) \tag{5.7}$$

On the other hand, the ML estimation is used when $\pi(\theta)$ is unknown, to maximize the likelihood function.

$$\hat{\theta}_{ML} = \arg\max_{\theta} P(Z \mid \theta) \tag{5.8}$$

$$P(Z \mid \theta) = P_{\eta}(Z - f(x, y) \mid \theta) \tag{5.9}$$

where P_{η} is the conditional pdf of an estimation error condition on θ.

In RSS-based estimation, the error vector is assumed to be independent and is modeled as a zero-mean Gaussian. Therefore, (5.9) can be written as follows:

$$P(Z \mid \theta) = \prod_{i=1}^{N} P_{\eta_i}(Z_i - f_i(x, y) \mid \theta) \tag{5.10}$$

$$P_{\eta_i} = \frac{1}{\sqrt{2\pi}\sigma_i} \exp(-\frac{\eta_i^2}{2\sigma_i^2}) \tag{5.11}$$

$$P(Z \mid \theta) = \frac{1}{(2\pi)^{N/2} \prod_{i=1}^{N} \sigma_i} \exp(-\sum_{i=1}^{N} \frac{\eta_i^2}{2\sigma_i^2}) \tag{5.12}$$

Hence the ML estimator can be calculated as follows:

$$\hat{\theta}_{ML} = \arg\min_{[x,y]^T} \sum_{i=1}^{N} \frac{(Z_i - f_i(x, y))^2}{\sigma_i^2} \tag{5.13}$$

However, if we assume correlated Gaussian error components instead of independent components, the estimated ML can be written as follows:

$$\hat{\theta}_{ML} = \arg\min_{[x,y]^T} (Z - f(x, y))^T \Sigma^{-1} (Z - f(x, y)) \tag{5.14}$$

Figure 5.3 shows the flowchart of an RSS-based positioning system.

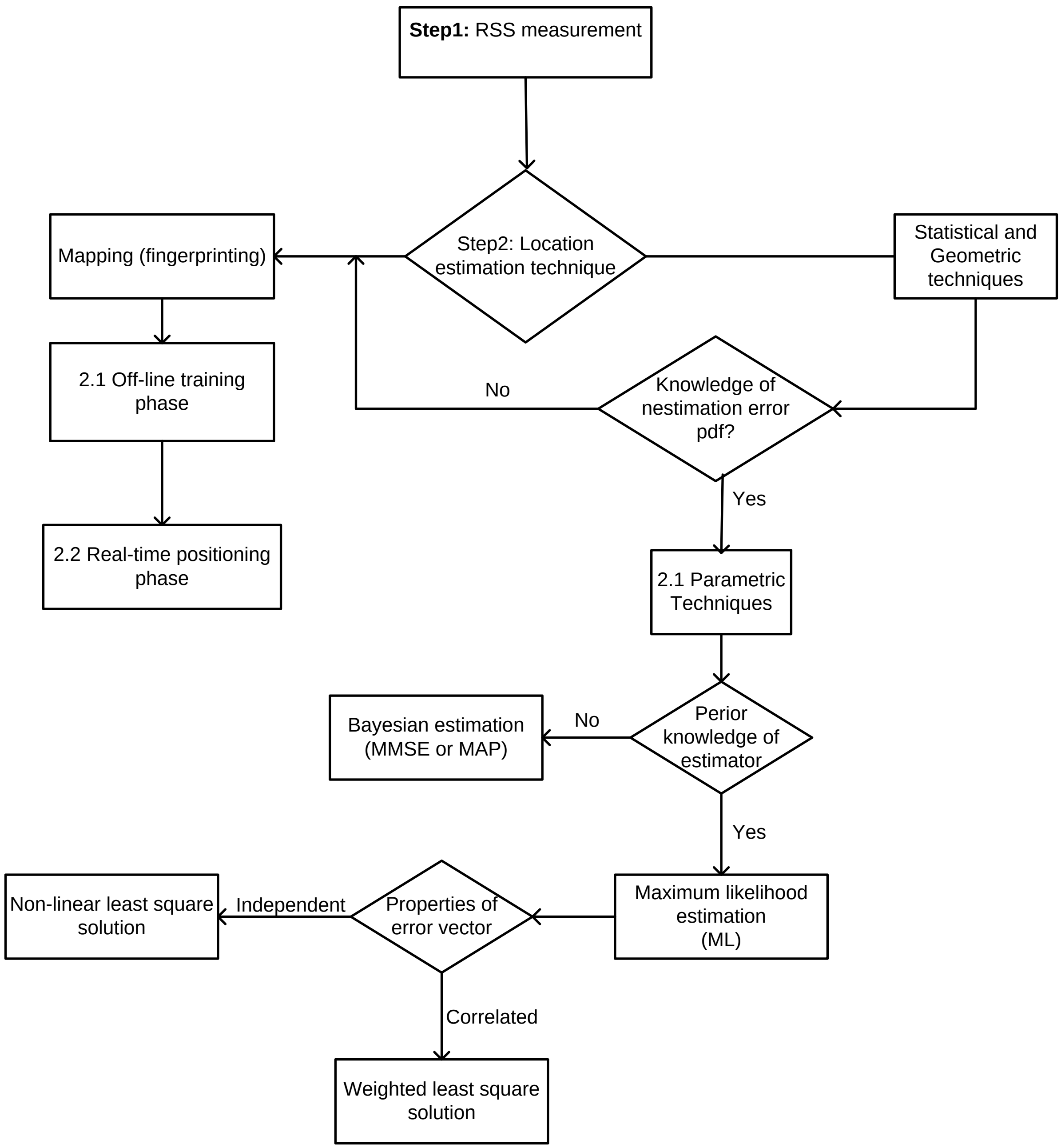


Figure 5.3: Wireless position estimation.

5.3 Related Work

Due to the open nature of wireless networks, hiding the transmitted wireless signals, and hence achieving physical layer location privacy is considered a challenging goal. In location privacy attacks, the attacker localizes the victim MNN by measuring its RSSs at certain reference points, as illustrated in Section 5.2.1. To thwart these attacks, [40] suggests employing a scheme in sensor networks called Hyberloc. In this scheme, the anchor nodes protect their location from the un-trusted nodes, while trusted nodes can easily localize those anchor nodes. The main idea of Hyberloc is to randomly choose a power for transmitting signals and attach this random power value in the transmitted encrypted packets. Therefore, having a shared key, only trusted nodes can identify the true sender's location. However, changing the transmission power values is considered to provide only weak location privacy, because the attacker can easily fix these changes by multiplying the RSS at all monitor devices by a factor. In our proposed scheme, in addition to changing power levels as is done in Hyberloc, we confuse the attacker's monitoring devices by letting their measured RSSs be equalized for different MNNs; therefore, it becomes difficult for the attacker to mitigate the increase in power.

Another scheme, hidden anchor, which relies on adding noise to the transmitted signals, is proposed in [42]. In this scheme, the anchor nodes use their neighbors' identities to hide their own identities from distrusted nodes, and at the same time encrypt and attach their real identities in the transmitted packets sent to trusted nodes. However, changing the nodes' identities does not achieve a sender's physical-layer privacy; rather, it helps in achieving link-layer location privacy. In addition, both anchor and trusted nodes add noise to their transmitted messages in order to prevent un-trusted nodes from measuring the RSSs and revealing their locations. However, adding noise to the transmitted messages affects transmission quality.

Obfuscation, *i.e.,* concealment, proposed in [41], is another way to protect a user's location privacy from location-based servers (LBSs). The idea of the obfuscation is to replace the real location information with fake information in order to decrease the accuracy of the localization process employed by LBS, and hence increase a user's location privacy. Three obfuscation techniques are proposed in [41]: enlarged area, shifted center, and reduced radius. In location-based applications, the user's location returned to the LBS represents an area rather than a specific location, therefore, obfuscation schemes are used to hide the true information about that area. However, these obfuscation schemes are not appropriate for Wi-Fi scenarios where the adversary gets a specific MNN's location rather than an area. In our proposed scheme, we modify the idea of obfuscation in order to return a wrong location point rather than a wide area.

With the goal of achieving obfuscation for users' information, [104] achieves user identity, time, and location obfuscation. User identity obfuscation, concealing the identity, is carried out by frequently changing a user's pseudonymity, while time obfuscation, concealing transmission time, is carried out by applying a silent period to thwart pseudonym correlation attacks. The silent period is defined in such a way as to increase a user's privacy level and hence decrease the positioning system's accuracy. Unlike the identity and time obfuscation that are mainly employed for link-layer obfuscation, location obfuscation is employed to achieve physical-layer location privacy. Assuming a fingerprinting positioning system, [104] achieves location obfuscation by proposing a silent Transmit Power Control (TPC) scheme that reduces transmission power at each user. Therefore, the number of APs that detect the transmitted signals decreases, as does the accuracy of the attacker's localization. The challenge of silent TPC is to allow users to change their transmission power without exchanging any information with their APs. Our proposed cluster-based scheme employs the same idea of TPC to reduce a user's transmission power. However, unlike our proposed scheme, the silent TPC scheme considers location attackers located only in neighbor networks rather than those located in the user's current network.

In [105], two strategies for a user's location privacy have been proposed with a main idea of using a smart antenna that emits a directional radiation pattern instead of using isotropic antennas. In the first strategy, using a smart antenna, the MNN maximizes the transmission power of the signals directed to the AP located in its network while preventing other APs from receiving any signals transmitted from this MNN. Therefore, other APs cannot triangulate this MNN and hence fail to reveal its location. On the other hand, if an MNN fails to prevent at least four APs from receiving its signals, then the MNN tries the second strategy in which the MNN maximizes the RSS localization bias at the APs around this MNN. By increasing the localization bias, the MNN guarantees that its surrounding APs estimate its position wrongly. To achieve the first strategy, the MNN first listens to the periodically received beacon packets that are transmitted by the nearby APs. The MNN then passively measures the RSSs of these beacon packets to estimate the APs' locations. However, if the APs change their power levels, then the MNN cannot estimate their locations and hence fails to protect this MNN's location privacy. In addition, the assumption of having a smart antennas in all MNNs is not reasonable due to their high cost.

In [106], a scheme called silent period is used to achieve physical and link-layer location privacy. It thwarts correlation attacks, so an attacker cannot relate two pseudonyms to the same MNN. A silent period is defined as a constant period, followed by a variable length period, in which an MNN changes its pseudonym and then keeps silent, not sending any messages. When an MNN starts sending frames after the silent period, the attacker cannot correlate between the MNN's new and old pseudonyms. However, this scheme degrades network performance when the MNN stops its transmission for some periods. In addition, a precise duplicate address detection scheme should be employed to ensure that the new pseudonym does not conflict with any other addresses in the network.

Phantom is another scheme proposed in [107], to achieve sender physical-layer location privacy by creating a group of ghost transmitters, which retransmit the original transmitter's messages. Therefore, the attacker that uses an RSS-based fingerprinting localization scheme to localize the original transmitter receives a combination of both original signals and ghost signals. The power of the phantom comes from the inability of the adversary to distinguish between those signals. Although phantom achieves a high level of privacy, it also adds a large overhead when the number of ghosts and hence the energy consumed increase.

5.4 System Models

5.4.1 Network Model

A NEMO-based public hotspot is installed inside a large van, which in turn, constructs VANET communications with its neighbor vehicles, as depicted in Figure 5.1. In addition to running a VANET routing protocol, the OBU of this van also works as a NEMO Mobile Router (MR) and runs a NEMO BS protocol; hence, it is denoted as OBU/MR. Inside the large van, Mobile Network Nodes (MNNs) represent different mobile devices such as cell phones, PDAs, and laptops.

We employ a MANET-centric approach to integrate NEMO and VANET protocols; therefore, only OBU/MR implements a NEMO BS protocol in addition to the MANET routing. All neighbor vehicles that are located on the OBU/MR-RSU path, including the RSU, implement only a MANET routing scheme, such as georouting protocols, as illustrated in Figure 2.6.

The communications among an OBU/MR and MNNs are generally structured using the IEEE 802.11 standard to form a Wi-Fi network, while the communications among OBU/MR and the road-side access points, which are employed to support the OBU/MR with the Internet connectivity, are applied by applying the NEMO BS protocol in VANET. In this paper, we focus on the communications of a vehicle's Wi-Fi network, which indeed are affected by the NEMO-VANET communications outside the vehicle.

Due to the varieties of link-layer connections in NEMO-based VANET, as illustrated in Figure 5.1, three different MR-passengers communications types can be found in the Wi-Fi hotspot: in-vehicle, neighbor vehicles, and nested communications. The in-vehicle communications, the focus of this paper, are constructed among the in-vehicle MR that works as a hotspot's AP and passengers' devices inside the same vehicle. Neighbor vehicle communications can be created among an OBU/MR inside one vehicle and some passengers's devices inside neighbor vehicles. This kind of communication relies on the connectivity between vehicles; however, due to the diversity of vehicles' speeds and mobility models, neighbor communications face connections intermittencies, which lead to a degradation in network performance. Nested communications, also called nested-NEMO, are formed among a vehicle's MR and some passengers' devices under the control of another MR, which in turn, is under the control of this vehicle's MR.

In our model of a hotspot, The OBU/MR is located in the front of the vehicle and controls the whole hotspot, while all other MNNs are located randomly in the van and the transmission power signal of OBU/MR is considered to be much higher than those of MNNs. In addition, considering the same transmission environment for all MNNs, we assume Gaussian noise with zero mean and σ^2 variance for all signals propagated inside the hotspot.

In addition, we assume that the OBU/MR logically divides the hotspots into k grid points, and attaches them to its periodically transmitted beacon, therefore, MNNs inside the hotspot use those grid points to implement our proposed scheme, as illustrated in Section 5.5.

5.4.2 Threat and Trust Models

A passive physical layer location privacy attacker deploys monitoring devices inside the whole network, in order to detect any transmitted signal and estimate the location of the sender using the received signal strength as illustrated in Section 5.2.1. The attacker's monitoring devices are assumed to have high sensing and processing capabilities, and their positions in the network can be changed by the attacker. Using the measured RSSs, each monitoring device estimates and transmits the distance to the intended sender to the attacker. Employing an ML estimation technique, the attacker uses the received distance estimations from all monitoring devices to estimate the exact location of the MNN. For more information about the ML statistical technique, the reader is referred to Section 5.2.1.

To attach itself to a hotspot, each MNN authenticates itself to the hotspot's MR and shares a secret key in order to encrypt its data-link frames, including its MAC address.

Being unable to decrypt the transmitted frames' MAC addresses, the attacker depends only on the RSS measurements to localize the MNN. Many data-link authentication and location privacy schemes [50], [25,108–113] can be used to secure a data-link layer's frames.

To apply a mutual authentication scheme among the MNNs and the OBU/MR, the OBU/MR periodically transmits its public-key certificate inside the hotspot, and we consider that there exists at least one online certificate verification server whom MNNs trust and use to verify the OBU/MR's certificate. Due to the multihoming technology that enables mobile devices to simultanously attach to different networks, the MNNs can access the online certificate verification by an alternative Internet connection other than the mobile hotspot connection. For example, a cell phone can use its cellular network to connect to the Internet and verify the received certificates.

5.5 Fake Point-Cluster based Physical Layer Location Privacy Scheme

The proposed fake point-cluster based scheme is a combination of two sub-schemes, fake point and cluster based, that can be employed individually to provide physical-layer location privacy for MNNs inside a NEMO-based VANET hotspot. The fake point sub-scheme achieves a higher location privacy level if the attacker's monitoring devices are located at the selected fake points' locations, while the cluster based sub-scheme achieves a higher location privacy when preventing attacker's monitoring devices from detecting the transmitted signals. In Section 5.6, we show that the proposed fake point-cluster based scheme increases the MNN's location privacy level. In the next subsections, fake point and cluster-based sub-schemes are presented, and then a scheme for their combination is explained.

5.5.1 Fake Point Location Privacy Sub-Scheme

The proposed fake point location privacy scheme is employed to protect MNNs' physical location privacy from insider passive attacks, which are explained in Section 5.4.2. The main idea is that, inside the hotspot, the MNNs select random locations, called fake points, that are used to confuse the attacker. The MNNs consider these fake points when calculating their transmission signals power. Therefore, if an attacker's monitoring devices are located at these fake points, then the measured RSS values at the monitoring devices are similar for all MNNs selecting the same fake point. In Section 5.6.2, the probability of having at least two MNNs choose the same fake point's location that contains an attacker's monitoring device is calculated. Therefore, these monitoring devices encounter some error when estimating the distances to MNNs. Depending on the error, the overall MNNs' location estimations also have some deviations, and hence the MNNs' location privacy is ensured.

Bootstrapping the hotspot

Working as an AP, the OBU/MR broadcasts inside its network some beacon frames that contain its location, ($X_{OBU/MR}$, $Y_{OBU/MR}$), and a unique received signal power, P_u, that all MNNs in the network must consider when calculating their transmission signal powers. Using the AP's location and the required received power, the MNNs can define the distances to their AP and hence calculate appropriate transmission signal powers. The beacon frames also contain the mobile network prefixes (MNPs) for each MNN to select a unique MNP, and hence to be able to attach to the MENO, AP's certificate (CERT) for the MNNs, to check the authenticity of the AP. An authentication scheme such as in [50] can be used to achieve mutual authentication between MNNs and AP. After successful mutual authentication between the MNN and AP, the AP virtually divides the hotspots into K spatial grid points and securely sends the grid points' list to the authenticated MNN. In the remainder of this chapter, we use AP, OBU/MR, and MR interchangeably to represent the Wi-Fi AP.

MNN attachment

To connect to the available hotspot, the MNN first calculates the distance d_{MNN-AP} to its AP as follows:

$$d_{MNN-AP} = \sqrt{(X_{MNN} - X_{AP})^2 + (Y_{MNN} - Y_{AP})^2} \quad (5.15)$$

where (X_{MNN}, Y_{MNN}) is the MNN's current location measured by the MNN's GPS. Using this calculated distance and the required received power at AP, P_u, the MNN calculates its transmission power,P_{tr}, as follows:

$$P_u = \alpha - 10\beta \log(d_{MNN-AP}) \quad (5.16)$$

where β is the path loss and α is a function of the transmission power P_{tr}. Instead of using the calculated transmission power, P_{tr}, the MNN uses another power, $\acute{P_{tr}}$, calculated related to a fake location that the MNN selects in the next step.

Identifying fake point

Inside its network, the MNN randomly selects a location, which we will call the fake point, from the grid points list that the AP securely sends to the authenticated MNN as mentioned in the Bootstrapping phase. Therefore, the fake point is one of the K spatial grid points that is defined by the AP, and represents a location (x, y) inside the hotspot. Using (5.15), the MNN recalculates its distance to the AP as the sum of the MNN-fake point distance and the fake point-AP distance, and then the MNN employs this distance to recalculate the transmission power ,$\acute{P_{tr}}$ using (5.16). Therefore, the MNN recalculates the transmission power, $\acute{P_{tr}}$, in such a way that the MNN's signal is transmitted first to this fake point then to the AP. However, in our scheme, the MNN does not send its signals to this fake point; rather, it sends the signals directly to its AP. This deceiving action is only to confuse attackers. As depicted in Figure 5.4, the distance between the MNN and its AP, d_{MNN-AP}, is always less than the sum of the distances of MNN-fake point, d_{MNN-F}, and fake point-AP, d_{F-AP}. Consequently the power transmitted from the MNN to the AP directly, P_{tr}, is less than that goes through the fake point, $\acute{P_{tr}}$. The main goal of selecting a fake point in the network is to have a possibility that one of the attacker's monitoring devices is located at this fake point. Therefore, when many MNNs select the same fake point, and an attacker's monitoring device is located in this fake point as depicted in Figure 5.5, the estimated distances calculated by this monitoring device encounter much more estimation error then those calculated by other monitoring devices. Since the measured RSSs at the monitoring device are functions of the distances to the MNN, the recorded error increases as the distance between MNNs that selected the same fake points increases. In Section 5.6, the error encountered at the monitoring devices is measured to show the strength of the MNN's location privacy when using our proposed scheme.

To calculate the transmission signal power, $\acute{P_{tr}}$, the MNN randomly selects a fake point, (X_F, Y_F). Given the received signal power at AP is P_u, the signal power at the fake point, P_{ftr}, can be calculated as follows:

$$P_u = f(P_{ftr}) - 10\beta \log(d_{F-AP}) \tag{5.17}$$

$$d_{F-AP} = \sqrt{(X_F - X_{AP})^2 + (Y_F - Y_{AP})^2} \tag{5.18}$$

The MNN can then calculate the transmitted power to the fake point as follows:

$$P_{ftr} = f(\acute{P_{tr}}) - 10\beta \log(d_{MNN-F}) \tag{5.19}$$

$$d_{MNN-F} = \sqrt{(X_F - X_{MNN})^2 + (Y_F - Y_{MNN})^2} \tag{5.20}$$

The MNN transmits its messages with the new calculated power, $\acute{P_{tr}}$. In addition, the MNN selects a new fake point for each transmitted signal; therefore, the possibility of having the same location as the attacker's location will be increased.

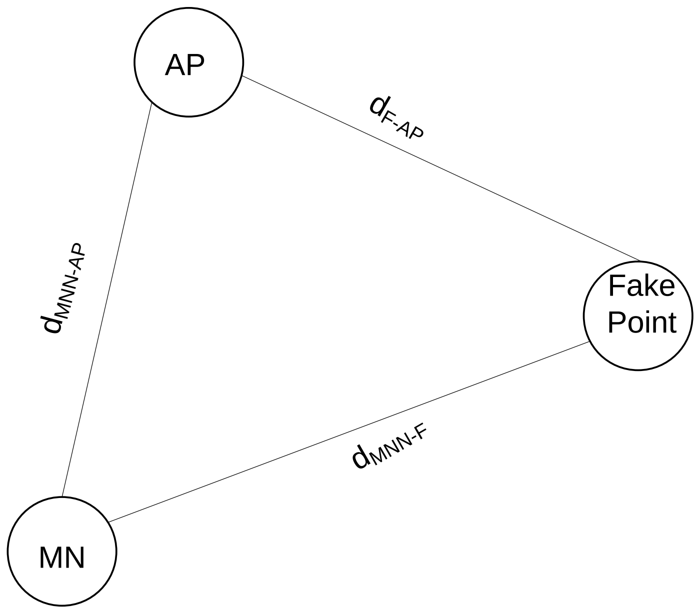


Figure 5.4: Fake point selection

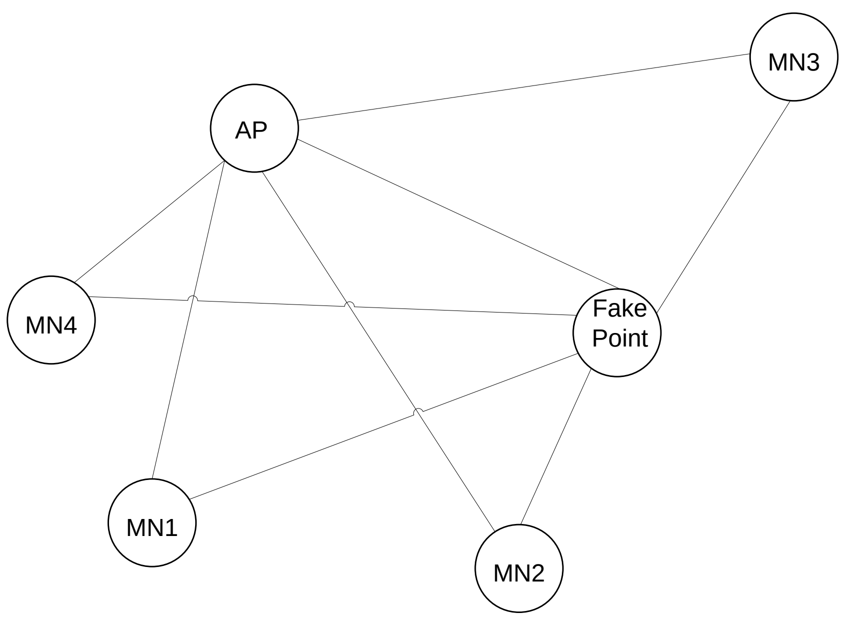


Figure 5.5: MNNs select same fake point

5.5.2 Cluster-based Location Privacy Sub-Scheme

In this sub-section, we propose another sub-scheme to achieve MNN location privacy in NEMO-based VANET. In Section 5.6, we show that the probability of successfully violating the MNN's location privacy, when our proposed fake point sub-scheme is employed, decreases as the ratio (A/K) of the number of the attacker's monitoring devices, A, to the number of defined spatial grid points, K, increases. Since K is always much larger than A, the probability of violating the MNN's location is quite large. Therefore, we propose the second, cluster-based sub-scheme, so when it is combined with the fake point scheme, the probability of violating the MNN's location is decreased. The main idea of the cluster-based sub-scheme is to divide the hotspot area into smaller cells, i.e., clusters, and assign a new AP for each cell. Thus the MNN uses little power value to transmit its messages, and so prevents an attacker's monitoring devices from detecting the MNN's signals. Hence, the attacker cannot employ the positioning scheme to localize the MNN, because the attacker cannot measure the RSS of the undetected transmission signal. The cluster-based sub-scheme consists of three steps: NEMO bootstrapping, MNN attachment, and reference point selection.

NEMO bootstrapping

At the time of constructing the Wi-Fi as NEMO-based VANET communications, the OBU/MR that works as an AP for the whole network divides the network area into smaller n sub-areas called cells, $c_1, c_2, ..., c_n$. For each cell, c_i, the OBU/MR assigns an AP, which is a reference point, RP_i, that works as a local AP for all MNNs located within a distance r around RP_i. Considering each cell's coverage area as a circle, r represents the cell's radius, and we assume that all cells have the same radius, and they may overlap with each other as depicted in Figure 5.6. From an attacker's perspective, we consider that there is at most one attacker's monitoring device in each cell.

MNN attachment

Working as a local AP, each RP broadcasts a beacon packet so only MNNs under its coverage area receive this beacon. The beacon message contains information about the RP, including its identity, ID_{RP}, its coverage area's radius, r, and its required received signal's power, P_{RRP}.

Considering the knowledge of its location, (X_{MNN}, Y_{MNN}), the MNN calculates the transmission signal power for its messages directed to its chosen RP, as follows:

$$FSPL(DB) = 20\log_{10}(r) + 20\log_{10}(f) + 32.45 \tag{5.21}$$

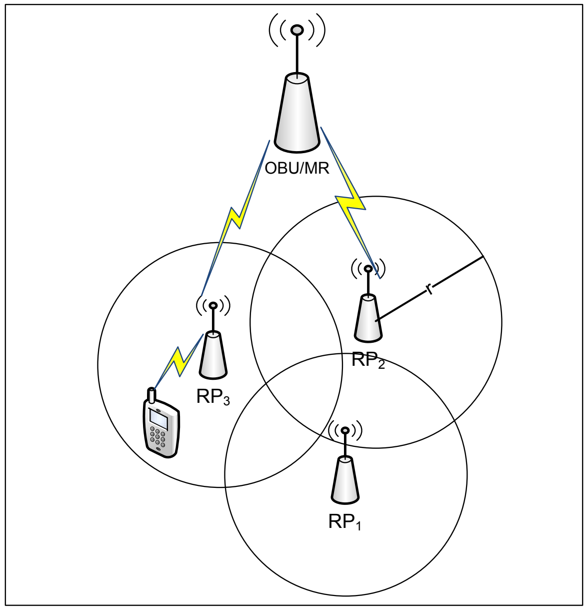


Figure 5.6: Cluster based sub-scheme

$$TP_{MNN} = P_{RRP} \times FSPL \tag{5.22}$$

where $FSPL$ is the free space path loss [114], which depends on the cell's radius in meters, r, and the transmitted signal frequency in megahertz, f.

Reference point selection

When an MNN attaches to the hotspot, it receives m beacons from m different RPs. The MNN sorts the received m beacons' signals' powers, and chooses the RP with the strongest signal to be its local AP. As depicted in Figure 5.6, the MNN transmits all its messages with the calculated low transmission power to the selected RP, which in turn, retransmits the messages to the OBU/MR that works as the hotspot's AP.

5.5.3 Fake Point-Cluster based Location Privacy Scheme

In our cluster based sub-scheme, since clusters can be spatially overlapped, the MNN's transmitted signals may be received by many clusters, not only the intended cluster. Therefore, if one attacker's monitoring device is in each cluster, the monitoring devices in the clusters that receive the MNN's signals can collude to reveal the MNN's location by applying a statistical positioning scheme. To increase the MNN's location privacy, a combination of the fake point based and the cluster based sub-schemes can be applied.

In addition to receiving OBU/MR beacon messages, the MNN also receives some RPs' beacon messages that contain RPs' positions, $\{(X_{RP_1}, YRP_1), (X_{RP_2}, YRP_2), ..., (X_{RP_m}, YRP_m)\}$. After calculating its transmission power as depicted in the cluster-based sub-scheme, the MNN randomly selects a fake point that is located in its cluster.

Using the fake point sub-scheme, the MNN calculates the required power at the fake point and then adjusts its transmit power to this power. Therefore, the MNN confuses some of the attacker's monitoring devices, and hence increases the estimation error resulting from the attacker's monitoring devices' collusion.

This combination between the fake point and the cluster-based sub-schemes prevents some attacker's monitoring devices located inside neighbor clusters from detecting the sender's transmitted signals. In addition, the fake point-cluster based selects a fake point inside the sender's cluster, in order to ensure higher location privacy and consume lower power.

5.6 Analytical Location Privacy Evaluation

In this section, an analytical analysis for the proposed scheme, the fake point-cluster based scheme, is presented. Similar to the evaluation analysis in [115], we employ three metrics: correctness, accuracy, and certainty. Correctness measures the additional estimation error that is added by our proposed scheme; accuracy measures the probability of an attacker's success in breaking the MNN's location privacy, and certainty measures the entropy of the achieved privacy.

5.6.1 Correctness

Fake-point based sub-scheme

When m different MNNs choose the same fake point, which in turn may be a location of an attacker's monitoring device, the attacker estimation error for the MNN's localization increases. Using the signal propagation model from [116], the MNN's RSS can be calculated as follows:

$$RSS = \frac{AP_t}{B + d^\alpha + C(\log_{10} d)^\beta + D} \tag{5.23}$$

where A, B, C, D, α, and β are a signal's parameters that can be estimated by the attacker. However, the attacker cannot estimate the MNN's transmission power, P_t, while the distance, d, to the target MNN is also unknown. Using Frii's formula, P_t can be expressed as:

$$P_t = RSS - G_t - G_r - 20\log_{10}\frac{\lambda}{4\pi d} \tag{5.24}$$

where G_t and G_r are the sending and receiving channel's gains. Therefore, substituting (5.24) in (5.23), RSS can be written as:

$$RSS = \frac{A(G_t + G_r + 20\log_{10}\frac{\lambda}{4\pi d})}{A - B - d^{\alpha} - C(\log_{10} d)^{\beta} - D} \tag{5.25}$$

By (5.25), the attacker can measure the RSS values, RSS_1, RSS_2,...... RSS_m, for m different MNNs that select the same fake point in the fake point sub-scheme, as follows:

$$RSS_i = \frac{A(G_t + G_r + 20\log_{10}\frac{c}{4\pi f d})}{A - B - d^{\alpha} - C(\log_{10} d)^{\beta} - D} \tag{5.26}$$

where c is the speed of light and f is the signal's frequency, which is one of the channel parameters. Assuming 2.4 GHZ is the frequency band that is used in the hotspot, m MNNs select any of the 14 channels that are assigned in this band. The channels' frequency bands are spaced 5 MHZ apart; therefore, the differences in the term $\log_{10}\frac{c}{4\pi f d}$ for each MNN are negligible. Thus, (5.26) yields the same RSS's value for all MNNs that share the same fake point.

From (5.26), the attacker estimates the distance between its location, which is the fake point's location, (x_f, y_f), and the target-point's location, (x_i, y_i) as follows:

$$d_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2} \tag{5.27}$$

Since d_i,$i = 1, 2, ...m$ has the same value and (x_f, y_f) is a fixed point for all MNNs, then the attacker calculates the same estimated location (x_e, y_e) for an MNN_i's true location (x_i, y_i). Hence, (5.4) is expressed as follows:

$$Z_i = d_i + \eta_i + \delta_i, \delta \geq 0 \tag{5.28}$$

where δ_i is a deviation of the estimated distance that is added when applying the fake point sub-scheme. It can be calculated as follows:

$$\delta_i = \frac{|y_i - y_e|}{|x_i - x_e|} \tag{5.29}$$

Therefore, (5.4) changes as follows:

$$Z = d + \eta + \delta, \delta \geq 0 \tag{5.30}$$

The attacker then uses ML estimation as in (5.13) to determine the MNN's position as follows:

$$\begin{aligned} \hat{\theta}_{ML} &= \arg\min_{[x,y]^T} \sum_{i=1}^{N} \frac{(\eta_i + \delta_i)^2}{\sigma_i^2} \\ &= \arg\min_{[x,y]^T} \sum_{i=1}^{N} \frac{\eta_i^2}{\sigma_i^2} + \frac{\delta_i^2 + 2\delta_i\eta_i}{\sigma_i^2} \end{aligned} \tag{5.31}$$

where N is the number of an attacker's monitoring devices. Note that the term $\frac{\delta_i^2+2\delta_i\eta_i}{\sigma_i^2}$ is the added value to the ML estimation. The additional estimation error is called the correctness of the estimated position and, as it increases, the MNN's location privacy increases as well.

Cluster based sub-scheme

The goal of this sub-scheme is to decrease the transmit power by employing transmit power control in such a way that only a small number of an attacker's monitoring devices, L, from all monitor devices, N, can detect the MNN's signal and measure the RSS. Therefore, the attacker calculates the ML estimation as follows:

$$\hat{\theta}_{ML} = \arg\min_{[x,y]^T} \sum_{i=1}^{L} \frac{(z_i - d_i)^2}{\sigma_i^2} \tag{5.32}$$

For $L = 1$, which means only one monitoring device can detect the MNN's signal, (5.32) can be written as:

$$\hat{\theta}_{ML} = \frac{(\eta)^2}{\sigma^2} + \delta_{cluster} \tag{5.33}$$

where $\delta_{cluster}$ is the added estimation error resulting from the lack of information as only one monitoring device measures the MNN's RSS. $\delta_{cluster}$ decreases as the number of monitoring devices increases, which in turn, gives an indication of a lower location privacy level.

Fake point-cluster based scheme Depending on the analysis of both fake point and cluster based sub-schemes, the estimation error for the combination of the two sub-schemes can be expressed as follows:

$$\begin{aligned}\hat{\theta}_{ML} &= \arg\min_{[x,y]^T} \sum_{i=1}^{L} \frac{(z_i - d_i)^2}{\sigma_i^2} \frac{\delta_{cluster}}{L} \\ &= \frac{\delta_{cluster}}{L} \arg\min_{[x,y]^T} \sum_{i=1}^{L} \frac{\eta_i^2}{\sigma_i^2} + \frac{\delta_i^2 + 2\delta_i \eta_i}{\sigma_i^2}\end{aligned} \tag{5.34}$$

5.6.2 Accuracy

In this sub-section, the accuracy of the fake point-cluster based scheme is calculated by measuring the accuracy of the positioning system employed by the attacker. We measure the accuracy of the positioning system by calculating the probability of attacking the hotspot while our proposed scheme is implemented. According to the fake point sub-scheme explained in Section 5.5.1, the accuracy of this sub-scheme depends on the possibility of confusing the attacker by having many MNNs select the same fake point and having an attacker's monitoring device located in this fake point. Assuming that the hotspot is spatially divided into K grid points that the OBU/MR periodically sends to all MNNs, the probability that at least two MNNs select the same fake point from those K points is calculated using the birthday paradox probability as follows:

$$Pr(x \geq 2) = 1 - \frac{K!}{(K-u)!K^u} \tag{5.35}$$

where $u > 1$ is the number of MNNs in the hotspot. In addition, the probability that the selected fake point is an attacker's monitoring device's location is $\frac{A}{K}$, where A is the number of an attacker's monitoring devices in the network. Therefore, combining the two probabilities, the probability that an attacker's monitoring device is located at the fake point's location selected by at least two different MNNs can be calculated as follows:

$$Pr(fake - point) = [1 - \frac{K!}{(K-u)!K^u}] \frac{A}{K} \tag{5.36}$$

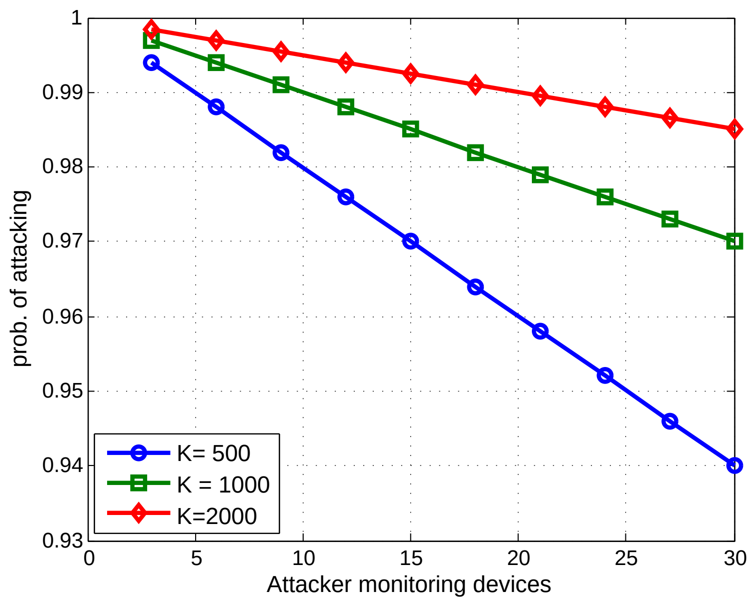


Figure 5.7: Fake point sub-scheme attacking probability.

Since the number of passengers inside the hotspot is always much less than the defined spatial grid points($u \ll K$), we consider $\frac{K!}{(K-u)!K^u} \approx 0$. Therefore, the probability of successfully attacking the hotspot when employing the fake point sub-scheme (Figure 5.7) is calculated as follows:

$$Pr(fake - pointattacking) = 1 - \frac{A}{K} \tag{5.37}$$

As illustrated in the figure, the probability of attacking decreases when the ratio (A/K) of the number of the attacker's monitoring devices, A, to the number of defined spatial grid points, K, increases, because the possibility that the selected fake point is an attacker's monitoring device's location increases and hence the attacker is confused. Intuitively, this ratio increases when A increases and/or K decreases.

For the cluster-based sub-scheme, the number of overlapping clusters, O, that intersect with the MNN's cluster affects the probability of achieving an MN's location privacy. This probability is calculated as follows:

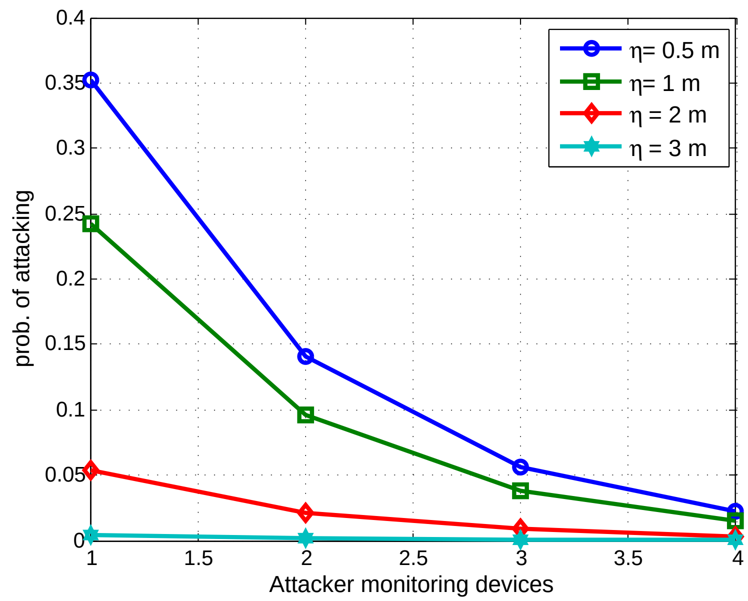


Figure 5.8: Cluster based sub-scheme attacking probability.

$$
\begin{aligned}
Pr(cluster) &= \Pi_{i=1}^{O} P_{\eta_i} \\
&= \Pi_{i=1}^{O} \frac{1}{\sqrt{2\pi}\sigma_i} \exp(-\frac{\eta_i^2}{2\sigma_i^2})
\end{aligned} \tag{5.38}
$$

As shown in Figure 5.8, we define the maximum number of overlapping clusters, and hence number of attacker monitoring devices, as four.

Combining the fake point with cluster-based probabilities, we get the probability of achieving location privacy with a fake point-cluster based scheme as follows:

$$[[1 - \frac{K!}{(K-u)!K^u}]\frac{A}{K}]\Pi_{i=1}^{O} \frac{1}{\sqrt{2\pi}\sigma_i} \exp(-\frac{\eta_i^2}{2\sigma_i^2}) \tag{5.39}$$

Figure 5.9 shows the combination of fake point and cluster-based probabilities.

5.6.3 Certainty

An entropy model measures the uncertainty of an attacker's location privacy scheme, calculated as follows:

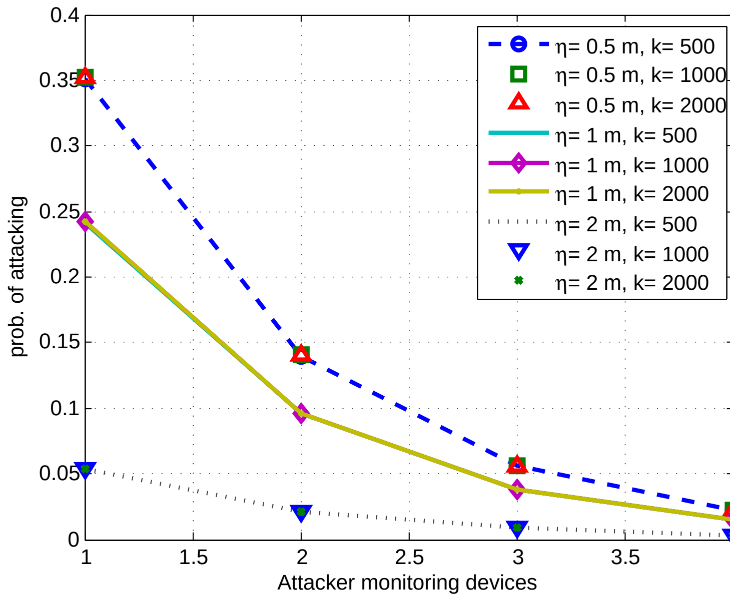


Figure 5.9: Fake point- Cluster based scheme attacking probability.

$$H(x) = \sum_i Pr(x_i) log \frac{1}{Pr(x_i)} \tag{5.40}$$

Therefore, the entropy for our proposed schemes is depicted in Figure 5.10.

5.7 Performance Evaluation

In this section, a simulation has been run to evaluate the performance of the fake point-cluster based scheme. We simulate a $45m \times 45m$ hotspot that is installed inside one of the vehicles connected together to create VANET communications. To simulate the overlapping clusters, a group of reference points has been deployed in such a way that each reference point, RP_i, covers an area of $25m^2$, with one meter overlapping area with each neighbor cluster. The centralized AP as well as all RPs define specific received powers that each MNN must consider while sending its signals to AP or any RP. Table5.1 shows our simulation parameters.

To show the impact of integrating NEMO protocol with VANET, Figure 5.11 presents the total sender's handover time when applying NEMO, MIPv6, and MIPv4 protocols.

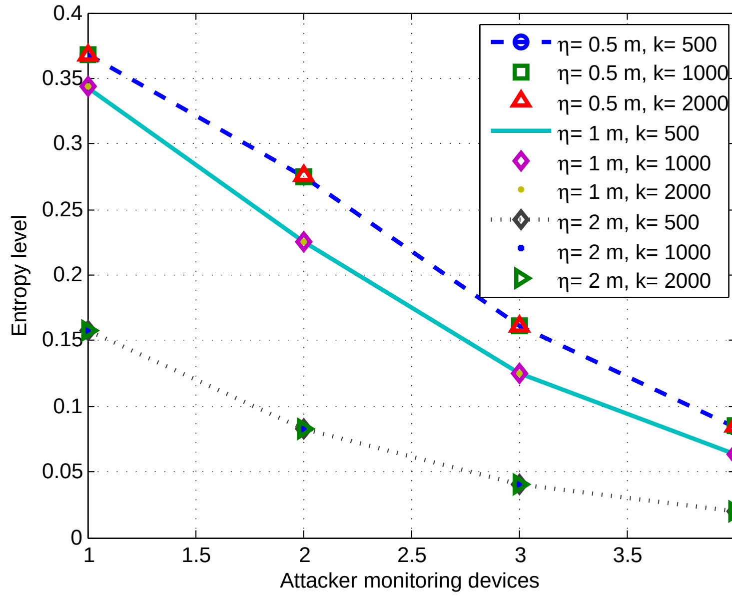


Figure 5.10: Fake Point Cluster based entropy.

Table 5.1: NEMO-based VANET Simulation Parameters.

Road width	$5500m \times 10m$
Road's network size	$1000m \times 10m$
Road's networks number	6
Spatial grid points, K	1000
Vehicles number	36000
WiFi size	$45m \times 45m$
Wi-Fi nodes number	600
Frequency	$2.4GHz$
AP transmission power	$5mW \simeq 7dBm$
cluster area	$25m^2$
AP required received power	$5dBm$
Cluster required received power	$3dBm$
overlapping area among clusters	$1m$
Length of the phy header	$0byte$
Thermal noise	$0dB$

Compared to other mobility protocols, a sender employing NEMO BS protocol requires the smallest handover delay, because only the MR implements the NEMO-BS, hence the delaying cost is distributed over all MNNs inside the Wi-Fi. In addition, this delay constantly increases with the vehicle speeds, allowing our scheme to be used for scalable networks. On the other hand, for the MIPv6 and MIPv4 protocols, the handover delays increase linearly with vehicle speeds, because the number of handovers increases accordingly. The MIPv6

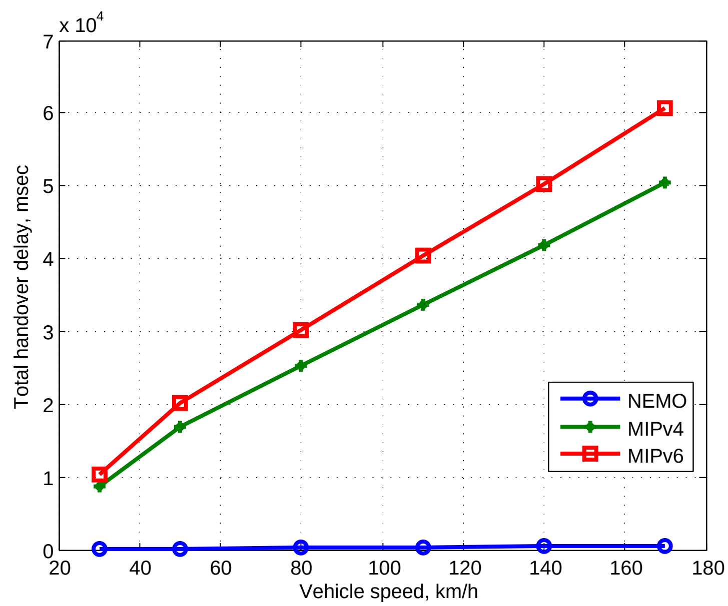


Figure 5.11: Total handover delay.

protocol costs much more delay than that in the MIPv4 protocol, because of the addition of the correspondent binding update messages transmitted to the sender's correspondent nodes.

Calculating the total message's routing delay, Figure 5.12 shows that NEMO protocol achieves 95% and 97% decreases comparing to the delays in MIPv6 and MIPv4, respectively.

Figure 5.13 shows the MNN transmission power for the fake point-cluster based, fake point sub-scheme, cluster based sub-scheme, and the original Wi-Fi communication scheme as a reference. As shown in the figure, the original communication scheme where a fake point-cluster based scheme is not implemented has the smallest transmission power. On the other hand, there is a 65.5% power increase when employing the fake point sub-scheme because the selected fake point can be found very far from the MNN, thus more power at MNN is needed to equalize RSS at this fake point. The power required in the cluster-based sub-scheme depends on the received power at the RP, which is always less than the received power at the AP; therefore, only a 37.5% increase in MNN transmission power is recorded. Compared to the fake point sub-scheme, when combining the fake point sub-scheme with the cluster-based sub-scheme, we get a 23% decrease in the transmission power. The reason for this power saving is that when employing the fake point-cluster based scheme, the MNN

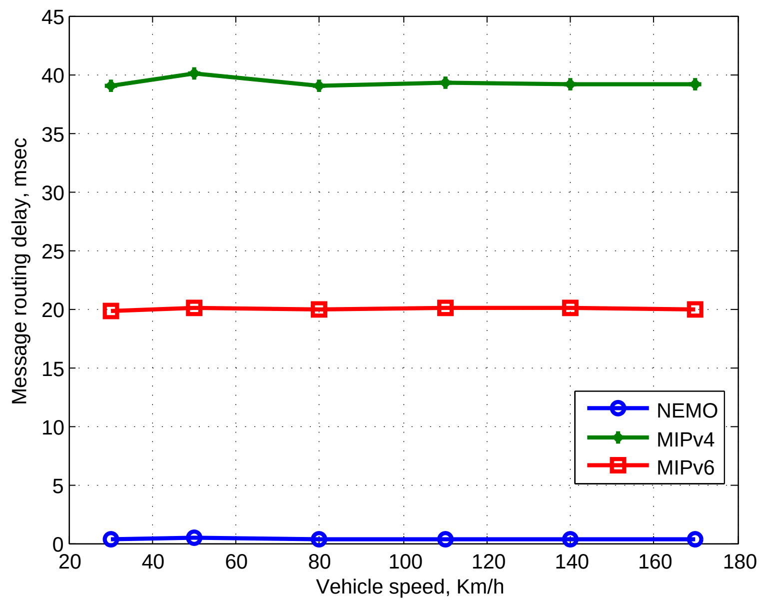


Figure 5.12: Message routing delay.

selects a nearer fake point, located in its cluster.

The distances between MNNs and APs contribute to increasing MNNs' transmission power, as illustrated in Figure 5.14. The shortest distance between MNN and AP, which is employed in an MNN-AP conventional scheme, always requires less transmission power, while the indirect distances from an MNN to the fake point then to the AP, which are employed in our proposed schemes, consume more power. Compared to the reference MNN-AP conventional scheme, the fake point, cluster-based, and fake point-cluster based schemes encounter distance increases of 135%, 17.6%, and 52.9%, respectively.

The increases in distances and powers are our cost to achieve high MNN location privacy. Figure 5.15 shows power consumed at different MNN-AP distances. Our proposed schemes achieve lower power consumptions than that in the conventional scheme at MNN-AP distances less than 5 meters. At such small distances, the location protection is much more important than it is at the large distances where MNNs locations can be revealed easily. Therefore, at lower distances, the fake point-cluster scheme achieves both less power consumption and high location privacy, while the conventional scheme has higher power consumption without protecting the MNN location.

In Section 5.6, we calculate the entropy of our proposed scheme, which relies on the probability that many MNNs have the same fake point. In this section, as shown in Figure

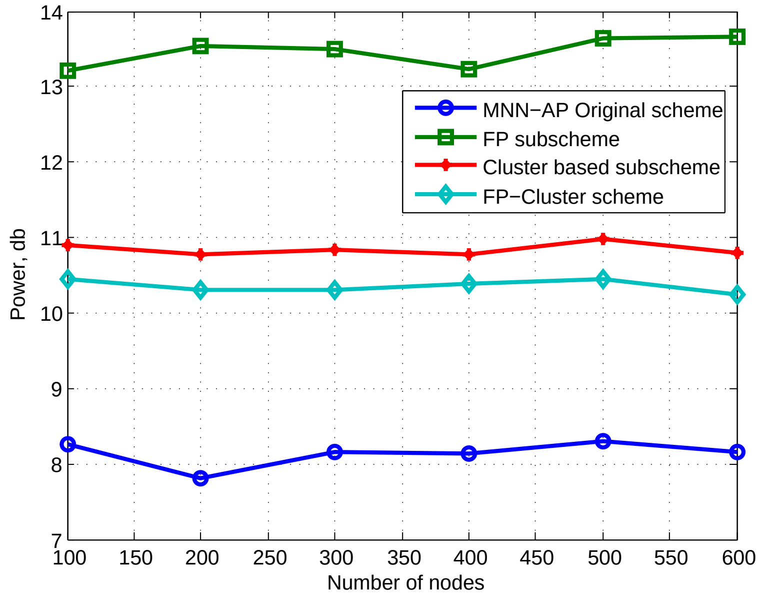


Figure 5.13: MNN transmission power.

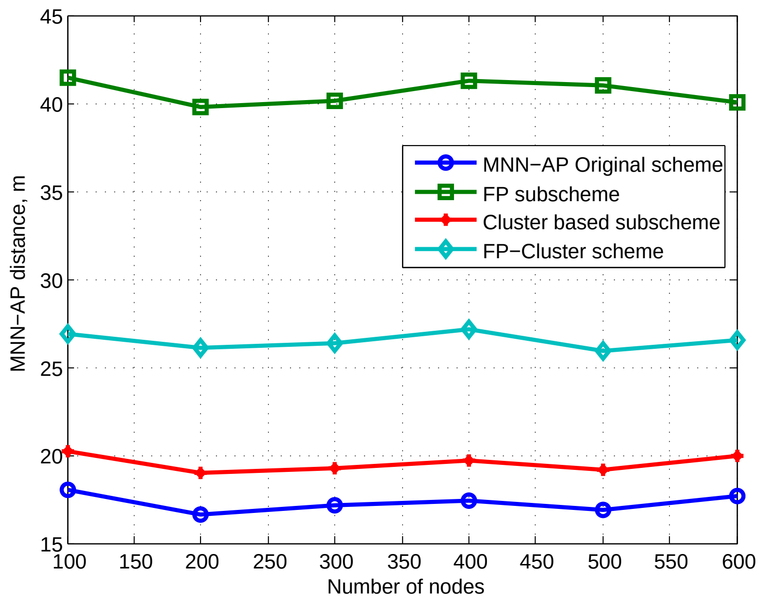


Figure 5.14: MNN-AP route distances.

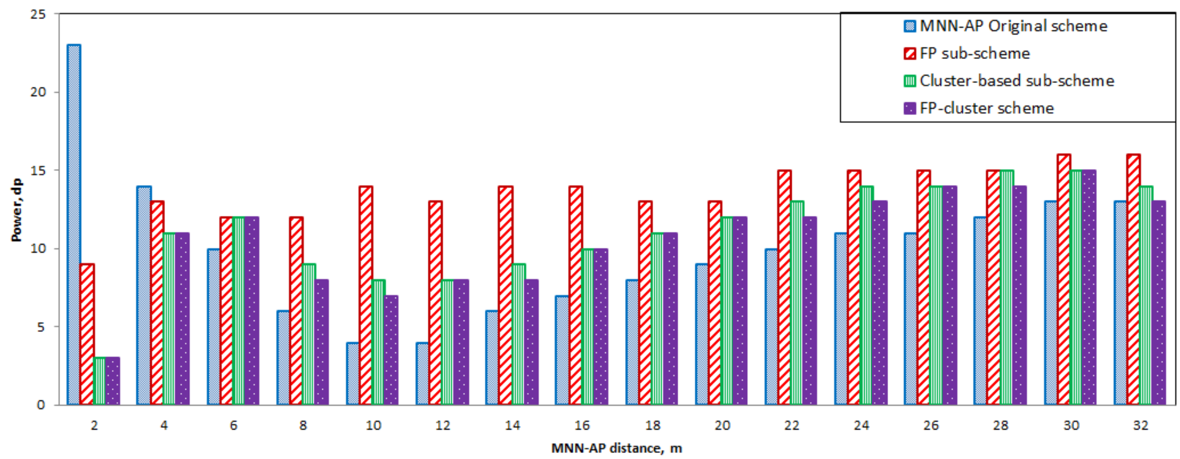


Figure 5.15: Average power consumption at different distances.

5.16 and Figure 5.17, we practically measure the histogram for both the fake point sub-scheme and fake-point cluster scheme, respectively. In Figure 5.16, the number of MNNs that select the same point reaches 6 while in Figure 5.17, it reaches 90 out of 300 MNNs. This difference occurs because in the fake point sub-scheme, each MNN can select its fake point among large varieties of fake points that are distributed all over the network, while in the fake point-cluster based scheme, these varieties have shrunk to only fake points in neighbor clusters. Therefore, the fake point-cluster scheme achieves higher location privacy than does the fake point sub-scheme.

5.8 Summary

In this chapter, in addition to the anonymity and location privacy schemes proposed in Chapter 3, and the multi-hop authentication scheme proposed in Chapter 4, we observe that location privacy in a network's lower-layers is a prerequisite for those higher-layer security schemes. Therefore, we adapt the ideas of the obfuscation and power variability to propose an efficient physical-layer location privacy scheme, the fake point-cluster based scheme. The proposed scheme thwarts physical-layer attackers occurring inside a public hotspot in a moving vehicle, in order to ensure mobile network nodes' location privacy.

The physical-layer attacker in our model exploits the wireless positioning systems, which are used for localization in a location-based system, to detect the mobile network node's location. Working in the physical layer where the signals are openly propagated and cannot

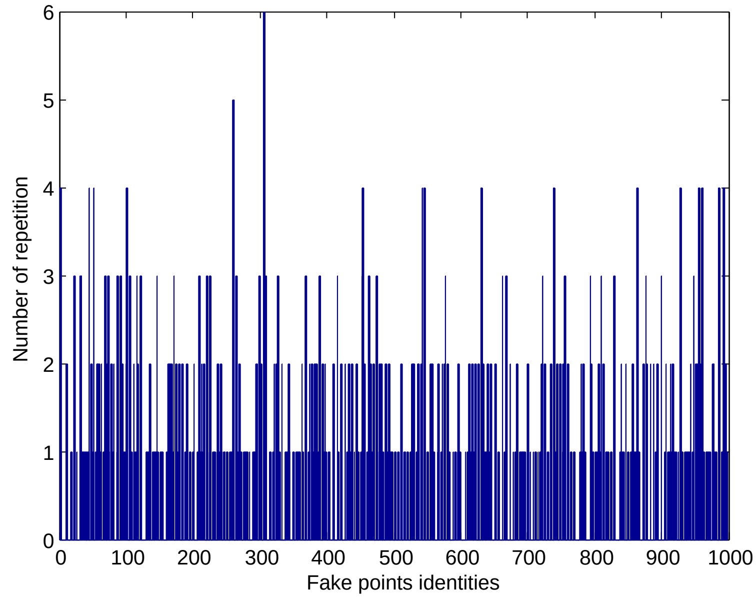


Figure 5.16: Fake point histogram.

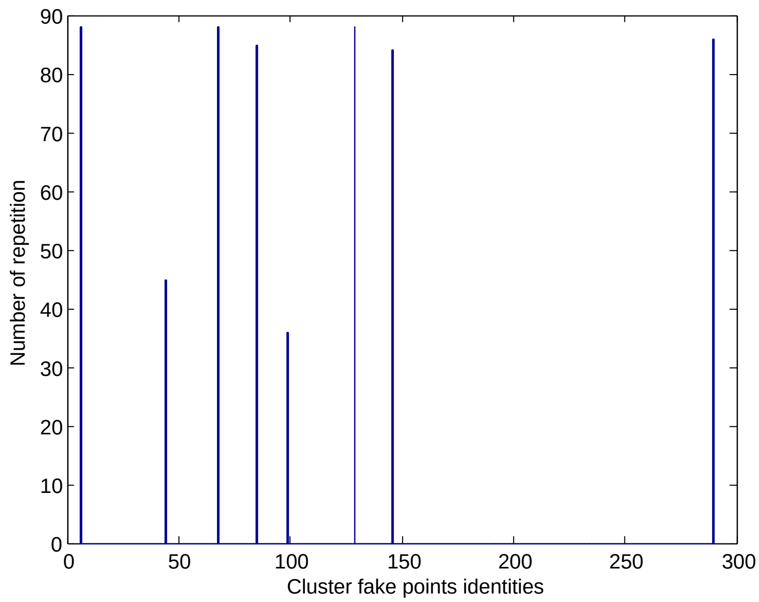


Figure 5.17: Fake point cluster based histogram.

be hidden, this attacker is a challenge to be mitigated. The attacker deploys a number of monitoring devices in the hotspot installed inside the moving vehicle. When an MNN transmits a signal to the mobile router, each monitoring device estimates the distance to this MNN by measuring the received signal strength (RSS) and sends the estimation to the attacker that uses the estimations to localize the MNN.

The fake point-cluster based scheme involves two sub-schemes, the fake point and the cluster based. The idea of the fake point sub-scheme, adaptation of obfuscation, is to increase the attacker confusion when measuring senders' received signals strengths. Therefore, the monitoring devices' estimation errors increase and consequently the localization error increases as well. In addition, the idea of the cluster-based sub-scheme is to decrease the number of monitoring devices that can detect the MNN's signals, meaning fewer monitoring devices can estimate the distances to the MNN. Combining the two sub-schemes increases the overall network performance, as well as ensuring the sender's location privacy.

Employing the correctness, accuracy, and certainty as metrics, we analytically measure the location privacy achieved by our proposed scheme. In addition, using extensive simulations, we evaluate the performance of the hotspot in NEMO-based VANET when employing our proposed scheme comparing to the traditional hotspots. Furthermore, we show that our proposed scheme can practically be implemented, due to the possibility of having at least two nodes select the same fake point.

Chapter 6

Conclusions and Future work

In this chapter, we present the main research results and discuss future work.

6.1 Major Research Results

Having the goal of securing a mobility management protocol that supports mobile nodes with seamless communications, this research has proposed three security and privacy schemes employed in three different mobility management for VANET scenarios. In our proposed schemes, we have considered the VANET mobility management challenges, including high speed vehicles, multi-hop communications, and scalability.

In Chapter 3, based on onion routing and anonymizer, we have proposed an anonymity and location privacy scheme, ALLP, to be employed in MIPv6 heterogeneous mobile networks, such as VANETs. With the goal of securing MIPv6 home binding update and return routability signalling messages, the ALPP scheme involves two complementary sub-schemes, anonymous home binding update (AHBU) and anonymous return routability (ARR). In addition, using the certificate-less public key cryptography, we present an efficient and secure authentication scheme between the mobile node and the foreign gateway. The proposed authentication scheme allows the two parties to authenticate each other without constructing a public key infrastructure in the network. Using the entropy model, we compare the achieved degree of anonymity of our proposed scheme with the mix-based scheme. When increasing the number of senders in our system, we observe that the degree of anonymity of our proposed scheme falls between 60% and 85%, whereas the mix-based scheme encounters a high delay while increasing the degree of anonymity. Regarding the location privacy, we prove that when implementing the ALPP scheme, no network entity except the mobile node itself can identify this node's location, which is represented by the mobile node's care-of address. Furthermore, we prove that when using our proposed key establishment scheme and under the assumption that the attacker knows the mobile node's private key, the attacker is still unable to create the shared key between the mobile node and the foreign gateway. In addition, we also prove that if either the mobile node identity or its public key is changed by an attacker, our proposed key establishment can detect this forgery. Therefore, based on these proofs, we show that the ALPP scheme thwarts traffic analysis, collusion, replay, and man-in-the middle attacks. Using extensive simulations, we show that our proposed sub-schemes decrease the routing delays by 42% for the AHBU sub-scheme, 43% for ARR-fixed correspondent node, and 30% for ARR-mobile node, compared to the triangle routing scheme. In our simulations, we consider different mobile node speeds, and show that routing delays decrease with the high mobility networks, such as VANETs.

In Chapter 4, another scenario for multi-hop PMIPv6 in VANETS has been address, and a novel efficient mutual authentication scheme, EM^3A has been proposed to be employed between a mobile node and a relay node in the multi-hop scenario. In addition, we employ symmetric polynomials to generate a shared key between those nodes. Compared to previous symmetric polynomial schemes that are used to generate a shared key between two arbitrary nodes, our proposed scheme increases the secrecy level achieved in the key establishment from $t-$secrecy to $t \times 2^n-$secrecy. This increase in secrecy level hardens against colluder attacks, to the extent that they require at least $t \times 2^n + 1$ colluders instead of only $t + 1$ colluders to reveal the shared key and break the secure system. Furthermore, we have mitigate the problem of mobile node's revocation by proposing new security steps that also achieve mobile node backward secrecy. Compared to the traditional revocation that changes the whole system keys, our revocation scheme changes only the keys of the mobile nodes sharing the same first-attached mobile access gateway (MAG). However, the trad-off is to store an MAG's list of identities in each authenticated mobile node. By means of simulations, we have shown that EM^3A results in a low delay and allows for seamless communications, even in highly mobile/heavy traffic demanding scenarios. Moreover, we present a case study of a proposed multi-hop authentication PMIP (MA-PMIP) that is implemented in vehicular networks. EM^3A has been implemented as the authentication step in MA-PMIP and compared to the AMA-PMIP scheme that implements the AMA authentication scheme, our MA-PMIP protocol with EM^3A achieves 99.6% and 96.8% reductions in authentication delay and communication overhead, respectively.

Finally, in Chapter 5, we direct our research to protect the mobile node's location privacy in the physical layer, which is a prerequisite to ensuring location privacy in upper-layers. Relating to our thesis, the scheme proposed in this chapter can be combined with any schemes proposed in chapters 3 and 4. In this chapter, we consider the NEMO-based VANET that supports public hotspots installed inside moving vehicles. We have modified the ideas of the obfuscation and power variability to propose the fake point-cluster based scheme, which thwarts physical-layer attacks that exploit a sender's received signal strength to localize this sender. The fake point-cluster based scheme involves two sub-schemes, the fake point and the cluster-based, that together increase the network performance and the achieved location privacy, rather than implementing each one separately. Using correctness, accuracy, and certainty, we have measured the location privacy achieved in our proposed scheme. In addition, using extensive simulations, we evaluate the performance of the hotspot in NEMO-based VANET when employing our proposed scheme compared to the traditional hotspots. Lastly, we show that our proposed scheme can practically be implemented, due to the possibility of having at least two nodes select the same fake point.

6.2 Future Work

Securing mobility management for vehicular ad hoc networks has many challenges. Therefore, many research directions can be outlined to extend our research.

Securing Nested NEMO for Vehicular Ad Hoc Networks

Nested NEMO is a topology type of the NEMO mobile network in which a NEMO mobile router manages the mobility of another mobile routers located in the same mobile network or in neighbor networks. Due to its inefficiency and highly routing delay, such a topology is considered a problem when it occurs in mobile networks, especially with vehicular networks due to their high mobility. Therefore, the trend is to propose a route optimization for nested NEMO, which mobile routers use to communicate with the correspondent nodes instead of directing the messages to all mobile router's home agents. Despite the great number of studies that have been done, there has been no route optimization standard issued yet.

As a next step of our proposal, we will suggest a route optimization scheme to be employed for nested NEMO-based VANETs. Unlike previous schemes, we will consider both the efficiency and the network security for the proposed scheme.

Securing Mobility Management for Electrical Vehicles

During the 1970s and '80s, the increase of investment in Canada's electrical grid was very noticeable. However, recently, with the overwhelming growth in electricity demand versus supply, coupled with the aging network facilities, catastrophic blackouts, such as the 2012 India blackouts, happen frequently. Therefore, Smart Grid, a worldwide trend, has been developed to support efficient and reliable electricity transformation by enabling time-of-use pricing, where electricity prices changes based on the time of the day. The idea is to create two-way communication between consumers and suppliers, to transform both the electricity and the information about the consumed power. The customers' interactions, resulting when the supplier supports them with real-time information about their consumed power, allow balancing of the electricity grid in its peak hours, and hence decrease the blackout probability. Benefits of the smart grid include self-healing from power disturbance events, enabling active participation by consumers in demand response, operating resiliently against physical and cyber attack, accommodating all generation and storage options, increasing investment, and optimizing assets and efficient operation.

As an application of the Smart Grid, electric vehicles increase the benefits, including lower operating and maintaining cost, reduced vehicle noise and making the "green" choice, and increased energy efficiency. Therefore, the Canadian government's vision is to have one electric vehicle among every 20 vehicles by 2020. The battery of the electrical vehicle is powered by plugging it in to the electricity grid in order to store energy. Accordingly, a new communication, namely Vehicle to Grid (V2G), has been considered recently. Furthermore, supporting seamless communication in V2G, where the activated IP connection of the electric vehicle is not interrupted while the vehicle is moving through different networks, is required.

In our future work, the security and privacy of the electrical vehicle in such communication will be considered. The smart grid uses Bad Data Detector (BDD) techniques to indicate erroneous measurements, however false data injection attacks could carefully change a selected set of measurements to add arbitrary errors in the state estimations without triggering the BDD's alarm. In addition, unauthorized customers and fake suppliers could steal electricity and deceive other entities in the grid. Moreover, privacy attackers may analyze the real-time transmitted data about customers and maliciously reveal customers' habits and locations.

APPENDICES

Author's Related Publications

Journal Papers

J1: **S. Taha**, and X. Shen,"ALPP: Anonymous and Location Privacy Preserving Scheme for Mobile IPv6 Heterogeneous Networks", accepted in 13-july-2012, Wiley Security and Communication Networks Journal, special issue: Security in Wireless Ad Hoc and Sensor Networks with Advanced QoS Provisioning, DOI: 10.1002/sec.625, to appear, http://onlinelibrary.wiley.com/doi/10.1002/sec.625/abstract.

J2: S. Cspedes , **S. Taha**, and X. Shen, " A Multi-hop Authenticated Proxy Mobile IP Scheme for Asymmetric VANET", IEEE Transactions on Vehicular Technology journal, IEEE TVT, VT-2012-01353, to appear.

J3: M. Mahmoud, **S. Taha**, Jelena Misic, and X. Shen, "Lightweight Privacy-Preserving and Secure Communication Protocol for Hybrid Ad Hoc Wireless Networks", in progress.

J4: **S. Taha**, and X. Shen, "Security and Privacy Challenges in IP Mobility Management for Vehicular Networks", Vehicular Technology Magazine, 11-41196, submitted.

J5: **S. Taha**, and X. Shen, "A Physical-layer Location Privacy Scheme for Mobile Public Hotspots in NEMO based VANET", IEEE Transactions on Intelligent Transportation systems, ITS, T-ITS-13-02-0067, in review.

Books and Book chapters

B1: **S. Taha**, S. Cspedes, and X. Shen, "Mutual Authentication in IP Mobility-enabled Multi-hop Wireless Networks", in Security for Multihop Wireless Networks, S. Khan, and J. Mauri, Auerbach Publications, Taylo & Francis Group, USA, in review.

B2: **S. Taha**, and X. Shen, "Securing IP Mobility Management for Vehicular Networks", SpringerBrief, Canada, in progress.

Conference Papers

C1: **S. Taha**, and X. Shen, "Anonymous Home Binding Update scheme for Mobile IPv6 Wireless Networking", in Proc. IEEE Globecom'11, Houston, Texas, USA, Dec. 5-9, 2011, Pp. 1-5.

C2: **S. Taha**, S. Cspedes, and X. Shen, "EM^3A: Efficient Mutual Multi-hop Mobile Authentication Scheme for PMIP Networks", in Proc. IEEE ICC'12, Ottawa, Canada, June 10 - 15, 2012. Pp. 883-887.

C3: **S. Taha**, and X. Shen, "A Link-layer Authentication and Key Agreement Scheme for Mobile Public Hotspots in NEMO based VANET", in Proc. IEEE Globecom'12-Communication and Information System Security Symposium, Anaheim, California, USA, Dec. 3-7, 2012, Pp. 1022- 1027.

C4: **S. Taha**, and X. Shen, " Fake Point Location Privacy Scheme for Mobile Public Hotspots in NEMO based VANETs", IEEE ICC'13, Budapest, Hungary, 9-13 June, 2013.

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