

RANDOM DELAY TECHNIQUES FOR LOCATION PRIVACY IN VANETS

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May, 2013

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ABSTRACT

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Vehicular ad hoc network (VANET) is an emerging new communication technology which has attracted a lot of research attention from academic community and industry. It is promising technology to provide safer and efficient traffic conditions. This is realized by letting vehicles to exchange safety messages. This messaging increases the awareness of vehicles about their neighboring vehicles positions and warns drivers about dangerous situations. However, availability of such information facilitates the tracking of vehicles. So, this information must be protected against the potential misuse.

In this thesis, we address the problem of achieving location privacy in VANETs with randomly changing identifiers (i.e. pseudonyms) in the presence of a global passive adversary. We suggest adding a random delay to message broadcast period after the vehicle update its pseudonym in mix zones. By this way, we want to mitigate the linkability between pseudonyms. This could help to make tracking more difficult and increase safety and confidence of drivers using VANET. Instead of adding delay to safety messages completely random, one step taken further and delay is added according to the silent vehicle number in mix zone. We also investigated the effects of different number of mix-zone placements in the network to the location privacy of users. Several simulations have been performed to evaluate the performance of the systems. The results of experiments show that adding delay to message broadcast period improves location privacy of drivers in VANET and also provide information about the relationship between the strength of the adversary and the level of privacy achieved by changing pseudonyms.

Keywords: pseudonym, mix zone, location privacy, vehicular ad hoc network.

ÖZET

ARAÇ TASARSIZ AĞLARINDA KONUM GÜVENLİĞİ İÇİN RASTGELE GECİKTİRME TEKNİKLERİ

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Araç tasarsız ağları (VANET) akademik ve ticari alandan birçok araştırmanın ilgisini çeken yeni bir iletişim teknolojisidir. Daha güvenli ve etkin bir trafik koşulları sağlamak için umut veren bir teknolojidir. Bu, araçlar arası güvenlik mesajı alışverişi sağlayarak gerçekleştirilir. Bu mesajlaşma komşu araçların pozisyonları ile ilgili araçların farkındalığını artırırken tehlikeli durumlar hakkında da sürücüleri uyarır. Fakat bu tür bilgilerin varlığı araçların takip edilmesine imkan verir. Dolayısı ile bu bilgiler potansiyel kötüye kullanmalara karşı korunmalıdır.

Bu tezde, küresel bir pasif saldırgan varlığında rastgele değişen takma adlar ile VANET'deki konum gizliliğini sağlama problemini ele aldık. Karma bölgelerde, araçların mesaj yayın sürelerine, takma adlarını güncelledikten sonra rastgele bir gecikme ekleyemeyi öngördük. Bu yöntemle, takma adlar arası bağlantı ihtimalini azaltmayı amaçladık. Bu yöntem, araçların takip edilmesini zorlaştırırken, VANET'e katılan sürücülerin güvenini artırmaya yardımcı oldu. Bir adım öteye giderek gecikmeleri tamamen rastgele değil de sessiz araç sayısına göre eklemeyi öngördük. Bunlara ek olarak, ağdaki karma nokta sayısının kullanıcıların konum gizliliğine etkisini de araştırdık.

Sistemlerinin performansını değerlendirmek için çeşitli simülasyonlar yaptık. Deneysel sonuçları, mesaj yayın dönemine gecikme ekleyerek VANET sürücülerinin gizliliğinin arttığını göstermekte ve aynı zamanda takma ad değiştirerek elde edilen gizlilik düzeyi ile saldırgan gücü arasındaki ilişki hakkında bilgi vermektedir.

Anahtar sözcükler: takma ad, karma bölge, konum gizliliği, araç tasarsız ağı .

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I hereby dedicate this thesis to all women who were deprived of educational opportunities for any reason.

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Chapter 1

Introduction

New technological developments in manufacturing technologies altered the manufacturing process for vehicles. They require state-of-the-art technological methods and processes. Modern automobiles are increasingly relying upon more advanced electronics, computer and wireless communication systems to assist drivers and enhance safety. When Karl Benz built the first vehicle in 1885, it was just pure mechanical device. Today's cars are almost fully controlled with software devices. Future smart cars will be fully controlled by software. For example, the concept model of Audi A9 is formed with nanotech material that repairs itself automatically if damaged [1].

According to the Organization Internationale des Constructeurs d'Automobies (OICA) [2], nearly 85 million vehicles had been manufactured in 2012, and now 3 vehicles are manufactured each second. If this trend continues, the number of vehicles in the world will double in the next 30 years. One may criticize vehicles for causing traffic congestion and pollution and many other issues. Those are not downgraded issues, but big benefits of vehicles cannot be forgotten. They are essential for the operation of global economy and welfare of citizens.

On the other hand, according to the World Health Organization [3], approximately 1.24 million people die each year on the world's roads, and between 20 and 50 million sustain non-fatal injuries. Nearly all data sources show that road

traffic injuries are leading cause of death among young people whose ages are between 15 and 29.

Now, it is time to act and more actions are needed to make world's road safer. Researches imply that most traffic accidents and jam can be avoided if the drivers are alarmed in advance about changing driving environment. One of the most promising efforts is enabling communication between vehicles and broaden the views of drivers. Vehicles disseminate messages to other vehicles in their vicinity. For example a vehicle can inform nearby vehicles about its position, speed, direction etc. This mechanism is expected to improve driving safety, traffic efficiency, driving assistance and transportation regulation.

VANET is a network devoted to provide communications among vehicles and between vehicles and fixed road side equipments. Vehicles equipped with On Board Units (OBUs) and wireless communication equipment, Road Side Units (RSUs) and backend infrastructure form a VANET. To better understand the relationship one could look at the relationship between computers and the Internet and connect it to the relationship between vehicles and VANET [4]. The main vulnerabilities in VANETs come from the wireless communication nature of the communication which is accessible to anybody. Collecting vehicle specific information becomes easy if a VANET is deployed without privacy-preserving countermeasures. An attacker can eavesdrop on all broadcast messages and collect the location visited by vehicles over a period of time. Consequently, vehicles could easily be tracked and identified anywhere anytime. This location information can be used to learn about places of interest of drivers and used to exploit advertisement and surveillance. Furthermore, it can be misused such as crimes, automobile thefts. These consequences prevent drivers to participate in VANETs that decrease the VANET potential to improve traffic safety and wide acceptance.

One approach to solve this problem is to think VANET as completely anonymous. Every vehicle will be anonymous all the time. However, complete anonymity will compromise the entire idea of secure network. First, anonymous vehicles may generate bogus report for their selfish purposes. For example, one may cause an area to be deserted for him at no cost. Moreover, anonymity makes

it difficult to identify the attackers and would not allow law enforcement to track vehicles. The law enforcement may need to track vehicles using VANET as aid in an investigation of a stolen car or hit-and-run accidents [5].

Considerable efforts have been made to guarantee vehicle privacy and a quite number of solutions have been proposed. Among them, pseudonym-based approaches are well-understood and frequently changing pseudonyms are accepted as a solution to protecting the privacy of VANET [6]. Pseudonym is a randomly chosen and changing identifier which can be either a set of public keys, network layer addresses or link layer addresses. With these pseudonyms, vehicles can anonymously authenticate their own vehicular reports. They have a short validity period and cannot be reused. A major shortcoming of pseudonyms is that each vehicle needs to pre-load a huge pool of anonymous certificates to achieve privacy, and trusted authority needs to keep the relation of the pseudonyms to driver's real identity secret which implied heavy burden of pseudonym management. It is not possible to load small amount of pseudonym to vehicles, since too often re-used pseudonyms might lead to vehicles re-identification. Indeed all messages authenticated with the same pseudonym can be linked and the more messages are linked, the easier is re-identification. Thus, pseudonyms should be generated in way that adversaries cannot link a new pseudonym to the previous ones of the same vehicle. This approach allows vehicles to be untraceable between two successive locations. Since pseudonyms cannot be linked to each other, they can provide a certain degree of privacy.

Unfortunately, an only changing pseudonym is not effective against a global eavesdropper that can get all communications in the network. Such an attacker can predict the movement of the vehicles based on the position and speed information in the beacon messages, and use this prediction to link different pseudonyms of the same vehicle together with high probability. For instance, as shown in Figure 1.1 if at time t_0 , a given vehicle is at position p_0 and moves with speed s , then after some time t_ϵ , this vehicle will be most probably at position $p_0 + t_\epsilon \cdot s$. As a result, the adversary will know that the vehicle that reports itself at or near to position $p_0 + t_\epsilon \cdot s$ at time $t_0 + t_\epsilon$ is the same vehicle as the one that reported itself at position p_0 at time t_0 even if the vehicle changed pseudonym in the meantime.



Figure 1.1: Attacker prediction for next position of a vehicle

On the other hand, the assumption that the adversary can eavesdrop all communications in the network is a very strong one. In many situations, it is more reasonable to assume that the adversary can monitor the communications only at a limited number of places and only in a limited range. In this case, if a vehicle changes its pseudonym within the non-monitored area, then there is a chance that the adversary loses its trace. However, it is advisable in the field of security, worst case is considered.

The basic idea used in this thesis is that vehicles should change pseudonyms in an area called mix zone where obfuscation of vehicles are most probable. That is where vehicle speed and positions changes most. The concept of mix zone was first introduced in [7], but it has not been used so much in the context of vehicular networks. Vehicles should change pseudonym in that area and add some random delay to beaconing message period. Adding random delay to message broadcast period at mix zone will ensure that large number of vehicles will change its pseudonym nearly at the same time at the same location. Thus, the proposed scheme will ensure the change of pseudonyms in an unlinkable fashion and prevent tracking of vehicles.

In the next chapter, background information related with thesis is given. Chapter 3 informs about related work done in the literature. Random delay technique effectiveness is examined in Chapter 4 with different delay periods with two different attacker models. The first attacker model uses only time information while second one also considers speed and position information as well. In Chapter 5, a step further is taken and random delay is not added as completely random way but density of silent vehicles in the pseudonym change area is considered as a factor to decide the random delay duration. High number of vehicles that change

pseudonym and not to start beaconing message yet causes the duration of added random delay to be low. On the other hand, random delay should be should be high if number of silent vehicles is low. By optimizing random delay duration according to silent vehicle number, attacker tracking capability is reduced. Also, unnecessarily being silent is prevented for the vehicles that may change its pseudonym in an unlinkable way. In Chapter 6 of the thesis, number of places where vehicles change their pseudonyms is changed. Since changing pseudonym is a costly job, attacker success in low number of mix-zone area is compared with large number of pseudonym change areas. Report on results and gained level of privacy is given with extensive simulation. Simulation results provide detailed information about the relationship between the strength of the adversary and the level of privacy achieved by changing pseudonyms and confirm that the level of privacy decreases as the strength of the adversary increases. Also, detailed information is obtained about relationship between random delay duration and adversary success ratio. As expected, increase in random delay duration causes decrease in adversary success.

Chapter 2

Background

This chapter gives an overview of the system model and thread model used in this thesis. Then two types of privacy metrics are discussed. It also introduces the features of the simulation tool that is used to perform simulations.

2.1 System Model

The system model (Figure 2.1) under consideration consists of the followings:

- **Certification Authority (CA)**, which is independent trusted third party and manages security and privacy of the network. Each vehicle must register to CA before entering the network and preload a large set of n pseudonyms denoted $\{P_{i,j}\}_{j=1}^{j=n}$, a public/private key pair $(K_{P_{i,j}}, K_{P_{i,j}}^{-1})$ and corresponding public key certificate $Cert_{i,j}(K_{P_{i,j}})$ for each pseudonym $P_{i,j}$. Only CA knows the link between the real identity of vehicle and its associated pseudonyms. In the case of liability issues, this association can be made public by law enforcement.
- **Roadside Units (RSUs)**, which are fixed units placed over whole network. RSUs are connected to CA by a wired network and communicate securely with CA.

- **On Board Units (OBUs)**, which provide communication either between OBUs through vehicle to vehicle (V2V) communication or between OBUs and RSUs through vehicle to infrastructure communication (V2I).

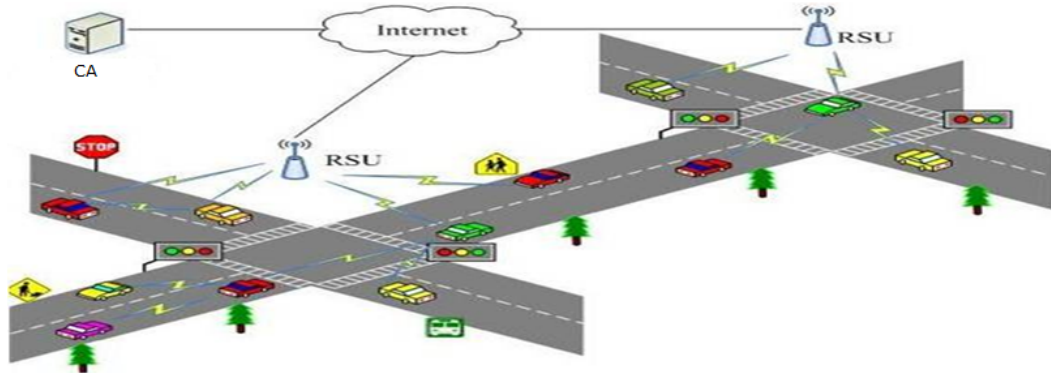


Figure 2.1: System model under consideration

It should be noted that system under consideration has suitable public key infrastructure model and certificate is attached to each message to provide secure communication between entities. Also, vehicles are equipped with Tamper Proof Devices (TPDs) that guarantee correct execution of cryptographic operations and non-closure of private keys.

As described in introduction part, location privacy is achieved by changing pseudonym in regions called mixed zones. The effectiveness of mix zone to provide location privacy highly depends on density of vehicles. Thus, mix zones should be placed in regions where mixing capability is high and vehicles should be forced to change pseudonyms at those regions. The highest mixing of vehicles occurs at road intersections since speed and direction of vehicles change the most. Thus, as in Freudiger [8] et al., mix zones are placed at road intersections. Figure 2.2 shows an example of mix zone. 5 cars with pseudonyms A to E enter the mix zone from different ports and exit with different pseudonyms with F to J at nearly same time. Mix zone tries to obfuscate the relation between incoming and outgoing vehicles. The links between old and new pseudonyms are not observable by any outsider and this mechanism is expected to achieve location privacy protection.

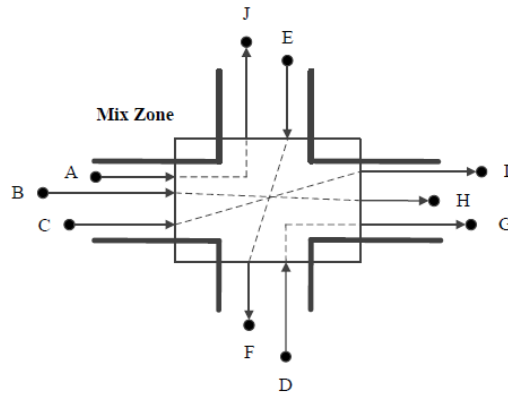


Figure 2.2: Mix zone obfuscates the relation

2.2 Threat Models

The nature of wireless communications makes eavesdropping particularly easy. Consequently, vehicles' positions can be monitored at all times. All an adversary needs to do is deploy its radio devices across the area of the network that it wishes to monitor. One may think that tracking vehicles can be done with cameras instead of radios. However, the granularity is higher in radio since eavesdropper obtains identifiers, locations and other information from beaconing messages. Also, cost of radios is low compared to cameras. In this application scenario, achieving location privacy against such an adversary is concerned. It is assumed adversary cannot inject or modify messages. She collects pseudonyms sniffed at every intersection where it has an eavesdropping station. Based on the collected information, it attempts to track the location of mobile nodes. The concerned adversary is called as global passive adversary who obtains complete coverage and tracks nodes throughout the entire network. It should be noted that, it is unlikely for an attacker to achieve such a comprehensive coverage of network, but there is no real measurements to approximate for this function, so as it is advisable in the field of security, worst case is considered.

In addition to eavesdropping abilities, the knowledge of the adversary depends on other information it has, e.g., background information about users' mobility and points of interest. While an adversary cannot observe the vehicles within the

mix zone, she can still have knowledge about model of mixed zones and observes events. Event in mix zone can be described as a pair consisting of a port and time step. There are entering events and existing events corresponding to vehicles entering and existing mix zone respectively. Entering event consists of the port where vehicle enter the mix zone and time step when it has happened. Similarly existing event consists of the port where vehicle left the mix zone and the time this happened. The objective of the adversary is to relate the entering event of the vehicle with the exiting event. Specifically, the adversary picks a vehicle v as a target vehicle and tracks it until entering the mix zone. Then adversary catches the exiting events during time t such that the target vehicle may exit. Then, for each exiting vehicle v_x adversary determines the probability that v_x being v . At the end, she decides the most probable v_x that corresponds v . Adversary is successful if decided v_x is real v . The above algorithm used by adversary is called as an Bayesian decision and it is ideal decision algorithm for the adversary since it minimizes the error probability [9].

Mix zones are effective in anonymizing the trajectory of mobile nodes if the adversary is unable to predict target vehicle. In particular, a mix zone becomes a confusion point for the adversary if the mixing attempt achieves high location privacy.

2.3 Privacy Metrics

There are various metrics to quantify the level of privacy provided by the mix zone. A natural metric is the success probability of the adversary when making her decision to decide target vehicle. If the success probability is large, then the mix zone and changing pseudonyms are ineffective. On the other hand, if the success probability of the adversary is small, then tracking is difficult and the system ensures location privacy.

Two types of privacy metrics are used in this thesis.

2.3.1 Event-based Metric

The goal of the event-based metric is to measure untraceability of all users in a mix zone. It measures the probability that the adversary finds the assignment of all entering events to all exiting events in a mix zone. Consider a sequence of entering and existing vehicles to a mix zone over a period of time steps. The adversary success is ratio of correct assignment of entering vehicles to existing vehicles in a mix zone. It should be noted that average correct assignment in mix zones mostly depends on factors beyond the vehicles (for example number of neighbouring vehicles). Thus, average location privacy should be computed.

2.3.2 User-centric Metric

The goal of the user-centric metric is to measure the untraceability of a particular user traversing mix zones, instead of the mix zone in general. Adversary picks a target vehicle and tries to find all its paths. This types of metric requires more coverage area for an adversary. In this type of privacy metric, to decide the adversary success again average number of tracked vehicles should be computed.

2.4 SUMO

Like other types of networks, VANET needs to be simulated to validate protocols and applications. There are many open sources, commercial tools, and software available in market for generating traffic simulation model which features motion of multiple vehicles under provided conditions. A microscopic traffic simulator computes the position of all the vehicles on road at the same time. These positions could be organized into a graphical user interface (GUI) or saved in a file. SUMO (Simulation of Urban Mobility) is this type of simulator and it is appropriate as an simulator [10].

SUMO [11] is selected for our research mainly considering the following features:

1. It is a microscopic model which records the movement every second, and these values are updated depending of the vehicle ahead and the street network that the vehicle is on ;
2. It is open source, highly portable, and can be further extended;
3. It is capable of making real-time simulations with a large amount of simulated vehicles in large area;
4. It supports several useful output formats like route generation
5. It has many extensions, which can enhance the traffic modeling and data processing.

In addition, the credibility of the SUMO tool has been demonstrated in various other projects, e.g., [12, 13].

The development of SUMO started from 2000 by the German Aerospace Center, in order to support the traffic research community with a tool into which own algorithms can be implemented and evaluated without the need to regard all the artefacts needed to obtain a complete traffic simulation. Such artefacts are related to the implementation and/or setting up methods for dealing with road networks, demand, and traffic controls. By supplying such an open source microscopic road traffic simulation tool, the German Aerospace Center wanted to make the implemented algorithms more comparable, as a common architecture and model base is used, and gain additional help from other contributors. Since 2002, SUMO is used popularly in the evaluation of vehicle-to-vehicle and vehicle-to-infrastructure communication and It is widely used in research community. SUMO simulator is perhaps the most scrutinized microscopic traffic simulator in the research community, with hundreds of scientific papers referring to it.

SUMO is a combination of more than a single application. There are other

modules that help build assigned data that are needed for simulations and research. In order to simulate in a proper format, SUMO requires the representation of road networks and traffic demand, both have to be imported or generated using different sources. SUMO allows to generate various outputs for each simulations run. The outputs are ranging from simulated induction loops to single vehicle positions. As a result of the SUMO simulation, useful datasets can be generated for further analysis. One is the location information of every vehicle called "net-state dumps". It records, at every timestamp, the location of every vehicle in the simulated road network. Each record consists of a vehicle ID, a timestamp, and the vehicle's coordinates. This data file is used as the basis for the simulation of the mobile traffic information system. The simulation of street vehicles is time-discrete and space-continuous.

2.4.1 Simulation Processes

To set up a simulation for SUMO three steps have to be followed. First the road network on which the vehicle traffic is moving on is needed. Second, each vehicle should recognize its route, which is a list of edges that have to be passed and can be known. The final step is to perform the simulation.

SUMO-NETGEN : Due to high level of complexity, the SUMO's network cannot be generated by a human. Instead, NETGEN generates abstract road networks, then calculates the necessary input for SUMO and writes the results into a XML-file. First, the topology of the road used for the simulation experiments is defined. Since no realistic road topology together with network's coverage area information is available, a rectangular road network topology is preferred to be implemented for investigation. The chosen rectangular road network allows the vehicle to loop in this road network. The output of NETGEN is a generated SUMO-road network optionally also other outputs connections, edges, nodes etc.

DEMAND MODELLING : Generate turn definition python script allows generation of the turn definitions based on the number of lanes allowing particular turns. The basic functionality distributes the traffic uniformly, that is:

- distribute the incoming traffic uniformly across the lanes forming the road
- distribute the amount of traffic assigned to each lane uniformly among the destinations that the lane allows turns to.
- sum up the values for each of the destinations that the road being processed allows turning to.

SUMO-JTRROUTER : The simulation not only consists of the stationary part, i.e. the network, but also the mobile part, i.e. moving vehicles. The JTRROUTER is a routing application which uses flows and turning percentages at junctions as input. The following parameter must be supplied:

- the network to route the vehicles through,
- the description of the turning ratios for the junctions and
- the descriptions of the flows.

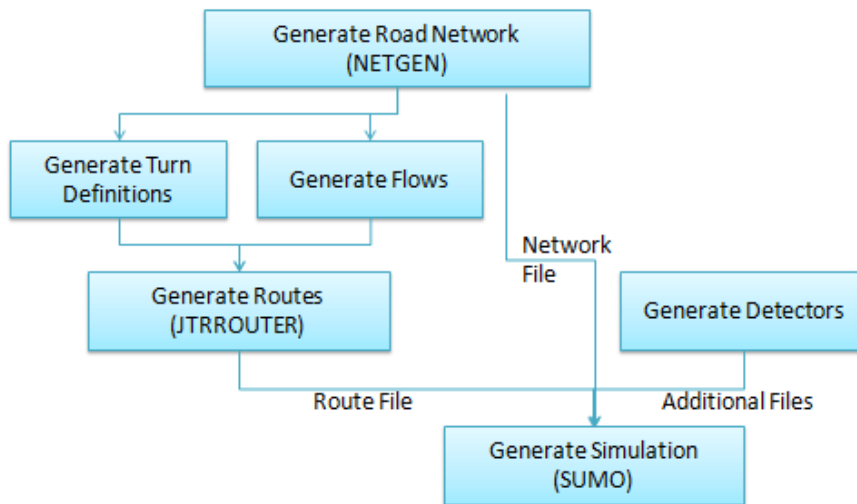


Figure 2.3: Simulation scenario on SUMO

GENERATE SIMULATION : execution step of simulation is performed. Two choices are available to perform simulation. The first one is using SUMO-GUI application, the other one is SUMO command line application.

The Figure 2.3 depicts the process of generating vehicular mobility with SUMO that is used in this dissertation.

Chapter 3

Related Work

The privacy of VANETs is a recent topic. Many authors addressed VANETs and its security and privacy in some papers. A good online bibliography for the security of VANETs can be found in [14].

Although pseudonyms were introduced to VANET to help drivers feel comfortable about safety of their identity, pseudonyms do not completely prevent tracking. A skillful attacker can link pre-existing pseudonyms to present pseudonyms, which will then aid to future pseudonyms [15]. In order to achieve location privacy in a pervasive computing environment, Beresford and Stajano [7] propose the concept of mix-zones where a natural mixing of mobile nodes occurs. Mix-zones are anonymized regions of the network wherein mobile nodes change their identifiers to obfuscate the relation between entering and exiting events. Because the locations of nodes in a mixzone cannot be estimated, the updating nodes can potentially mix their identifiers and constitute an anonymity set. However, the spatial and temporal relation between the locations of a mobile node can enable its entry and exit locations and times from a mix zone to be correlated [16], hence lowering privacy.

In [8], the authors suggest to construct mix zones for vehicles by cryptographic means. They propose to install such cryptographic mix-zones by deploying a special RSU at places with high traffic density such as crossroads. Once a vehicle

enters a cryptographic mix-zone, they obtain a symmetric key from the RSU. While the vehicle is inside of the cryptographic mix-zone, all communication is encrypted and therefore an adversary cannot read-out useful information (including meta-information) from its messages. Vehicles in the mix-zone forward the symmetric key to vehicles that are in direct transmission range outside of the mix-zone such that these vehicles are also able to decrypt messages. Vehicles then change pseudonyms while being inside of the mix-zone. In addition, all the vehicles in the mix zone are forced to change their anonymous certificates. As a result of the forced certificate change and the random direction change of each vehicle at road intersections, an attacker on the roadside cannot link a certificate to a particular vehicle, hence, providing location privacy. The accumulation of CMIXes throughout the vehicular network forms what is called mix-network, which maximizes the degree of the location privacy

In the vehicular density based location privacy scheme provided in [17] to address attacks that correlate pseudonyms of vehicles entering and exiting a mix-zone, a node must change its pseudonym only when it finds a threshold number of nodes within such a region. A vehicle permanently assesses its neighborhood, and changes its pseudonyms only if the vehicle detects k vehicles with a similar direction in a confusion radius. The approach is an intuitive for achieving location privacy in VANETs. However, how to detect k vehicles in neighborhood and how to guarantee neighboring vehicles to react similarly should be further exploited.

In two of the most relevant papers to our approach, in [16, 18], Huang et al. propose the random silent period technique to allow the nodes to update at random locations and times. Nothing that such updates are not able to mitigate correlation tracking, they suggest utilizing the AP as a coordinator to synchronize the updates as well as enforce the neighboring nodes to update with the target, thereby increasing the resulting entropy of the anonymity set distribution. However, this work assume that the wireless nodes have unrestricted and independent mobility, hence, not considering the unique constraints of VANET.

The other relevant paper is SLOW method proposed in [19]. The main idea of the scheme is that vehicles should not transmit safety messages when their

speed drops below a given threshold, and they should change pseudonym during each such silent period. SLOW is not a full solution to untraceability, as it does not cover the safe use of silent periods at high speeds.

In the research line of the placement of mix zones, Freudiger et al. [20] analyze the optimal placement of mix zones with combinational optimization techniques, and show that the optimal mix zone placement performs comparatively well to the fully deployment scenarios. This work is instructive, which guides the placement of mix zones in VANETs. This work inspire us to work on mix zone number effect on location privacy.

Chapter 4

Basic Random Delay Technique

In this chapter, privacy level a driver can achieve by adding random delay to beaconing message period in VANETs is investigated. First, the used method is explained, and then experiments details are given. Lastly, the experiments results are discussed. Prior to give details as mentioned in background part, attacks consist of listening transmission messages is dialed, and intersections are chosen as pseudonym change points, that is mix-zones.

4.1 Proposed Method

It is obvious that untraceability of vehicles is an important requirement in future vehicle communication systems. Transmitting beaconing messages under pseudonyms and changing pseudonyms regularly provide some degree of privacy. Unfortunately beaconing messages provide a constant stream of spatial and temporal data and without any protection mechanism, tracking a vehicle will be easy even for very simple passive eavesdropper. Changing pseudonyms will be effective if some delaying occurs in message transmitting period. That is, vehicles should be silent for some period so that several vehicles change their pseudonym nearly at the same time at the same location so that obfuscation of vehicles occurs.

The basic idea used in this chapter is, vehicles should not start to transmit messages immediately after changing pseudonym. Some random delay should be added to broadcast period so that more vehicles change their pseudonym nearly at the same time at the same location. After random delay time, vehicles automatically continue sending beaconing messages. Since not all vehicles start and end their silent period at the same time, safety message transmissions occur in pseudonym change area but with less number. Thus, this makes it possible to provide communication with less expensive equipments since large amount of digital signature verification is refrained.

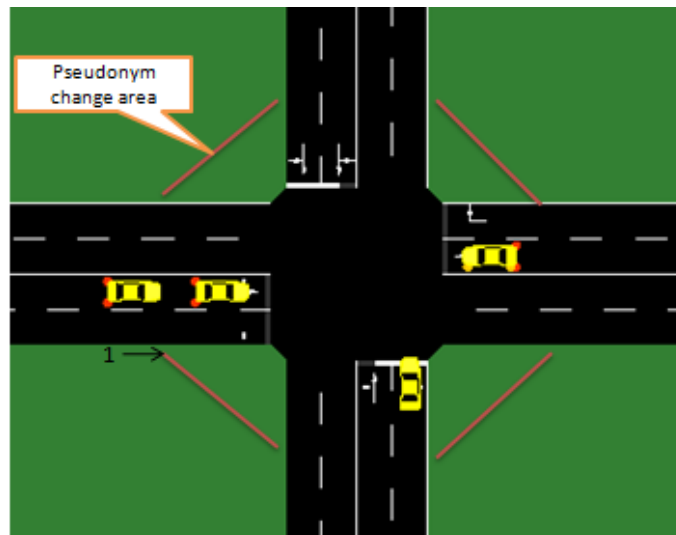


Figure 4.1: Mix zone entering event

Efficiency of provided solution is considered in intersection based and averaged over all intersections. Each vehicle that comes close to intersection stops transmitting safety messages and changes its pseudonym. After that, it adds some random delay to message broadcast period before restarting transmission. The scenario is shown in Figure 4.1. Target vehicle with pseudonym 1 enters the intersection, changes its identifier and stops transmitting safety messages. When vehicle 1 entered the mix-zone, there are 3 more vehicles that are in silent mode. After a while, one of the silent vehicles finishes its delay period and restarts the transmission with new pseudonym 50 (Figure 4.2). Attacker goal is to find which one of silent vehicles start retransmission. As a side note, this retransmission provides information about mix-zone safety condition although not all

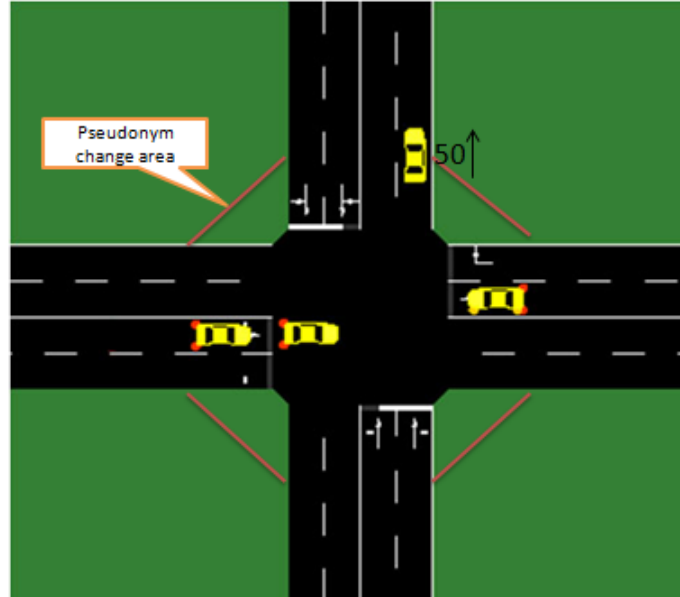


Figure 4.2: Mix zone existing event

vehicles provide transmission.

For the attacker that uses no information from beaconing messages, all four vehicles have equal chance and the probability of successfully guess the target vehicle is $1/4$. However, the considered attacker in this dissertation is not as weak as this one.

4.1.1 Attack Models

Two types of attack model are considered:

4.1.1.1 Simple attack model

In the first attack model, attacker uses the following information to guess the target vehicle:

1. the last transmission time of target vehicle t_{last}
2. speed limits $[s_{min}, s_{max}]$,

3. random delay limits $[t_{dmin}, t_{dmax}]$

Attacker applies the following algorithm to guess the target vehicle. First, she calculates the minimum ($t_{last} + t_{dmin}$) and maximum ($t_{last} + t_{dmax}$) retransmission times to have temporal information. Then, spatial information is calculated by finding minimum ($s_{min} \cdot t_{dmin}$) and maximum ($s_{max} \cdot t_{dmax}$) place that target vehicle may reappear, that is she calculates reachable area. Attacker wants to select vehicles that start to retransmit safety messages with new pseudonym between reasonable minimum and maximum time for target vehicle start transmission and between minimum and maximum location that target vehicle may reach. After that, attacker considers all vehicles have equal changes and selects one of them randomly. If the guessed vehicle is really the target vehicle attacker is successful, if not attacker lost the target vehicle. The algorithm is applied for each vehicle for each intersection, and averaged over all intersection.

4.1.1.2 Correlation based attack model

In the second type of attack model, attacker uses all information that simple attacker has and also the following additional information:

1. Last transmission speed (s_{last}) and position (p_{last})
2. New transmission speed (s_{new}) and position (p_{new})
3. Delay characteristics of intersections(average time required to turn left, right or to go straight)

Attacker uses the algorithm to correlate candidate vehicles with the target vehicles. First, to be a candidate vehicle, vehicle starting retransmission with new pseudonym should start transmission between reasonable minimum and maximum time in reachable area as discussed in simple attack model. In addition to this, attacker correlates the last transmission position and speed of target vehicle with candidate vehicle speed and position.

The decision algorithm used by the adversary is intuitive and straightforward: the adversary knows that the selected vehicle v entered the mix zone at position p , with speed s and at time t . For each exiting event at position p' , with speed s' and time t' that the adversary observes afterwards, she computes the P that exiting event corresponds to the selected vehicle as computing absolute difference between distances.

$$P = |P_{real} - P_{estimate}| \quad (4.1)$$

where P_{real} is the real distance between p and p' and $P_{estimate}$ is the estimate distance taken using average speed. It is computed as $(t' - t) \cdot ((s + s')/2)$.

The adversary decides for the vehicle for which P is minimal. The adversary is successful if the decided vehicle is indeed v , if not attacker lost the target vehicle. The algorithm is applied for each vehicle in for each intersection, and averaged over all intersection.

It can be better explained with the following example.

Example: In VANETs, vehicles periodically change their pseudonyms when they are broadcasting safety messages and each safety message is a 4-tuple including speed, position, time and content. Assume last safety message broadcasted by target vehicle V is (speed, position, time) = (10.4, 78, 25) where units are meter/second, meter and second respectively. After reasonable time attacker observes two new broadcasts with pseudonyms T and U . The obtained new broadcasts in reachable area have the following beaconing information:

T: (speed, position, time) = (3.6, 83, 26), and

U: (speed, position, time) = (5.4, 89, 27).

Find which one of new pseudonyms (T or U) is more probable to be a target vehicle V ?

Solution: The attacker observed the times, speed and position and pseudonyms of ingress event of target vehicle and two different egress events. Her goal is to reconstruct the correct mapping between the egress events with

the target vehicle ingress event. This is equivalent to discovering the mapping between T to V or T to U . She first calculates the real and estimate differences between ingress event and egress events. Then, according to formula (4.1), she tries to find minimum absolute difference between real and estimate differences. Finally, she selects vehicle which has minimum absolute difference.

$$\text{Real Distance between } V \text{ and } T = 83 - 78 = 5$$

$$\text{Guess Distance between } V \text{ and } T = ((10.4 + 3.6)/2) \cdot (26 - 25) = 7$$

$$\text{Real Distance between } V \text{ and } U = 89 - 78 = 11$$

$$\text{Guess Distance between } V \text{ and } U = ((10.4 + 2.4)/2) \cdot (27 - 25) = 12.8$$

Since $|12.8 - 11| < |7 - 5|$, U is more probable to be a target vehicle.

4.1.2 Choosing Delay Distribution

The proposed technique requires to add random delay to safety message broadcast period. Short time delays may prevent obfuscation of vehicles. On the other hand, long time delays may cause vehicles to lose connection from network long times. Hence, delay times should be decided carefully. It is a good idea to find maximum delay times by using the some multiplies of edge passing time with average of allowed speed.

The following procedure is applied to decide the delay times:

1. Average speed of vehicles (μ_s) is computed. Speed of vehicles are uniformly distributed between 0 and s_{max} . Thus,

$$\mu_s = s_{max}/2 \tag{4.2}$$

2. Passing time (τ) from an edge with length d is calculated using average of speed .

$$\tau = \frac{d}{\mu_s} \tag{4.3}$$

3. For different c coefficients, t_{max} is decided using the following formula.

$$t_{max} = c \cdot \tau \quad (4.4)$$

4. Lastly delay times are generated uniformly random from interval $[t_{min}, t_{max}]$.

$$delay \sim U(t_{min}, t_{max}) \quad (4.5)$$

4.2 Experiments

The purpose of experiments is to calculate attacker success on real mobility data. In the following, first simulation setup parameters is explained, and then simulation results are presented.

4.2.1 Experimental Setup

The simulations are performed in three steps. In the first step mobility patterns of vehicles is simulated using SUMO and simulation states are dumped in a file for every time step. This dump files contains time, position and speed information for each vehicles. Then, attacker observations about changing pseudonyms related with new and old pseudonyms are obtained. Lastly, attack algorithms are applied on observed data and compared with the real data.

It is assumed that all vehicles participate in the anonymization process at every road intersection and attacker is global. For the purpose of simulations, 10x10 Manhattan network with 4 road segments that meet intersections is used as shown in Figure 4.3. The simulation parameters can be seen in Table 4.1.

Each edge consists of two lanes to simulate lane change for vehicles and overtaking a vehicle. Default speed for the vehicles is set as $25m/s$. Most of the examples in SUMO use the standard vehicle values in Stefan Krauß's thesis [21]. So, some of simulation parameters such as vehicle length, edge length, driver imperfection are chosen from those values. Speed distribution of vehicles as chosen

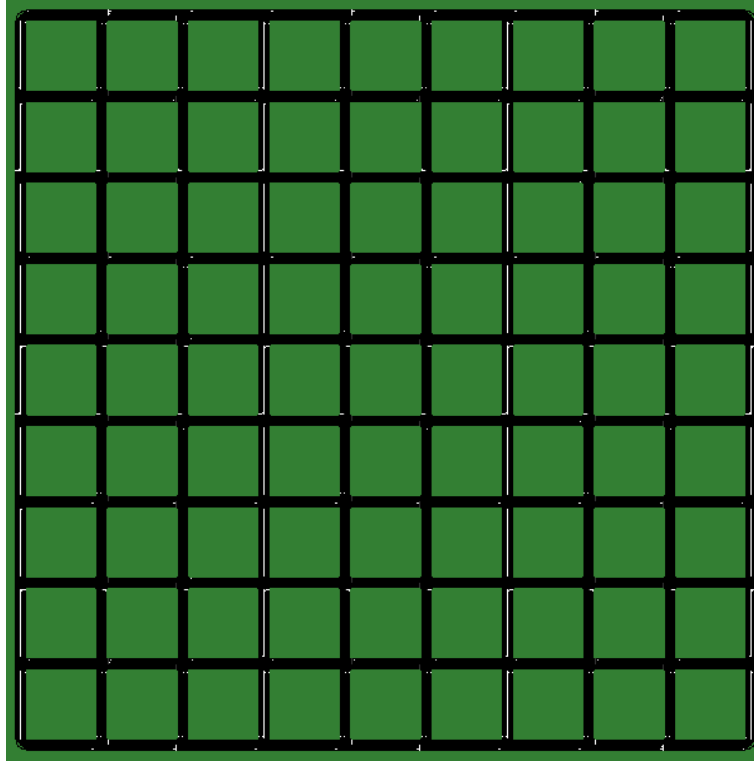


Figure 4.3: Snapshot of used network topology

from normal distribution with mean 1 and standard deviation 0.1 so that 95% of vehicles drive between 80% and 120% of the legal speed limit [22].

The Table 4.1 shows the vehicles parameters that are used by SUMO to represent vehicles and driving behavior.

Simulations are performed with 100 to 600 vehicles, increasing by 100 vehicles. 6 different trace file is obtained with different density of vehicles per intersection.

Parameters	Values
Network Density(vehicle/intersection)	1,2,3,4,5,6
Default Vehicle Speed	25 m/s
Vehicle Length	5 m
Edge Length	100 m
Lane Number	2
Driver Imperfection	0.5

Table 4.1: Simulations parameters

c values	$t_{max} = c \cdot \tau$ (seconds)
0.5	4
1.0	8
1.5	12
2.0	16

Table 4.2: Delay Times

If there are N vehicles in the network then average number of vehicle per intersection is set as $N/10 \times 10$. Average number of vehicle per intersection changed and the adversary success per intersection is obtained. In traces, vehicle routes are computed as uniform turning percentage and simulation ended in 2500s. U turns are forbidden. Running network simulation can be seen in Figure 4.4.

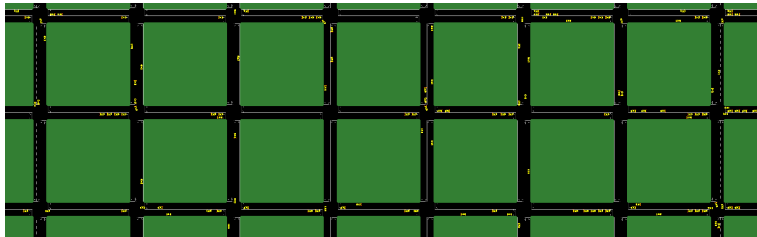


Figure 4.4: Running simulation snapshot

From the simulation parameters (as shown in Table 4.1) edge length is 100m and default speed is 25m/s. An edge passing time with average speeds(τ) for the chosen simulation parameters is 8 ($\tau = 100/(25/2)$) . Delay times are generated uniformly random from the interval $[t_{min}, t_{max}]$. Value of minimum delay that is t_{min} is chosen as 0 second and t_{max} values are calculated for different c coefficients such as 0.5, 1.0, 1.5, and 2.0 using the Formula (4.4). Thus, used delay times for different c values are given in the Table 4.2.

4.2.2 Simulation Results

Simple attack model: For this type of attack model, attacker records the last safety message transmission of each vehicles with old pseudonym and first retransmission safety message information of vehicles with new pseudonym. At the end of observations, there are two data set in attacker hands. The first one

old pseudonym set with transmission details and the other set is new pseudonym sets. Attacker aim is to match the old pseudonym with the new pseudonyms so that vehicles uncertainty in mix zone mitigated.

From the first data set (with old pseudonyms), she computes the minimum and maximum place that vehicle may reappear in reasonable minimum and maximum time. Then vehicles in the second data set reappeared with those times and places are decided. Since this attack model is simple, no more information is used and all candidate vehicles selected in second data set is given equal chance to be a target vehicle and one of them is selected as target vehicle. Simple attacker model essentially assumes that traffic at an intersection follows the First In First Out (FIFO) principle. While this is clearly not the case in practice, the attacker still achieves a reasonable success rate in a single intersection. Attacker success ratio is obtained by ratio of the total number of successfully mapped vehicles to the total number of vehicles in an intersection and averaged over all intersections.

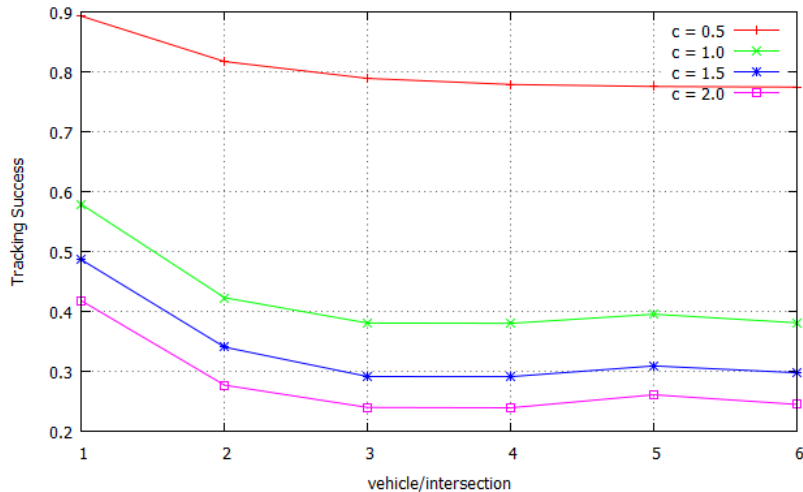


Figure 4.5: Attacker success with simple attack

Figure 4.5 presents the average location privacy obtained in an intersection for various vehicle densities for various delay times. It can be shown that achieved location privacy varies with respect to vehicle density. It is observed that the less number of vehicles in intersection is, the easier it is for adversary to track vehicles based on their delay characteristics. One can see, for instance, that for $c = 1.5$, when vehicle per intersection is 1, the attacker can track a target vehicle

through a single intersection with probability around 50 percent. However, when vehicle per intersection is 5, the attacker tracking success dramatically decreases to nearly 30 percent.

On the other hand, the more delay time added to vehicle beaconing period, the more candidate vehicles reappear, thus attacker success decreases. As it is expected, success ratio decreases as the delay amount increases (c increases). The quantitative results of the simulation experiments presents that when $c = 2.0$ attacker success is between 25 and 42 percent while for $c = 0.5$ her success is between 75 and 90 percent.

Correlation based attack model: For correlation based attack model, attacker again constructs two data sets which are old pseudonyms set and new pseudonyms set. To link between two data sets, she correlates speed and position information as well. From the old pseudonyms data set, she computes the minimum and maximum place that vehicle may reappear in reasonable minimum and maximum time. Then vehicles in the second data set reappeared with those times and places are decided. For each candidate vehicle, guess vehicle is decided as mention in section 4.1.1.2 using formula 4.1. Attacker success ratio is obtained by ratio of the total number of successfully mapped vehicles to the total number of vehicles in an intersection and averaged over all intersections.

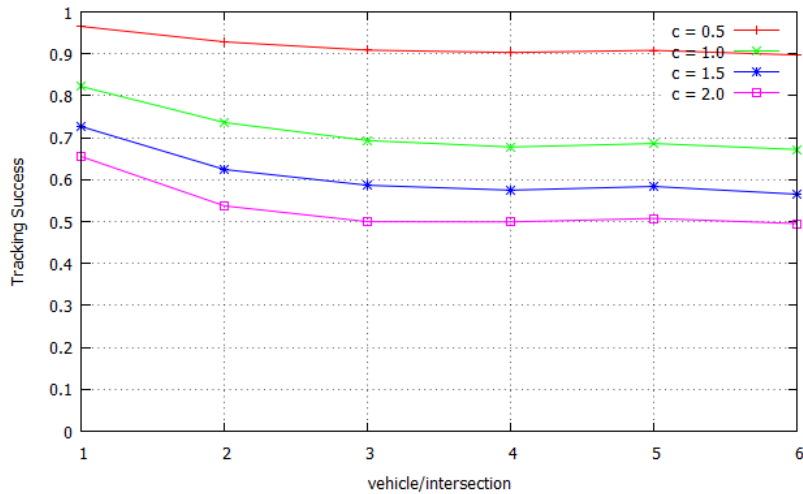


Figure 4.6: Attacker success with correlation based attack

Figure 4.6 show the same metrics for correlation based attacker model. In correlation based attacker model attacker uses more information such as speed and position to guess the target vehicle. Since attacker knowledge about vehicle increases, success on attack also increases. Thus, location privacy decreases. For example, for $c = 1.0$ simple attacker success is 42 percent but when attacker corralates the speed and position information, her success rate increases to 72 percent for 2 vehicles per intersection.

On the other hand, when delay time increases, attacker success is again reasonable high. For instance, for $c = 1.5$ attacker success is between 55 and 70 percent while for $c = 0.5$ her success is between 90 and 98 percent.

Even with more knowledge of attacker, high location privacy can be achieved with high delay times.

Generally, attacker tracking success is expected to decrease when the number of vehicles increases in the network. However, this is not the case for all situations. The reason is while making attack; attacker considers all vehicles as a candidate vehicle that start retransmission in a meaningful time in the reachable area. In other words, any vehicle that appears in the reachable region with a new pseudonym between minimum and maximum delay times is a possible candidate for the target to the adversary. The high number of vehicles causes more vehicles to satisfy this condition. However, movement is an important requirement for vehicles. In congested traffic scenarios, vehicles that changed pseudonym may not move enough in road, and it prevents more vehicles to be candidate vehicle. Congestion prevents more vehicles to reappear with a new pseudonym. Thus, attacker success may be high in congested traffic scenarios. This situation can be seen from the attacker success graph for vehicle per intersection values 4, 5 and 6. In addition, a small increase in attacker success in simulation for 5 vehicles per intersection is due to accidents happened in network. It eliminates some vehicles from network and prevents some other vehicles from movement.

Chapter 5

Vehicle Density Based Randomization

In the previous chapter (Chapter 4), completely random delay is added in beaconing message period of vehicles. This method is problematic in some conditions and it can be improved. The vehicle density based random delay is proposed as a solution and effectiveness of this solution together with provided location privacy is given and discussed in this chapter. This chapter starts with problem definition and continues with detailed proposed solution. Then, evaluation of proposed solution is presented. Finally, privacy provided with basic random delay and vehicle density based random delay is compared.

5.1 The Problem Statement

The main problem that is tried to be solved is the alleviating unauthorized tracking of target vehicles by adversaries in VANETs. Frequently changing pseudonyms are proposed as a solution, but these pseudonyms can also be linked by determined attackers using temporal and spatial relations. As a first solution, random delay periods added to beaconing message period is proposed in the previous chapter (Chapter 4). This method provides some degree of privacy.

However, the disadvantage of this method is vehicles safety could be affected badly if silent period is large. Since not all vehicles in mix-zone start silent period at the same time and not restart at the same time, it may be possible to get beaconing message about safety of mix-zone from vehicles. But, the duration of this silent period is important and some optimization can be made.

Added random delay duration to provide location privacy is closely related with vehicle density. If vehicle density is very low then adding very long delay period may not provide high location privacy. On the other hand, if vehicle density is high and added random delay period is high, then vehicles will be silent unnecessarily long time. Instead of adding long delay, they may be unlinkable with short random delay periods. Thus, vehicle density should be considered as a parameter to decide random delay period.

5.2 Proposed Solution

As a solution to the above problem, vehicle density based random delay is proposed. Vehicles that enter the mix-zone should get silent vehicle number from the RSUs which are placed in each mix-zone and should decide the random delay period according to this number. If the number of silent vehicles is high then no need to add so much random delay to its message beaconing broadcast and vice versa.

The random delay period is generated uniformly random from interval t_{min} and t_{max} . The parameter t_{min} is set as 0 and the parameter t_{max} is calculated using the Equation (5.2). Since high vehicle density causes more obfuscation of vehicles, delay should be inversely proportional to the silent vehicle numbers.

The following algorithm is used to add vehicle density based random delay to vehicles.

1. Delay is generated between 0 and t_{max} .

$$delay \sim U(0, t_{max}) \tag{5.1}$$

2. The parameter t_{max} is calculated using the following formula:

$$t_{max} = c' \cdot \left(1 + \frac{a}{n_{silent}}\right) \cdot \tau \quad (5.2)$$

The parameter n_{silent} represents the number of silent vehicle number in mix zone. Upper limit for delay, that is t_{max} value is calculated for different a coefficients. The values 0.5, 1, 2, 3, 4 and 5 are selected a values for evaluation.

To compare the density based randomization with basic random delay method c' value is chosen related with c values in Chapter 4. Two methods will be comparable if they cause the same unconnectivity from network. In other words, if average vehicle unconnectivity from network are similar in two methods, then privacy level they expose can be compared. Thus, c' values are chosen so that same unconnectivity can be provided.

The coefficient c' is computed by using expected values of $1/n_{silent}$ represented by $\mu = E(1/n_{silent})$.

$$c' = \frac{c}{\mu_\beta} \quad (5.3)$$

where $\mu_\beta = 1 + a \cdot \mu$.

By using this solution, when vehicle density is high, unnecessarily being silent is prevented. The effectiveness of proposed solution is evaluated with different a values (0.5, 1, 2, 3, 4 and 5) for different c values (0.5 and 1).

5.3 Experiments and Results

In this chapter, simulation parameters given in Table 4.1 is used to get mobility pattern of vehicles. vehicle enter the mix zone gets the silent vehicle number from RSU, then delay period is added according to the this number using the Formula (5.2). Evaluation is done for different c and a coefficients to test the scenario for different values. After end of delay time, vehicles restart transmission.

Attacker knows that vehicles add random delay according to the silent vehicle number in the mix zone and she uses the vehicle densities in mix-zones to predict

the target vehicle next position. Thus, she computes the maximum and minimum delay time vehicles can add to message broadcast period and then tries to find target vehicles. Again two types of attacker model is implemented as simple attacker model (4.1.1.1) and correlation based attacker model (4.1.1.2). In simple attack model attacker computer vehicles as candidates vehicles if there are in the reachable area in reasonable minimum and maximum time. In correlation based attack model, vehicles in reachable area are evaluated using their speed and positions to be guessed vehicle for target vehicle. Adversary success is computed as ratio of number of successful mapped vehicles to the total number of vehicles in mix zone. Achievable location privacy is computed mix zone based and averaged over all mix zones.

Figures 5.1 and 5.2 show the network unconnectivity from the network. It is obtained that average unconnectivity for different a values are nearly same. Thus, normalization with expected values of silent vehicle number is successful to get same average delay.

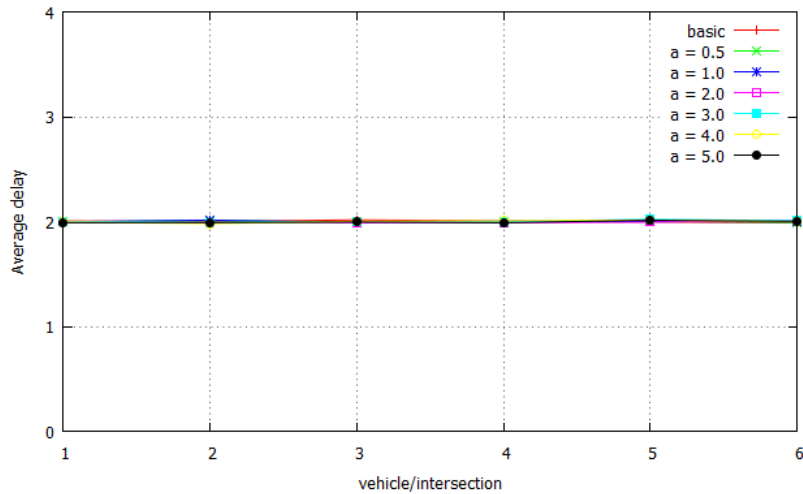


Figure 5.1: Average delay for $c = 0.5$

Figures 5.3 and 5.4 present the average location privacy obtained in an intersection for various vehicle densities ranging from 1 to 6 vehicles per intersection using simple attack model. Plots are obtained for different c values 0.5 and 1 respectively. As you can see, giving the same average random delay to vehicles density based randomization outperforms the basic random delay methods. The

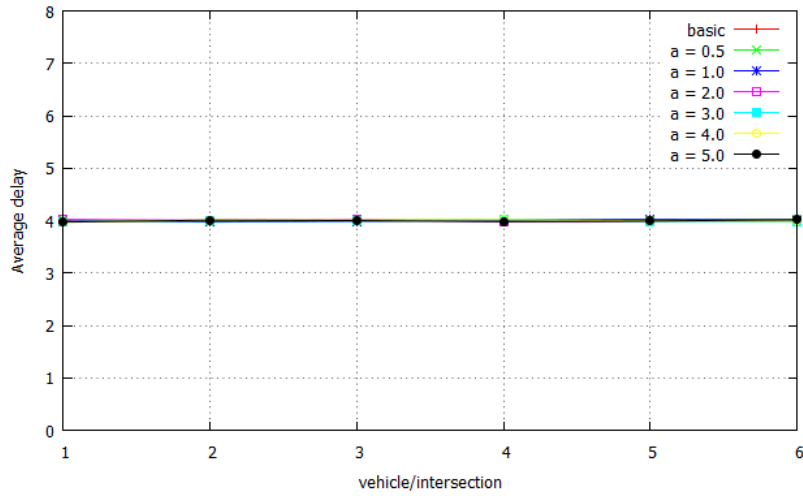


Figure 5.2: Average delay for $c = 1.0$

evaluation of solution with respect to the different a values shows that the best a values are around 3. Higher values are also evaluated but it does not affect privacy so much. For example, attacker success for $a = 5$ is nearly same for $a = 3$.

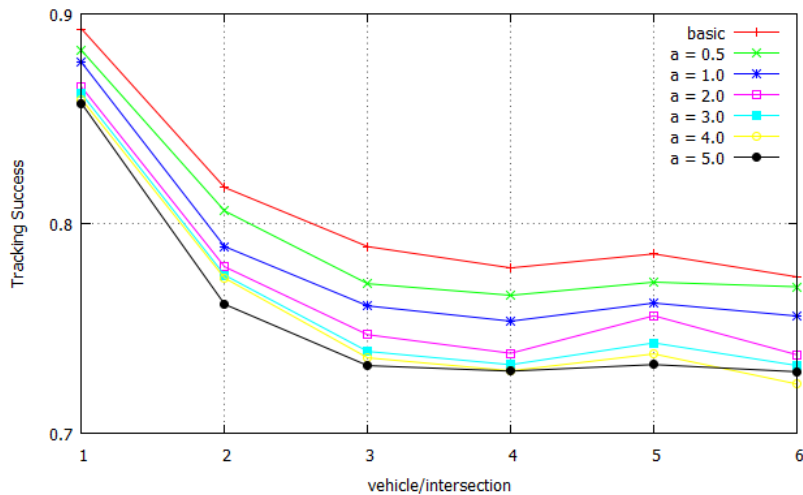


Figure 5.3: Attacker success with simple attack for $c = 0.5$

Figures 5.5, 5.6 show the same metrics for the attacker that makes position and speed correlations. It can be shown that the proposed solution provides achieved location privacy varies with respect to vehicle densities.

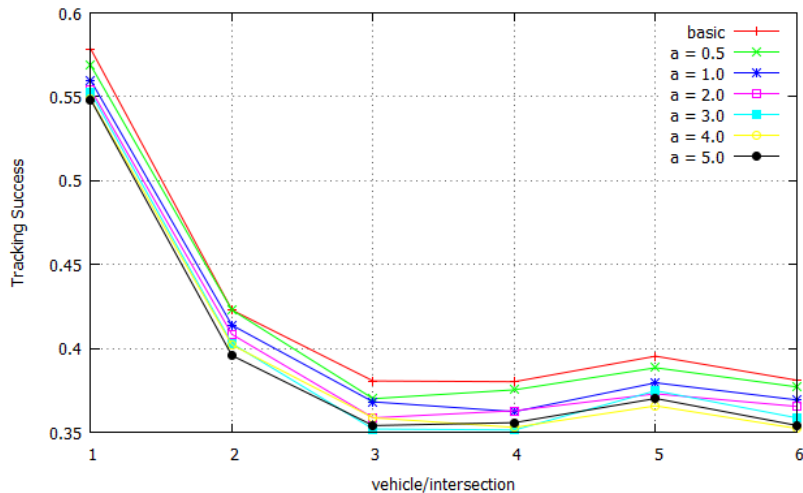


Figure 5.4: Attacker success with simple attack for $c = 1.0$

It can be seen from basic attack model and correlation based attack model figures, if attacker uses more information about vehicle, tracking success on vehicles increases. Thus, location privacy decreases. For example, for $c = 1.0$ and $a = 1.0$, simple attacker success is between 35 and 60 percent but when attacker correlates the speed and position information, her success rate increases to between 65 and 85 percent.

5.4 Comparison to Basic Random Delay Technique

When the privacy level obtained from different delay adding method compared, it can be seen that density based randomization performs better than random delay method. For example, simple attack model with $c = 0.5$, tracking success of an adversary between 78 and 90 percents for basic random adding technique. This is very good values from adversary perspective. However, when vehicle density based randomization technique applied, her success drops below 88 to 70 percent for suggested a values.

The other obvious advantages of the density based randomization method

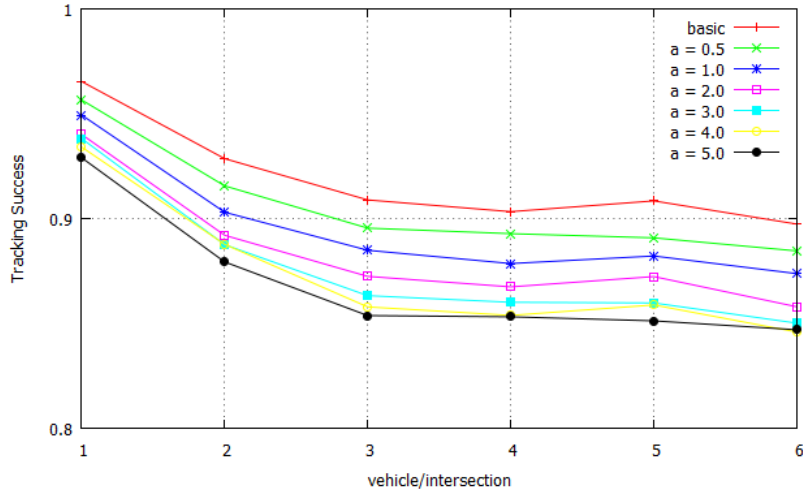


Figure 5.5: Attacker success with correlation based attack for $c = 0.5$

appears in the following situations.

Situation1: There are low numbers of vehicles which are in silent mode and the newly entering vehicle in mix-zone enters the mix-zone and adds short delay time to its beaconing message period. In short delay time period, vehicle reachable area will be very low, and candidate vehicle numbers will be also low. Thus, without using position and speed correlation information attacker may easily identify the target vehicle.

Situation2: There are high numbers of vehicle which are in silent mode and newly entering vehicle in mix-zone enters the mix-zone and adds long delay time to its beaconing message period. In long delay time period, vehicle reachable are will be high and also other vehicles in mix-zone may start retransmission and eliminated from being target vehicle. If target vehicle delay period would be low, obfuscated vehicle number will be high, which decreases linkability of vehicles. Also, redundantly being silent is prevented and obfuscation is provided.

Both of methods come with short-coming in issues with that if delay period is too long and accident happens in mix-zone. In this situation, there will be vehicles in intersection that start retransmission at the same time or not in silent period yet that may alert its surroundings, save the data to its on-board unit and execute message to authority, or other vehicles once out of region. In that

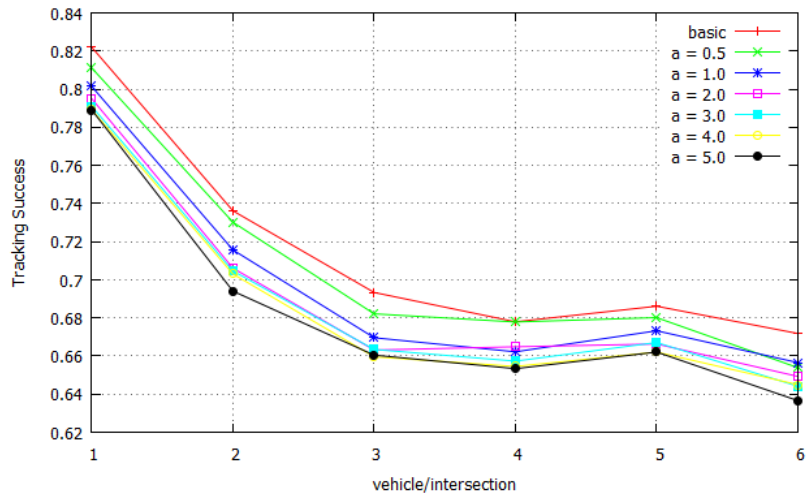


Figure 5.6: Attacker success with correlation based attack for $c = 1.0$

situation safety becomes more important than privacy and vehicles which are in silent mode cause accident are alarmed constantly by other vehicles or nearby road side unit and disable silent mode.

Chapter 6

Partial Mix Zone Placement

In this chapter, effects of partial mix zone placement in the network on location privacy are investigated. Chapter starts with motivation and used method, and then evaluation of proposed solution through simulations is given. At the end simulation results are discussed.

6.1 Motivation and Method

In VANET, vehicles broadcast safety messages disclosing their trajectory information in order to warn drivers of impending accidents. Precise location information needed for these safety applications, combined with the need to exclude attackers through the use of authentication, creates a significant privacy risk. One method proposed to improve privacy is the use of many pseudonyms, and changing pseudonyms while in a mix zone where all other vehicles also change pseudonyms.

Previous mix zone solutions mainly focus on single mix zone construction to achieve k -anonymity (a privacy metric denoting a state that the information of each individual cannot be distinguished from at least $k - 1$ others) for location privacy protection. However, using a single mix zone is insufficient to handle

the aforementioned attacks using side information, since side information may correspond to any part of a users trajectory. In order to achieve a desired level of protection, multiple mix zones are needed for a certain region to minimize the identity correlation over all point-of-interests recorded in a users trajectory. If multiple mix zones are deployed alongside a users routes, the users continuous trajectory is broken into a set of discrete segments, where each segment is associated with a unique pseudonym. This causes an adversary to lose the tracking target. Each single mix zone lowers the privacy risk in the users next trajectory segment.

Unlike wired mix networks such as Tor [23] where packets can be freely routed, the sequence of mix zones traversed by mobile nodes depends on the mobility of each node. In other words, the flow of mobile nodes cannot be controlled to maximize location privacy. Instead, the placement of mix zones to impede the adversary from tracking the nodes location can be controlled. However, similarly to the delay introduced by mix nodes on packets, mix zones induce a cost for mobile nodes: with random delay technique in mix zones, mobile nodes cannot communicate while they are in the mix zone. On the other hand, when one passes by a mix zone area, she might lose services temporarily due to pseudonym changes and synchronization. Similarly, the cost also depends on the number of used pseudonyms. Pseudonyms are costly to use because they are a limited resource that requires contacting the CA for refill. The traffic density at each location also affects the effectiveness of mix zone deployment, e.g., mix zone works better at busy road intersections. Hence, mix zones must be carefully deployed in the network to reduce the cost induced on mobile users and to provide high location privacy.

In principle, mix zones can be placed anywhere in the considered area. Their placement determines the accumulated location privacy provided by each mix zone. Thus, the optimal solution consists in placing mix zones on the entire surface of the considered area. For aforementioned reasons, deploying mix zones at all intersections is both expensive and inefficient. Hence, the total number of mix zones deployed in the network should be limited to minimize the disruptions caused to mobile nodes.

As mentioned in background part of thesis, a central authority, responsible for the establishment of security and privacy in the system, is confronted with the problem of organizing mix zones in the network. Thus, users must trust that the central authority will protect their privacy. This trusted central authority deploys a limited number of mix zones in a given area to protect the location privacy of mobile nodes. Multiple mix zone placement is challenging for two reasons. First, in the physical dimension, as the effectiveness of a mix zone highly relies on the population and traffic characteristics of the deployed area, the traffic heterogeneity should be carefully considered. Second, in the logical dimension, distinct levels of protections may be required at different locations, e.g., a user's appearance at a special hospital may demand a higher level of protection. As a result, multiple mix zone deployment should also incorporate fine-grained protection priorities. There is a need to strategically plan mix zone placement locations in the system to achieve the maximum location privacy protection subject to cost and service constraint. However, for this thesis, all intersections have equal chances to be a mix zone. Thus, random placements of mix zones are preferred.

In random delay technique (Chapter 4) and density-based random delay technique (Chapter 5) attacker success on a mix zone is investigated. Attacker aim was to correctly link the pseudonym of a vehicle before entering the mix zone with the pseudonym after exiting the mix zone. Thus, all intersections are considered as a mix-zone and all vehicles attend pseudonym change process in all intersections. This logic is meaningful if intersection-based location privacy is investigated. Event-based privacy metric (discussed in Section 2.3.1) is appropriate for intersection-based location privacy. But, if the investigated topic is the mix-zone number effect then the used method should be changed. In this type of investigation, the threat model as well as privacy metric is different. Attacker aims to track the single vehicle through its journey. Thus, user-centric based privacy metric should be used (discussed in Section 2.3.2). The goal of the user-centric metric is to measure the untraceability of a particular user traversing mix zones, instead of the mix zone in general. Adversary picks a target vehicle and tries to find all its paths. Again, assumption about adversary is worst case

assumption. Adversary is global which means she obtains complete coverage. Adversary selects target vehicle v and can track throughout the entire area. If vehicle v passes through large number of mix zone then adversary success for traceability will reduce.

6.2 Evaluation

In this chapter, simulation parameters given in Table 4.1 is used to get mobility pattern of vehicles. Attacker aim is to find all the journey path of the target vehicle. Thus, for an attacker to track a vehicle from start to end of journey is of course affected by journey times. Thus, different journey times of vehicles should be another parameter that must be considered. For the investigation maximum travel times are set as 40, 20, 10 and 5 minutes. Maximum 40 minutes journey time means at the end of 2400 seconds no more vehicle will be in the network while some of vehicle may already finish its journey before reaching that time. Traffic density in intersections is set as 3 vehicles per intersection. More vehicles on intersection make attacker job more difficult. But, the effects of number of vehicle per intersection on attacker success are examined in detail in Chapter 4 and 5. Hence, concentrating on tracking a vehicle during its journey is more important for this chapter purpose and vehicle density on intersection is not examined as a changing parameter.

The focus of this chapter is how the changing number of mix zone in network affects the adversary success. Certainly, more mix zone causes more confusion points and decreases attacker success. However, as mentioned in motivation part of this chapter more mix zone deployment comes with many costs. The evaluation of proposed method is done as follows. First, full deployment of mix zone is constructed and attacker success is computed. Then, mix zone is decreases with the different percents. 100%, 50%, 25%, 12.5% and 6.25% of intersections are deployed as a mix zone and attacker success is compared for different number of delays. Delay durations are generated uniformly random from interval 0 and t_{max} , t_{max} is computed using the Formula 6.1 to provide the same network

unconnectivity.

$$t_{max} = \gamma \cdot \tau \cdot \frac{1}{\psi} \quad (6.1)$$

where ψ is density of mix zone (ratio of deployed mix zone to the total number of mix zone in full deployment). ψ values are computed for 100%, 50%, 25%, 12.5% and 6.25% of intersections deployed as mix zone; 0.1 and 0.2 are chosen γ values.

Two types of attacker model are implemented to track a vehicle. One is uses the time and reachable area information to decide candidates vehicles (see Section 4.1.1.1) and the second type of adversary uses the position and speed information of vehicles to correlate target and candidates vehicles(see Section 4.1.1.2). Adversary success is computed as ratio of number of tracked vehicle during whole network to the total number of vehicles in network. Achievable location privacy is computed vehicle based and averaged over all vehicles.

6.3 Experimental Results

The purpose of experiments is that while keeping network unconnectivity is similar, same privacy can be obtained with full deployment with the partial deployment. In other words, we can compensates the mix zone partial deployment with adding extra delay to delay periods of vehicles.

Vehicles unconnectivity graphs can be seen from Figure 6.1 and 6.2.

Basic random delay method is chosen for giving random delay at intersections and obtained results are shown in the following figures. Tracking success of adversary is computed for two different attack models.

Tracking success of adversary for simple attack model can be seen from Figures 6.3 and 6.4 for γ values 0.1 and 0.2 respectively.

Attacker success that uses more information has high tracking success and it can be seen from Figures 6.5 and 6.6.

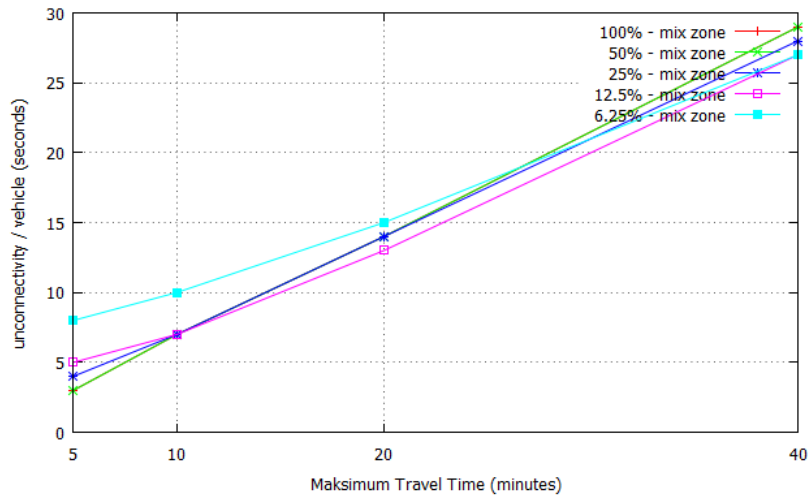


Figure 6.1: Vehicle unconnectivity from network ($\gamma = 0.1$)

It can be easily seen that if the journey time increases attacker success decreases considerably. For example, in Figure 6.3, in 25% of mix zone deployment, attacker success decreases from 65 percent to 8 percent if attacker journey time increases 35 minutes.

For simple attack model, an adversary monitoring 50% of the intersections can successfully track 23% of the vehicles while another adversary monitoring 12.5% of the intersections can successfully track 21% of vehicles with very high probability. While dropping monitoring region to 1/4 and increasing the delay duration to 4 multiplies, similar privacy level can be achieved.

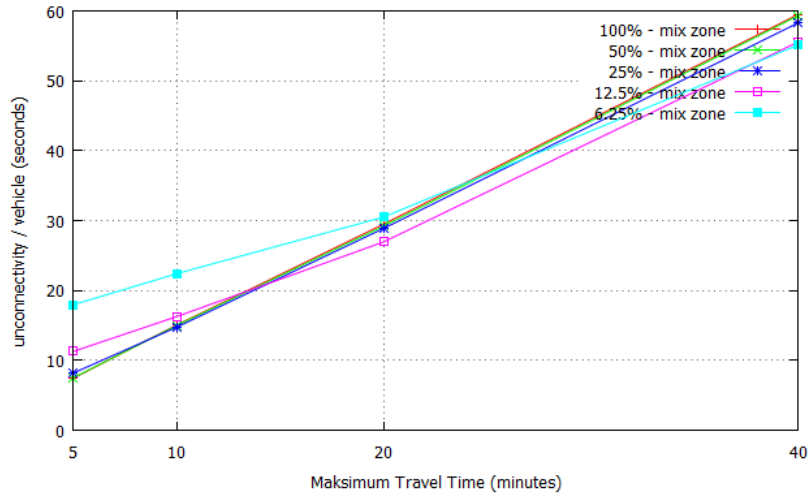


Figure 6.2: Vehicle unconnectivity from network ($\gamma = 0.2$)

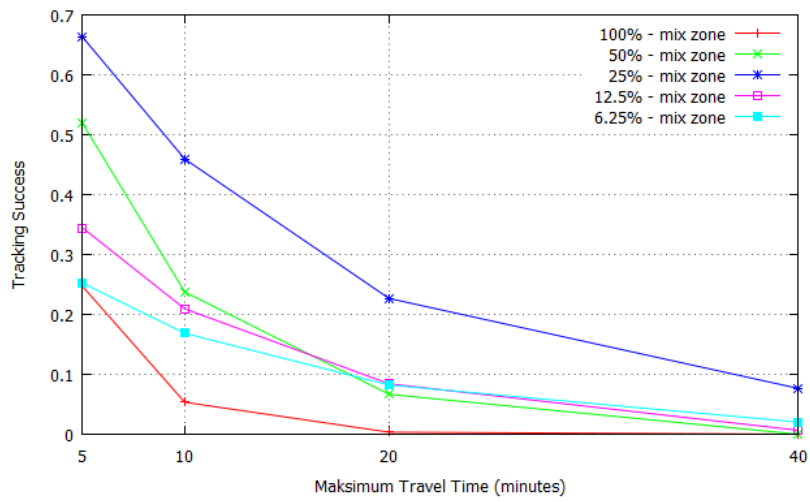


Figure 6.3: Attacker success with simple attack ($\gamma = 0.1$)

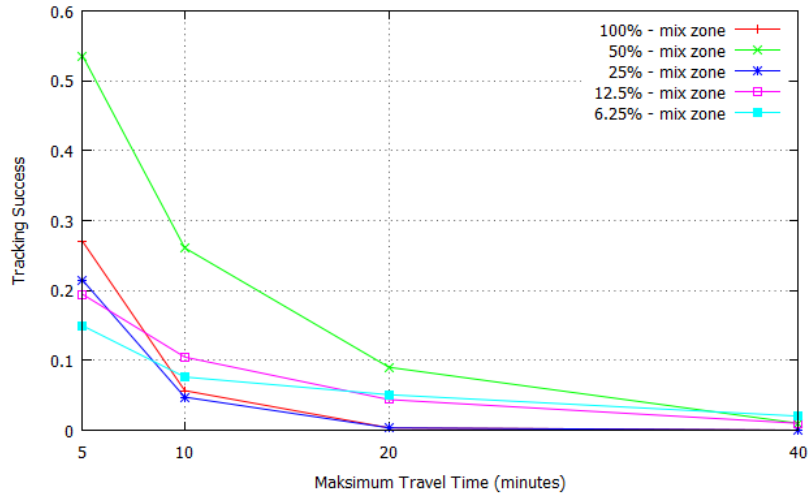


Figure 6.4: Attacker success with simple attack ($\gamma = 0.2$)

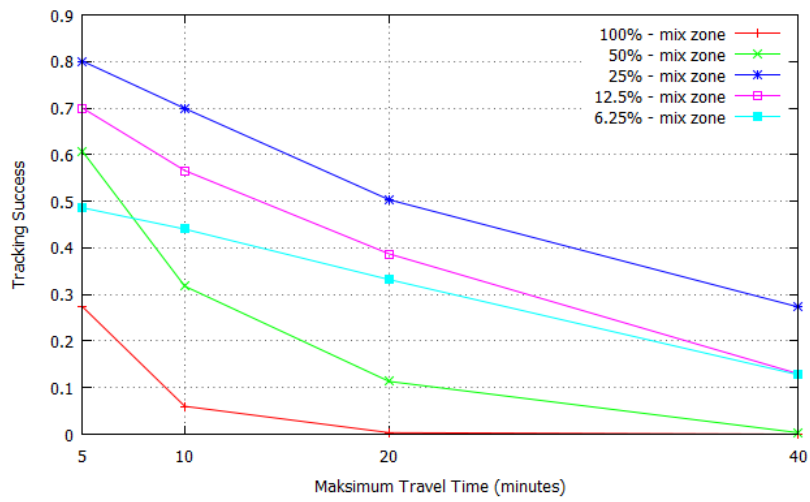


Figure 6.5: Attacker success with correlation based attack ($\gamma = 0.1$)

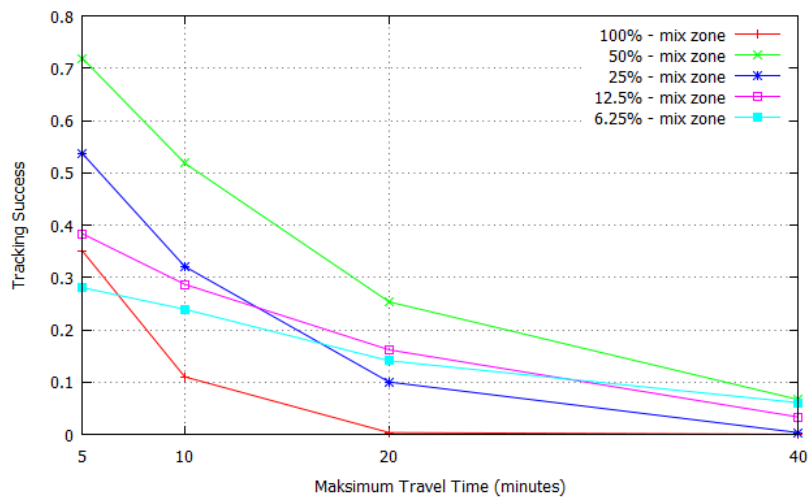


Figure 6.6: Attacker success with correlation based attack ($\gamma = 0.2$)

Chapter 7

Conclusion

In this thesis, I proposed three different location privacy enhancing techniques for vehicular ad hoc networks. I considered the effectiveness of changing pseudonyms to provide location privacy for vehicles in vehicular networks. The approach of changing pseudonyms to make location tracking more difficult was proposed in prior works, but its effectiveness has not been investigated so much on vehicular network. In order to address this problem, I studied the pseudonym change in the area called mix zone. I assumed adversary has some knowledge about mix zone and tries to associate the exit event with the enter event. I performed extensive simulations to study the behavior of proposed techniques by varying the strength of the adversary and by varying the number of her monitoring points.

Traffic accidents are one of the biggest problems of the world roads and VANET is the most promising technology for solution to this problem. In the introduction part of the thesis, general motivation about the issue is given. In background part of the thesis; system overview, threat models, privacy metrics and simulation details are given. Then, thesis continues with top most related works that dealt with similar problem and provide inspiration for our work.

In Chapter 4, adding random delay in a completely random way is analyzed through simulations. Analysis of tracking success of adversary for different delay periods is given. Based on my results presented in this chapter, I can conclude

that increasing random delay increases privacy of drivers at intersections. Also, stronger attacker (means uses much more information about system to track vehicles) has higher success compared to the basic one.

In Chapter 5 of thesis, random delay addition method is changed according to the silent vehicle density based. If density of silent vehicle in the intersection is high then no need to add high random delay unnecessarily. Density based randomization method seems to be more efficient to deal with unconnectivity problem of the vehicles. Using the same unconnectivity, density based randomization performs better than basic random delay technique.

Evaluation of mix zone placement is studied in Chapter 6 of thesis. Different number of mix zone placement is evaluated in two different attacker models. If number of confusion point in a network (mix zone number) is high, then tracking will be more difficult. However, keeping mix zone number in a network is costly job for reasons mentioned in the chapter. Thus, we proposed that decrease in mix zone number can be compensated with increasing delay durations. Many simulations are performed to test different number of mix zone deployment while keeping unconnectivity similar. Results shows that privacy obtained in full deployment of mix zones can be gained with low number of mix zones with high delayed messages.

The more people use VANET, the more useful information can be obtained for roads. Along with our proposed solutions retaining privacy of drivers can be improved. This may help VANET to be accepted by more vehicle owners.

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