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PRIVACY IN RFID AND MOBILE OBJECTS

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requirements of the degree of Doctor of Philosophy
in Computer Science

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I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy in Computer Science.

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Resum

Els sistemes RFID permeten la identificació ràpida i automàtica d'etiquetes RFID a través d'un canal de comunicació sense fils. Aquestes etiquetes són dispositius amb cert poder de còmput i amb capacitat d'emmagatzematge de informació. Es per això que els objectes que porten una etiqueta RFID adherida permeten la lectura d'una quantitat rica i variada de dades que els descriuen i caracteritzen, com per exemple un codi únic d'identificació, el nom, el model o la data d'expiració. A més, aquesta informació pot ser llegida sense la necessitat d'un contacte visual entre el lector i l'etiqueta, la qual cosa agilita considerablement els processos d'inventariar, identificació o control automàtic.

Perquè l'ús de la tecnologia RFID es generalitzi amb èxit, es convenient complir amb diversos objectius: eficiència, seguretat i protecció de la privadesa. No obstant això, el disseny de protocols d'identificació segurs, privats i escalables és un repte difícil d'abordar ateses les restriccions computacionals de les etiquetes RFID i la seva naturalesa sense fils. Es per això que, en la present tesi, partim de protocols d'identificació segurs i privats, i mostrem com es pot aconseguir escalabilitat mitjançant una arquitectura distribuïda i col·laborativa. D'aquesta manera, la seguretat i la privadesa s'aconsegueixen mitjançant el propi protocol d'identificació, mentre que l'escalabilitat s'aconsegueix per mitjà de nous protocols col·laboratius que consideren la posició espacial i temporal de les etiquetes RFID.

Independentment dels avenços en protocols d'identificació sense fils, existeixen atacs que poden superar amb èxit qualsevol d'aquests protocols sense necessitat de conèixer o descobrir claus secretes vàlides, ni de trobar vulnerabilitats a les seves implantacions criptogràfiques. La idea d'aquests atacs, coneguts com atacs de "repetidor", consisteix en crear inadvertidament un pont de comunicació entre una etiqueta legítima i un lector legítim. D'aquesta manera, l'adversari utilitza els drets de l'etiqueta legítima per superar el protocol d'autenticació utilitzat pel lector. En aquesta tesi proposem un nou protocol que, a més d'autenticació, realitza una revisió de la distància a la qual es troben el lector i l'etiqueta. Aquests tipus de protocols es coneixen com a protocols de fitació de distància, els quals no impedeixen aquests tipus d'atacs, però sí que poden frustrar-los amb alta probabilitat.

Per últim, afrontem els problemes de privadesa associats amb la publicació de informació recollida a través de sistemes RFID. En concret, ens concentrem en dades de mobilitat, que també poden ser proporcionades per altres sistemes àmpliament utilitzats tals com el sistema de posicionament global (GPS) i el sistema global de comunicacions mòbils. La nostra solució es basa en la coneguda noció de k -anonimat, obtingut mitjançant permutació i microagregació. Per a aquesta finalitat, definim una nova funció de distància entre trajectòries amb la qual desenvolupen dos mètodes diferents d'anonimització de trajectòries.

Resumen

Los sistemas RFID permiten la identificación rápida y automática de etiquetas RFID a través de un canal de comunicación inalámbrico. Dichas etiquetas son dispositivos con cierto poder de cómputo y capacidad de almacenamiento de información. Es por ello que los objetos que contienen una etiqueta RFID adherida permiten la lectura de una cantidad rica y variada de datos que los describen y caracterizan, por ejemplo, un código único de identificación, el nombre, el modelo o la fecha de expiración. Además, esta información puede ser leída sin la necesidad de un contacto visual entre el lector y la etiqueta, lo cual agiliza considerablemente los procesos de inventariado, identificación, o control automático.

Para que el uso de la tecnología RFID se generalice con éxito, es conveniente cumplir con varios objetivos: eficiencia, seguridad y protección de la privacidad. Sin embargo, el diseño de protocolos de identificación seguros, privados, y escalables es un reto difícil de abordar dada las restricciones computacionales de las etiquetas RFID y su naturaleza inalámbrica. Es por ello que, en la presente tesis, partimos de protocolos de identificación seguros y privados, y mostramos cómo se puede lograr escalabilidad mediante una arquitectura distribuida y colaborativa. De este modo, la seguridad y la privacidad se alcanzan mediante el propio protocolo de identificación, mientras que la escalabilidad se logra por medio de novedosos métodos colaborativos que consideran la posición espacial y temporal de las etiquetas RFID.

Independientemente de los avances en protocolos inalámbricos de identificación, existen ataques que pueden superar exitosamente cualquiera de estos protocolos sin necesidad de conocer o descubrir claves secretas válidas ni de encontrar vulnerabilidades en sus implementaciones criptográficas. La idea de estos ataques, conocidos como ataques de “repetidor”, consiste en crear inadvertidamente un puente de comunicación entre una etiqueta legítima y un lector legítimo. De este modo, el adversario usa los derechos de la etiqueta legítima para pasar el protocolo de autenticación usado por el lector. En esta tesis proponemos un nuevo protocolo que además de autenticación realiza un chequeo de la distancia a la cual se encuentran el lector y la etiqueta. Este tipo de protocolos se conocen como protocolos de acotación de distancia, los cuales no impiden este tipo de ataques, pero sí pueden frustrarlos con alta probabilidad.

Por último, afrontamos los problemas de privacidad asociados con la publicación de información recogida a través de sistemas RFID. En particular, nos concentramos en datos de movilidad que también pueden ser proporcionados por otros sistemas ampliamente usados tales como el sistema de posicionamiento global (GPS) y el sistema global de comunicaciones móviles. Nuestra solución se basa en la conocida noción de k -anonimato, alcanzada mediante permutaciones y microagregación. Para este fin, definimos una novedosa función de distancia entre trayectorias con la cual desarrollamos dos métodos diferentes de anonimización de trayectorias.

Abstract

Radio Frequency Identification (RFID) is a technology aimed at efficiently identifying and tracking goods and assets. Such identification may be performed without requiring line-of-sight alignment or physical contact between the RFID tag and the RFID reader, whilst tracking is naturally achieved due to the short interrogation field of RFID readers. That is why the reduction in price of the RFID tags has been accompanied with an increasing attention paid to this technology. However, since tags are resource-constrained devices sending identification data wirelessly, designing secure and private RFID identification protocols is a challenging task. This scenario is even more complex when scalability must be met by those protocols.

Assuming the existence of a lightweight, secure, private and scalable RFID identification protocol, there exist other concerns surrounding the RFID technology. Some of them arise from the technology itself, such as *distance checking*, but others are related to the potential of RFID systems to gather huge amount of tracking data. Publishing and mining such moving objects data is essential to improve efficiency of supervisory control, assets management and localisation, transportation, etc. However, obvious privacy threats arise if an individual can be linked with some of those published trajectories.

The present dissertation contributes to the design of algorithms and protocols aimed at dealing with the issues explained above. First, we propose a set of protocols and heuristics based on a distributed architecture that improve the efficiency of the identification process without compromising privacy or security. Moreover, we present a novel distance-bounding protocol based on graphs that is extremely low-resource consuming. Finally, we present two trajectory anonymisation methods aimed at preserving the individuals' privacy when their trajectories are released.

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Introduction

This chapter introduces the issues we are facing in this dissertation. In addition, it briefly describes the solutions we propose to tackle those issues. Finally, the structure and organisation of the present thesis are outlined.

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1.1 Motivation

Radio frequency identification (RFID) allows the simultaneous identification of multiple RFID tags. The identification process is performed over a wireless channel without requiring line-of-sight alignment or physical contact between the RFID tags and the RFID reader. These features together with others like low deployment costs, being flexible and manageable, computational power, etc., are causing the RFID technology to be preferred to traditional options (*e.g.* barcodes systems). Indeed, nowadays several RFID systems are massively deployed worldwide, namely for *assets tracking* (*e.g.* Air Canada decided to use this technology to control their food trolleys so as to reduce more than \$2 million in unexplained losses [206]), *manufacturing* (*e.g.* Boeing uses RFID to track parts as they arrive, and as they move from one shop to another within their facilities, thus reducing errors and the need for people to look for parts [207]), *supply chain management* (*e.g.* Paramount farms, the largest producer of pistachio in the US, receives 50% of its production from a network of about 400 partners; the shipments are processed by using RFID that reduces processing times to up to 60% [219]), *retailing* (*e.g.* Walmart started to explore the RFID technology in 2003 and devoted at least three billion dollars to implement it [98]), and for other applications such as *payments*, *security* and *access control*.

The RFID technology also has the capability of naturally collecting trajectories of moving objects. Differently to other positioning systems like the GPS, RFID systems do not continuously track a moving object. Instead, RFID readers located at different

waypoints create trajectories by identifying tags passing through those waypoints. In this sense, the RFID technology can be considered a simple and low-cost tracking system where complex trilateration and precisely timing of signals are not required. This type of *coarse-grained* tracking is particularly useful to improve the quality of diagnostic processes and business decisions in the healthcare industry [112], to monitor animal behaviour [129], to enhance bike races [215], to provide location based services in indoor environments [227], etc.

However, all those potential benefits have been partially overshadowed by important security and privacy threats. RFID tags are resource-constrained devices that respond to any reader interrogation through an insecure channel. This means that both the data stored in the tags' memory and the data transmitted to readers cannot be protected by cryptographically strong primitives and/or large key sizes. Instead, lightweight cryptography requiring no more than 3000 logic gates should be used [183]. In this scenario, the privacy of tag bearers could be seriously compromised by disclosing the individual's locations or other sensitive information contained in the RFID tag's memory. Moreover, other security risks like tag impersonation and counterfeiting increase due to the lack of randomness and computational power in the tag's side.

In recent years, several efforts have been made on designing secure and private RFID identification protocols. Among those protocols, the Randomised Hash-Lock Scheme [119] has been widely accepted due to its strong privacy and security properties, and its low computational requirements in the tag's side, *i.e.* it only needs a pseudo-random numbers generator and a one-way hash function. However, this protocol is not scalable. This is particularly problematic if we consider that millions or billions of tags should be managed by typical RFID applications (*e.g.* for supply chain management or inventory control). That is why many other RFID identification protocols have been proposed aimed at being secure and private, yet scalable. Nevertheless, none of them has achieved those three goals at the same time [18], especially when strong privacy definitions must be met. In the present dissertation, we mainly focus on designing collaborative algorithms that improve the scalability of the Randomised Hash-Lock Scheme [119]. The algorithms are collaborative in the sense that several readers deployed in the system exchange information in order to efficiently identify RFID tags. By doing so, our proposals are able to improve the scalability, being as private and secure as the Randomised Hash-Lock Scheme [119], though.

Regardless of the improvements on designing identification/authentication protocols, Desmedt, Goutier and Bengio [65] presented in CRYPTO'87 a novel attack called *mafia fraud* that defeated any authentication protocol. In this attack, an adversary succeeds by simply relaying the messages between a legitimate reader and a legitimate tag. Initially, the mafia fraud attack was thought to be rather unrealistic because the legitimate prover should take part on the execution of the protocol. However, the RFID technology clearly opens the door to this type of attack since RFID tags answer to

any reader’s interrogation without any awareness or agreement of their holders. Other types of frauds are also applicable to RFID systems. Among them, the *distance fraud* attack [44], in which a dishonest prover claims to be closer to the verifier than he really is, is very important. Both mafia and distance frauds may be accomplished despite of the authentication protocol used by tags and readers. This means that even assuming secure, private, and scalable RFID identification/authentication protocols at the application layer, there exists the need for designing protocols that thwart the mafia and distance fraud attacks. Among the countermeasures against these attacks, *distance bounding* protocols based on the measurement of the round trip time of exchanged messages [33, 35] are considered the most suitable for RFID systems. We contribute by designing a novel distance bounding protocol based on graphs that is highly resilient to mafia and distance fraud attacks. Our protocol also deals with other RFID systems’s requirements such as efficiency and low memory consumption.

Seemingly, an increasing number of articles are being written on RFID security and privacy areas, namely ultralightweight protocols, distance-bounding protocols, privacy-preserving lightweight protocols, cryptographically secure pseudo-random numbers generators, cryptosystems based on elliptic curves, RFID privacy models, zero-knowledge authentication protocols for RFID systems, ownership transfer protocols, among others [1]. All these efforts contribute to the establishment of a technology that may help to do business as much as other revolutionary technologies like internet do. This means that, in the near future, billions of RFID tags will send information to thousands of RFID readers so as to enrich our interaction with the environment and make our processes more efficient and resilient. Therefore, gathering huge databases of trajectories by using the potential of the RFID technology to track moving objects will be a reality.

Analysing this kind of databases can lead to useful and previously unknown knowledge. However, even when tracking is performed by legitimate parties, the privacy of individuals may be affected by the publication of such databases of trajectories. Simple de-identification realised by removing identifying attributes is insufficient to protect the privacy of individuals. Just knowing some locations visited by an individual can help an adversary to identify the individual’s trajectory in the published database. In this context, privacy preservation means that no sensitive location ought to be linkable to an individual. The privacy threat grows if such a trajectory is linked with sensitive personal data like, price of products, name of drugs, etc, which are usually stored in the tags’ memory.

These privacy issues motivate our last research line in this thesis. We note that the boom of the RFID technology strongly promotes the design of privacy-preserving trajectory anonymisation methods. In this sense, we finally focus on mitigating the privacy issues that may arise from the publication of databases of trajectories, rather than on providing security and/or privacy to the RFID technology. In particular, we propose a novel distance measure for trajectories which naturally considers both spatial

and temporal aspects of trajectories, is computable in polynomial time, and can cluster trajectories not defined over the same time span. Mainly based on this metric, we propose two methods for trajectory anonymisation which yield anonymised trajectories formed by fully accurate true original locations.

1.2 Contributions

The main contributions of this dissertation are the following:

1. **Efficient RFID identification protocol by means of collaborative readers:** Designing secure, private, and scalable, RFID identification protocols in a multiple tags to one reader scenario is a challenge. However, in scenarios where multiple readers are deployed in the system, scalability may be achieved without compromising privacy or security. In particular, we consider a scenario where readers should continuously monitor moving tags in the system. Under such an assumption, we propose a scheme that has been proven to be efficient in terms of both server and network overhead.
2. **Predictive protocol for the scalable identification of RFID tags:** We improve the state-of-the-art of RFID identification schemes based on collaborative readers by proposing a protocol that predicts future and past locations of RFID tags. By doing so, readers are aware of which tags may be identified at some slot of time. Therefore, the identification process is considerably improved.
3. **A new distance-bounding protocol:** RFID systems are specially susceptible to mafia and distance frauds. Among the countermeasures to thwart these attacks, distance-bounding protocols are considered the most suitable solutions for RFID systems. We propose a novel distance-bounding protocol only requiring a single hash computation and a linear amount of memory in the tag's side. Despite those limitations, our proposal is highly resilient to both mafia and distance frauds.
4. **Privacy-preserving publication of trajectories:** It is hard to say how much personal information and tracking data may be collected by RFID readers in the near future. Nevertheless, trajectories are massively gathered by GPS and/or GSM technologies, and apparently the RFID technology is strongly supporting this massive collection of moving objects data. We focus on designing trajectory anonymisation algorithms that may work over trajectories not defined over the same time span. In particular, we propose two algorithms based on microaggregation and permutation aimed at achieving trajectory k -anonymity and location k -diversity. Both algorithms are based on a novel distance measure that effectively considers both dimensions: space and time.

1.3 Organisation

This thesis is organised as follows:

- Chapter 2 provides an overview of RFID systems and describes some challenges that the RFID technology should address in order to be successfully deployed worldwide. Also, the controversy between privacy, security, and scalability in RFID systems is discussed in detail. Other ramifications of RFID systems are introduced as well, namely distance checking and trajectory anonymisation.
- Chapter 3 presents our first contributions to the scalability issue of RFID identification protocols. In particular, it describes a protocol based on collaborative readers that outperforms previous proposals in terms of both number of cryptographic operations and bandwidth usage.
- Chapter 4 introduces the concept of RFID identification protocols based on location prediction. This new proposal is also based on collaborative readers, but it is able to improve the identification process by predicting the next reader that should identify a tag.
- Chapter 5 is devoted to the description of a novel distance-bounding protocol based on graphs. The goal of this proposal is to reduce memory requirements while still achieving high security properties regarding both distance and mafia fraud. To do so, the concept of distance bounding protocols based on graphs is introduced and defined.
- Chapter 6 presents our contributions to the anonymisation of moving objects data. In particular, two anonymisation methods releasing trajectories that contain true original locations are proposed. Both methods are able to effectively deal with trajectories not defined over the same time span thanks to a novel distance measure presented in this chapter.
- Finally, Chapter 7 summarises our contributions and describes possible future research lines.

Background

This chapter briefly describes RFID systems, from the very beginning of the technology to the most recent applications and challenges. Among all the challenges, it focuses on the security, privacy, and scalability issues of RFID systems, distance checking, and the anonymisation of mobility data collected by either the RFID or the GPS technologies. In addition, the main contributions aimed at facing all those challenges are reviewed.

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2.1 A brief history of the RFID technology

The first RFID system dates from the Second World War [191]. In those days, radar technology was used to detect approaching aircrafts by sending pulses of radio energy and receiving the echoes generated by those aircrafts. However, visual contact was the only way to identify an incoming plane as enemy or allied. The Germans solved this problem by rolling their aircrafts in response to a signal from the ground radar station so as to change the radar reflection's polarisation and thus, creating a distinctive blip on

the radars. In military terms, this is considered a huge advantage over previous radar systems. Actually, some people believe that this ingenious German military strategy could have helped the US army to prevent the attack on Pearl Harbor.

Later, the British army introduced a more sophisticated system called Identify Friend or Foe (IFF). Closer to current RFID systems, each plane was equipped with a transponder that modulated back the radar signal, thereby allowing identification of that aircraft as friendly. Due to its simplicity and resiliency, this technology is still being used by the aviation industry to keep airplanes tracked. However, a *not* friendly aircraft should be treated with care since there is no proof of it being an enemy. Apparently, this inconvenience has been the cause of unfortunate accidents (*e.g.* in 1983, the Soviet Union army shot down a Korean civilian airplane that was confused with a spy plane [4]. Similarly, an Iranian civilian plane was shot down in 1988 by the United States army, and all 290 passengers and crew were killed, including 66 children [3]).

As advances in radio frequency communications systems and low-cost embedded computers continued through the 1950s, 1960s, and 1970s, several technologies related to radio waves were developed (*e.g.* the Electronic Article Surveillance application (EAS) designed to prevent shoplifting from retail stores). Nevertheless, the first patent for a passive, read-write RFID tag, was received by Mario Cardullo in 1973. This is considered the first true ancestor of modern RFID as it was a passive radio transponder with memory. Since then, RFID systems hardly seem recognisable. Modern RFID tags may be similar in size to a grain of rice; may have computational capabilities, Read Only Memory (ROM), Electrically Erasable Programmable Read-Only Memory (EEPROM); may be active in the sense of using batteries rather than RFID readers' power, etc.

Consequently, over the years, the number of solutions based on RFID has considerably grown. In fact, RFID systems are nowadays more related with business than with the military industry. In the 1980s and 1990s, RFID applications emerged in transport, access control, animal identification, tracking nuclear material and trucks and electronic toll collection [136]. This trend is increasing exponentially in the 21st century due to tags's price reduction [8] and RFID standardisation [10]; over 33 billion RFID tags were produced in 2010¹ and 2.31 and 2.88 billion tags were sold in 2010 and 2011, respectively².

2.1.1 RFID systems

An RFID system is supposed to identify and track objects by using radio waves. Similar to other identification systems such as barcodes, fingerprints or eyes' iris, the reader (RFID reader) reads from some source of identification data (RFID tag). Then, the

¹According to a study of In-Stat (<http://www.in-stat.com>) - <http://www.instat.com/press.asp?Sku=IN0502115WT&ID=1545>

²According to an extensive research by IDTechEx (http://www.idtechex.com/research/reports/rfid_forecasts_players_and_opportunities_2011_2021_000250.asp)

identification data are usually processed by a data processing subsystem or server. However, RFID systems stand out from other identification systems because they may be nearly as cheap as barcode systems, use a wireless channel like GPS or GSM, and have some computational capabilities like magnetic cards. That is why more and more attention has been paid to this technology in recent years.

In technical terms, an RFID system consists of three key elements:

- The RFID tag, or *transponder*, that contains information and identification data.
- The RFID reader, or *transceiver*, that queries transponders for information stored on them. This information can range from static identification numbers to user or sensory data.
- The *data processing subsystem or server*, which processes the data obtained from readers.

Intuitively, all objects to be identified shall be physically tagged with RFID tags. Then, RFID readers should be strategically distributed to interrogate tags where their data are required (*e.g.* a bicycle race timing system needs to place, at least, a reader at the start line and another one at the finish line). Other properties, namely readers' interrogation field size, computation capabilities, and memory size of tags, vary from application to application.

2.1.1.1 RFID tags

Typical *transponders* (*transmitters/responders*) or RFID tags (see examples in Figure 2.1), consist of integrated circuits connected to an antenna [79]. The memory element serves as writable and non-writable data storage, which can range between few bytes up to several kilobytes. Tags can be designed to be read-only, write-once, read-many, or fully rewritable. Therefore, tag programming can take place at the manufacturing level or at the application level. A tag can obtain power from the signal received from the reader, or it can have its own internal source of power. The way tags get their power generally defines their category:

- **Passive tags** use power provided by the reader by means of electromagnetic waves. The lack of an onboard power supply means that the device can be quite small and cheap.
- **Semi-passive tags** use a battery to run the microchip's circuitry but communicate by harvesting power from the reader signal.
- **Active tags** have their own internal power source, usually a battery, which is used to power the outgoing signal.



Figure 2.1: Pictures of some types of RFID tags

RFID tags may also be classified according to their processing power. A *dumb* tag has no significant processing power, while *smart* tags have on-board processors able to perform cryptographic operations [137]. Dumb tags are considered the heart of RFID systems. Manufacturers and retailers claim that reducing tags' cost is indispensable for the success of RFID systems. In some cases, sending a unique identifier would not necessarily be a problem. For instance, Canada, Israel, Japan, Belgium and The Netherlands, among other countries, require owners of pets to implant an RFID tag on their pets. These tags contain information that allow a fast and efficient localisation of pet owners in case of loss of their pets. Since those tags have a really short identification range and pets normally do not have enemies aimed at counterfeiting their identities, dumb tags could be the most practical option for this type of application. In turn, smart tags are used in those applications requiring some level of security and/or privacy, namely for e-passports, supply chain management or access control.

Considering that RFID systems rely on radio waves, tags operate in a well-defined frequency. There are four main bands: low frequency (LF), high frequency (HF), ultra-high frequency (UHF), and microwave. The exact frequency varies depending on the application and the regulations in different countries. The frequency bands and the most common RFID system frequencies are listed in Table 2.1.

Frequency Band	Operating Range	Applications
125kHz to 134kHz (LF)	\approx 0.5 Meters	Access control and Animal identification
13.56MHz (HF)	\approx 1 Meters	Library books and Smart cards
860MHz to 930MHz (UHF)	\approx 3 Meters	Logistic and Parking access
2.4GHz (Microwave)	\approx 10 Meters	Electronic toll collection and Airline baggage tracking

Table 2.1: RFID frequency bands and characteristics.

2.1.1.2 RFID readers

Typical *transceivers* or RFID readers consist of a radio frequency module, a control unit and a coupling element to interrogate RFID tags via radio frequency communication. Readers may issue two types of challenge: multicast and unicast. Multicast challenges are addressed to all tags in the range of a reader whereas unicast challenges are addressed to specific tags. In order to keep readers as simple as possible, they have, in general, an interface that allows them to forward the received data to a *data processing subsystem, back-end database or server*. By doing so, readers delegate most of the computational effort to other computationally more powerful devices.

2.1.1.3 Data processing subsystem

The *data processing subsystem or server* is used to overcome the computational limitations of tags and readers. On the one hand, tags may not be able to store in their memory all the information required by readers. Thus, this information is usually stored in indexed databases. On the other hand, aimed at reducing the cost of RFID readers, cryptographic functions or processing data algorithms should rely on a data processing subsystem or server. It should be remarked that a secure connection between readers and back-end databases is generally assumed; anyway, secure communication between two computationally powerful devices does not belong to the problems addressed by the RFID technology. Refer to Figure 2.2 for a graphical representation of the RFID components and their basic relations/connections.

2.1.2 RFID standards

Nowadays, most technologies we use are governed by standards. Basically, these define the minimum requirements of some technology in order to achieve interoperability,

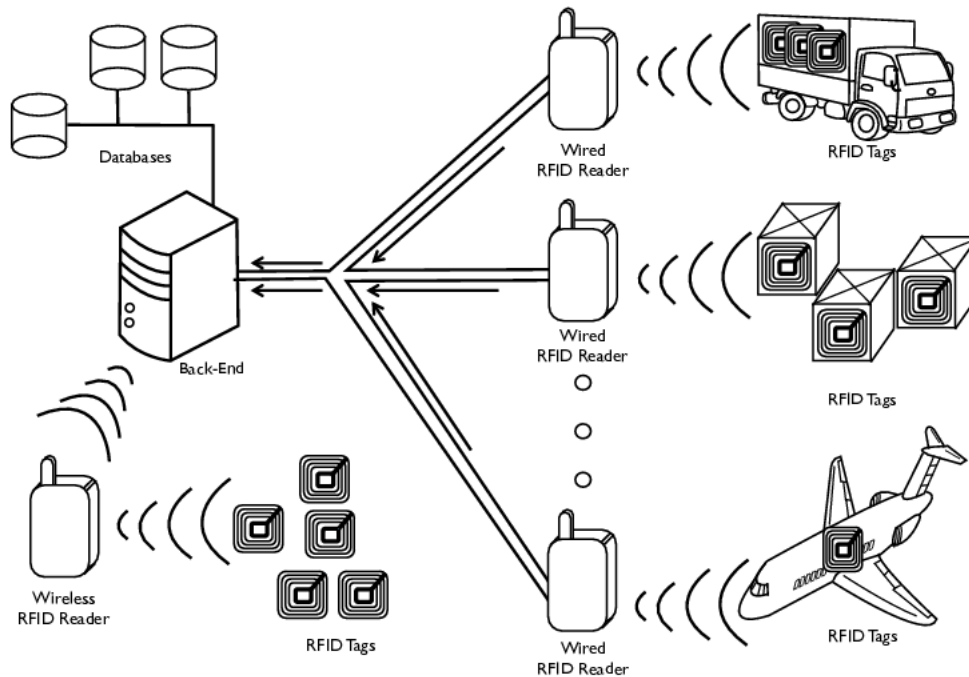


Figure 2.2: Basic components of an RFID system. From left to right: a back-end, RFID readers, and RFID tags. The back-end uses databases to store identification information. RFID readers are used to query RFID tags (that can take a variety of embodiments), retrieve their information, and forward it to the back-end through a wireless or wired channel.

which is particularly important in RFID systems. To illustrate the need for interoperability in the RFID technology it is important to understand the problems of supply chains. We may say that a supply chain management begins in a mine or a farm and it ends on a recycling or garbage plant [86]. In between, the initial material is modified or processed from stage to stage, it may change hands from one owner to another, etc. In this globalised world, such material or item, presumably attached to an RFID tag, could travel around the world more than most people in their whole life (*e.g.* from manufacturers to warehouses, from warehouses to points of sale, from points of sale to retailers, from retailers to customers, from customers to customers or second-hand retailers, etc). This means that RFID tags should be correctly read by everyone and everywhere, in the present and in the future, and without any restricted access or implementation, *i.e.* RFID systems should be interoperable.

Continuing the work of Auto-ID Labs [2], EPCGlobal is leading the development of industry-driven standards for the Electronic Product Code (EPC) to support the use of RFID systems [10]. Their task has been to specify frequencies, coupling methods, types of keying and modulation, information storage capacity, and modes of interoperability [89]. Table 2.2 shows the classification of RFID tags according to the EPCGlobal organisation.

Class	Description
Class 0	Passive, read-only.
Class 0+	Passive, write-once but using class 0 protocols.
Class I	Passive, write-once.
Class II	Passive, write-once with extras such as encryption.
Class III	Rewritable, semi-passive, integrated sensors.
Class IV	Rewritable, active, may communicate with other active tags.
Class V	Rewritable, active, can power and read other tags.

Table 2.2: EPC global tag classes.

On the other hand, the International Organisation for Standardisation (ISO) has also created standards for RFID. Initially, there was some conflict between EPCGlobal and ISO specially due to the air interface protocol. At EPCGlobal, the ISO UHF protocol was thought to be too complex and costly. That is why they developed their own UHF protocol. Finally, in 2004, EPCglobal developed a second-generation protocol (Gen 2) aimed at creating a single, global standard that would be closer to the ISO standards and lastly accepted by ISO. Undoubtedly, this new generation has been the cornerstone of a massive deployment and global adoption of the RFID technology.

2.1.3 Applications

RFID technology has been characterised by its growing popularity. Consequently, a large and diverse number of RFID solutions are being used by more and more business companies. Not surprisingly, national governments have also noticed the benefits of RFID systems in their ordinary tasks, namely for passport control and document tracking. Therefore, it is hard to say exactly how many RFID systems are already deployed worldwide. However, it is clear that these systems are becoming more popular with each passing day.

2.1.3.1 Identification

Since the very beginning of the RFID technology during the Second World War, identification was its primary goal. Nowadays, the scenario is not so different; animal identification, inventory systems, human implants for identification of patients and drug

control, are just a few examples of identification by radio frequency. Indeed, other RFID's features like tracking implicitly identify their targets, otherwise it would not be possible to track them.

2.1.3.2 Tracking

There exist several scenarios in which RFID systems are the most suitable for tracking (*e.g.* indoor environments or for animal surveillance). Also, in comparison with other tracking systems like GPS or GSM, the RFID technology is considered much less costly. That is why tracking, together with identification, is considered one of the primary goals of RFID systems.

For tracking, tags operating at high frequency are usually required because they have a larger reading range. Those types of tags are used for tracking in libraries or bookstores, pallet tracking, building access control, airline baggage tracking, and apparel and pharmaceutical items tracking (*e.g.* in February 2008, the Emirates airline started a trial of RFID baggage tracking at London and Dubai airports [220]; in May 2007, Bear River Supply began to utilise ultrahigh-frequency identification tags to help monitor their agricultural equipment [30]).

2.1.3.3 Healthcare

The healthcare industry has been heavily investing in RFID. The healthcare supply chain, prevention of drug counterfeiting or patient safety, are just some examples of critical processes monitored by RFID. By doing so, patients of a hospital in England might avoid exposure to diseases caused by infected equipment that was not properly tracked and classified [7]. Furthermore, discarded drug packaging will not be reusable by companies attempting to sell counterfeit pharmaceuticals, as noted by Colombian pharmacy chain Medicarte [5]. Indeed, it is expected that investments in RFID technology by the healthcare industry rise from 90\$ million in 2006 to 2.1\$ billion in 2016 [6].

2.1.3.4 Electronic passports

Electronic passports (e-passports) or passports with an embedded RFID tag have been introduced in many countries, including Malaysia (1998), New Zealand (2005), Belgium, The Netherlands (2005), Norway (November 2005), Ireland (2006), Japan (2006), Pakistan, Germany, Portugal, Poland (2006), Spain (August 2006), The United Kingdom, Australia and the United States (2007), Serbia (July 2008) and Republic of Korea (August 2008). Contrary to most RFID applications, RFID tags on passports are a sort of smart card rather than a low-cost tag. They are able to execute computationally complex public key cryptosystems with large key size and are tamper-proof. Also, plenty of information may be stored on the tag's memory such as, name, birthdate, biomet-

ric information, photo, etc. Such information may be contrasted with the information available on paper, thereby reducing the risk of passport forgery and fraud. However, several weaknesses have been found in e-passports [171]. Especially disturbing are those that allow an adversary to effectively clone an e-passport so that a reader cannot distinguish between a legitimate and a cloned passport [104, 37]. Anyway, governments claim that cloning is not a big problem as the electronic information must match the physical characteristics of users. Furthermore, a third generation of e-passports has been released in which, to the best of our knowledge, no cloning attack has been reported yet.

2.1.3.5 Transportation payments

Public transportation payments with RFID cards is probably one of the first perceptible contacts we have with this technology. By this solution neither we need to have coins in our pockets nor the bus drivers need to regularly manage and change cash. Hence, the bus drivers' workload decreases, thereby reducing the risk of a traffic accident due to distractions and increasing the compliance with the schedule.

Conforming to the Calypso³ (RFID) international standard, several countries in Europe and America use RFID passes for public transport systems. In Asia, in particular Hong Kong, other type of RFID cards, called *Octopus Cards*, are also being used for transport systems. Those cards also have grown to be similar to a cash card, and they may still be used in vending machines, fast-food restaurants and supermarkets. Many other public transport payments based on RFID exist (*e.g.* the Moscow Metro pay system or the bike sharing system that prevents bicycle theft in Barcelona).

2.1.4 RFID challenges

There are many challenges associated with the deployment of RFID systems (*e.g.* false or missing reads due to radio wave corruption, scalability, security and privacy, antenna design, deployment cost, among others). However, there are other challenges that may not seem so obvious. The introduction of a new order of things might create a maelstrom of uncertainty. For many industries, RFID deployment will change their business process, forcing new investments on personal training, infrastructure, testing, etc. For example, the McCarran International Airport in Las Vegas had to invest around 125,000,000\$ to RFID-enable its baggage-tracking system [174]. Therefore, companies are requiring to carefully evaluate the economic viability of what may represent a big initial investment of money.

³Calypso is the international electronic ticketing standard for microprocessor contactless smartcards. It ensures multi-sources of compatible products, and makes possible the inter-operability between several transport operators in the same area.

On the other hand, although an RFID system provides plenty of data essential to control and understand business processes, applications like supply chain management or real-time tracking may generate such a huge volume of information that could not be handled by traditional transactional databases (*e.g.* it is predicted that WalMart will generate over 7 terabytes of operational RFID data per day [179]). Therefore, software architectures and back-end databases should be rethought for the collection, correlation, filtering, and cleansing of RFID data.

Strongly related with technical and deployment details, three different challenges, namely security, privacy and, scalability, are the main subject of discussion in this dissertation. Almost every object is likely to be attached to an RFID tag. Therefore, billions of tags will need to be managed efficiently and in a scalable way. On the other hand, due to the wireless nature and the computational constraints of RFID tags, guaranteeing the security of tags' data and the privacy of tags' bearers is a challenging task. The privacy threats grow if we consider all personal data surrounding the huge amount of information collected from tags. If such data are not properly treated, sensitive information might be disclosed without the awareness of RFID's users. This means that the need for efficient and scalable privacy-preserving methods for microdata and trajectories increases with the massive deployment of RFID solutions.

2.2 Security, privacy and scalability issues in RFID identification protocols

The rapid proliferation of RFID solutions strongly supports the vision of ubiquitous computing, in which tags interacting with readers throughout our everyday life improve our experiences with the environment. Consequently, in most applications, readers must be able to identify one or several tags among a set of millions or billions. This scenario characterises an important property that an RFID identification protocol should meet: scalability.

As for most identification systems, being secure and private are another two mandatory properties of RFID systems. These two features are even more relevant in the RFID context due to the insecure and easily accessible communication channel between tags and readers. Generally speaking, security means that data stored in a tag's memory should be accessed only by authorised parties and that impersonating or counterfeiting a tag may be achieved just with a negligible probability. On the other hand, privacy-preservation may be defined as the ability of tags to generate uncorrelated identification messages.

2.2.1 Security

RFID systems are subject to plenty of attacks, from attacks operating on the physical layer to attacks exploiting weaknesses on those protocols executed at the application layer [159, 158, 233]. Physical attacks may be as simple as wrapping an RFID tag in aluminum foil, which potentially causes denial of services (DoS) because readers will be not able to communicate with such tag. Other physical attacks are more sophisticated (*e.g.* jamming attacks that permanently damage radio devices or side-channel attacks that obtain information from the physical implementation of cryptosystems). However, in the present dissertation, we focus on adversaries aimed at breaking the identification/authentication schemes by using theoretical weaknesses of such algorithms. To do so, we assume that the adversary can observe, block, modify, and inject messages in the communication between a tag and a reader. Furthermore, as tags are not tamper-resistant, we assume an adversary able to clone and tamper with any RFID tag.

The most relevant attack to RFID systems is the so-called *spoofing* or *impersonation* attack. In this attack, an adversary is able to clone a tag without physically replicating it. By doing so, the adversary gains the privileges of such tag, which is considered an important security threat for almost every RFID applications. The worst situation occurs when the adversary is able to break the cryptosystem used during the authentication process (*total break*), *i.e.* the adversary gains knowledge of the authentication protocols and the secrets. In other cases, the adversary does not even need to spend too much time breaking the cryptographic protocol. Instead, the adversary could impersonate a tag by replaying and/or manipulating some tag's responses recorded from past transactions (*forgery*). Although these attacks have been successfully thwarted by lightweight and symmetric key cryptography suitable for low-cost RFID tags [221], there still exist open issues when privacy and scalability must be also considered.

2.2.2 Privacy

There exist two main privacy concerns in RFID systems: information leakage and traceability. Information leakage is potentially dangerous because tags may reveal sensitive information about products (*e.g.* the name of drugs or the price of expensive products). Such data may be used for quick, easy, and low-cost profiling of individuals, or even for industrial espionage. The basic idea to prevent information leakage in RFID systems is to move all the tags' data to one or several servers. By doing so, only authorised parties may retrieve those data when required. However, this may not prevent traceability. For instance, a tag sending its unique identifier does not reveal trivial information about the object to which is attached, but it is traceable. To thwart traceability, readers and tags should exchange *fresh* information at each identification so as to make the response of two different tags *indistinguishable*.

The challenge is that indistinguishability is an application-dependent concept where

the abilities of adversaries, tag's owners, physical constraints, etc, must be taken into account in order to provide a fair privacy definition for RFID systems. This is why different privacy models for RFID have been defined [169, 97, 22, 218, 138]. Among them, we recall two well-known notions of privacy proposed by Avoine in [22]:

Definition 1 (Universal untraceability). *Universal untraceability is achieved when any pair of tag's responses, separated by a successfully identification with a legitimate reader, cannot be correlated with high confidence by an adversary.*

Definition 2 (Existential untraceability). *Existential untraceability is achieved when any pair of tag's responses cannot be correlated with high confidence by an adversary.*

Intuitively, existential untraceability is stronger than universal untraceability. Note that the latter ensures privacy against passive adversaries only. That is why protocols that achieve universal untraceability are usually referred as *passively private*, whilst those protocols achieving existential untraceability are referred as *actively private* [18].

There exist other notions of privacy in RFID systems like forward and backward untraceability. Both notions rely on the fact that RFID tags are not tamper-resistant and thus, an adversary may be able to get full access to the internal state of a tag. Informally, backward and forward untraceability ensure that revealing the internal state of a tag cannot help an adversary to identify previous or future transactions of such tag. However, both are beyond the scope of this dissertation (interested readers may refer to [34, 186, 64, 202, 51, 192, 186, 34, 138]).

2.2.3 Why is secure, private, and scalable identification hard?

An RFID identification system where tags send their unique identifier in plain text to readers is scalable (*e.g.* EPC Radio Frequency Identity Protocols Class-1 Generation-2 UHF RFID [10, 9]). In some way, this is how the barcode systems work. However, from the security point of view, it would be quite easy to counterfeit an RFID tag just by building a device able to replay the unique identifier of this tag, which was previously eavesdropped or maybe read from the tag's embodiment. Some RFID manufacturers argue that, in any case, counterfeiting an RFID tag is much more difficult than counterfeiting a barcode label. Actually, this is true for RFID tags intended as the replacement of barcode labels. But RFID systems aimed at being an active part of the future of pervasive computing need anti-counterfeiting measures; they need entity authentication [156].

Public key cryptography (PKC) is known to achieve private and scalable authentication. Actually, most of the applications we use nowadays are protected by PKCs, namely secure remote login (SSH), digital signatures, internet key exchange (IKE), digital cash and secure transparent voting. That is why so many efforts have been devoted

to designing and implementing asymmetric cryptosystems such as Elliptic Curve Cryptosystem (ECC) [32] and N-th Degree Truncated Polynomial Ring (NTRU) [105], in RFID tags. However, they require a high number of logic gates to be implemented in tags. Therefore, the price of tags will increase drastically to accommodate those cryptosystems in RFID tags. Even though other proposals [155] reduce the number of required logic gates by performing some pre-computation and storing partial results in tags, they increase the memory usage to around 1700 bits. It is an open problem whether public key cryptography will be suitable for low-cost RFID tags. Therefore, most RFID identification protocols are based on symmetric key cryptography rather than on public key cryptography.

However, symmetric key cryptography does not satisfy all the requirements of RFID systems because, in general, it draws scalability problems on the server's side. Since tags are not tamper-resistant, each tag must contain a unique and private key with which encrypt its response. The paradox is that, in order to determine the tag's identity the server needs to decrypt the message using the tag's key, but retrieving the tag's key is only possible when the server knows the tag's identity. Consequently, the server should perform an exhaustive search looking for the proper key to decrypt the message. Several protocols overcome this scalability problem by performing an update phase after the identification process (stateful protocols) [170, 17, 149, 226, 230, 56, 21, 123]. This means that the tag and the reader should share and synchronously update the next identification message. However, it has been shown [231] that this synchronisation process must be carefully designed in order to resist Denial of Services attacks. On the other hand, the update phase is not only useless against active adversaries, but also is rather inefficient on the tag's side. Note that a write operation in a tag may take roughly 16.7 milliseconds, while a read operation just needs around 0.007 milliseconds [61]. Indeed, writing in the tag's memory is a time consuming operation; roughly five times more time consuming than a classical AES-128 encryption, which needs around 2.8 milliseconds.

In conclusion, three main techniques have been proposed for the private identification of RFID tags: (i) Public key cryptosystems that are secure, private, and scalable, but not suitable for low-cost tags. (ii) Stateful protocols which are scalable, but they are not strong against active attacks and may be less efficient than other symmetric key protocols due to the writing operation in the memory of the tags. (iii) Stateless protocols based on symmetric key cryptography that could be lightweight, private, and secure, but not scalable. As a result, designing lightweight, secure, private, yet scalable, RFID identification protocols still is a challenging task.

2.2.4 Advances in RFID identification protocols

As stated in [59], a tag can be classified according to the operations it supports. *High-cost* tags are those that support on-board conventional cryptography like symmetric encryption and public key cryptography. In turn, *simple* tags are also considered high-cost tags, but they only support random number generators and one-way hash functions. Likewise, low-cost tags can be classified as *lightweight* tags or *ultralightweight* tags. Both are able to compute simple bitwise operations like XOR, AND, OR, etc, but the former also support a random number generator (RNG) and simple functions like a cyclic redundancy code (CRC) checksum. Undoubtedly, low-cost and simple tags, intended as the replacement of the barcode labels, represent the greatest challenge in terms of security and privacy preservation.

2.2.4.1 Identification protocols for low-cost tags

Several efforts have been made in order to achieve some level of security in low-cost tags [222, 73, 48]. One of the first proposals in this direction is due to Duc *et al.* [73]. They designed a protocol where messages are encrypted using a CRC-16 function and randomised by an updating key process. Although this protocol is not resilient to desynchronisation attacks [60], its main weakness lies in the linearity of the CRC-16 function. Indeed, Burmester and Medeiros [48] show how to successfully implement an impersonation attack by eavesdropping only one session of the protocol. In the same article, four protocols with different levels of privacy are proposed. The first encrypts messages using the RNG defined in the EPCGlobal2 standard seeded with a key shared by the tag and the reader. The security of this protocol is based on the statistical behaviour of the RNG. However, the key is of size 16 bits; therefore, an exhaustive search on all possible 2^{16} key values can be enough to recover the key. On the other hand, EPCGen2 does not specify any protection of the RNG against the *related-key* attack, in which it is possible to find a correlation between a sequence of outputs given by the RNG defined in the EPCGlobal2 [48]. Therefore, an adversary could be able to disambiguate tags that respond with pseudonyms drawn from a EPCGlobal2 RNG complaint. The solution proposed in [48] is to build a Pseudo Random Function (PRF) from a RNG [90]. The new PRF has an input size of 32 bits and it is defined by recursively executing a RNG 16 times.

Other proposals do not even consider tags generating random numbers. In such protocols, the randomness on the tag's side is provided by readers. It should be noted that, those protocols either do not provide anonymity or ensure privacy by updating tags' internal state. In 2006, the first three ultralightweight protocols were proposed: M²AP [182], EMAP [181] and LMAP [184]. Although it was a step forward on the security of low-cost tags, and many other ultralightweight protocols [48, 185, 59] have been proposed so far, all of them have been proven to be insecure [229, 25, 55, 187,

147, 148]. According to Peris-Lopez *et al.* [185], the main weakness of these protocols is the use of triangular functions like AND, XOR, etc. This problem was detected by Chien [59] and he incorporated a left rotation operation (which is non triangular) to his proposal named SASI. Nevertheless, the SASI protocol has other weaknesses that can be found in [25, 55, 187, 185]. As a consequence, Peris-Lopez *et al.* designed the Gossamer protocol [185] aimed at being more secure than previous ultralightweight protocols, though more computationally expensive. In a similar line, Juels proposed a protocol [113] where each tag has a list of one-time pads that together with the tag's keys identify the tag. The protocol is minimalist in the sense that involves only low-cost operations like: rudimentary memory management, string comparisons, and a basic XOR. However, the security of this protocol depends on the size of a list that should be updated at each session.

A completely different approach to the security of RFID systems was proposed by Juels in [118]. Juels adopts the human-to-computer authentication protocol designed by Hopper and Blum (HB) [109], and shows it can be practical for low-cost pervasive devices. HB is a probabilistic protocol consisting of several rounds (around 128 according to Hopper and Blum [109]). In each round, the verifier sends n bits of challenge and the prover responds correctly to each bit with a probability greater than $1/2$. At the end of the protocol, the verifier decides whether the prover gave a sufficient number of correct bits of response. The HB protocol can be also considered an ultralightweight protocol. Later, Juels modified slightly the HB protocol proposing a new protocol [118] (HB^+) that claims to be secure against active adversaries. Although HB^+ is suitable for EPC-Gen 2 tags, it has a high false rejection rate (for 80 bits of security, the false rejection rate is estimated at 44% [88, 87]). Furthermore, the communication overheads increase linearly with the security parameter, which may be chosen around the 80 bits [82]. Another protocol based on an NP-complete problem was proposed by Castelluccia and Soos [54] at RFIDSec'07. Their protocol (ProbIP) is based on the hardness of the boolean satisfiability problem (SAT), which is proven to be in the NP class of complexity. However, the protocol is neither private nor secure as was shown in [177].

A recent proposal [224] based on the hardness of the *noisy polynomial interpolation* problem aims to be private and scalable. However, this protocol presents some shortcomings: (i) it has been shown in [36] that the *noisy polynomial interpolation* problem can be easier than expected, (ii) the server needs to solve mb polynomials of degree k where m , b , and k , are predefined security parameters and, considering that typical values for m and b are 16 and 8 respectively [224], then, the server needs to solve around 128 polynomials which can be considered still too heavy, (iii) tags should be designed with about 10,000 gates more than regular tags capable of hashing computation.

2.2.4.2 Identification protocols for simple tags

In general, lightweight RFID identification protocols use a pseudo random number generator and a symmetric key cryptographic primitive on the tag's side (*e.g.* a hash function or some lightweight block cipher). In this vein, the first AES implementation devoted to RFID tags was proposed in 2004 [75, 77] (other cryptographic primitives may be found in [76]). However, these implementations require no less than 3400 logic gates, which is beyond the capabilities of extremely constrained devices such as RFID tags [183]. That is why several other attempts have been made in order to find cryptographic primitives designed specifically for low-cost RFID tags. To the best of our knowledge, one of the most relevant block ciphers dedicated to RFID tags is PRESENT [193, 38]. Surprisingly, PRESENT only requires between 1000 and 1600 logic gates depending on its variants. Undoubtedly, this improvement supports the rapid proliferation of RFID identification protocols based on symmetric key cryptography. Nevertheless, even considering that those protocols are suitable for very resource-constrained RFID tags, they should face the scalability issues inherent to these type of proposals. Next, we discuss some of those proposals according to their time complexity on the server's side.

2.2.4.3 Lightweight protocols with linear time complexity

The Improved Randomised Hash-lock Scheme [119, 120] is a popular RFID identification protocol due to its strong privacy and security properties at a low cost; it only uses a pseudo-random function generator and a hash function on the tag's side. This protocol works as follows. The reader sends a random nonce r_1 to the tag. Upon reception, the tag generates a nonce r_2 and computes the response $r = h(r_1, r_2, ID)$ where ID is its identifier and $h(\dots)$ is a one-way hash function. Finally, the reader receives both the response r and the nonce r_2 , with which it performs an exhaustive search on its database looking for an identifier ID_i such that $r = h(r_1, r_2, ID_i)$. Figure 2.3 shows a detailed description of this protocol. Although the improved randomised hash-lock scheme [119, 120] is a private, and secure, RFID authentication protocol, it is not acceptable when a large number of tags should be managed (*e.g.* manufacturing processes). Note that this protocol performs an exhaustive search in the database in order to identify a tag. That is why several other protocols based on hash functions have been proposed in order to reduce this linear time complexity.

Another hash-based protocol was proposed by Ohkubo *et al.* [133]. This protocol uses hash-chains in order to guarantee forward secrecy. However, a high memory consumption and a linear time complexity $O(N)$ are its main drawbacks. Although Avoine *et al.* [26, 28] reduced this time complexity to $O(N^{2/3})$ by applying a time-memory trade-off, their improvement demands even more memory on the database than the original protocol [133]. Another protocol based on hash-chains and resistant to denial-

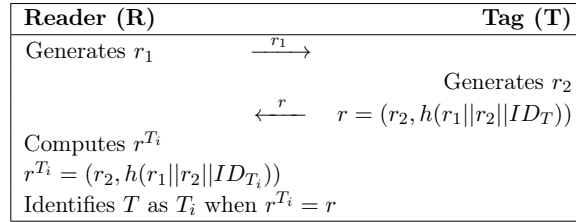


Figure 2.3: Scheme of the Improved Randomised Hash-locks Protocol

of-service attacks (DoS) is proposed in [64]. This protocol also achieves forward secrecy, but it presents some privacy issues as shown in [177].

In order to increase efficiency and reduce resource requirements, some protocols use a counter instead of a pseudo-random number generator on the tag’s side [62]. By this technique, tags may dedicate more logic gates to the encryption function and privacy could be guaranteed without updating the key material. However, this type of protocols may be vulnerable to impersonation attacks [135].

2.2.4.4 Lightweight protocols with logarithmic time complexity

When looking for scalability, the tree-based protocol proposed by Molnar and Wagner [161] is considered a secure and highly scalable protocol. It achieves a time complexity in the identification process of $O(b \log_b^N)$ where N is the number of tags and b is the branching factor of the tree used to store the tag’s identifiers. The idea is that each tag in the system is represented by a unique path in the tree, which is simply defined as a sequence of nodes. Then, each tag T_i contains a unique secret key k_i and also contains the keys of the nodes that represent its path in the tree (cf. Figure 2.4).

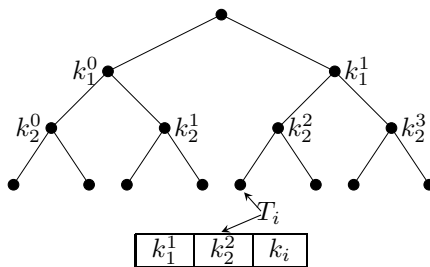


Figure 2.4: A tree of depth 3 and branching factor 2. The tag T_i is represented by the path k_1^1, k_2^2 and by its unique and secret key k_i .

Undoubtedly, the unique secret key of each tag is enough to identify it as the im-

proved randomised hash lock [119, 120] does. However, the tree-based protocol uses the path’s keys in order to rapidly discard large sets of tags whose keys do not match the received response. It may do so because tags allow readers to check their paths from the root to the leaf. Consequently, assuming that a reader knows a sub-path that matches the tag’s response, it may discard all those tags that do not match this sub-path. However, since tags share sub-paths and hence they share keys, compromising some tags is enough to trace other tags in the system [26, 172]. Although a trade-off between privacy and efficiency may be achieved considering the privacy measure proposed in [173], the tree-based protocols are considered non-private.

There exist two other tree-based protocols aimed at resisting compromise [153, 143]. However, both use an update phase in order to change the tag’s keys in each successful execution of the protocol. As shown below, protocols based on updating the key material do not need complex structures, like trees, in order to be scalable. Furthermore, as shown in [143], synchronising keys that are shared by several tags is challenging.

2.2.4.5 Lightweight protocols with sub-linear time complexity

A similar idea to the tree-based protocols yields the group-based protocols [24]. In these protocols each tag belongs to a group and has two keys: a group key (GK) and an identification key (IDK). Once the tag receives a nonce r_1 from the reader, it generates another nonce r_2 and sends back $E_{GK}(r_1, r_2, ID)$ and $E_{IDK}(r_1, r_2)$, where E is a symmetric key encryption function and ID is the tag’s identifier. The server iterates over all the group’s keys until the decryption of $E_{GK}(r_1, r_2, ID)$ succeeds. If so, it recovers ID and then it just needs to check the decryption of $E_{IDK}(r_1, r_2)$. The time complexity of this protocol is $O(\frac{N}{k})$ where k is the number of tags in each group. However, if a tag T is compromised by an attacker, she will be able to recover the identity of every tag belonging to the group of T just by using the group key.

Another type of group-based protocol was proposed in [58]. However, this protocol is different in the sense that a “meet-in-the-middle” strategy is used to efficiently identify tags. By this strategy, they reduce the reader computation to $O(\sqrt{N} \log N)$, which may be considered sub-linear. However, this protocol is not resistant to compromising attacks either.

2.2.4.6 Lightweight protocols with constant time complexity

Privacy-preserving RFID identification protocols with constant time complexity are based, in general, on synchronisation between tags and readers. The idea is that any response coming from a legitimate tag is somehow expected by the reader. However, in order to preserve privacy, all the responses might be *fresh* at each session. Therefore, at some point, tags should update their key material or renew their next responses. At the same time, the reader must be sure whether and how the tag updated its internal

state. Otherwise, the reader should be provided with a mechanism to identify legitimate tags even when their internal states are unknown or unexpected [231]. Note that this *desynchronisation* between tags and readers could easily occur due to communication failures or active attacks to the protocol.

The basic idea to keep a tag and a server synchronised is to design a mutual authentication protocol so that both update the key material once they have mutually authenticated [66, 103, 27, 60, 49, 140]. In any case, the server should keep the last correct key used by every tag in order to resist desynchronisation attacks. The problem with this approach is that tags are traceable in isolated environments, *i.e.* as long as a tag has not been identified by a legitimate reader, it will send the same response to any reader's interrogation. Note that this type of protocols are passively private only (cf. Definition 1).

To tackle this problem, some protocols consider the scalability and privacy issues as a matter of agreement between tags and readers [203, 197]. This means that a reader is able to identify a tag in constant time only if the reader was the last one who interrogated such a tag. Otherwise, the tag's response looks random for the reader and thus the tag cannot be identified in constant time. Therefore, this type of protocols is actively private (cf. Definition 2), but not *unconditionally* scalable.

Both passively and actively private approaches may be improved by pre-computing more than one future tag's responses [152]. Typically, in these approaches tag's responses are based on hash chains [197, 78]. Then, the server may efficiently identify a tag because it had stored *enough* values of the hash chain used by this tag. Therefore, by increasing memory requirements on the server, both privacy and scalability may be improved. However, it should be noticed that the improvement is achieved by demanding more of a resource that is already quite constrained in tags and servers [179].

2.2.4.7 Identification protocols for high-cost tags

High-cost tags are similar to smart cards. They are far more expensive than low-cost RFID tags, which could cost as little as 0.05\$. Nevertheless, there exist some applications requiring a high level of security and privacy in which high-cost tags are not only appropriate, but recommended (*e.g.* passports or toll payment).

In such tags, there exists the possibility of implementing some public key cryptosystems, especially those requiring less computational capabilities on tags, namely Elliptic Curve Cryptosystems (ECC) or lattice-based cryptosystems. A typical ECC implementation could need more than 30K logic gates [124], others are able to reduce the computational requirements between 10K and 18K logic gates [134, 102], though.

In general, the reduction of computational requirements is achieved by optimising, manipulating, or removing some operations of the original proposal [131]. The idea is to reduce as much as possible the computational requirements of public key cryp-

tosystems while guaranteeing security and privacy. However, as shown in [45], the task could be challenging. In a nutshell, they show that previous ECC proposals for RFID systems [141, 142] may be vulnerable to tracking and impersonation attacks.

Other approaches perform some pre-computation in order to reduce the computational overhead on the tag's side. In [176], Oren and Feldhofer improve Shamir's public key scheme [196] by replacing a 260-byte long pseudo-random sequence by a reversible stream cipher of less than 300 bits. Another trade-off between efficiency and memory is shown by Hoffstein *et al.* in [105]. They propose a lattice based cryptosystem referred to as NTRU, which claims to be faster than ECC during the signature and verification processes.

The well-known randomised Rabin encryption scheme has been also adapted to fit the RFID requirements [175]. Even though this protocol initially had some shortcomings, it was later improved in [225]. Finally, differently to classical public key cryptosystems, a lightweight identification protocol requiring around 3000 logic gates was proposed in [130]. This protocol uses some ECC elements to strengthen RFID security. However, in order to decrease computational demands it does not provide a trapdoor function as ECC cryptosystems generally do. Hence, this approach presents the same scalability problem of other symmetric key cryptosystems.

2.2.4.8 Other approaches

According to the EPC standard, each tag contains a KILL password. A reader knowing the KILL password of a tag is able to disable this tag permanently. Therefore, after the shipping check-out process tags could be "killed" in order to preserve the privacy of their holders. Although this measure prevents privacy disclosure, it may not be practical in the long-term because tags cannot be reused. That is why Spiekermann and Berthold proposed a simple scheme so that users are able to disable/enable RFID tags when needed [205]. A more sophisticated, yet complex idea, is proposed in [74]. When a tag enters the post-purchase phase, it supports the ability to change into *privacy mode*. In this mode, tags only accept zero-knowledge proofs from legitimate devices.

There exist other proposals relying on re-encryption in which tags offload most of the computational effort during encryption to the readers or third devices [194, 115, 91]. Those proposals are somehow based on updating the key material in tags. However, they use public key cryptography to re-encrypt the plaintext stored in tags. Therefore, readers knowing the proper private key can obtain the plaintext by decrypting only once, instead of several times as it is usually the case with symmetric key cryptography. Other examples of proposals using a third device are RFID guardian [190], RFID enhancer proxy [117], noisy tags [53] and the blocker tag [116, 114]. In addition to those proposals, there exist other proposals based on assumptions not considered by most RFID solutions. In particular, implementation of physically unclonable functions

(PUF) in tags have been shown to be useful to cope with the tampering issues of RFID tags [217, 40, 46].

2.3 Other issues in RFID systems

Tracking and identifying are the main goals of an RFID system. In consequence, those challenges related to the identification process may seem much more relevant than others. However, RFID systems should face many other challenges depending on their application. For instance, RFID solutions for access control require tags to be in the near proximity of readers. However, the RFID technology is not able to measure the distance from readers to tags as the GPS technology can do. This clearly opens the challenge of designing *distance-bounding protocols* dedicated to RFID tags [100]. Furthermore, the proper use of RFID data still is an open issue. Thanks to the RFID technology, the trajectories of individuals could be easily collected and released by supermarkets, hospitals, or amusement parks. Therefore, efficient *trajectory anonymisation algorithms* are a need for protecting the privacy of RFID users.

2.3.1 Distance checking

In 1987, Desmedt, Goutier and Bengio [65] presented an attack that defeated any authentication protocol. In this attack, called *Mafia Fraud*, the adversary passes through the authentication process by simply relaying the messages between a legitimate reader (the verifier) and a legitimate tag (the prover). In that way, she does not need to modify or decrypt any exchanged data. Initially, this attack was thought to be rather unrealistic because the prover should actively participate in it. However, RFID tags respond to any reader request without any agreement or awareness of their bearer, a feature that clearly opens the door to this type of attack.

Actually, there exist some proofs of concept showing the feasibility of the mafia fraud. In 2005, Hancke showed that two colluders 50 meters apart can perform a mafia fraud attack through a radio channel [99]. This is particularly dangerous because that distance is long enough to mount a mafia fraud attack in almost every payment or access control systems. Not surprisingly, this attack has been successfully applied to other technologies [84, 101, 125, 144] namely, Bluetooth, contactless smart card, and NFC.

Another attack based on cheating the distance between provers and verifiers was introduced in 1993 by Brands and Chaum [44]. In this attack, named *Distance Fraud*, a dishonest prover claims to be closer to the verifier than she really is. Figures 2.5 and 2.6 illustrate both mafia and distance fraud respectively. For both figures, the circle represented the maximum distance at which a prover should be authenticated. Formally, we may define both frauds as follows [23]:

Definition 3 (Mafia fraud). *A mafia fraud is an attack where an adversary passes an authentication protocol by using a man-in-the-middle strategy between the reader and an honest tag located outside the neighbourhood of the verifier.*

Definition 4 (Distance fraud). *A distance fraud is an attack where a dishonest and lonely prover claims to be in the neighbourhood of the verifier when actually she is not.*

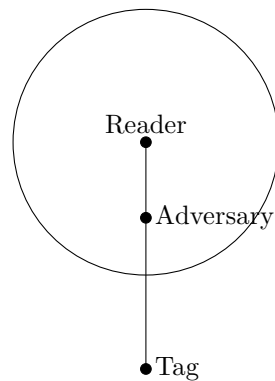


Figure 2.5: Mafia fraud: an adversary trying to be authenticated by applying a man-in-the-middle attack.

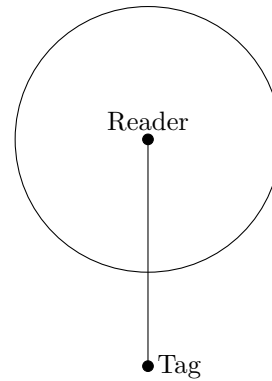


Figure 2.6: Distance fraud: a legitimate prover is farther from the verifier than it is expected.

2.3.1.1 RFID distance-bounding protocols

In 1993, Brands and Chaum [44] proposed a countermeasure that prevents such attack by computing an upper bound of the distance between the reader and the tag to authenticate: the *distance-bounding protocol*. By doing so, mafia and distance frauds could not be completely prevented, but these protocols may effectively thwart them. However, it was not until 2005 that the first distance-bounding protocol dedicated to RFID came to the light [100]. The protocol is split in two phases: a *slow phase*, in which reader and tag exchange two nonces, and carry on resource-consuming operations; followed by a *fast phase* divided into n rounds where, in each one, the reader measures the *round trip time* (RTT) of the challenge/response process. Considering that radio waves cannot propagate faster than light, the reader is able to bound the distance between itself and the tag. These communications also provide an identity proof of the tag. Unfortunately, the adversary success probability regarding mafia and distance frauds is $(3/4)^n$ while one may expect $(1/2)^n$ (the adversary's success probability at each round is expected to be $\frac{1}{2}$). Since then, several RFID distance-bounding protocols have been proposed in order to improve the resistance to both frauds.

Among all the RFID distance-bounding protocols, we differentiate two main families. (i) Those requiring an additional slow phase after the fast phase. This final phase may be used to sign the messages transmitted during the fast phase or to check any other information. (ii) Those that, closer to the Hancke and Kuhn proposal [100], end the protocol after the fast phase.

Brands and Chaum [44] proposed the first distance-bounding protocol relying on a signature after the fast phase. In the first slow phase, the prover commits to the verifier a sequence of n bits m_1, \dots, m_n . Then, during the fast phase, the verifier sends a challenge c_i to the prover, who should reply with $r_i = c_i \oplus m_i$. Also, the prover concatenates and signs with his private key all the challenges and responses, *i.e.* he sends to the verifier $Sign_k(c_1||r_1||\dots||c_n||r_n)$. If some response r_i delays more than a threshold Δ_t , the verifier assumes the prover is out its neighbourhood. Finally, if the prover succeeds in all rounds, the verifier checks the received signature in order to authenticate the prover. This protocol is considered strong in the sense that both mafia and distance fraud attacks cannot succeed with probability higher than $(\frac{1}{2})^n$.

There exist other distance-bounding protocols based on the Brands and Chaum proposal [128, 50]. Since both distance and mafia fraud resistance cannot be improved, those protocols aim at improving the resistance to a new type of fraud called *terrorist fraud* [23] (cf. Definition 5), this type of fraud is out of the scope of this dissertation, though.

Definition 5 (Terrorist fraud). *A terrorist fraud is an attack where an adversary defeats a distance bounding protocol using a man-in-the-middle strategy between the reader and a dishonest tag located outside of the neighbourhood, such that the latter actively helps the adversary to maximise her attack success probability, without giving her any advantage for future attacks.*

In practice, the final signature represents an additional delay. Besides, according to [29], as the authentication entirely relies on this phase, if the latter is interrupted or not reached, then the whole process is lost. This means that secure distance-bounding protocols not requiring a final signature are preferred.

Among the protocols without a final signature, Avoine and Tchamkerten's protocol [29] is the most resilient to mafia and distance frauds. They introduced the notion of distance-bounding protocols based on trees. The idea is that prover and verifier agree on a decision tree of depth n , which contains in its nodes the correct responses for any sequence of challenges c_1, \dots, c_i ($1 \leq i \leq n$). Since the values of the nodes are randomly chosen at the beginning of the protocol, the probability that two different sequences of challenges c_1, \dots, c_i and $\tilde{c}_1, \dots, \tilde{c}_i$ contain the same response is $\frac{1}{2}$. Intuitively, this property dramatically reduces the mafia and distance fraud success probability. However, storing a tree of depth n is prohibitive for most RFID tags.

In comparison with Avoine and Tchamkerten's protocol [29], just Kim and

Avoine’s [126, 127] protocol achieves such a high resistance to mafia fraud. Furthermore, their protocol only requires $4n$ bits of memory on the tag’s side where n is the number of rounds. In this protocol, the prover is armed with a mechanism to detect whether it is the target of a mafia fraud attack. Then, once the prover detects the attack, it responds randomly to the subsequent rounds. Therefore, the probability of success of the adversary considerably decreases. However, the more efficient the mechanism, the weaker the protocol against a distance fraud attack. In consequence, the Kim and Avoine’s protocol [126, 127] might not be appropriate when both mafia and distance frauds need to be thwarted.

2.3.2 Trajectory anonymisation

The location of an individual can be determined by different techniques. Possibly, the most conventional and ancestral of these techniques is the visual identification of that individual in some place at some moment. Nowadays, this task is far easier since there is no need for a person monitoring or harassing another person. Instead, several technologies widely adopted worldwide can perform this task for us automatically (*e.g.* surveillance cameras, credit card transactions, RFID identification, among others). In addition, today’s pervasiveness of location-aware devices like mobile phones and GPS receivers helps companies and governments to easily collect huge amount of information about the movements of people.

Analysing and mining this type of information, also known as trajectories or spatio-temporal data, might reveal new trends and previously unknown knowledge to be used in traffic, sustainable mobility management, urban planning, supply chain management, etc. By doing so, resources can be optimised and business and government decisions can be solid and well-founded. As a result, it is considered that both companies and citizens profit directly from the publication and analysis of databases of trajectories. However, there are obvious threats to the privacy of individuals if their trajectories are published in a way which allows re-identification of the individual behind a trajectory.

A tentative solution to preserve individuals’ privacy is de-identification, that is, to remove all the identifying attributes of individuals. However, this is often insufficient to preserve individuals’ privacy. Another set of attributes, known as *quasi-identifiers*, together with external information, can be used to re-identify the individual behind a record. For instance, it has been shown that the tuple {zip-code, gender, and date of birthday} is unique for the 87% of the population of United States [209]. As an example in the context of spatio-temporal databases, let us consider a GPS application recording the trajectories of some people. Daily routine indicates that a user’s trajectory in the morning is likely to begin at home and end at her work place. This information can be easily linked to a single user, whose identity might be obtained from an external source of information like telephone directories or social networks.

Estimating how much external information is available to an adversary is a challenging task [122]. Furthermore, the time information and its relation with the spatial information gives a distinctive nature to the spatio-temporal data over the microdata, *i.e.* over records describing users' data without a sequential order. That is why traditional anonymisation and sanitisation methods for microdata [85] are not suitable for spatio-temporal data and viceversa. Therefore, specific anonymisation algorithms devoted to thwarting privacy attacks on published databases of trajectories are increasingly needed.

2.3.2.1 k -Anonymity and ℓ -diversity

A lot of work has been done in anonymising microdata and relational/transactional databases [195, 209, 214, 154, 223, 145, 168, 71, 232, 201, 208, 146]; see also the recent survey [85]. A usual goal in anonymisation is to achieve k -anonymity [195, 209], which is the "safety in numbers" notion.

An anonymised microdata set is said to satisfy k -anonymity if each combination of quasi-identifier attribute values is shared by at least k records. Therefore, this property guarantees that an adversary is unable to identify the individual to whom an anonymised record corresponds with probability higher than $1/k$.

Another useful privacy notion is ℓ -diversity [154], which improves k -anonymity by diversifying the sensitive attributes values of each group of records that can be isolated by an attacker. This privacy notion is motivated by the fact that even when an adversary cannot identify the individual's record among a set of k records with probability greater than $1/k$, she could easily retrieve the individual's sensitive values with high level of confidence, *e.g.* if the k records have the same sensitive attributes values. In [154, 145], different considerations regarding the ℓ -diversity privacy notion can be found.

2.3.2.2 Microaggregation

k -Anonymity cannot be directly achieved with spatio-temporal data, because any point or time can be regarded as a quasi-identifier attribute [12]. Direct k -anonymisation would require a set of original trajectories to be transformed into a set of anonymised trajectories such that each of the latter is identical to at least $k - 1$ other anonymised trajectories. This would obviously cause a huge information loss.

Generalisation was the computational approach originally proposed to achieve k -anonymity [195, 209]. Later, Zhang *et al.* introduced the permutation-based approach [232], that has the advantage of not being constrained by domain generalisation hierarchies. In [72] it was shown that k -anonymity could also be achieved through microaggregation of quasi-identifiers. Microaggregation [68] works in two stages:

1. *Clustering.* The original records are partitioned into clusters based on some similarity measure (some kind of distance) among the records with the restriction that

each cluster must contain at least k records. Several microaggregation heuristics are available in the literature, some yielding fixed-size clusters all of size k , except perhaps one (*e.g.* the MDAV heuristic [72]), and some yielding variable-size clusters, of sizes between k and $2k - 1$ (*e.g.* μ -Approx [69] or V-MDAV [200]).

2. *Anonymisation.* Each cluster is anonymised individually. Anonymisation of a cluster may be based on an aggregation operator like the average [68] or the median [72], which is used to compute the cluster centroid; each record in the cluster is then replaced by the cluster centroid. Anonymisation of a cluster can also be achieved by replacing the records in the cluster with synthetic or partially synthetic data; this is called hybrid data microaggregation [67] or condensation [14].

2.3.2.3 Clustering algorithms for trajectories

Just like in microdata records, suppressing direct identifiers from trajectories is not enough for privacy [121]. Consequently, several anonymity notions and methods for trajectories have been proposed [106, 96, 107, 42, 180, 41, 12, 166, 211, 160, 167, 228, 162, 13, 108, 11, 163]. Among those works, we next review the ones that try to achieve some notions of trajectory k -anonymity. Other comparisons of several trajectory anonymisation methods can be found in [41, 13].

A naive approach for achieving k -anonymity is by suppression of attribute values, which is generally used on categorical nominal data where perturbation methods are not well suited. One of the first suppression-based methods for trajectory anonymisation is due to Terrovitis and Mamoulis [212]. They consider trajectories to be sequences of addresses taken from an address domain \mathcal{P} and adversaries controlling subsets of addresses of \mathcal{P} . Thus, the adversary's knowledge can be represented as a database of projections of original trajectories over the addresses in \mathcal{P} that she controls. Then, they propose a greedy algorithm aimed at guaranteeing that no address unknown by the adversary can be linked with any user with probability higher than some threshold. The main problem with this approach is that dealing with all possible adversary's knowledge causes an anonymisation problem harder than the simpler k -anonymity problem in relational databases, which is already known to be NP-Hard [157].

Abul, Bonchi and Nanni proposed a notion of trajectory k -anonymity assuming uncertainty on the data provided by technologies like GPS [12, 13]. They also proposed two methods to achieve privacy according to their notion of privacy. In the original method –Never Walk Alone (NWA) [12]–, the set of trajectories is partitioned into disjoint subsets in which trajectories begin and end at roughly the same time; then trajectories within each set are clustered using the Euclidean distance. In the follow-up method –Wait For Me (W4M) [13]–, the original trajectories are clustered using the edit distance on real sequences (EDR) [57]. Both approaches proceed by anonymising each cluster separately. Two trajectories T_1 and T_2 are said to be co-localised with respect

to δ in a certain time interval $[t_1, t_n]$ if for each triple (t, x_1, y_1) in T_1 and each triple (t, x_2, y_2) in T_2 with $t \in [t_1, t_n]$, it holds that the spatial Euclidean distance between both triples is not greater than δ . Anonymity in this context means that each trajectory is co-localised with at least $k - 1$ other trajectories ((k, δ) -anonymity). Anonymisation is achieved by spatial translation of trajectories inside a cluster of at least k trajectories having the same time span. In the special case when $\delta = 0$, the method produces one centroid/average trajectory that represents all trajectories in the cluster. *Ad hoc* preprocessing and outlier removal facilitate the process. Utility is evaluated in terms of trajectory distortion and impact on the results of range queries. The problem with the NWA method is that partitioning the set of all trajectories into subsets sharing the same time span may produce too many subsets with too few trajectories inside each of them; clearly, a subset with less than k trajectories cannot be k -anonymised. Also, setting a value for δ may be awkward in many applications (*e.g.* trajectories recorded using RFID technology).

Another k -anonymity based notion for trajectories consisting of ranges of points and ranges of times has been proposed in [166] and [167]. It uses clustering to minimise the “log cost metric”, which measures the spatial and temporal translations with user-provided weights. Minimising the log cost therefore maximises utility. The clusters are anonymised by matching points of the trajectories and generalising them into minimum bounding boxes. Unmatched points are suppressed and so are some trajectories. The anonymised data are not released; instead, synthetic “atomic” trajectories (having unit x-range, y-range and time range) are generated by sampling the bounding boxes. This approach does not release standard trajectories but only trajectories with unit ranges.

In [162], k -anonymity means that an original trajectory T is generalised into a trajectory $g(T)$ (without the time information) in such a way that $g(T)$ is a sub-trajectory of the generalisations of at least $k - 1$ other original trajectories. Ignoring the time information during anonymisation and complex plane tessellations used to achieve the k -anonymity are the main drawbacks of this method. Utility is measured by comparing clustering results.

[111] is another proposal for achieving k -anonymity of trajectories by means of generalisation. The difference lies in the way generalisation is performed: the authors propose a technique called *local enlargement*, which guarantees that user locations are enlarged just enough to reach k -anonymity, which improves utility of the anonymised trajectories.

The adapted k -anonymity notion for trajectories in [228] is stated in terms of a bipartite attack graph relating original and anonymised trajectories such that the graph is symmetric and the degree of each vertex representing an anonymised trajectory is at least k . The quasi-identifiers used to define identities are the times of the positions in a trajectory, and the anonymity is achieved by generalising points of trajectories into areas on the grid. An information loss metric defined for such areas is used to evaluate

the utility of the anonymised data.

Some approaches assume that the data owner anonymising the database knows exactly what the adversary's knowledge is. If the adversary is assumed to know different parts of the trajectories, then those are removed from the published data [211]. However, this work only considers sequential place visitation without real time-stamps. If the adversary is assumed to use some prediction of continuation of a trajectory based on previous path and speed, then uncertainty-aware path cloaking [107, 108] can suppress these trajectories; this procedure, however, results in high information loss.

Additional related work about anonymisation of spatio-temporal data can be found in the literature about location privacy, focused on applications such as privacy-aware location-based services (LBS) or privacy-aware monitoring of continuously moving objects. Location privacy in the LBS-setting was first proposed in [95]. See [178, 110] for recent papers on location privacy, in which mobile objects protect the privacy of their continuous movement. Location privacy is enforced on individual sensitive locations or unlinked locations in an on-line mode; often, data are anonymised on a per-request basis and in the context of obtaining a location-based service. In this dissertation, we focus on off-line publishing of whole spatio-temporal databases rather than protecting specific individuals from LBS providers or on-line movement monitoring. In general, a solution to location privacy is not a solution for publishing anonymised trajectories, and vice versa.

Improving Scalability by Means of Distributed Readers

This chapter describes our first RFID identification proposal, which is based on collaborative readers. Its aim is to improve flexibility and efficiency.

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The idea of making tags and/or readers collaborate has been proposed and tested. With regard to tags, in [39] and [151] a distribution of tags is used to guide mobile robots equipped with RFID readers and perform precise indoor positioning, respectively. Also, in [63] tags cooperate in order to detect when and for how long a tag has been tampered with. With regard to readers, to improve the scalability of hash-based solutions without increasing the number of rounds of the protocol, Solanas *et al.* proposed an approach that used collaborative readers deployed in a grid structure [199]. Instead of having a centralised database with all the tag IDs, each reader maintains a local database (*e.g.* in a local cache) in which it stores the IDs of the tags located in its cover area and the ones in its adjacent neighbours' area. By doing so, readers no longer need to check all possible IDs to identify a tag but only a smaller subset of IDs in their local cache. Although the proposal in [199] is a step forward in terms of scalability, it replicates too many tag IDs and imposes several constraints to the system (*e.g.* readers must

know the exact distance to the tags and the reader distribution is very rigid). In [16], Ahamed, Rahman and Hoque modified the proposal of Solanas *et al.* and proposed a more natural neighbourhood structure using a hexagonal grid (cf. Figure 3.1). Note that this solution reduces the number of neighbours from nine (in the squared grid) to six (in the hexagonal grid). However, this proposal has the same limitations of [199].

The idea of distributing tags amongst a number of readers placed in a grid or in hexagonal cells might resemble the antenna structure of the well-known GSM system for mobile communications. In fact, readers store information about tags similarly to what visitor location registers (VLR) do with cell phones in GSM. However, there are some fundamental differences that make this problem different in the RFID context:

- In GSM, cell phones are active and they are responsible for the registration of their ID in the VLR.
- Visitor location registers (generally) do not exchange information amongst them. They mainly communicate with a centralised database known as the home location register (HLR).
- A centralised database such as the HLR might not exist.

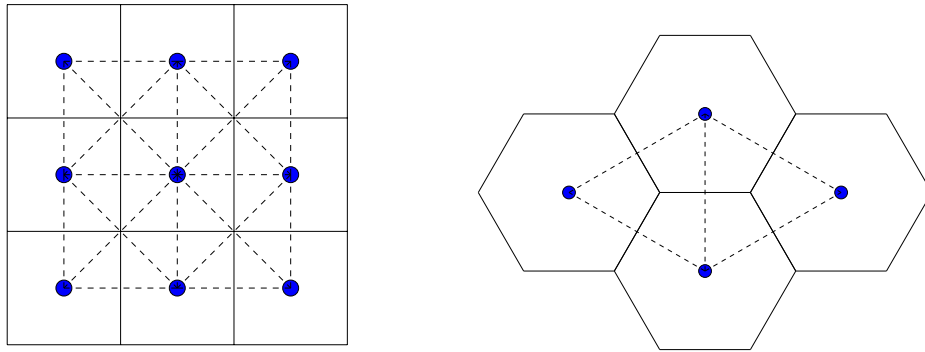


Figure 3.1: **Left:** Scheme of nine collaborative readers using a squared grid neighbourhood [199]. **Right:** Scheme of four readers using a hexagonal grid neighbourhood [16]. Dashed lines represent neighbourhood relations amongst readers.

3.1 An efficient RFID identification protocol by means of collaborative readers

Hash-based identification protocols for RFID tags have shown to be private and secure but they require a significant computational effort on the readers' side that is generally overcome by using a centralised mainframe, which can lead to bottlenecks and delays. Specifically, the number of operations performed by the mainframe to identify a single tag is a function of the number of tags (n) in the system, *i.e.* $f(n)$.

An alternative to the centralised solution is the collaborative approach that was first described in [199], whose main idea is to distribute the list of tag IDs amongst all the readers in the system and allow them to identify tags within their cover range without contacting a central mainframe. The solution proposed by Solanas *et al.* improves the scalability of the system with regard to the centralised solution. Ideally, if we consider a number of readers (m) and a number of tags (n), the number of operations that must be performed by a reader to identify a tag is a function of $(\frac{n}{m})$, *i.e.* $f(\frac{n}{m})$. Unfortunately, the protocol proposed by Solanas *et al.* requires the readers to store the IDs of the tags controlled by neighbour readers and this leads to a significant increase of redundant IDs. If we assume that the redundancy can be expressed by a factor k , the number of operations that a reader performs to identify a tag using the protocol described in [199] is $f(\frac{k \times n}{m})$, where

$$f\left(\frac{n}{m}\right) < f\left(\frac{k \times n}{m}\right) < f(n)$$

Our protocol leverages the idea of collaboration from [199], but implements a new set of messages that permit the reduction of redundant information. Ideally, we want $k \rightarrow 1$. To do so, thanks to our protocol, readers can be initialised with a parameter $p \in [0, 1]$ that represents the probability for a reader to store tag IDs from its neighbours. Note that when $p = 0$, the number of redundant IDs is zero and we reach the optimal situation where the number of operations required to identify a tag is $f(\frac{n}{m})$.

In addition, network designers/engineers can balance the reader's computational cost and its bandwidth usage by tuning p . The smaller p the lower the number of operations, but the bandwidth requirements are higher.

3.1.1 Brief recap of the *Original* protocol

The protocol described in [199], that we call *original*, was designed to allow multiple readers to collaborate in order to exchange information about tags so as to improve the scalability of the improved randomised hash-locks (IRHL) identification procedure.

In the *original* protocol, each reader was responsible for a squared cell and they were all distributed in a grid structure. Note that, using this distribution, the areas covered by each reader were disjoint and, by construction, a tag in a given location

could only be queried by a single reader (this is an important difference with regard to the protocol described in this chapter).

In the *original* protocol three main procedures/subprotocols were described:

1. Tag arrival protocol: This protocol is applied when a tag enters the system through a System Access Point or SAP. A reader controlling this SAP identifies the tag using IRHL and communicates to **all** its neighbours the ID of that tag. Then if that tag moves to any of the cells controlled by these neighbours, they will be able to identify it.
2. Roaming protocol: This protocol is used when a tag changes its location from a cell controlled by a reader to another cell. In this case, the reader controlling the destination cell informs all its neighbours that he is the new owner of the tag and forwards the ID information of the tag to all its neighbours. Also, the previous owner sends a message to its neighbours so as to inform that it is no longer the owner of the tag.
3. Departure protocol: This protocol is used when a tag leaves the system. In this case a reader controlling a System Exit Point (SEP) simply forwards to its neighbours the message of deleting that tag from their caches.

3.1.2 Assumptions and definitions

In our proposal, instead of using the concept of *unshared cover area*, as described in [199], we use the more general concept of *shared cover area*.

Definition 6 (Unshared Cover Area (A^u)). *The unshared cover area of a reader R is the set of locations controlled by R from which tags can communicate **only** with R .*

Definition 7 (Shared Cover Area (A^s)). *The shared cover area of a reader R is the set of locations from which tags in the system can communicate with R and possibly with other readers.*

From these definitions it can be derived that given two shared cover areas A_i^s and A_j^s , $A_i^s \cap A_j^s$ might be different from the \emptyset , whilst given two unshared cover areas A_i^u and A_j^u , $A_i^u \cap A_j^u$ is always \emptyset . Although this property of the unshared cover areas might be theoretically useful, it is extremely hard to realise it in practise. Thus, from now on, when we use the term *cover area* we will refer to the more realistic concept of *shared cover area* described in Definition 7 and, for the sake of clarity, we avoid using the superscript s .

Let A_i be the cover area of a reader R_i and let A be the area covered by all the readers in the system. We assume that $A \subseteq \bigcup^i A_i, \forall i$.

Considering our definition of shared cover area, we define the neighbourhood relation as follows:

Definition 8 (Neighbourhood relation). *Two readers R_i and R_j are neighbours if their cover areas A_i and A_j are not disjoint, i.e. $A_i \cap A_j \neq \emptyset$.*

Our notions of cover area and neighbourhood are more flexible and realistic than those proposed in [199] and [16]. Also, they lead to a simple criterion for connecting readers, *i.e.* only neighbour readers will share a communication link to exchange protocol messages. We assume that each reader in the system is connected to its neighbours (*e.g.* using WLAN + SSL) and maintains a local database with a list of pairs (ID_T, ID_R) , where ID_T is the identifier of a given tag and ID_R is the identifier of the reader. We also assume that each tag is controlled by a single reader, which is its owner.

Note that by using the notion of shared cover areas the tags moving in a region shared by two readers are controlled by only one of them. On the contrary, if unshared cover areas are used, a tag moving from one unshared cover area to another leads to the change of owner from one reader to another. In Figure 3.2, an example of this behaviour is shown. If we use shared cover areas, the tag T is controlled by $R2$ throughout its way. However, if we consider the notion of unshared cover area, the tag T is controlled by $R2$ at locations (1), (3) and (5); and it is controlled by $R1$ at locations (2) and (4). This unnecessary change of ownership requires communication between readers and increases the bandwidth usage. Consequently, using shared cover areas may decrease the utilised bandwidth.

3.1.3 Messages

In our protocol, readers use a number of messages to exchange information about the ownership of tags and collaborate to identify them. Each message sent by a source reader (R_{ID_S}) to a destination reader (R_{ID_D}) makes the latter perform an action regarding a tag (ID_T) (cf. Figure 3.3 for a graphical scheme of the message format and its flow). Depending on the message, the information sent about the tag can be:

- **The tag ID** – (ID_T): If R_{ID_S} can identify the tag because it has the required information in its cache, it can send ID_T to R_{ID_D} . This might happen for the following messages of the protocol: *Delete*, *I am the owner*, *You are the owner*, and *Search* messages.
- **The response of the tag** $r = (r_2, h(r_1 || r_2 || ID_T))$ **and the challenge** $r1$: If R_{ID_S} is not able to identify the tag, it sends to R_{ID_D} the challenge $r1$ that it sent to the tag and the answer r received from the tag. This happens for the *Identify* message.

The messages of the protocol are explained in more detail below:

- **Delete - (ID_T)** When R_{ID_D} receives this message, it removes the identifier ID_T from its local cache.

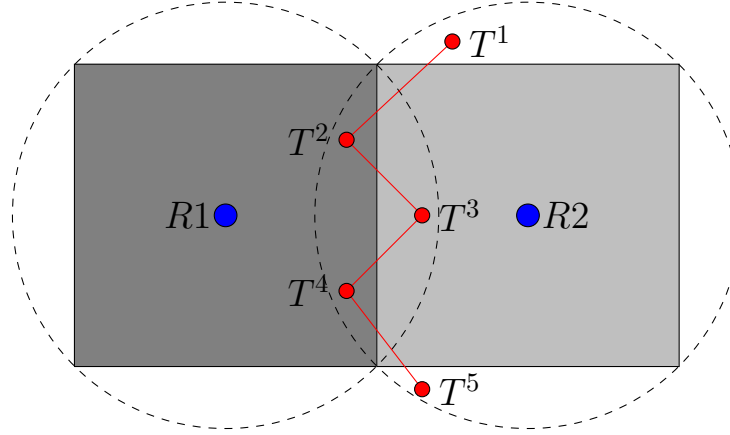


Figure 3.2: Graphical example of two readers $R1$, $R2$ and a moving tag T . The tag T is captured in different positions at different instants T^1 , T^2 , T^3 , T^4 , and T^5 (T^x indicates the position of tag T at time x). The squares represent the unshared areas of $R1$ and $R2$. The circles represent the shared areas of $R1$ and $R2$.

Message			
Operation	Source	Destination	Tag
3 bits	32 bits	32 bits	128 bits
	ID_S	ID_D	ID_T
	ID_S	ID_D	r, r_1

Flow	
R_{ID_S}	R_{ID_D}
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Message about the tag (ID_T)</div>	
R_{ID_S}	R_{ID_D}
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Information, ACK or NACK</div>	

Figure 3.3: Message format and flow

- I am the owner - (ID_T)

 When R_{ID_D} receives this message, it realises that R_{ID_S} claims the ownership of the tag ID_T . If R_{ID_D} was the former owner, it sends a *Delete* message to its neighbours, excepting R_{ID_S} and its neighbours, to let them know that it is no longer the owner of that tag. If R_{ID_D} was not the former owner, then it would generate a random number $x \in [0, 1]$, and if $x \geq p$ it would update its cache with the

new ownership information.

- **You are the owner - (ID_T)** When R_{ID_D} receives this message, it takes control over the tag ID_T . It stores the new ownership information in its cache and sends an *I am the owner* message to all its neighbours, so as to propagate the new ownership information.
- **Identify - (r, r_1)** This message is sent by R_{ID_S} when it is not able to determine the ID of a tag (using the Hash Lock protocol). With this message, R_{ID_S} asks R_{ID_D} to identify the tag and return the ownership information stored in its cache. If R_{ID_D} identifies the tag and finds its owner, it sends the ID of the owner back to R_{ID_S} , otherwise it responds with a NACK message.
- **Search - (ID_T)** When R_{ID_D} receives this message it checks whether the tag ID_T is in its cover area. If it finds the tag, it sends an ACK message back to R_{ID_S} , otherwise it responds with a NACK.

3.1.4 Protocol execution

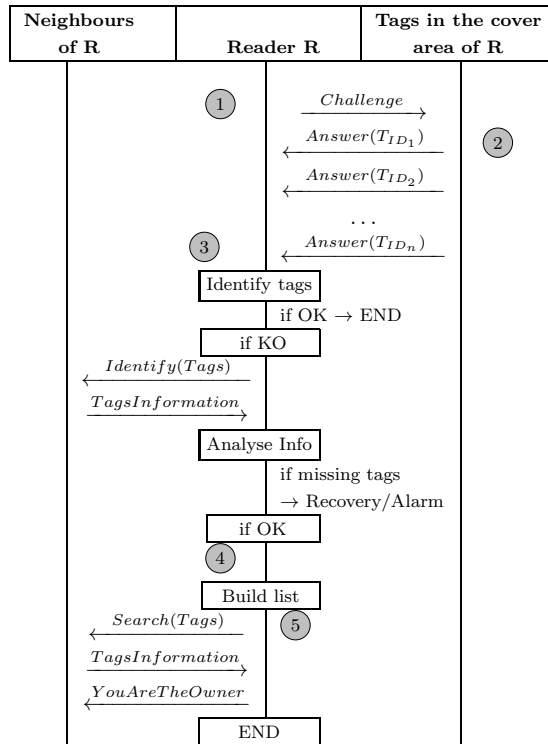


Figure 3.4: Scheme of the flow of the identification protocol

Thanks to the probabilistic nature of our protocol, the number of IDs stored in the local caches of the readers can be reduced with respect to the protocols presented in [199] and [16]; however, the flow of messages is a bit more complex. The identification protocol proposed in this chapter considers three main actors: (i) the tags in the system, (ii) a reader, and (iii) the neighbours of that reader. The protocol depicted in Figure 3.4 works as follows:

1. A reader (R) sends a challenge (r_1) to the tags in its cover range.
2. All tags in the cover range of R answer the challenge.
3. For each tag (T) responding to the challenge, R tries to identify it using the hash-locks scheme [119] applied to its local cache.
 - (a) If it identifies the responding tag, the process finishes.
 - (b) Otherwise, R sends an *Identify* message to its neighbours and stores their answers in its cache. If any of its neighbours identifies the tag, R executes a recovery procedure described in the next section.
4. Then, R builds a list (L) containing all the tags that it owns (*i.e.* which are under its control) and that have not responded to the challenge (*e.g.* those tags that have left its cover range).
5. For each tag $T \in L$, R sends a *Search* message to its neighbours. After receiving the answers from its neighbours, R sends a *You are the owner* message to the first neighbour that responded positively (*i.e.* ACK) to the search message.

All the readers in the system periodically use this protocol. By doing so, all tags can be controlled without the intervention of a centralised database. In addition, due to the fact that readers only store information about the tags of their neighbours with a given probability p , the number of redundant IDs is reduced with respect to [199, 16] and, therefore, the computational effort performed by the readers is also reduced.

3.1.5 Alarm/recovery protocol

When a reader is not able to identify a tag and its neighbours do not have information about this tag either, one may be in two possible situations:

- An unauthorised tag has entered the system.
- A tag has been covered (so as to hide it from the readers) and uncovered in a different location controlled by another reader whose neighbours have no information about the tag.

When this situation arises, we propose two possible solutions:

- A centralised solution: This solution is based on maintaining a backup of all tag's IDs in a centralised server. Doing so, when neither a reader nor its neighbours could identify a tag, that reader could request the identification of this tag to the centralised server. Note that, this solution has a high computational cost but does not create bottlenecks because the centralised server is supposed to be used in exceptional cases only.
- A fully decentralised solution: In this case readers can iteratively query their neighbours so as to find the previous owner of the tag in the system. First the reader queries its adjacent neighbours (located at one hop), then it queries the neighbours located at two hops, etc. This procedure finishes when the tag ID is found or when all readers have been queried. In the first case, our protocol keeps working normally, in the second case, an alarm is raised. This procedure is depicted in Figure 3.5. Note that in the worst case, in which all readers in the system were to be queried, the computational cost would be linear in the number of tags n . Although the computational cost is high and the communication overhead might be significant, this situation should happen rarely; hence, it should not affect the overall efficiency of the proposed protocol.

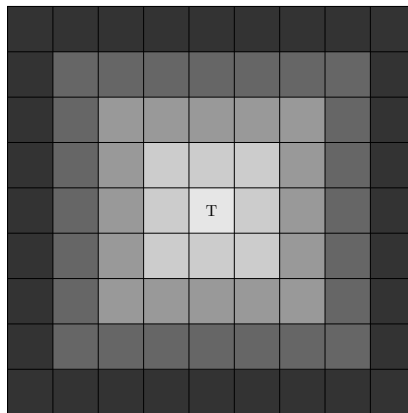


Figure 3.5: A representation of cells covering the monitored area. An unidentified tag is located in the central cell. The reader in that cell will iteratively query other readers to identify T . Readers in lighter coloured cells are queried first.

3.1.6 The role of p

The number of operations performed in a reader to identify a tag is linear with the number of tag IDs stored in its cache. A reader stores the IDs of the tags in its cover area (for which it is responsible) – we say that that reader is the **owner** of those tags. In addition, a reader may store the IDs of tags located in the cover area of its neighbours. This way, if a tag moves from the cover area of one of its neighbours, it can identify that tag without querying its neighbours.

Each reader is initialised with a parameter p . This parameter defines the probability for a given reader to store neighbour tag’s IDs in its cache. If $p = 1$ the reader stores all the IDs of its neighbour tags, on the contrary if $p = 0$ the reader stores no information about its neighbours’ tags. If p takes a value in $(0, 1)$ the reader stores a number of IDs *proportional* to that value. The main goal of p is to reduce the number of redundant IDs stored in the cache of neighbour readers.

The number of IDs stored by a reader i ($\#ID^i$) can be computed as

$$\#ID^i = n_i + p_i \sum_{j=1}^{b_i} n_j^i$$

where n_i is the number of tags owned by i , b_i is the number of neighbours of reader i , n_j^i is the number of tags owned by the j -th neighbour of reader i , and p_i is the probability for the reader i to store IDs of tags owned by its neighbours. The total number of IDs stored in the system ($\#ID$) can be computed as $\sum_{i=1}^m \#ID_i$, where m is the total number of readers.

In the example shown in Figure 3.6, it is apparent that, by reducing the value of p , the number of IDs stored in the caches of the readers is also reduced. Consequently, the number of operations required to identify a tag is also reduced and the whole process of identifying tags scales better.

Note that the protocols described in [199] and [16] do not support the addition of this probabilistic property. Thus, the main goal of the proposed protocol, explained in the following sections, is to allow the use of the parameter p and, as a result, to improve the scalability of the identification process on the readers’ side.

3.1.7 Our protocol in a centralised back-end

Although our protocol has been designed to work in a distributed way, it could be “simulated” by a centralised database (*i.e.* a back-end) connected to a properly distributed set of readers. By doing so, the back-end would be able to identify tags and “logically” cluster them in regions (*e.g.* virtually covered by the readers). Thus, intelligent search of a tag into these regions might be scalable in terms of computational cost. In addition, this approach averts the communication overhead associated with the exchange of

2	2	2	5	7	5	8	12	8
2	2	2	7	10	7	12	18	12
2	2	2	5	7	5	8	12	8

$p = 0$ $p = 0.5$ $p = 1$

Figure 3.6: Number of IDs stored in the readers for different values of p considering that each reader is the owner of 2 tags. The neighbourhood relations are the ones described in Figure 3.1-left.

messages between readers because all the communication might be “simulated” within the back-end.

The main problems of using this approach are: (i) using a single centralised database leads to a single point of failure and, (ii) the communication of a single back-end with a (possibly) large number of readers might create bottle-necks and undesired delays.

It might be said that, depending on the special characteristics of the environment in which the RFID system is to be deployed, engineers may decide whether to use our protocol “simulated” within a back-end, or use it as a fully distributed non-centralised protocol.

3.2 Experimental results and evaluation

We have developed a simulator to analyse the number of operations performed by the collaborative readers during the execution of our probabilistic protocol, and their bandwidth usage. The simulator allows the deployment of readers without constraints. The number of readers, their cover range, their location, the number of moving tags, and the scenario in which they move can be defined at the beginning of the simulation.

We have concentrated on simulations to analyse the theoretical properties of our protocol and we have left for the future the implementation and testing of a practical prototype. Although there are some limitations in the off-the-shelf RFID tags, there exist some EPC UHF Gen 2 tags that can compute hash functions and random numbers (using ARMADILLO [31]) and can be read at distances of up to 1 meter. Currently, newer versions with larger reading distances (*i.e.* 3 m) are under development (cf. www.oridao.com).

With the aim to evaluate our probabilistic protocol, we compare it with the *original* protocol presented in [199]. Although our protocol has no limitations related to the deployment and range of the readers, the *original* protocol does have some. Consequently, we simulate the regular distribution of 24 readers (4×6) depicted in Figure 3.8 that the *original* protocol can handle.

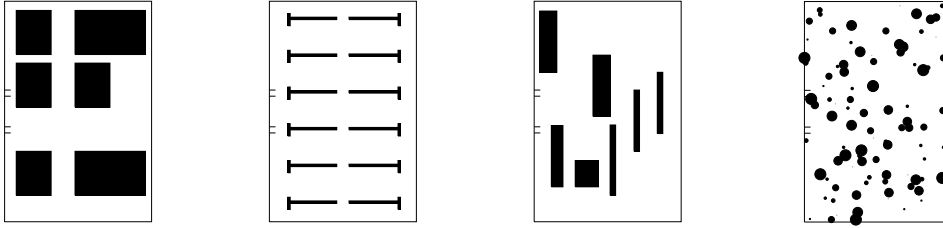


Figure 3.7: Graphical scheme of the simulated scenarios. (From left to right) Scenario with narrow corridors, scenario with wide corridors, scenario with random large obstacles, scenario with random small obstacles.

We have considered five different scenarios¹: (i) An empty scenario in which tags can freely move, (ii) a scenario with narrow corridors, (iii) a scenario with wide corridors, (iv) a scenario with randomly placed large obstacles and, (v) a scenario with randomly placed small obstacles (cf. Figure 3.8 for a screenshot of the simulator and Figure 3.7 for a graphical scheme of the four non-empty scenarios). For each scenario we have simulated the movement of 10^3 and 10^4 tags. We have considered two different tag behaviours: (i) a random movement and, (ii) a semi-directed movement: tags move half of the times randomly and half of the times toward a far, randomly-selected point within the scenario. Each simulation has been repeated 30 times for each value of p in $(0, 1)$ with 0.1 increments. Globally a total of 7200 simulations have been conducted: 2 types of movement \times 5 different scenarios \times 12 protocols (11 different p + the *original* one) \times 30 repetitions \times 2 different tag populations (10^3 , 10^4).

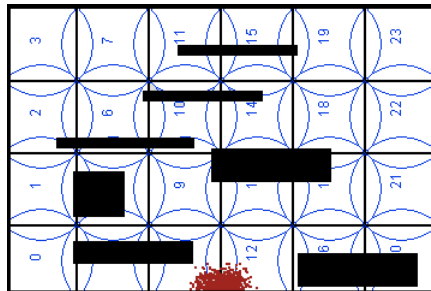
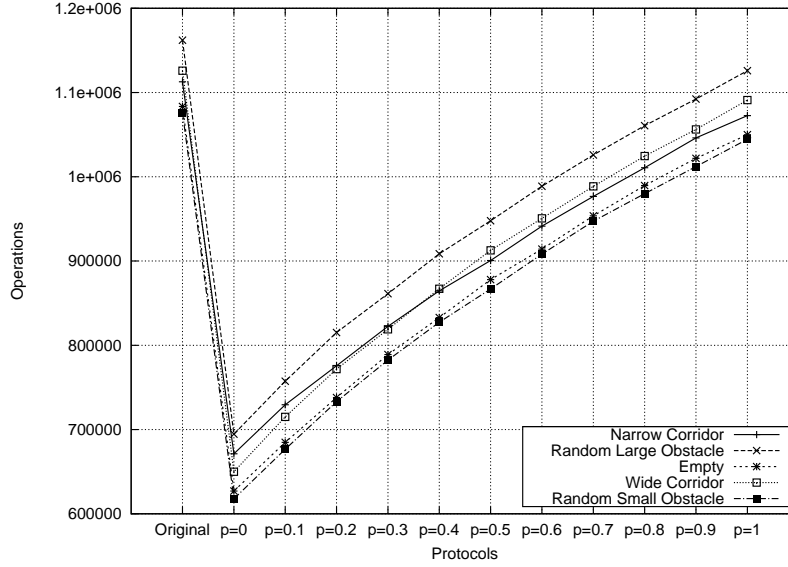
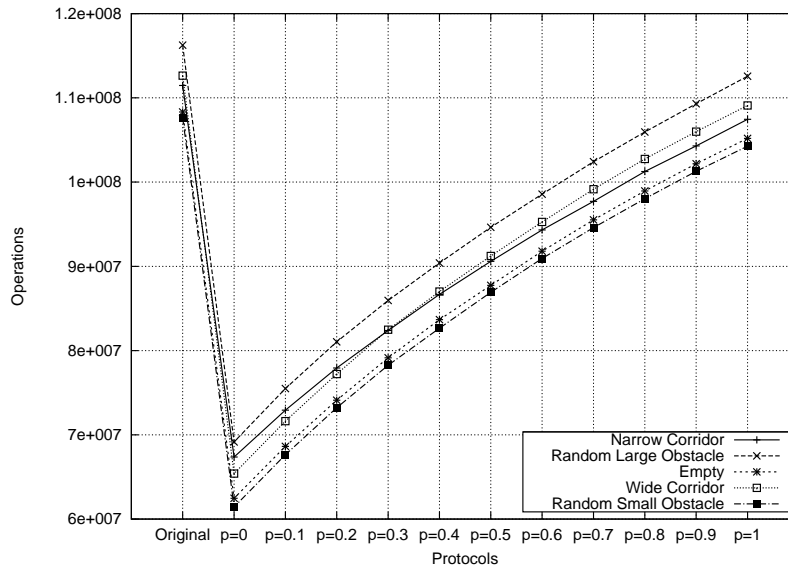


Figure 3.8: Screenshot of the simulator. The cloud of red dots represents the tags entering the system. Blue circles represent the **shared** cover area of the readers, which are identified by a number. Thick black lines represent obstacles. Finally, thin black lines represent the **unshared** cover areas that the protocol in [199] would use.

¹Some of these scenarios were already used in [199]

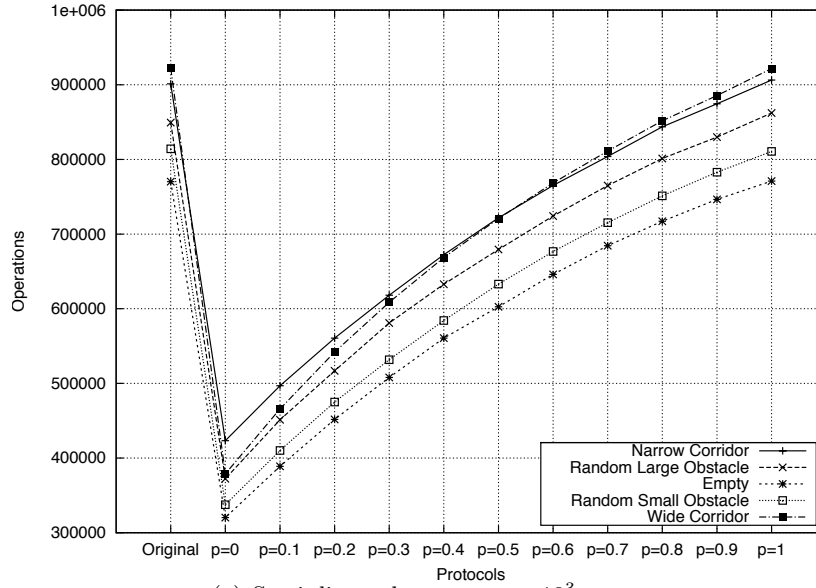


(a) Random movement - 10^3 tags

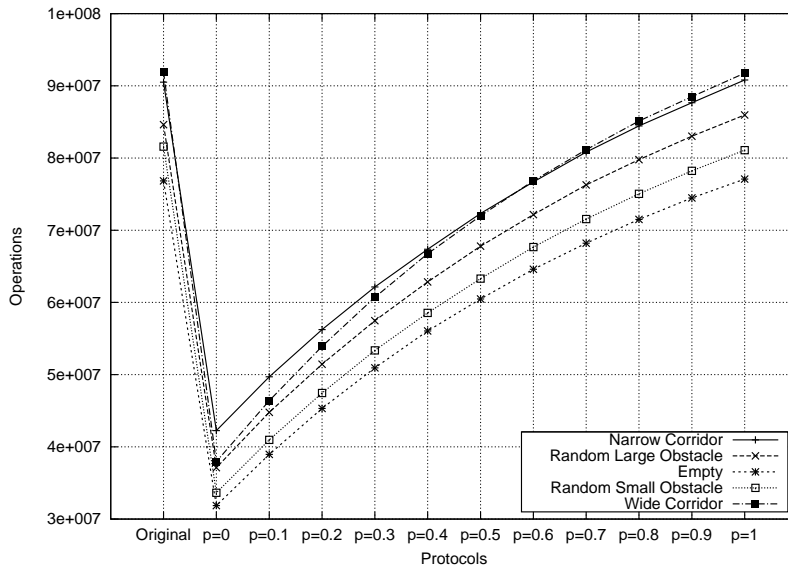


(b) Random movement - 10^4 tags

Figure 3.9: Operations performed by the readers controlling 10^3 and 10^4 tags for different values of p in all scenarios and considering a random movement pattern. **The lower the better.**

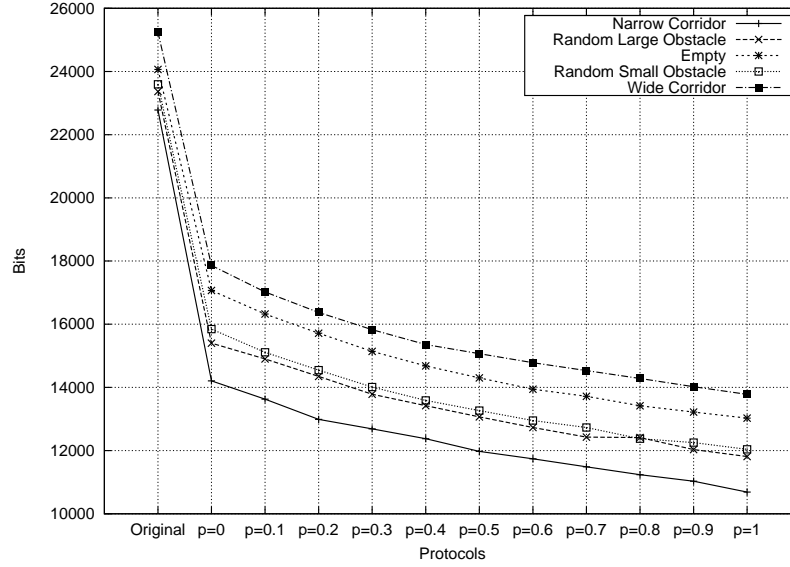


(a) Semi-directed movement - 10^3 tags

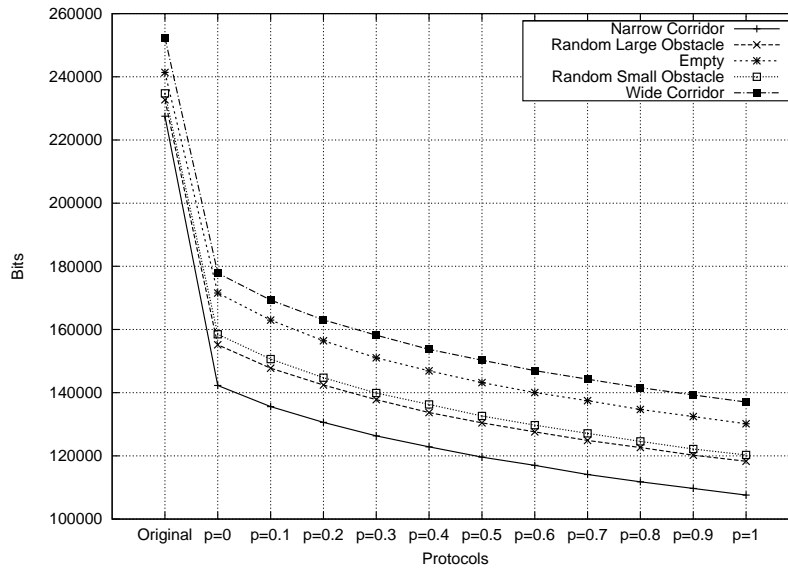


(b) Semi-directed movement - 10^4 tags

Figure 3.10: Operations performed by the readers controlling 10^3 and 10^4 tags for different values of p in all scenarios and considering a semi-directed movement pattern. **The lower the better.**

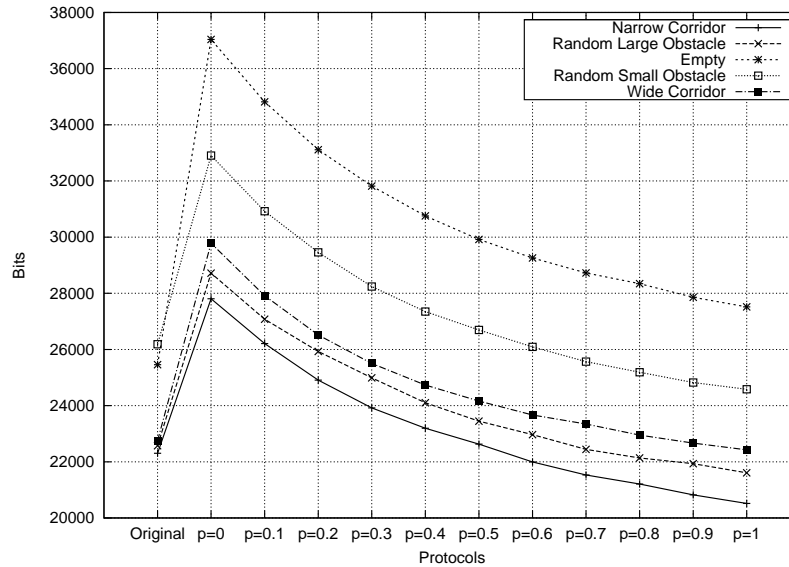


(a) Random movement - 10^3 tags

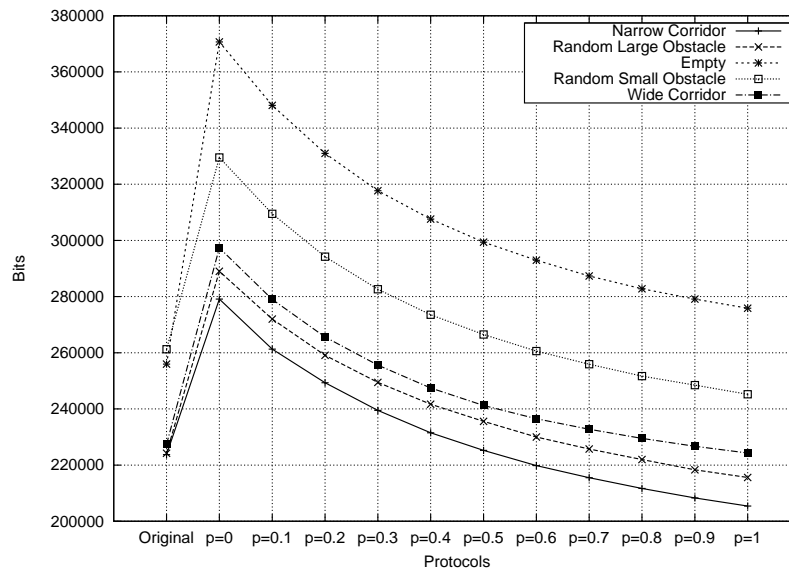


(b) Random movement - 10^4 tags

Figure 3.11: Total number of bits transmitted by the readers controlling 10^3 and 10^4 tags for different values of p in all scenarios and considering a random movement pattern. **The lower the better.**



(a) Semi-directed movement - 10^3 tags



(b) Semi-directed movement - 10^4 tags

Figure 3.12: Total number of bits transmitted by the readers controlling 10^3 and 10^4 tags for different values of p in all scenarios and considering a semi-directed movement pattern. **The lower the better.**

For each scenario, we have concentrated on analysing the computational cost (in terms of number of operations performed by readers) and the bandwidth usage (in terms of total number of bits sent). Figures 3.9 and 3.10 show the results for the computational cost and Figures 3.11 and 3.12 show the results for the bandwidth usage. It can be observed that our protocol has a significantly lower computation cost than the *original* protocol. This is especially apparent when the probability p is low².

Regarding the bandwidth usage, two different behaviours can be observed:

- With random movements: Tags change from a cell to another with low probability (in our protocol). Thus, the number of required messages to update the state of the readers' caches is smaller. In this situation our protocol is clearly more efficient than the *original* one.
- With semi-directed movements: Tags follow a clear path and change from one cell to another with a higher probability. In this case, our protocol requires more messages (especially in the case of using a low p). Thus, in this situation the *original* protocol is more efficient for smaller p .

In general, the computational cost is the main concern in RFID identification protocols and, as we have shown above, our proposal clearly outperforms the *original* protocol in this regard for all scenarios. Indeed, if bandwidth usage is not a concern at all, our proposal with $p = 0$ is the optimal solution. However, our protocol requires more bandwidth to improve the computational cost.

Capturing the trade-off between computational cost and bandwidth is not trivial. Note that the computational cost and the bandwidth usage are measured in different units. However, it is possible to define a measure in order to compare our proposal with the *original* protocol in terms of both computational cost and bandwidth usage.

Definition 9 (Trade-off measure). *Let α be a real value in the range [0..1]. Let c and b be the computational cost and the bandwidth usage, respectively, of the original protocol for a given configuration³. Let c_p and b_p be the computational cost and the bandwidth usage of our protocol using the same configuration and p the probability value. Then, the trade-off measure that we propose is computed as follows:*

$$d(\alpha, p) = \left(\left(\frac{c_p}{c} - 1 \right) \times 100 \right) \times \alpha + \left(\left(\frac{b_p}{b} - 1 \right) \times 100 \right) \times (1 - \alpha)$$

Intuitively, the proposed trade-off measure $d(\alpha, p)$ represents the performance of the *original* protocol with regard to our protocol using p as the probability value and

²Note that when the probability p tends to 1, our protocol tends to resemble the *original* protocol in terms of computational cost. However, it is still better in most cases.

³A configuration will be defined by the number of tags in the system, the number of readers and their distribution, the scenario, etc.

considering α the weight given to the computational cost and $1 - \alpha$ the weight given to the bandwidth usage. Note that when $\alpha = 0$ the bandwidth usage is the only concern, whilst when $\alpha = 1$ only the computational cost is considered.

Figures 3.13, 3.14, 3.15, 3.16 and 3.17 depict the performance of the *original* protocol with regard to our protocol using the trade-off measure described above. At the bottom of each figure there is a three-dimensional chart showing the values of $d(\alpha, p)$ for each $\alpha \in \{0, 0.1, \dots, 0.9, 1\}$ and each $p \in \{0, 0.1, \dots, 0.9, 1\}$. Also, at the top left side and at the top right side of the figure there are the projections of the three-dimensional charts for the x-axis and y-axis, respectively. In the x-axis projection, for each value of α the values of $d(\alpha, p)$, $\forall p \in [0, 1]$, are shown, whilst in the y-axis projection the plot of the linear functions $d(\alpha, p)$ with α fixed is shown.

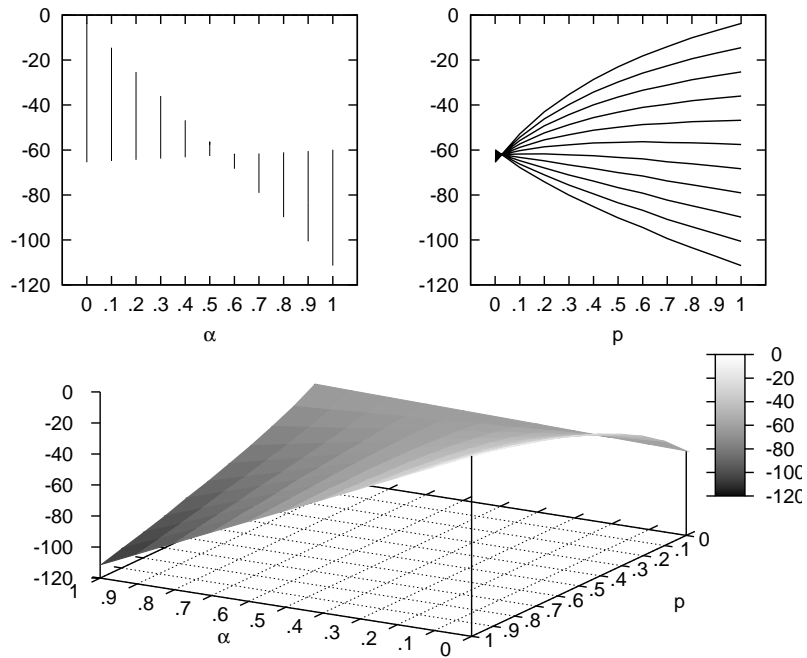
It can be observed that our protocol outperforms the previous proposal in most cases. When the movement of the tags is random, our protocol is always better for all possible configurations. When the movement of the tags is semi-directed our proposal is better in 81% of the cases. That leads to a global improvement in more than 90% of all configurations.

3.3 Conclusions

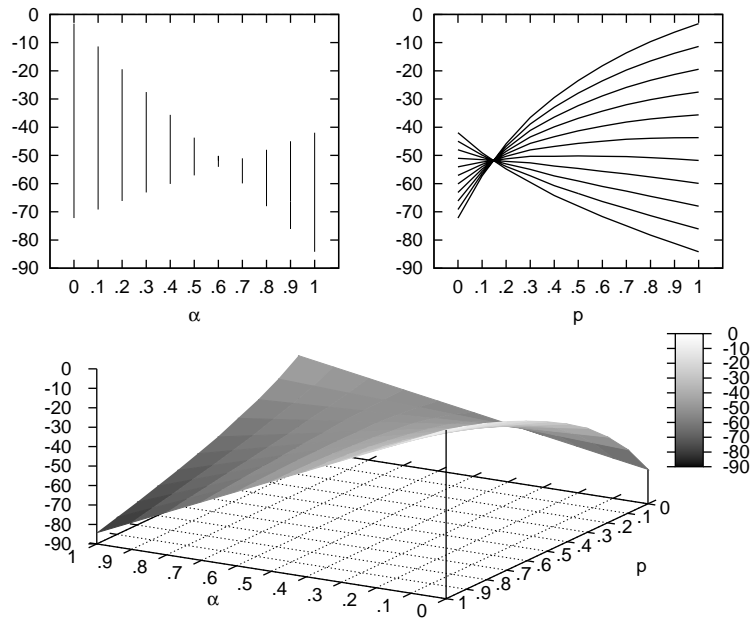
In this chapter, we have presented an efficient communications protocol for collaborative RFID readers to privately identify RFID tags. With the presented protocol, the centralised management of tags can be avoided along with bottlenecks and undesired delays.

Our protocol is not a simple modification of previous proposals but a completely different approach that clearly improves the efficiency and flexibility of the whole system. In addition, due to the probabilistic nature of our protocol, the system becomes very flexible, *i.e.* the relation between computational cost and communications overhead can be easily tuned by means of p . The simulation results confirm that our protocol outperforms previous approaches like [199].

Although the presented protocol is an improvement, there are some open issues that should be considered in the future, namely (i) study the effect of the number of neighbours, (ii) propose methods to dynamically vary p so as to adapt it to the movements of tags, (iii) propose hybrid methods that mix hash-based solutions and tree-based solutions with collaborative readers, etc.

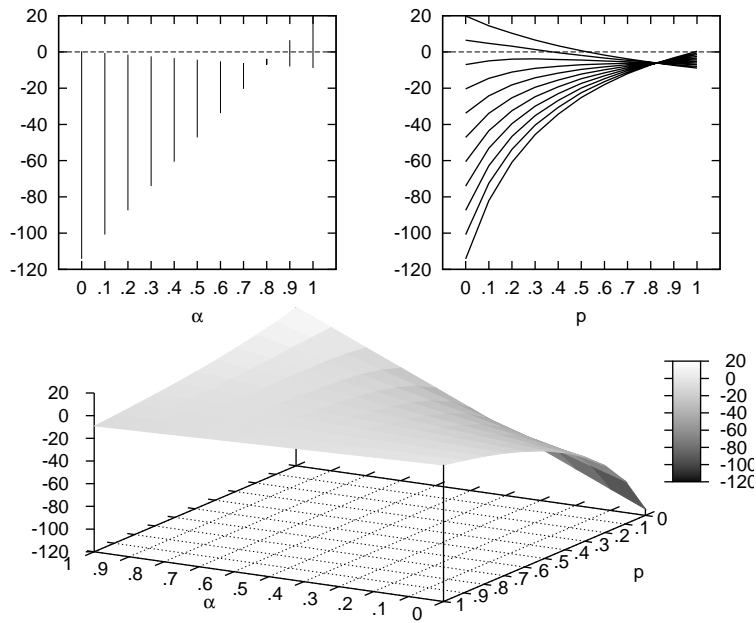


(a) Random movement - "Narrow corridor" scenario

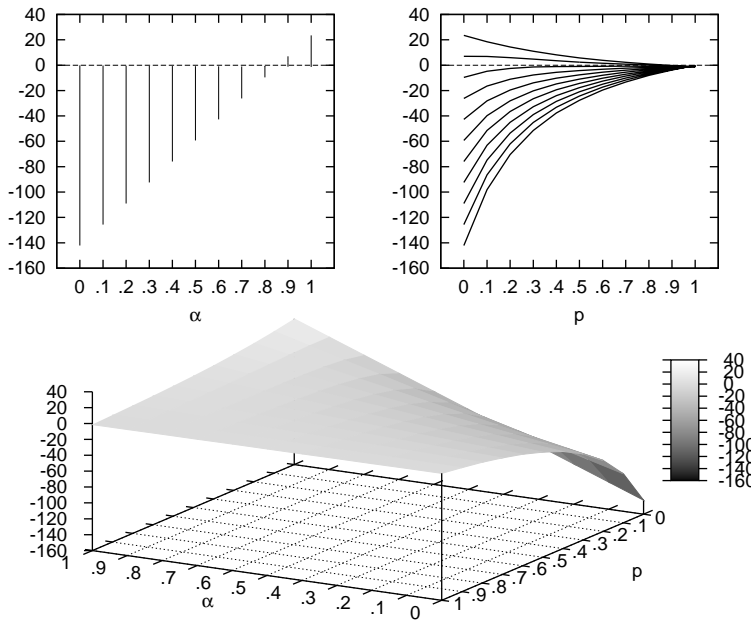


(b) Random movement - "Wide corridor" scenario

Figure 3.13: $d(\alpha, p)$ results for 10^4 tags and different values of p and α in the scenarios with corridors and with a random movement pattern. **Values below zero indicate that our protocol is better with respect to the *original* protocol.**

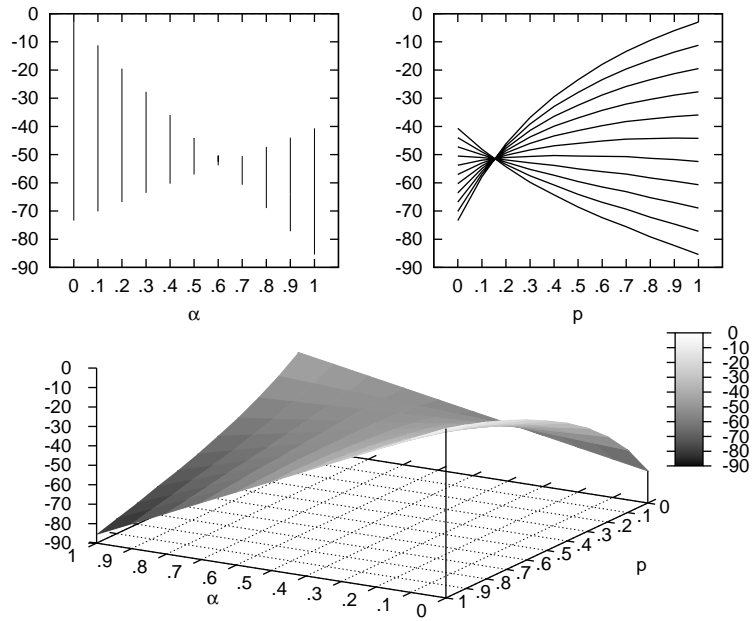


(a) Semi-directed movement - “Narrow corridor” scenario

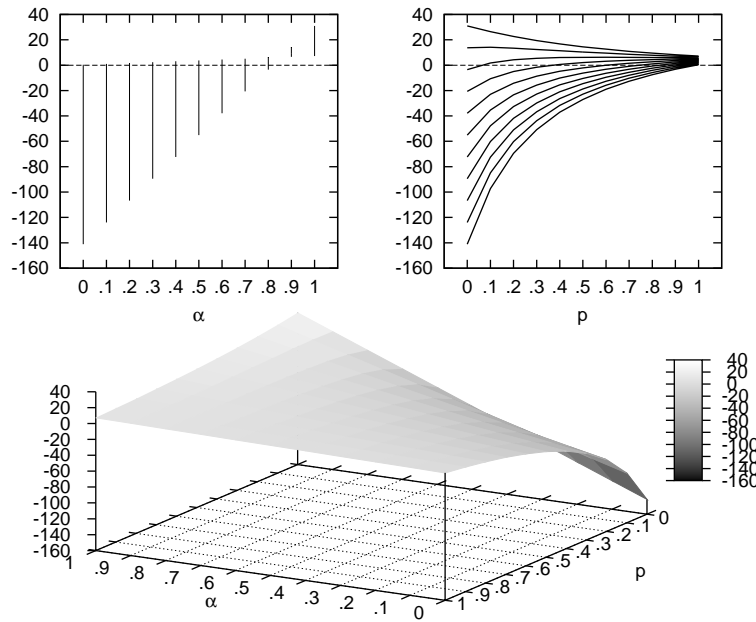


(b) Semi-directed movement - “Wide corridor” scenario

Figure 3.14: $d(\alpha, p)$ results for 10^4 tags and different values of p and α in the scenarios with corridors and with a semi-directed movement pattern. **Values below zero indicate that our protocol is better with respect to the original protocol.**

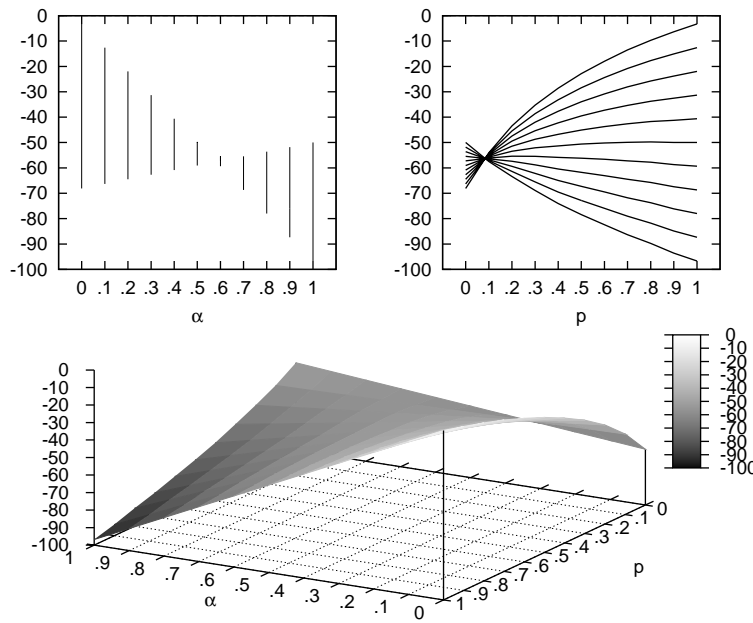


(a) Random movement

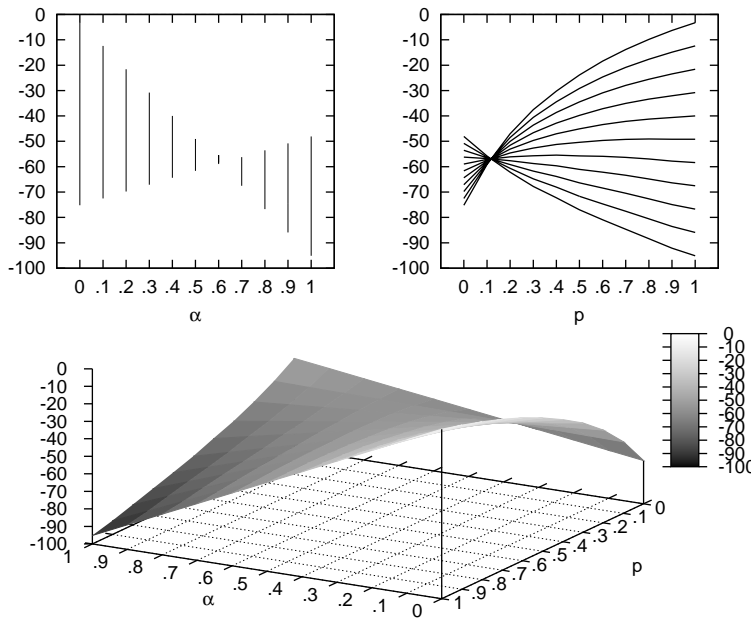


(b) Semi-directed movement

Figure 3.15: $d(\alpha, p)$ results for 10^4 tags and different values of p and α in the empty scenario. Values below zero indicate that our protocol is better with respect to the *original* protocol.

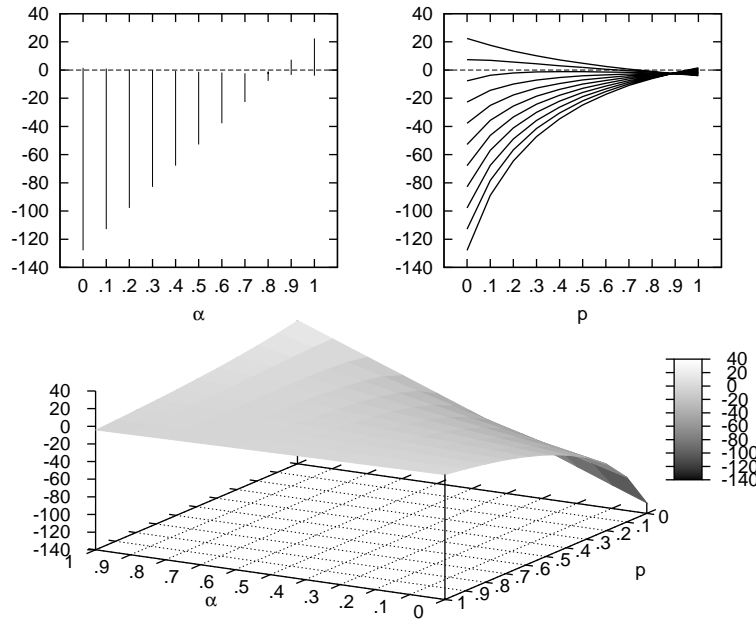


(a) Random movement - "Random Large Obstacles" scenario

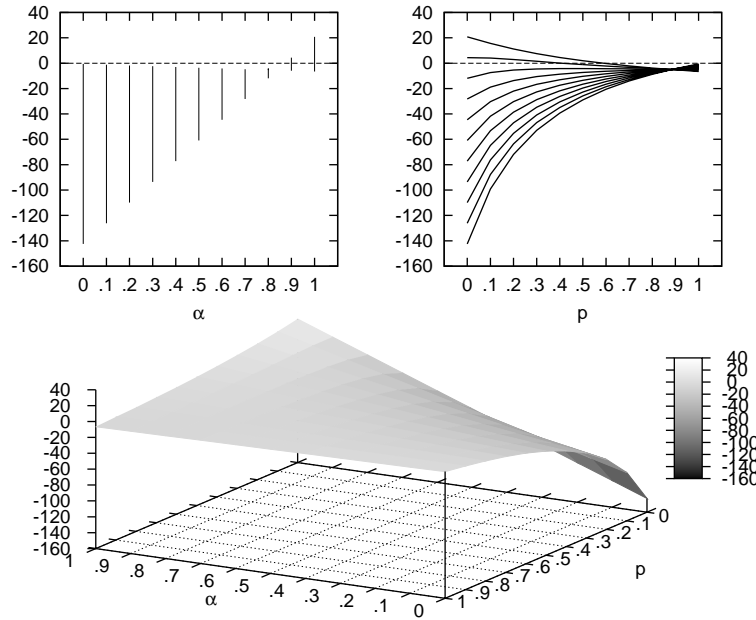


(b) Random movement - "Random Small Obstacles" scenario

Figure 3.16: $d(\alpha, p)$ results for 10^4 tags and different values of p and α in the scenarios with random obstacles and with a random movement pattern. **Values below zero indicate that our protocol is better with respect to the original protocol.**



(a) Semi-directed movement - “Random Large Obstacles” scenario



(b) Semi-directed movement - “Random Small Obstacles” scenario

Figure 3.17: $d(\alpha, p)$ results for 10^4 tags and different values of p and α in the scenarios with random obstacles and with a semi-directed movement pattern. **Values below zero indicate that our protocol is better with respect to the *original* protocol.**

Predictive Protocol for Scalable Identification of RFID Tags through Collaborative Readers

This chapter presents a natural improvement of previous RFID identification protocols based on collaborative readers. The described protocol improves the identification process by predicting the locations of the moving tags.

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Let us consider an RFID system intended for identification and tracking (*e.g.* tracking of goods in a supply chain or luggage control in an airport). In such applications, several RFID readers are distributed over the system in order to identify tags passing through the RFID reader positions [199, 83, 210, 43, 15, 52]. By doing so, it is possible to obtain the trajectory of a tag by concatenating the reader's positions where the tag has been identified. Even in applications without tracking purposes, it makes sense to distribute a set of readers covering strategic points or the whole monitored area [199] in order to identify the tags moving in it. Supermarkets with several entry/exit doors or department stores are genuine examples of such applications.

Although there are several applications where many tags should be identified using some readers, to the best of our knowledge, only two protocols [199, 83] exploiting this particular property have been proposed so far. The first of them [199] introduced the idea of using multiple collaborative readers to make the identification process scalable

whilst maintaining the high level of privacy of the IRHL scheme [119]. Their proposal is aimed at efficiently identifying tags in applications where each tag must be continuously monitored while it remains in the system. This implies that readers must cover the whole system. Under this assumption, tags are constrained to move along neighbour readers¹ and therefore, neighbour readers collaborate in order to guarantee efficiency during the identification process. Efficiency is achieved by means of the so-called *reader's cache*, which is defined as a storage device where a reader saves tag identification data². The protocol reduces the size of the readers' cache by considering that only the closest reader to some tag and its neighbours must store the identification information of this tag. By reducing the size of the cache the identification procedure becomes more efficient. Despite the benefits in terms of computational cost provided by this protocol, assuming that readers are able to compute their accurate distance to tags is a bit unrealistic.

On the other hand, in the context of using multiple readers (connected to a centralised back-end), Fouladgar and Afifi [83] point out that, in many applications, tags are usually queried by the same set of readers. Therefore, they propose to cluster tags according to the readers that identify them more often. This idea improves the group-based proposals in the sense that tags are not randomly assigned to groups, but intelligently clustered according to the spatial location of the readers that identify them. By doing so, when a reader receives a tag's response, it first performs a search on the group of tags that it usually identifies. If it does not succeed, an exhaustive search is performed over the whole set of tag identifiers. The problem of this proposal is that tags may have a long life-cycle and move through a wide variety of readers. In this scenario, the protocol could scale as poorly as previous protocols based on symmetric key cryptography [119].

We show that the scalability problems of some private protocols can be alleviated not only distributing readers throughout the system, but also by exploiting the spatial location of tags. Indeed, a tagged item usually follows a pre-established life-cycle and then it could be intelligently identified according to its expected spatial location. In this chapter, we propose an adaptive and distributed architecture aimed at efficiently identifying RFID tags based on their expected spatial location. Unlike previous proposals [199], our architecture is suitable for all possible scenarios and adapts itself to the type of tag movement. We show empirical results based on synthetic data confirming the superiority of our architecture with respect to previous proposals [199] and [83].

¹Two readers are said to be neighbours if their cover areas are not disjoint.

²This cache can be either an external database securely connected to the reader or a database internally managed by the reader itself.

4.1 Trajectory-based RFID identification protocol

In the Solanas *et al.* proposal [199], the readers' cache contains identification data of tags but it lacks information about the expected time at which the tags might next be identified by a reader or where they were identified in the past. Assuming that it is possible to approximately know the instant at which a tag will be identified by a given reader, it is greatly beneficial to use this spatio-temporal information to speed up the searching process in the readers' cache. Therefore, we propose to structure the readers' cache as an ordered list where the expected time of arrival (ETA) is the ordering criterion.

Definition 10 (Cache). *Given the set of tags \mathcal{T} and readers \mathcal{R} in the system, the cache of a reader $R \in \mathcal{R}$ consists of a sequence of ordered tuples*

$$C(R) = \langle t_1, ID_1, R_{prev}^{ID_1}, R_{next}^{ID_1}, Y|N \rangle, \dots, \\ \dots, \langle t_N, ID_N, R_{prev}^{ID_N}, R_{next}^{ID_N}, Y|N \rangle$$

where the order is given by the timestamps $t_1 \leq \dots \leq t_N$. The tag identifiers $ID_i \in \mathcal{T}$, $\forall 1 \leq i \leq N$, and $R_{prev}^{ID_i} \in \mathcal{R}$ and $R_{next}^{ID_i} \in \mathcal{R}$ are the reader that sent the ID_i to R and the reader that will receive the ID_i from R , respectively. $Y|N$ is used as a flag to show whether the tag has been already identified by this reader.

From the above definition it can be observed that our protocol will use the spatial information about the trajectory of the tags to predict which reader will be the next reader to receive a given tag. Our protocol will also use the temporal information of such trajectories to predict when a given tag will be read in the future by the next reader. Table 4.1 is an example of the cache of a reader. In this example, the reader R_{512} expects to receive the tag $T_{90876534}$ from reader R_{1012} at time *2011-07-28 11:31:38*, and will forward the identification information to the next reader R_{201} . Also, it can be seen that the tag has not been identified by the reader yet.

By using this ordered cache, when a tag response arrives at a given timestamp t , a reader is able to optimise the searching process in its cache by first considering the tags that it expects to identify at a timestamp t' close to t . Note that if the ETA is accurate, the identification of tags might be very fast. The better the prediction, the faster the identification process. In the worst case the computational cost is $O(n)$, where n is the number of identifiers in the cache of the reader.

Cache of Reader 512				
ETA	Tag ID	Previous Reader	Next Reader	First Time
2011-07-28 11:31:38	90876534	1012	201	Yes
2011-07-28 11:41:33	10311299	1011	1201	No
...
2011-07-30 22:01:08	21134211	1012	201	No

Table 4.1: Example of the cache of a reader.

4.1.1 Trajectory prediction algorithms

We propose to use trajectory predictors extensively so as to be able to inform readers about which tags they will receive and when, before they actually receive them. However, when this prediction fails, we propose to use other predictors to find the reader that might have the information about a tag. These latter predictors consider the movement of all tags globally, *i.e.* they look for global trends instead of predicting the moves of a single tag as does by the former predictors.

In general, a trajectory is understood as a timely ordered set of consecutive points (\mathcal{P}) defined in an n -dimensional space (\mathcal{S}). However, due to the fact that we can only control the location of the tags when they are detected by a reader, we define our concept of trajectory as follows:

Definition 11 (Trajectory). *Given a set of readers \mathcal{R} and tags \mathcal{T} . The trajectory of a tag $T_i \in \mathcal{T}$ is defined as a sequence*

$$S_i = \langle t_1, R_1 \rangle, \langle t_2, R_2 \rangle, \dots, \langle t_{s(i)}, R_{s(i)} \rangle$$

where $s(i)$ is the size of the sequence, $t_1 < t_2 < \dots < t_{s(i)}$ are timestamps and, $R_j \in \mathcal{R} \forall 1 \leq j \leq s(i)$ are the readers that identified the tag T_i at the timestamp t_j .

When a tag arrives at the cover area of a reader, the reader tries to identify it by applying the already explained IRHL protocol. During the identification process two situations could arise:

1. **Identification success:** The reader finds the identification information of the tag in its cache and can identify it. Then it has to decide to which reader should this information be forwarded (see the example of Figure 4.1).

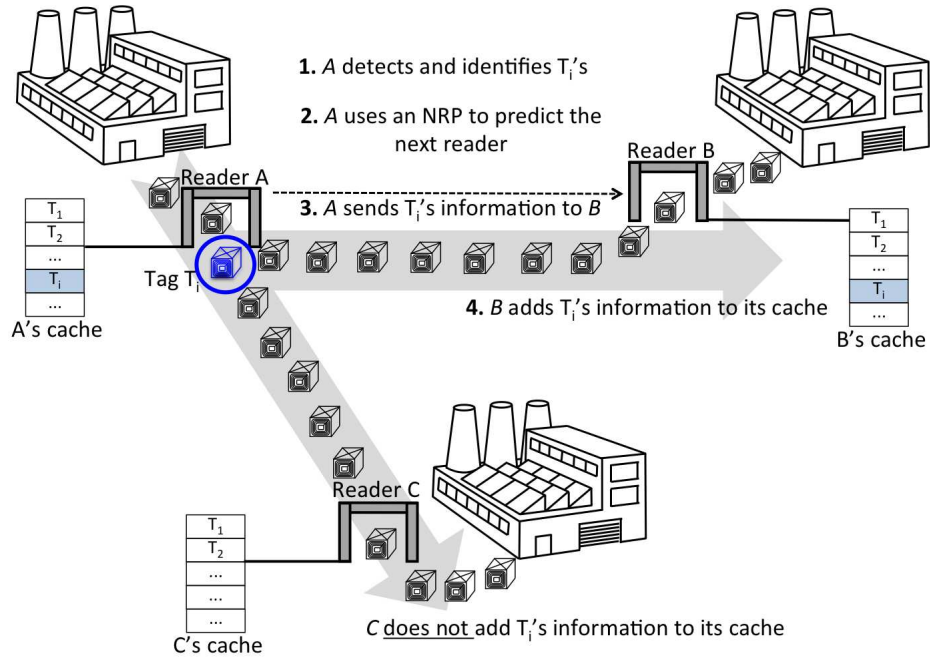


Figure 4.1: Illustration of the identification success of the tag T_i by reader A. After successfully identifying T_i , the reader A applies a Next Reader Predictor (NRP) to predict the next reader (in this case, reader A decides that reader B is the best candidate) and sends the T_i identification information to reader B. The reader B stores the information about T_i in its cache so as to be able to identify it (if necessary).

2. **Identification failure:** The cache of the reader does not contain the identification information of the tag and the reader cannot identify it. The reader has to decide which other reader to ask for help (see the example of Figure 4.2).

In the first case (*identification success*), after properly identifying a tag, the reader will proceed by using a *Next Reader Predictor* (NRP) algorithm to determine which reader will be the next one to which the tag will move. Once this next reader is determined, the current reader sends the identification information of the tag to that reader. An NRP can be defined as follows:

Definition 12 (Next Reader Predictor (NRP)). *Let T_i be a tag of the system and let $S_i = \langle t_1, R_1 \rangle, \langle t_2, R_2 \rangle, \dots, \langle t_j, R_j \rangle$ be its trajectory. An NRP is a polynomial-time algorithm (let us call it \mathcal{A}_{next}) that, on input T_i*

and S_i , outputs the pair $\langle t_{j+1}, R_{j+1} \rangle$.

$$\mathcal{A}_{next}(T_i, S_i) \longrightarrow \langle t_{j+1}, R_{j+1} \rangle$$

This output pair means that it is expected that the tag T_i will be identified at time $t_{j+1} > t_j$ by the reader R_{j+1} .

Note that the result of the NRP is correct only with a probability that highly depends on the utilised algorithm and the degree of regularity of the movement of tags³. Thus, if the prediction is wrong, the reader which is currently identifying the tag T_i will forward the identification information to a wrong reader. As a consequence, when that tag reaches the next reader, the latter will not be able to identify the tag (because the identification information will not be in its cache) and will need the help of other readers to do so (this is the second case enumerated above).

In the second case (*Identification failure*), when a reader cannot identify a tag, it proceeds by using a *Previous Reader Predictor* (PRP) algorithm to identify the reader that might have identified the tag previously and might have the identification information of the tag. A PRP can be defined as follows:

Definition 13 (Previous Reader Predictor (PRP)). Let $\mathcal{T} = \{T_1, \dots, T_N\}$ be the set of tags in the system and let $\mathcal{S} = \{S_1, \dots, S_N\}$ be the set of trajectories of the tags in \mathcal{T} until a given time t . Let $\mathcal{T}^{\mathcal{R}} \subset \mathcal{T}$ be the subset of tags known by reader \mathcal{R} and let $\mathcal{S}^{\mathcal{R}} \subset \mathcal{S}$ be the trajectories of the subset of tags known by reader \mathcal{R} . A PRP is a polynomial-time algorithm (let us call it \mathcal{A}_{prev}) that, on input a reader \mathcal{R} and a set of trajectories of tags $\mathcal{S}^{\mathcal{R}}$, outputs the sequence of k readers R_1, R_2, \dots, R_k that are candidates to be the previous reader that identified a tag:

$$\mathcal{A}_{prev}(\mathcal{R}, \mathcal{S}^{\mathcal{R}}) \longrightarrow \langle R_1, R_2, \dots, R_k \rangle$$

Remark 1. The order of the sequence of candidate readers depends on the specific implementation of the predictor. However, the following condition must hold:

$$P(\text{success}|R_1) \geq P(\text{success}|R_2) \geq \dots \geq P(\text{success}|R_k)$$

This means that R_1 has more chances of being the actual previous reader than R_2 , etc.

³It is apparent that in a chaotic system where no regularities exist, the prediction of the next move of a tag would be extremely inefficient.

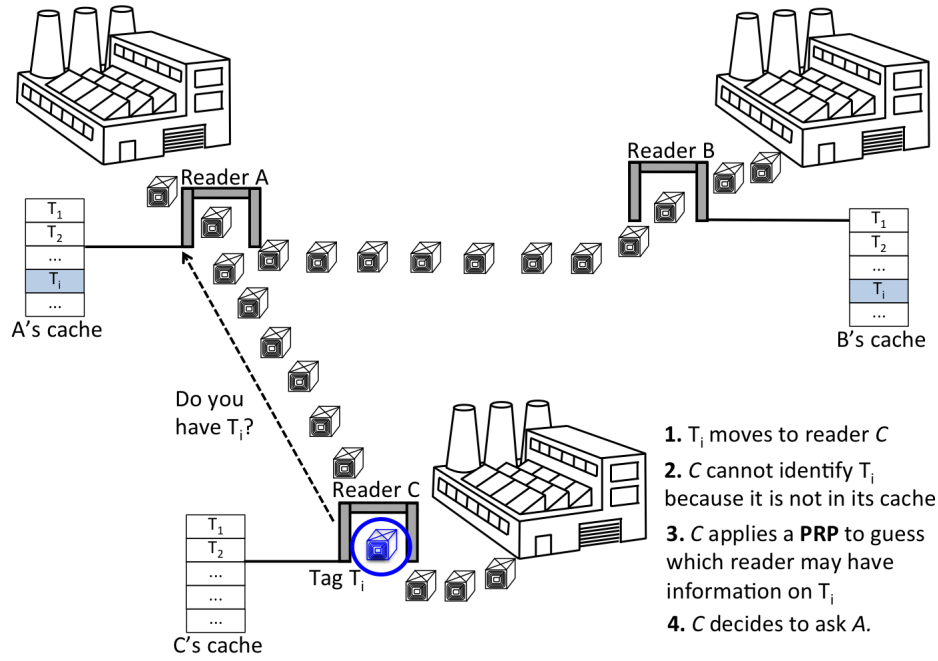


Figure 4.2: Illustration of the identification failure. Reader C tries to identify T_i but it fails because it has not got the information in its cache. It uses a PRP to decide which reader to ask for help (in this case C asks A).

Note that we have defined the theoretical concept of NRP and PRP algorithms. However, the specific implementation of these algorithms would highly affect the performance of the whole system. Further below, we will give details on the implementations that we have used for our experimental analysis.

4.1.2 Our protocol

We define our protocol as a distributed algorithm in the context of a set of collaborative readers \mathcal{R} that share identification information on a number of tags \mathcal{T} . For the sake of completeness, in addition to \mathcal{R} , we consider a special reader \mathcal{O}_R that acts as an oracle, *i.e.* it has the same role of classical back-ends that have the information of all tags in the system. \mathcal{O}_R can identify any tag in \mathcal{T} , hence no false negative identifications occur. However, in our collaborative context, the oracle should be understood as the “*last resort*” to identify a tag if all the other mechanisms fail⁴, because the computational

⁴Note that this situation might happen rarely and probably it would be caused by a communication failure amongst the collaborative readers or by an active attack.

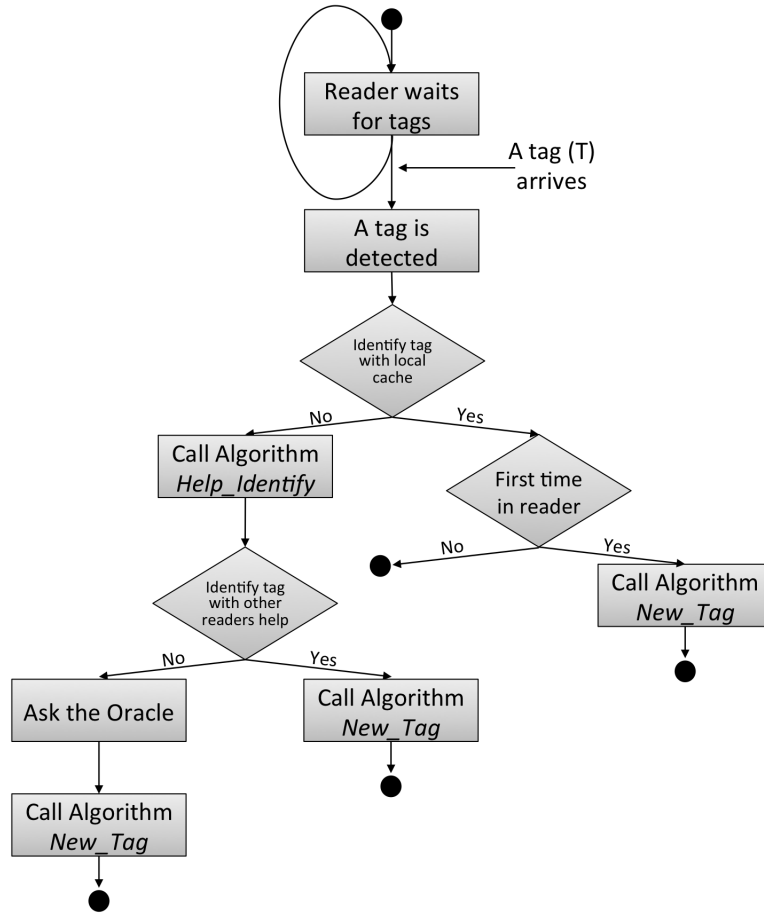


Figure 4.3: Conceptual logical flow of the protocol.

cost associated to the identification of tags by the oracle is very high.

Algorithm 1 shows a pseudocode description of our protocol and Figure 4.3 depicts the logical flow of the proposal. Our protocol works as follows. The reader R , that receives an identification message from an unidentified tag T at time t , tries to identify it by following the Improved Randomised Hash Lock Scheme (IRHL) [119, 120] but using the identification information stored in its own cache only (*lines 1 to 10 in Algorithm 1*). In order to perform this identification efficiently, the reader uses the cache structure described above. First, it tries to identify T as one of the tags that were expected to arrive at time t . If the tag is not identified amongst these candidate tags, the reader tries with tags that were expected to arrive a bit later at time $t + 1$ and a bit earlier at time $t - 1$, and so on. Searching in this way, if the ETA of T was properly predicted and forwarded, T is identified almost instantly. However, if the prediction was wrong, the

Algorithm 1 Main protocol

```

1: Require: (i) A tag  $T$  to be identified by a reader  $R$  at time  $t$ ; (ii) The set of tags'
   trajectories  $\mathcal{S}^{\mathcal{R}}$  known by  $R$ ; (iii) The cache of reader  $R$ ,  $C(R)$ .

   - - Try to identify  $T$  using the local cache
2: for all  $t' \in \{t, t+1, t-1, t+2, t-2, \dots\}$  do
3:   for all  $T_i \in C(R)$  with  $ETA = t'$  do
4:     if  $T$  is identified as  $T_i$  then
5:       if  $T_i$  is a “first time” tag then
6:         Call New_Tag ( $R, T_i, t, R_{prev}^{T_i}, S_i$ )
7:       end if
8:       Return: (Tag identified correctly);
9:     end if
10:  end for
11: end for
   - - Try to identify the tag with the help of other readers
12: for all  $R' \in \langle R_1, R_2, \dots, R_k \rangle \leftarrow \mathcal{A}_{prev}(R, \mathcal{S}^{\mathcal{R}})$  do
13:   Call Help_Identify ( $T, R'$ )
14:   if  $R'$  identifies  $T$  then
15:      $R$  receives  $\langle t', T_i, R_{prev}^{T_i}, R_{next}^{T_i} \rangle$  from  $R'$ .
16:     Call New_Tag ( $R, T_i, t, R'$  and,  $S_i$ ).
17:     Return: (Tag identified correctly);
18:   end if
19: end for
   - - (last resort) Ask the Oracle
20: if  $\mathcal{O}_R$  identifies  $T$  then
21:   Call NewTag ( $R, T, t, \mathcal{O}_R, \emptyset$ ).
22:   Return: (Tag identified correctly);
23: end if
24: Return: Invalid tag  $T$  found

```

reader R might need to search over all its cache. If T is identified, R checks whether it is the first time that this tag enters its interrogation zone, *i.e.* it is a “first time” tag. If it is, it calls the procedure *New_Tag*($R, T_i, t, R_{prev}^{T_i}, S_i$) and the identification finishes. If the tag is not a “first time” tag, the identification procedure simply finishes.

If the identification information of T was not properly forwarded to R^5 , it will search over all its cache and will not be able to identify T . In this situation, it has to ask for help to the other collaborative readers that might have the information it needs (*lines*

⁵Note that this might happen due to a wrong prediction of the next reader by the previous reader.

11 to 18 in Algorithm 1). To do so, R calls the PRP algorithm $\mathcal{A}_{prev}(R, S)$ so as to obtain a list of readers that may have information about T . For each reader R' in the list returned by \mathcal{A}_{prev} , the procedure *Help_Identify* (T, R') is called. If this procedure succeeds in identifying T , the collaborative reader that succeeds sends the tuple of its cache that contains the information about T , *i.e.* the tuple $\langle t', T_i, R_{prev}^{T_i}, R_{next}^{T_i} \rangle$ is sent to R . By using the information in this tuple, the identification process correctly finishes after calling the procedure *New_Tag*(R, T_i, t, R', S_i).

Finally, if no reader R' can identify T , R asks the oracle \mathcal{O}_R (lines 19 - 23 in Algorithm 1). If \mathcal{O}_R cannot identify T , the latter can be considered an illegitimate tag⁶. Otherwise, R finishes successfully the identification process by calling procedure *New_Tag* ($R, T, t, \mathcal{O}_R, \emptyset$).

Algorithm 2 *New_Tag*

- 1: **Require:** (i) A reader R that has identified a tag T_i at time t ; (ii) The reader R_{prev}^i ; (iii) The trajectory S_i of T_i .
 - 2: R asks $R_{prev}^{T_i}$ to remove T_i from its cache;
 - 3: R predicts the next reader and ETA $\langle t_i, R_{next}^{T_i} \rangle = \mathcal{A}_{next}(T_i, S_i)$;
 - 4: R asks $R_{next}^{T_i}$ to insert the record $\langle t_i, T_i, R, null, Y \rangle$ in its cache;
 - 5: R removes the record about T_i from $C(R)$ (if it exists);
 - 6: R inserts the record $\langle t, T_i, R_{prev}^{T_i}, R_{next}^{T_i}, N \rangle$ into $C(R)$;
 - 7: R adds $\langle t, R \rangle$ to T_i 's trajectory (S_i);
-

The main protocol described in Algorithm 1 uses two procedures (*New_Tag* and *Help_Identify*) to update the state of the caches of other collaborative readers and to identify tags for which the identifying reader has no information.

The *New_Tag* procedure, described in Algorithm 2, is called when a reader R determines that a newly identified tag, T_i , has entered its interrogation zone for the first time, *i.e.* it is a “First time” tag, and thus, T_i 's trajectory must be updated. In this case, R sends a message to the previous reader $R_{prev}^{T_i}$ that identified T_i so as to let it remove the information it has about T_i ⁷ (note that when $R_{pre}^{T_i} = \mathcal{O}_R$ this message is not sent). Then, R uses an NRP to determine the next reader that will be visited by T_i and sends a message to it to let it insert the tuple $\langle t_i, T_i, R, null, Y \rangle$ in its cache (this way, when the tag reaches this reader, it will be able to identify it efficiently). Finally, the record corresponding to T_i in $C(R)$ is updated with proper information about the next reader $\langle t, T_i, R_{prev}^{T_i}, R_{next}^{T_i}, N \rangle$.

⁶In this case, the proper actions are to be taken, namely raise an alarm, locate and eliminate the tag, etc.

⁷This information is no longer necessary and removing it from the cache speeds up the identification procedure.

Algorithm 3 Help_Identify

```

1: Require:  $T$  a tag to be identified by a reader  $R$ ;
2: Determine  $t_{old}$  the oldest timestamp in  $C(R)$ ;
3: for all  $t' \in \{t_{old}, t_{old} + 1, t_{old} + 2 \dots\}$  do
4:   for all  $T_i \in C(R)$  with  $ETA = t'$  do
5:     if  $T$  is identified as  $T_i$  then
6:        $R$  asks  $R_{prev}^i$  to remove the information of  $T_i$  from its cache;
7:       Return:  $\langle t', T_i, R_{prev}^{T_i}, R_{next}^{T_i} \rangle$ 
8:     end if
9:   end for
10: end for
11: Return:  $\langle null \rangle$  (Tag not identified)

```

The *Help_Identify* procedure, described in Algorithm 3, is called when a reader R cannot identify a tag with the information stored in its cache. This procedure is executed by the readers that collaborate with R . Due to the fact that these collaborative readers might have seen the unknown tag quite in the past, they start searching tuples in their caches whose timestamps are old. If a collaborative reader R' identifies T as T_i it sends a message to $R_{prev}^{T_i}$ in order to let it remove the information on T_i from its cache. Finally, R' returns the tuple about T_i stored in its cache.

4.1.3 Practical implementation of the predictors

Previously, we have theoretically defined the concepts of Next Reader Predictor (NRP) and Previous Reader Predictor (PRP). Below, we propose practical implementations for each of these predictors.

4.1.3.1 Next reader predictor

We propose to use a location prediction algorithm based on a Markov model [204]. A Markov-based predictor of order k , $O(k)$, is defined over the sequence of the last k locations of a given moving entity. Let $L = \ell_1, \dots, \ell_n$ be the location history of a given entity and let $L(i, j) = \ell_i, \dots, \ell_j$ be a subsequence of L . Let X_i be the random variable that represents a location at time t . Then, the Markov assumption is that:

$$\Pr(X_{n+1} = x | X_1 = \ell_1, \dots, X_n = \ell_n) = \Pr(X_{n+1} = x | X_{n-k+1} = \ell_{n-k+1}, \dots, X_n = \ell_n) \quad (4.1)$$

And that for every $i \in \{1, 2, \dots, n - k\}$:

$$\Pr(X_{n+1} = x | X_{n-k+1} = \ell_{n-k+1}, \dots, X_n = \ell_n) =$$

$$\Pr(X_{i+k} = x | X_{i-k} = \ell_{n-k+1}, \dots, X_{i+k-1} = \ell_n) \quad (4.2)$$

Simply stated, Equation 4.1 says that the probability of being in a given location depends on the previous k locations only, whilst Equation 4.2 says that this probability is time independent. Therefore, this probability can be represented by a transition matrix M labelled with all possible sequences of locations of size k :

$$\begin{aligned} \Pr(X_{n+1} = x | X_1 = \ell_1, \dots, X_n = \ell_n) = \\ M(L(n-k+1, n), L(n-k+1, n) || x) \end{aligned} \quad (4.3)$$

And the value of $M(a, b)$ may be estimated by

$$M(a, b) = \frac{N(a, L)}{N(b, L)} \quad (4.4)$$

Where $N(s_1, s_2)$ is the number of times the subsequence s_1 occurs in the sequence s_2 .

In our protocol, locations are represented by the readers \mathcal{R} and a next reader predictor (NRP) is only used by readers \mathcal{R} once they realise that a tag T is in their interrogation zone. Thus, the last location of T is the current reader R , *i.e.* $\ell_n = R$. Therefore, we believe that a reader could be able to implement a Markov-based predictor of order 1 or 2 using a reasonably small amount of memory. In addition, counting the number of times that a tag is identified by a reader after having been identified by another reader can be easily done when calling the *New_Tag* procedure described in Algorithm 2. Our Markov-based predictor is computationally efficient. It has a logarithmic computational cost with respect to the number of readers \mathcal{R} .

Regarding the time prediction, we use a very simple approach. Let t_m be the average time in which a tag T is identified by two consecutive readers. Let t be the current time in which T is identified by a reader. We estimate that the next reader will identify T at time $t + t_m$. Note that the readers store, share and update t_m . To update the value of t_m , the reader applies the following equation:

$$t_m = \frac{t_m \times (c - 1) + t - t_{last}}{c},$$

where c is the number of times that the tag has been identified and t_{last} is the last time in which that tag was identified.

4.1.3.2 Previous reader predictor

We propose the use of an heuristic to implement the previous reader predictor (\mathcal{A}_{prev}). In a nutshell, the proposed predictor works as follows: When a reader R_i identifies a

tag, it increments a counter $G(R_i, R_j)$, where R_j is the last reader that identified that tag. By doing so, when $\mathcal{A}_{prev}(\mathcal{R}_i, \mathcal{S}^{\mathcal{R}_i})$ is called, it outputs the sequence,

$$R_1, R_2, \dots, R_k$$

such that

$$G(R_i, R_1) \geq G(R_i, R_2) \geq \dots \geq G(R_i, R_k).$$

The computational cost of \mathcal{A}_{prev} is logarithmic with respect to the number of readers \mathcal{R} . Note that there is no need for sorting the output list every time the algorithm is called, *i.e.* this might lead to a computational complexity $O(|\mathcal{A}| \log |\mathcal{A}|)$. On the contrary, the list could be stored already sorted and simply updated after increasing the value of $G(R_i, R_j)$ for any pair of readers R_i and R_j .

Note that the PRP is essentially a “global” predictor in the sense that it is based on the information of the trajectories of multiple tags. Consequently, it can be seen as a trend analyser (*e.g.* if most of the tags that are identified by a reader R_y move to a reader R_x , when the reader R_x uses the PRP, the first result will be R_y). On the contrary, the NRP previously described is essentially “local” in the sense that it only depends on the information of a single tag.

4.2 Experimental results and evaluation

We split this experimental section in two subsections. The first is devoted to comparing our proposal with both the Solanas *et al.* [199] and the Fouladgar and Afifi [83] proposals. The second subsection does not consider the Solanas *et al.* [199] proposal anymore because it was designed over assumptions quite different from ours. In turn, we show in this part of the experimental section how a good implementation of the next reader predictor algorithm (\mathcal{A}_{next}) improves the efficiency of the identification process.

4.2.1 Experiments considering the Solanas *et al.* proposal

As we explain above, the Solanas *et al.* [199] proposal considers a scenario where tags are continuously monitored by readers. To do so, readers must have a large interrogation field so as to cover the whole scenario. Consequently, a tag is likely to be identified several consecutive times by the same reader. Under this assumption, a next reader predictor algorithm (\mathcal{A}_{next}) does not make sense. Note that $\mathcal{A}_{next}(T_i, S_i)$ will output, with high probability, the last reader of the trajectory S_i because that reader is likely to identify again T_i in the next slot of time. Then, in this first part of the experiments, we remove \mathcal{A}_{next} from our protocol and we recall this variant as *Partial-predictive*. In turn, our proposal using both predictors is simply called *predictive* and it will be evaluated in the second half of the experimental section.

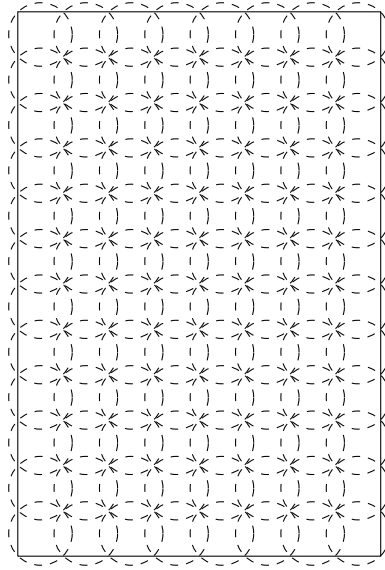


Figure 4.4: Open area completely covered by 96 readers

4.2.1.1 Scenarios

With the aim to overcome the limitation of obtaining real datasets of tag movement in a fine-grained fashion as required in [199], we define two types of tag movements and three different scenarios with which we evaluate and compare our partial-predictive proposals with [199] and [83].

The first scenario is an open area (cf. Figure 4.4) where tags can freely move. The area is completely covered by 96 readers uniformly distributed over the whole area. By doing so, we meet the constraints of the Solanas *et al.* protocol w.r.t. the distribution of readers [199].

The second and third scenarios are representations of the seven bridges of Königsberg⁸. In these scenarios, people's movements are constrained by the river and thus, they can only use bridges in order to move to different sides of the city. Like people, we assume that tags should not be on the river and we design the second and third scenarios using two different distributions of readers. The second scenario (cf. Figure 4.5) is a representation of the Königsberg city where 14 readers cover the entire city. Note that this scenario also meets the constraints of the Solanas *et al.* protocol w.r.t. the reader

⁸The seven bridges of Königsberg is a notable historical problem in mathematics. In 1735, Leonhard Euler proved that no Eulerian path existed for the Königsberg city. This result laid the foundations of graph theory.

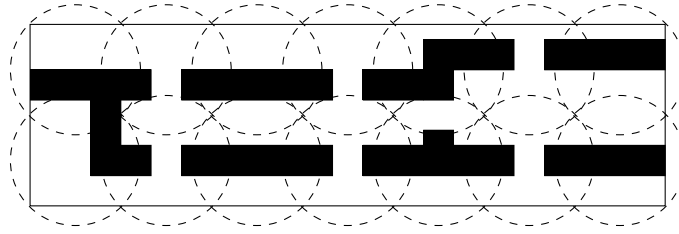


Figure 4.5: Königsberg city representation where 14 readers cover the entire city. Black blocks represent the river water and the seven bridges are represented by the square spaces between black blocks.

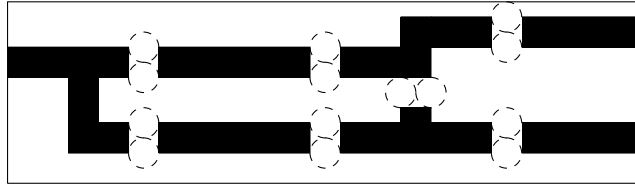


Figure 4.6: Königsberg city representation where 14 readers are monitoring the two ends of each bridge. Black blocks represent the river water and the seven bridges are represented by the square spaces between black blocks.

distribution [199]. Since covering a city by 14 RFID readers can be not practical, we design a third scenario (cf. Figure 4.6) that only differs from the previous one in the reading ranges and positions of the readers. Notice that in the second scenario a tag can be monitored in every part of the city, while in the third scenario a tag can only be read when passing through a bridge. However, due to the movement constraints in the city and the strategic position of the readers, it is easy to know in which side of the city each tag is located. This is a good example of how, by cleverly placing readers, it is possible to obtain accurate trajectories of tags.

4.2.1.2 Movement of tags

In this stage of the experiments, we should generate fine-grained moving data as required by [199]. To do so, we consider that tags move according to two types of movement:

- **Random movement.** At each step, a tag chooses a random direction and moves in this direction.

- **Semi-directed movement.** In this movement, a tag always has a target point. Once the tag reaches its target, it changes the target point to a new random and valid point in the scenario. Then, at each step, with probability 0.5 the tag chooses whether to move randomly or move in the target's direction.

Between both movements, semi-directed movement can be considered closer to real movement patterns of people. However, unpredictable movement patterns can be only evaluated using a random movement.

4.2.1.3 Simulations

In order to compare our partial-predictive proposal against the two previous proposals [199, 83], we perform simulations on the three scenarios defined above. For each scenario, different settings defined by the number of tags in the system and the type of movement are used. A simulation process consists of 10^4 tags moving according to some pattern (random or semi-directed) in one of the three scenarios. For each simulation process, tags are identified using four different methods:

1. The Fouladgar *et al.* method [83] assuming that each tag is in the cache of only one reader. We refer to this method as **Fouladgar 1-1**.
2. The Fouladgar *et al.* method [83] assuming that each tag may be in the cache of several readers. The authors propose to store the tag data in the cache of those readers that may read it most often. As this is not possible for the two data sets considered in this work, we make the assumption that a tag will be in the cache of the readers that have identified it previously. We refer to this method as **Fouladgar 1-M**.
3. The Solanas *et al.* method [199]. We refer to this method as **Solanas**.
4. The previously mentioned **partial-predictive** proposal.

In order to give statistically sound results, each simulation process is executed 30 times and the average number of cryptographic operations performed by each method is computed. Figure 4.7 and Figure 4.8 show the experimental results obtained for 10^4 tags moving according to the random movement and the semi-directed movement, respectively. In both figures, it can be observed that the Partial-predictive proposal improves on the previous ones by more than 50%. This means that, for any scenario and any type of movement, our partial-predictive proposal needs, in the worst case, half the number of cryptographic operations executed by previous proposals [199, 83].

The partial-predictive proposal performs better than previous ones mainly due to three reasons: (i) after the identification of a tag, the reader saves in its own cache the

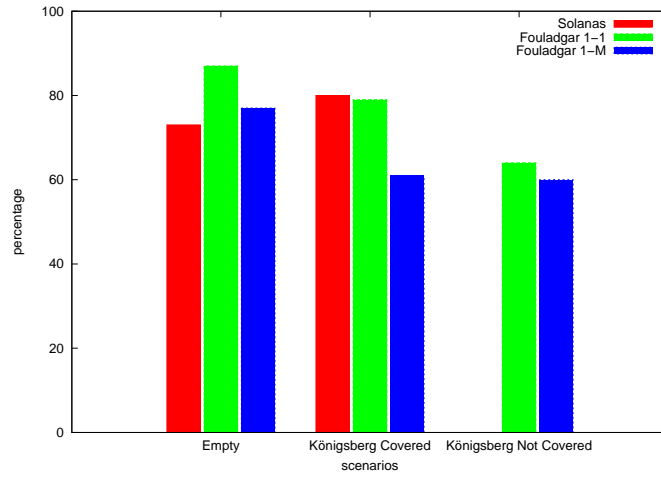


Figure 4.7: Percentage of improvement of the partial-predictive proposal w.r.t. previous ones considering random movement and 10^4 tags

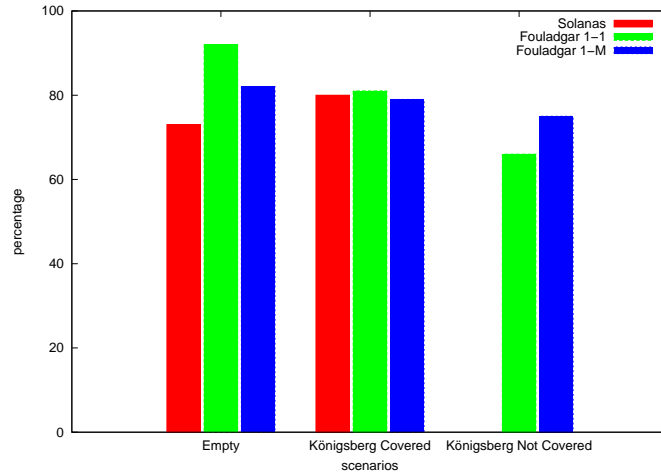


Figure 4.8: Percentage of improvement of the partial-predictive proposal w.r.t. previous ones considering semi-directed movement and 10^4 tags

tag's data in order to identify it faster in the future, (ii) the size of the caches of readers is minimised in such a way that two readers never share tag information, (iii) and when a reader can not identify a tag using its own cache, it is able to heuristically (\mathcal{A}_{prev}) find another reader that could identify this tag.

4.2.2 Experiments considering the \mathcal{A}_{next} algorithms

In the second half of the experimental section, we consider coarse-grained datasets of tag movement (data sets of trajectories), in the style of tracking data recorded by RFID systems. A data set of trajectories contains a historical log with all the identification events produced by readers during the identification of tagged objects in a given scenario. Thus, with these data sets, it is possible to determine the precise moment in which a tagged object was identified by a given reader in an exact location. By using these data sets of trajectories, whether real or synthetic, we are able to measure the performance of our proposal in terms of computational cost and bandwidth usage, and compare it to others without the need for an expensive and very time consuming implementation of real prototypes.

However, obtaining real data sets of trajectories of RFID tagged objects moving through, for example, supply chains is very difficult, *i.e.* these data are generally kept by private companies that are quite reluctant to share them. Hence, the use of synthetic data obtained by means of simulation is a common practice [92] [93] [94]. However, a synthetic data set might fall short of capturing the real complexity of the motion of objects. With the aim to lessen this problem and in order to perform a comprehensive comparison of our proposal with previous ones, we use two different data sets of trajectories:

1. A synthetic data set generated by simulating the movement of tagged objects in supply chains. This data set has been generated by using techniques proposed in previous articles [92] [93] [94], which deal with moving objects in supply chains.
2. A real data set consisting of a historical log of the movement of wireless cards through several access points at Dartmouth College [132]. This real data set of trajectories captures the movement of students in the Dartmouth College when they connect to the wireless access points of the campus.

4.2.2.1 Generating the synthetic data set

As stated above, we generate a synthetic data set of moving objects in supply chains. Similarly to [93], we consider several distribution centres or factories that may exchange tagged products/items in both directions by means of input/output gates (controlled by RFID readers). Once a distribution centre has M items in any of its output gates, it sends these items to another randomly selected distribution centre. Upon reception of a set of items by a distribution centre, these items are processed according to the distribution centre policy. Like in previous models [92] [93] [94], the distribution centre policy is defined by a graph. Locations where items arrive and depart are the nodes of the graph, whilst the edges represent the possibility of moving between locations. In particular, we define a random graph for each distribution centre and random Poisson

distributions to model the departure of items in each location. By doing so, we simulate that items move in small groups or individually inside each distribution centre whilst they move in large groups between distribution centres. Note that this kind of movement is similar to the one given in [139] where two types of data are considered: (i) groups of items (GData) and (ii) single items (IData).

Similarly to [92], we define five distribution centres and twenty locations in each of them. For each distribution centre we define a random graph using an Erdős-Rényi model $G(n, p)$ where $n = 20$ and $p = 0.5$. Also, we assign to each location a Poisson distribution $P(\lambda)$ where $\lambda = 10$. Finally, the minimum number of items that are sent as a group between distribution centres is defined as $M = 100$.

In order to define the movement pattern of items we consider that they have different probabilities to departure towards different locations. For each out-edge of the graph, each item has a probability of taking this edge to leave. In our experiments, we have defined that for every node having n out-edges, the sequence of probability values assigned to these out-edges is a permutation of the sequence $\{\frac{1}{2}, \frac{1}{2^2}, \dots, \frac{1}{2^{n-1}}, \frac{1}{2^{n-1}}\}$ (note that any other probability distribution could be defined.) Finally, considering all these settings, we generate a synthetic data set with 10^5 trajectories having an average length of 200 points.

4.2.2.2 Generating the real data set

Dartmouth College has 566 Cisco 802.11b access points installed to cover most of its campus. The college has about 190 buildings with 115 subnets so that clients roaming between buildings can change their IP addresses. This roaming information is recorded in different files for different clients by using syslog events [132]. In total, more than 14,000 trajectories collected over almost 2 years can be found in this data set.

For our experiments, we have selected the shortest 10,000 trajectories of this data set. This subset of trajectories is created by parsing all the files having less than 46 Kb. We have selected the shortest trajectories because longer trajectories have useless, larger gaps in the data, generally caused by power failures, access points failures, or long periods of time in which clients were not in the campus. Note that those big gaps should not appear in data sets of items moving through supply chains because, in this scenario, items cannot be considered lost for a long time. The trajectories of the resulting data set have an average length of 400 points.

4.2.2.3 Implementing predictors

In Section 4.1.3, we have defined an effective algorithm to predict the next location of a moving object based on a Markov model. Also, we have shown that it is possible to give an estimation of the time when an object should visit the next location.

In order to provide a better evaluation of our proposal, we have run experiments using two different predictors:

1. A Markov-based predictor: The predictor described in Section 4.1.3 used to estimate both the next location and the time when the object should visit that location.
2. An Oracle predictor: A predictor that always correctly guesses the next location and the time when the object should visit that location.

It should be emphasised that the Oracle predictor is only possible because we know in advance the trajectories of the data sets, otherwise it is not possible to create it. The Oracle predictor can be understood as the optimal predictor, *i.e.* an upper bound in prediction accuracy.

The Markov-based predictor that we have implemented for our experiments guesses correctly the next location and ETA of tags 41% of the times with synthetic data, and 67% of the times with real data. The Oracle predictor has 100% of success for both data sets.

As it has previously been stated, the performance of our protocol in terms of computational cost and bandwidth usage strongly depends on the accuracy of the predictors. Although the obtained results outperform all previous proposals, there is still room for improvement (*e.g.* by developing better predictors).

4.2.2.4 Performance of protocols

We will compare the performance of the following proposals:

1. The previously mentioned **Fouladgar 1-1**, **Fouladgar 1-M**, and **Partial-predictive** proposals.
2. Our proposal using a Markov-based predictor. We refer to this proposal as **Predictive (Markov)**.
3. Our proposal using an Oracle predictor. We refer to this proposal as **Predictive (Oracle)**.

From a scalability point of view, the number of cryptographic operations performed on the server side is the main concern. Consequently, most of the hash-based protocols are not considered scalable. However, RFID protocols based on collaboration between readers have less computational cost than hash-based protocols but may require more bandwidth. Therefore, for all the studied protocols we compute the number of cryptographic operations and, also, the number of messages sent between readers.

With the aim to study both the computational cost and the bandwidth usage simultaneously, we have defined a measure that for every protocol outputs the percentage of *closeness* of the protocol to the optimal case; the higher (*closer*) the better.

Definition 14 (Trade-off measure). *Let \mathcal{P} be the set of protocols under evaluation. Let α be a real value in the range $[0..1]$. Let P_c and P_b be the number of cryptographic operations and the number of sent messages of a given protocol $P \in \mathcal{P}$. Let $min_c = \min(P_c^i), \forall P^i \in \mathcal{P}$, $min_b = \min(P_b^i), \forall P^i \in \mathcal{P}$, $max_c = \max(P_c^i), \forall P^i \in \mathcal{P}$, and $max_b = \max(P_b^i), \forall P^i \in \mathcal{P}$. Then, the trade-off measure that we propose is computed as follows:*

$$d(\alpha, P, \mathcal{P}) = \left(\frac{max_c - P_c}{max_c - min_c} \times 100 \right) \times \alpha + \left(\frac{max_b - P_b}{max_b - min_b} \times 100 \right) \times (1 - \alpha)$$

Using this measure, it is possible to globally analyse the performance of all protocols at the same time. In addition, thanks to the use of α , it is simple to weight the importance of either the computational cost or the bandwidth usage. Thus, it can be easily observed which of the analysed protocols performs best in given conditions.

4.2.2.5 Experiments with the synthetic data set

Figure 4.9 depicts the number of cryptographic operations performed by each protocol over the synthetic data set. In the beginning of the simulation (in the start-up phase) the “Predictive (Oracle)” and the “Predictive (Markov)” have a performance similar to the “Partial predictive” protocol. However, after *learning* the movement pattern of items, they immediately outperform the “Partial predictive” protocol. It can also be observed that the predictive protocols and the “Partial predictive” protocol are clearly superior to the “Fouladgar 1-1” and the “Fouladgar 1-M”, thus confirming the results presented in the first part of the experimental section. Figure 4.10 shows the average number of cryptographic operations per identification. From this figure, it is clear that our new proposals outperform the previous ones in terms of computational cost and, by extension, they improve scalability also.

Figure 4.11 shows the number of messages sent by readers in the studied protocols over the same data set, and Figure 4.12 depicts the number of those messages on average. It can be observed in both figures that the “Fouladgar 1-M” method sends fewer messages because it replicates the identification information of tags in several readers, at the cost of a poor scalability. It is also clear that our new proposals send a very similar number of messages to the “Fouladgar 1-M” proposal but they perform significantly better in terms of scalability.

Using the trade-off measure described in Definition 14 we have compared all the protocols considering different values of α (cf. Figure 4.13). It is apparent that the protocol presented in this chapter (in its two variants) is the best for almost all values

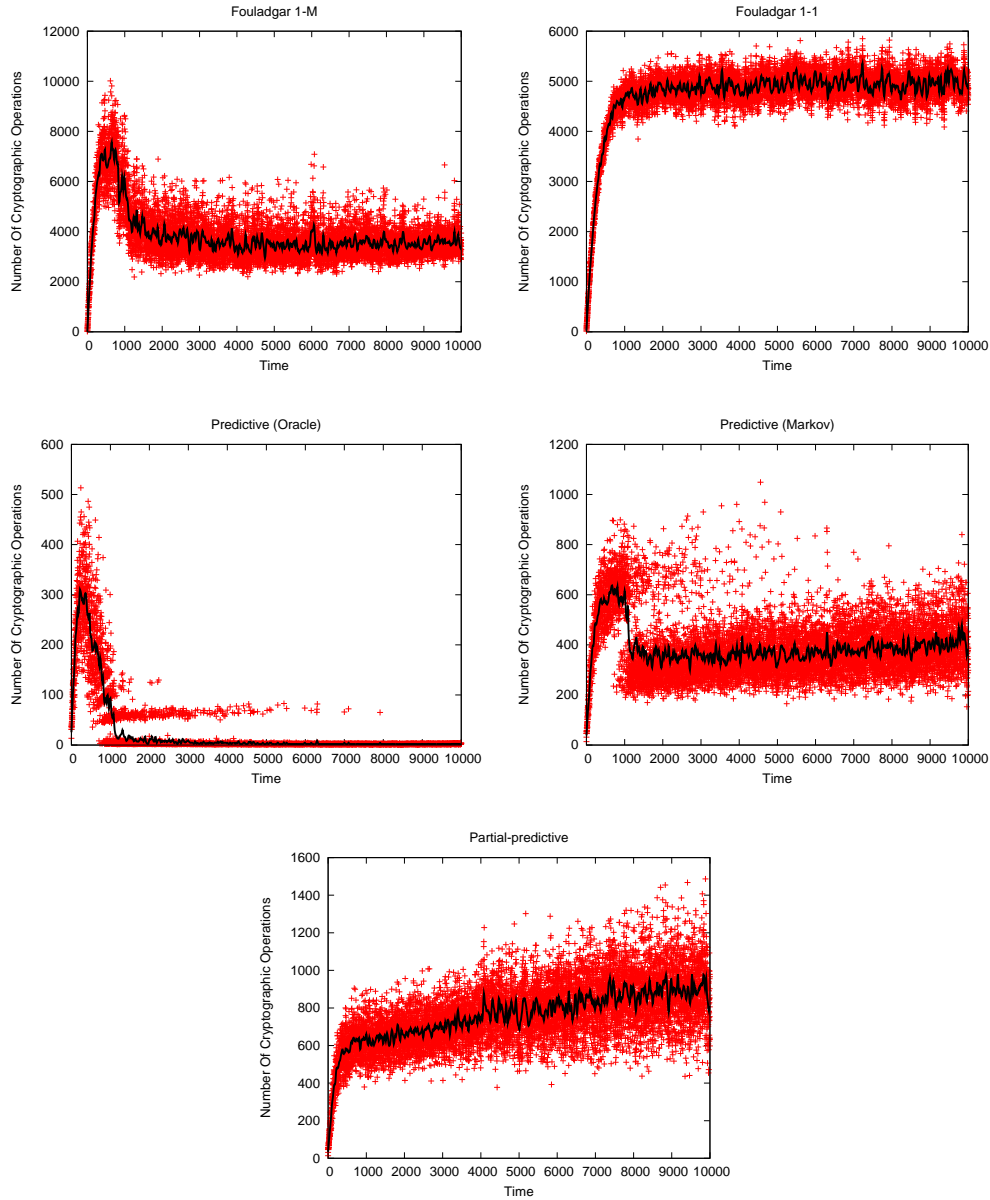


Figure 4.9: Average number of cryptographic operations performed by each protocol during the complete simulation with the synthetic data set (in red). The black line represents the moving average of those values in subsets of 100 elements. The time axis represents simulation steps.

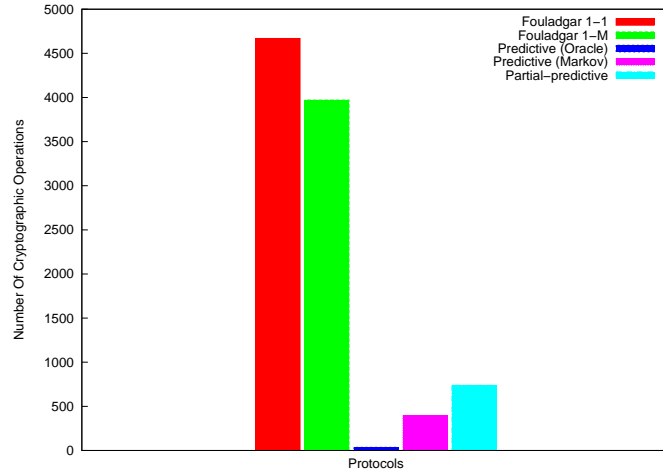


Figure 4.10: Average number of cryptographic operations per identification for the simulation with the synthetic data set. (The lower the better)

of α . Only in the region of α values very close to 0 (meaning that only the number of messages counts) our proposal is not the best. Hence, we can conclude that our proposal is better than previous proposals for the analysed synthetic data set.

4.2.2.6 Experiments with the real data set

In the case of the real data set, we consider the same measures described above, *i.e.* the number of cryptographic operations, the number of sent messages, and the trade-off measure. Figure 4.14 and Figure 4.16 show the number of cryptographic operations and the number of sent messages for each protocol. Figure 4.15 and Figure 4.17 show those values on average. Finally, Figure 4.18 depicts the *closeness* of all protocols to the optimal case by using the trade-off measure described in Definition 14.

The results are very similar to the ones obtained with synthetic data. Again, our proposal outperforms all previous proposals. Note that the different shape of Figures 8 and 10 with respect to Figures 13 and 15 is due to the very nature of the analysed data (*i.e.* synthetic vs. real).

4.3 Conclusions

In this chapter, we have presented a novel protocol that allows efficient identification of RFID tags by means of a set of collaborative readers. Our proposal uses location and time of arrival predictors to improve the efficiency of the widely accepted IRHL scheme. We have shown that our protocol outperforms previous proposals in terms of scalability whilst guaranteeing the same level of privacy and security.

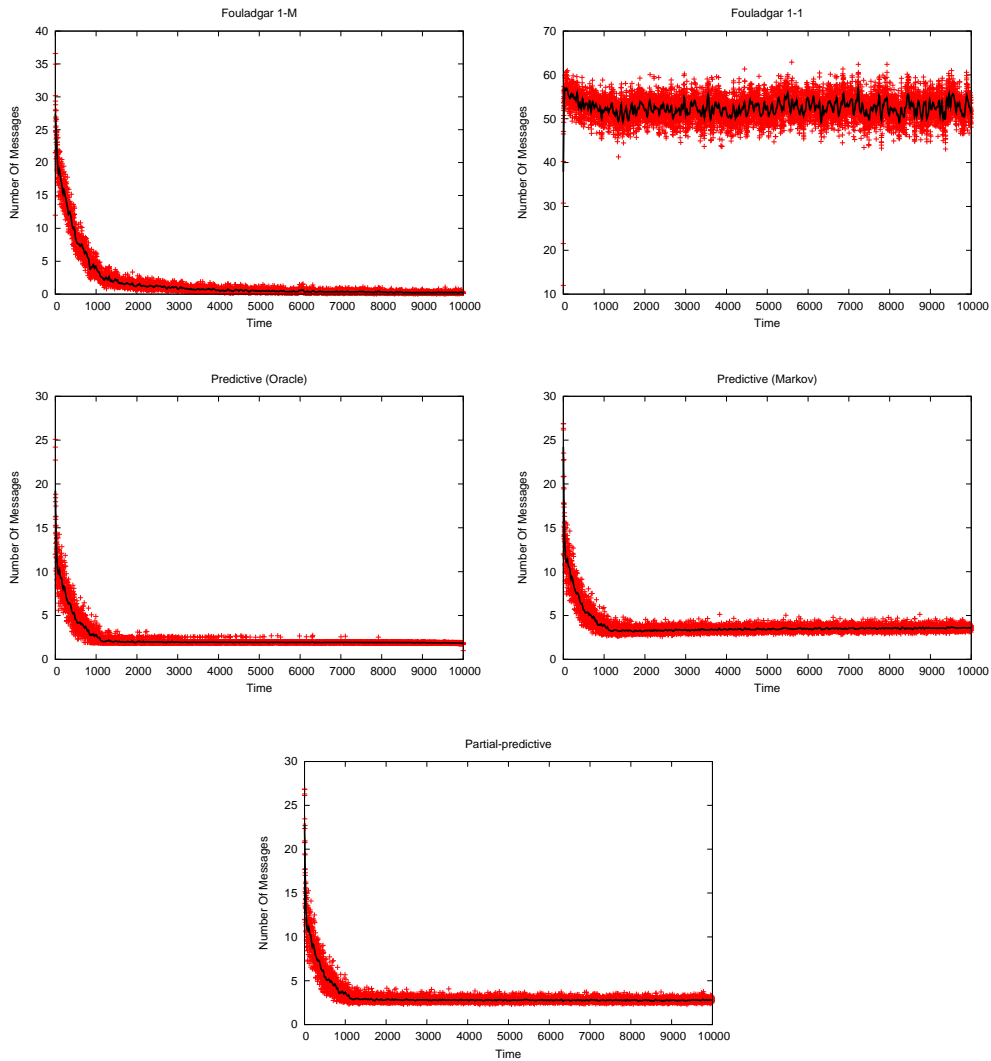


Figure 4.11: Average number of messages sent by each protocol during the complete simulation with the synthetic data set (in red). The black line represents the moving average of those values in subsets of 100 elements. The time axis represents simulation steps.

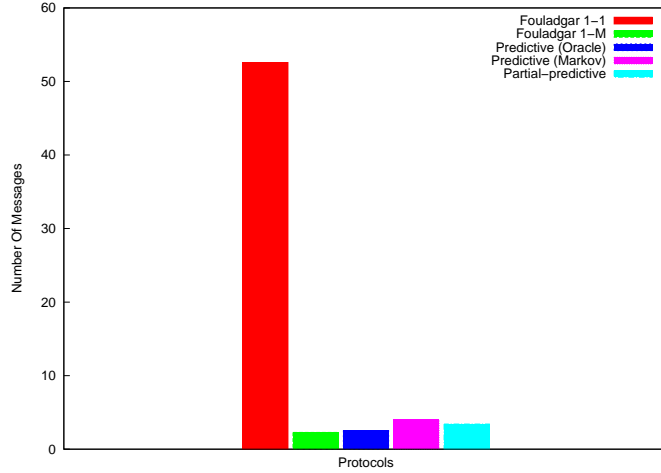


Figure 4.12: Average number of messages sent per identification with the synthetic data set

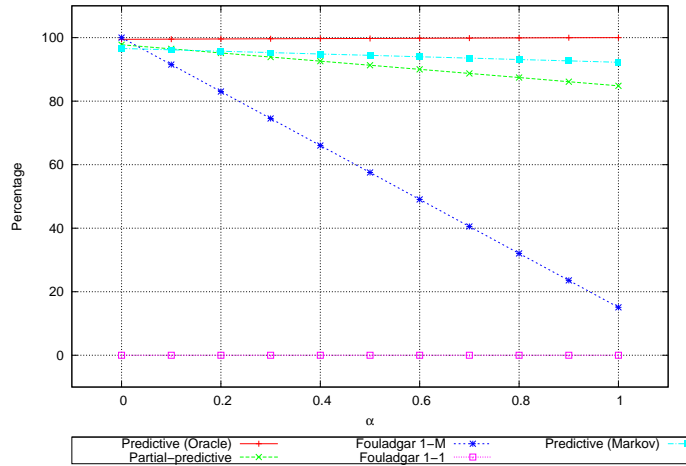


Figure 4.13: The trade-off measure for each protocol and different values of $\alpha = \{0, 0.1, 0.2, \dots, 1.0\}$ for the synthetic data set. The higher the better. (Note that the colours assigned to the protocols do not coincide with the colours of Figure 4.12).

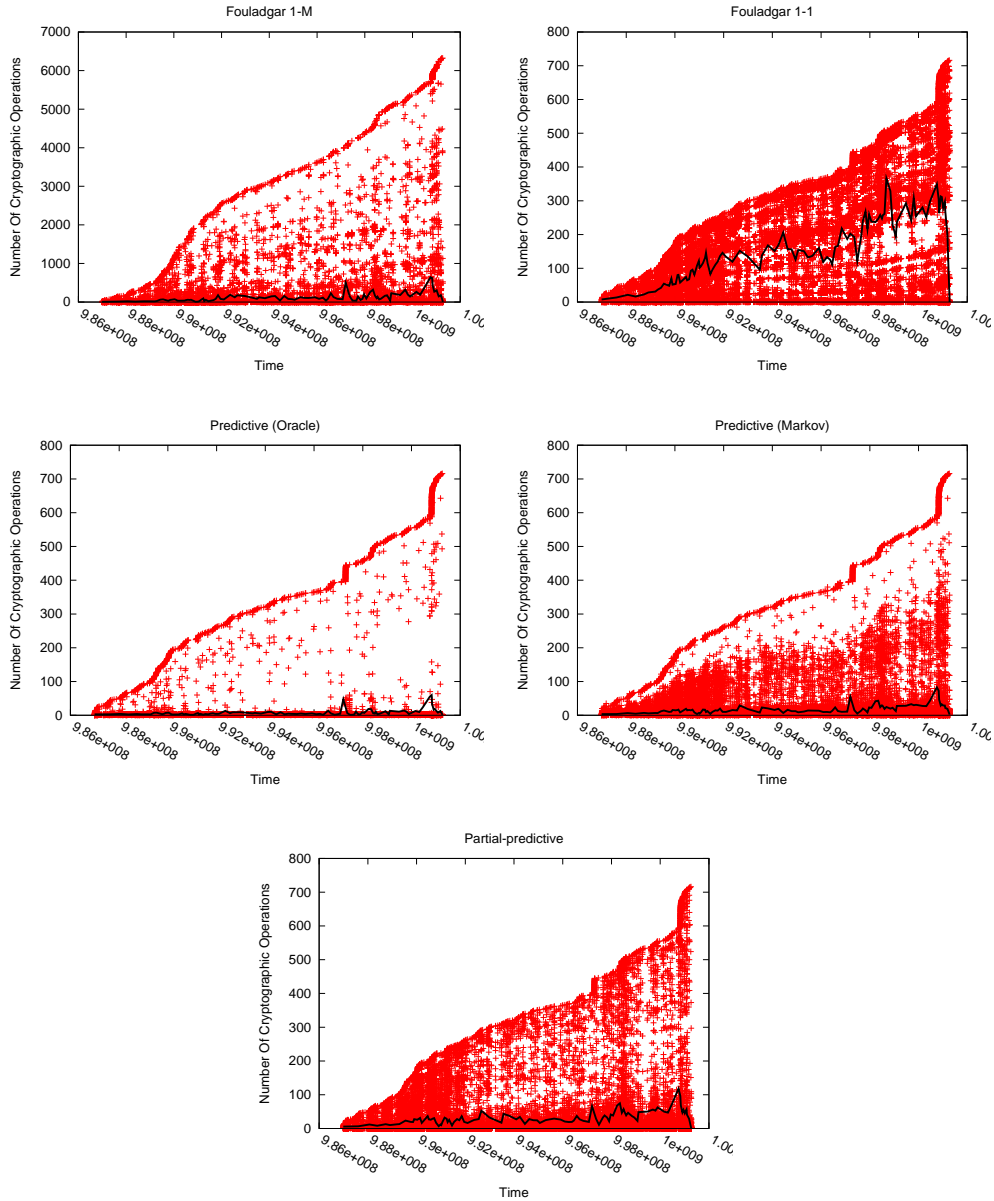


Figure 4.14: Average number of cryptographic operations performed by each protocol during the complete simulation with the real data set (in red). The black line represents the moving average of those values in subsets of 1000 elements. The time scale is in milliseconds.

From the experimental results obtained, we can conclude that our proposal could be comparable to highly scalable protocols like the tree-based protocols. However, we do not sacrifice any privacy to achieve this goal.

Usually, algorithms aimed at location prediction work well in some scenarios, but their performance decreases in others. Although we have provided some practical implementations for the predictors, the definition of our protocol is flexible enough to accept the use of any location predictor. Due to the fact that the efficiency of our proposal highly depends on the accuracy of the predictors, in the future we plan to study and compare a variety of predictors in different scenarios.

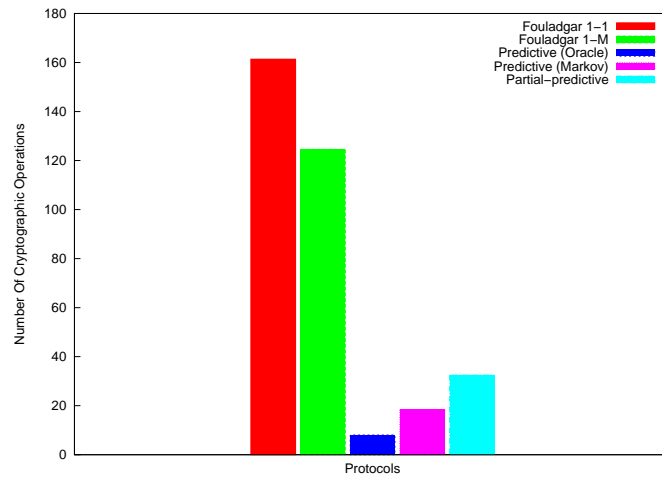


Figure 4.15: Average number of cryptographic operations per identification with the real data set

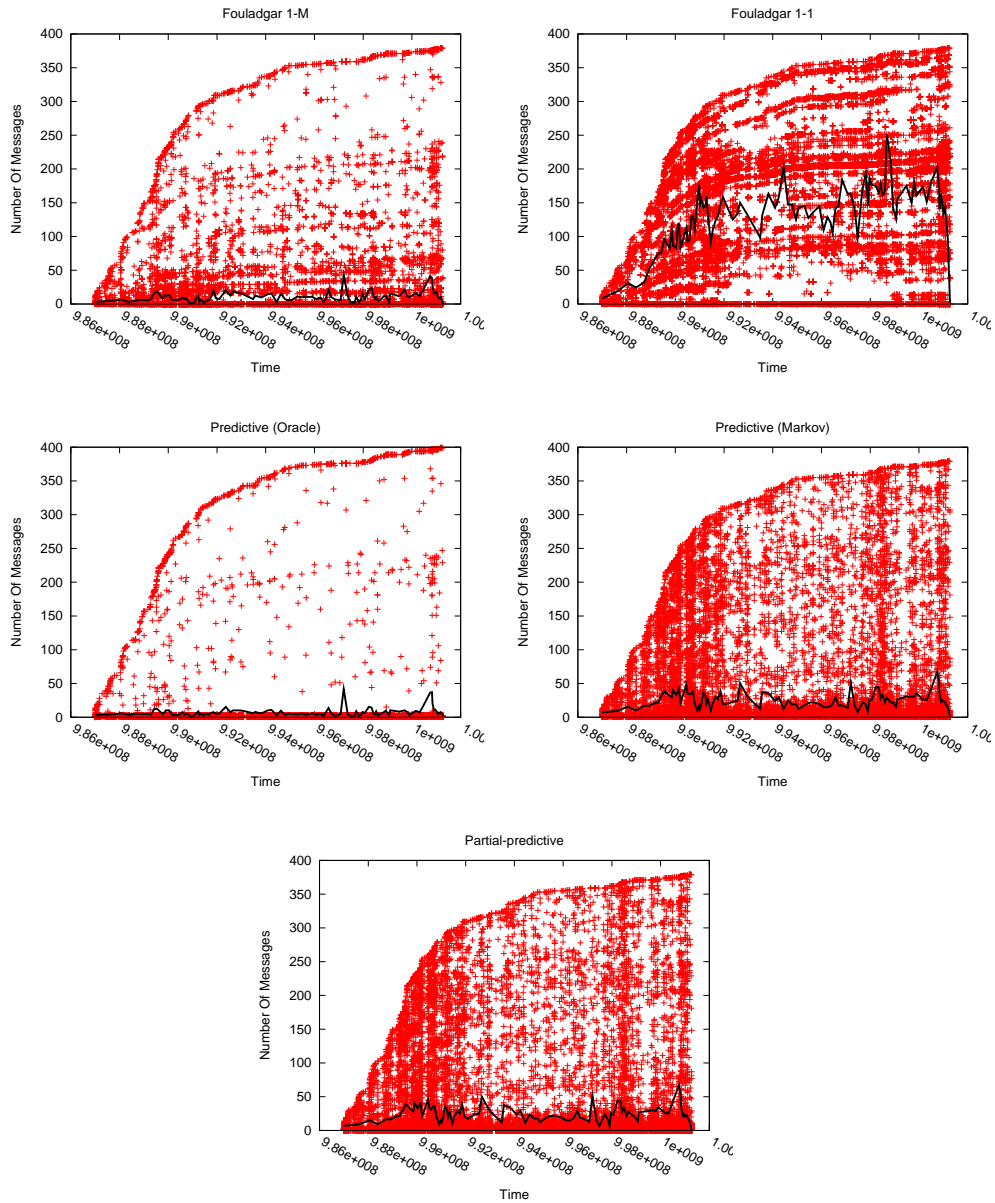


Figure 4.16: Average number of messages sent by each protocol during the complete simulation with the real data set (in red). The black line represents the moving average of those values in subsets of 1000 elements. The time scale is in milliseconds.

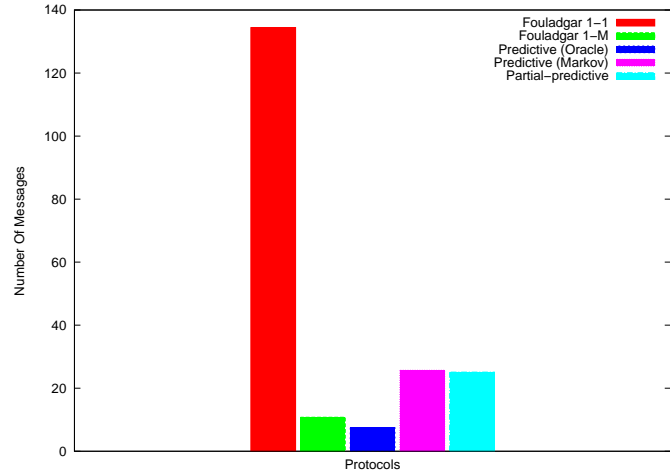


Figure 4.17: Average number of messages sent per identification with the real data set

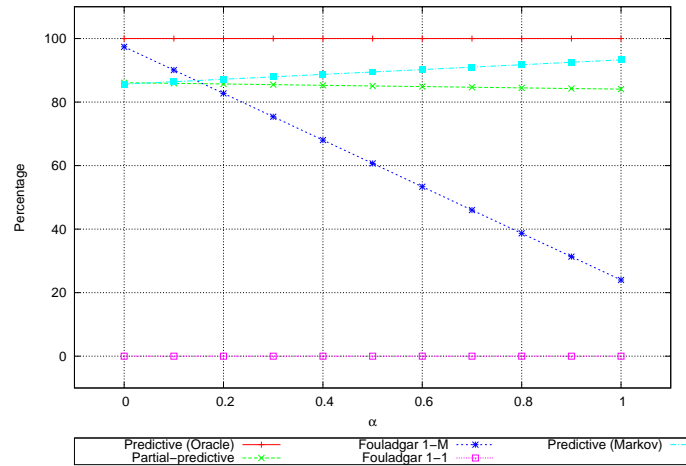


Figure 4.18: The trade-off measure for each protocol and different values of $\alpha = \{0, 0.1, 0.2, \dots, 1.0\}$ for the real data set. The higher the better. (Note that the colours assigned to the protocols do not coincide with the colours of the previous Figure).

The Poulidor Distance-bounding Protocol

This chapter describes a novel distance-bounding protocol resistant to both mafia and distance fraud. The experimental results show that this new proposal strikes a good balance of memory usage, mafia fraud resistance, and distance fraud resistance.

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The most widespread and low-cost tags are *passive*, meaning that they do not have their own power source, and are supplied by the electromagnetic field of a reader. Although the capacities of such tags are quite limited, some of them benefit from cryptographic building blocks and secure authentication protocols. Nevertheless, Desmedt, Goutier and Bengio [65] presented in 1987, an attack that defeated any authentication protocol. In this attack, called *mafia fraud*, the adversary passes through the authentication process by simply relaying the messages between a legitimate reader (the verifier)

and a legitimate tag (the prover). Thus she does not need to modify or decrypt any exchanged data. Later in 1993, Brands and Chaum [44] proposed a countermeasure that prevents such attack by estimating the distance between the reader and the tag to be authenticated: the *distance-bounding protocol*. They also introduced in [44] a new kind of attack, named *distance fraud*, where a dishonest prover claims to be closer to the verifier than she really is.

Since then, many distance-bounding protocols have been proposed to thwart these attacks. In 2005, Hancke and Kuhn [100] proposed the first distance-bounding protocol dedicated for RFID. The protocol is considered simple in the sense that it only requires an initial *slow phase* followed by a *fast phase* in order to perform both authentication and distance checking. Unfortunately, the adversary success probability regarding mafia and distance frauds is $(3/4)^n$ while one may expect $(1/2)^n$. As a result, many other protocols [29, 126, 128, 165, 189, 216] have been proposed attempting to improve the Hancke and Kuhn proposal.

Amongst them, to the best of our knowledge, the Kim and Avoine protocol [126] and the Avoine and Tchamkerten protocol [29] have the best resistance considering only mafia fraud. However, the Kim and Avoine protocol [126] severely sacrifices the distance fraud security, whereas the Avoine and Tchamkerten proposal [29] requires an exponential amount of memory ($2^{n+1} - 2$ in its standard configuration) to achieve such a high mafia fraud resistance. Neither the Hancke and Kuhn protocol nor the two latter protocols achieve a good balance between memory, mafia fraud resistance and distance fraud resistance.

In this chapter, we perform a detailed analysis of the mafia and distance fraud resistance of the protocols [29] and [126]. Then, we introduce the concept of distance-bounding protocols based on graphs, and we propose a new distance-bounding protocol based on a particular type of graph. Our goal is not to provide the best protocol in terms of mafia fraud or distance fraud, but to design a protocol that ensures a good trade-off between these concerns, while still using a linear amount of memory with respect to the number of rounds. This means that our protocol is never the best one when considering only one property, but is a good option when considering the three properties altogether. This is why we name our protocol *Poulidor* after a famous French bicycle racer known as *The Eternal Second*: never the best in any race, but definitively the best on average.

5.1 Previous proposals

In terms of efficiency and resource consumption, our proposal is comparable to the Hancke and Kuhn [100] and Kim and Avoine [126] protocols. Therefore, we explain below those two proposals. We also detail the Avoine and Tchamkerten protocol [29] because our aim is to be as resilient as this protocol to mafia and distance frauds.

5.1.1 Hancke and Kuhn’s protocol

Hancke and Kuhn’s protocol (HKP) [100], depicted in Figure 5.1, is a key-reference protocol in terms of distance bounding devoted to RFID systems. HKP is a simple and fast protocol, but it suffers from a high adversary success probability.

5.1.1.1 Initialisation

The prover (P) and the verifier (V) share a secret x and agree on: (i) a security parameter n , (ii) a public hash function H , whose output size is $2n$, and (iii) a certain timing bound Δt_{\max} .

5.1.1.2 Protocol

HKP consists of two phases: a slow one followed by a fast one. During the slow phase V generates a random nonce N_V and sends it to P . Reciprocally, P generates N_P and sends it to V . Both V and P compute $H^{2n} := H(x, N_P, N_V)$. In what follows, H_i ($1 \leq i \leq 2n$) denotes the i -th bit of H^{2n} , and $H_i \dots H_j$ ($1 \leq i < j \leq 2n$) denotes the concatenation of the bits from H_i to H_j . Then V and P split H^{2n} into two registers of length n : $R^0 := H_1 \dots H_n$ and $R^1 := H_{n+1} \dots H_{2n}$. The fast phase then consists of n rounds. In each of them, V picks a random bit c_i (the challenge) and sends it to P . The latter immediately answers $r_i := R_i^{c_i}$, the i -th bit of the register R^{c_i} .

5.1.1.3 Verification

At the end of the fast phase, the verifier checks that the answers received from the prover are correct and that $\Delta t_i \leq \Delta t_{\max}$ ($1 \leq i \leq n$).

5.1.2 Kim and Avoine’s protocol

Kim and Avoine’s protocol (KAP) [126], represented in Figure 5.2, basically relies on *predefined* challenges. Predefined challenges allow the prover to detect that an attack occurs as follows: the prover and the verifier agree on some predefined 1-bit challenges; if the adversary sends in advance a challenge to the prover that is different from the expected predefined challenge, then the prover detects the attack and since then, it sends random responses to the adversary. The complete description of the KAP protocol is provided below.

5.1.2.1 Initialisation

The prover (P) and the verifier (V) share a secret x and agree on: (i) a security parameter n , (ii) a public hash function H , whose output size is $4n$, and (iii) a certain timing bound Δt_{\max} .

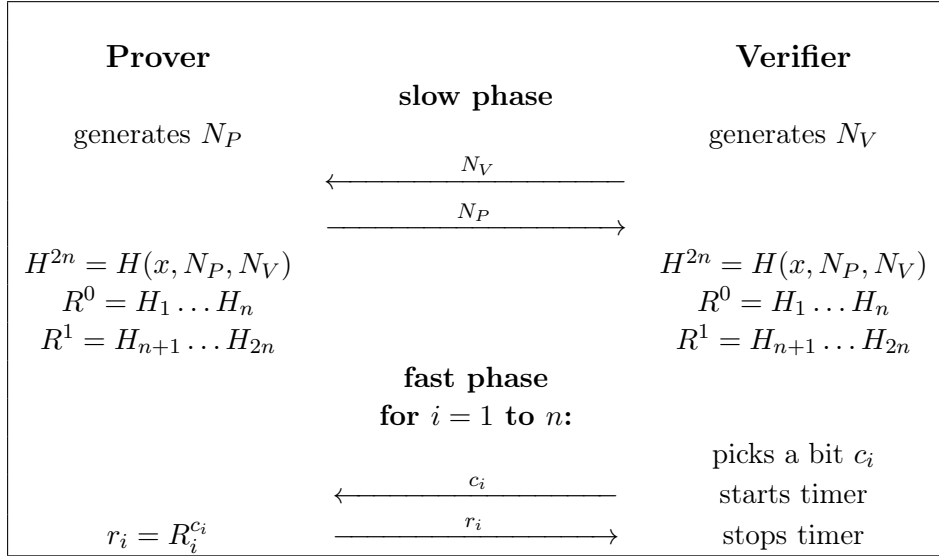


Figure 5.1: Hancke and Kuhn's protocol

5.1.2.2 Protocol

As previously, V and P exchange nonces N_V and N_P . From these values they compute $H^{4n} = H(x, N_P, N_V)$, and split it in four registers. $R^0 := H_1 \dots H_n$ and $R^1 := H_{n+1} \dots H_{2n}$ are the potential responses. The register $D := H_{3n+1} \dots H_{4n}$ contains the potential predefined challenges. Finally, the register $T := H_{2n+1} \dots H_{3n}$ allows the verifier to decide whether a predefined challenge should be sent: in round i , if $T_i = 1$ then a random challenge is sent; if $T_i = 0$ then the predefined challenge D_i is sent instead.

5.1.2.3 Verification

At the end of the fast phase, the verifier checks whether the answers received from the prover are correct and that $\Delta t_i \leq \Delta t_{\max}$ ($1 \leq i \leq n$).

5.1.3 Avoine and Tchamkerten's protocol

The Avoine and Tchamkerten's protocol (ATP) [29] is slightly different from the other existing distance bounding protocols. This protocol is also based on single bit challenge/response exchanges. However, the authors propose the use of a decision tree to set up the fast phase. Figure 5.3 depicts the protocol detailed below.

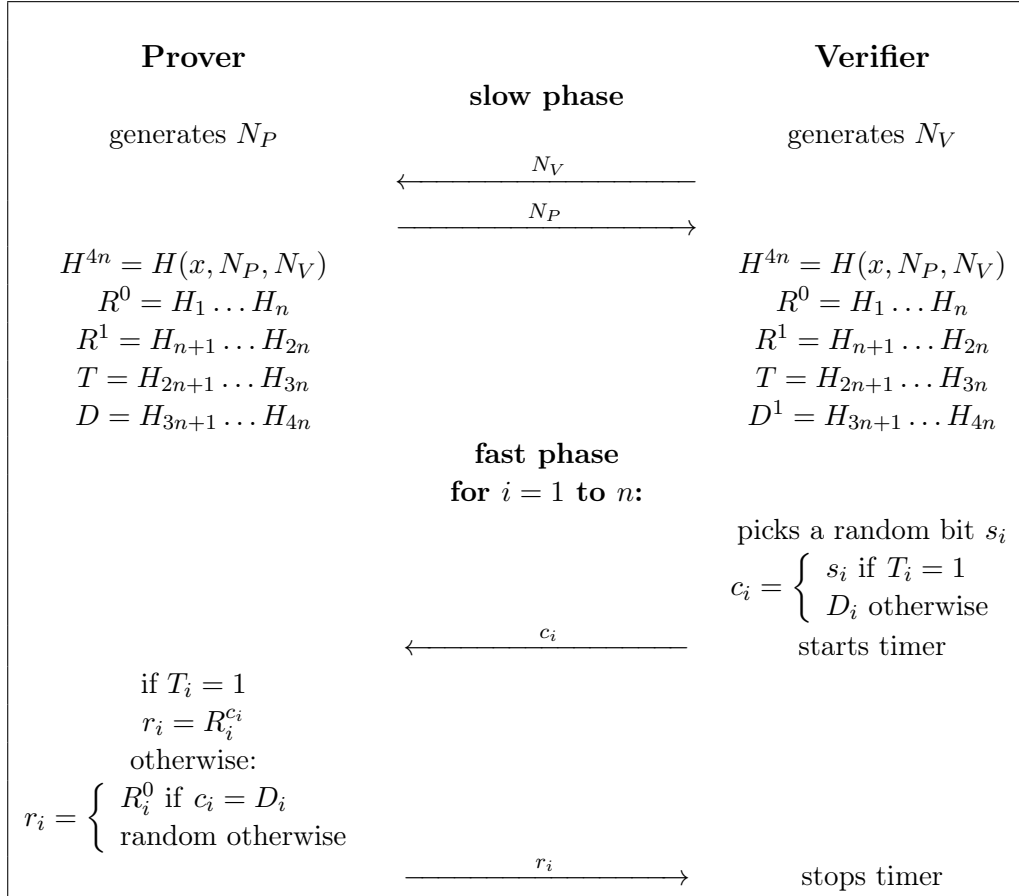


Figure 5.2: Kim and Avoine's protocol

5.1.3.1 Initialisation

The prover and the verifier share a secret x , and they agree on: (i) two security parameters $n = \alpha k$ and m , (ii) a pseudo-random function PRF whose output size is at least $m + \alpha(2^{k+1} - 2)$ bits, and (iii) a timing bound Δt_{\max} .

5.1.3.2 Protocol

The prover P and the verifier V generate two nonces N_P and N_V respectively. The verifier sends his nonce to P . Upon reception, the latter computes $PRF(x, N_P, N_V)$ and sends $[PRF(x, N_P, N_V)]_1^m$, the first m bits of $PRF(x, N_P, N_V)$, and P also sends N_P . These bits are used for the authentication.

P and V use the remaining $\alpha(2^{k+1} - 2)$ bits to label the nodes of α binary

decision trees of depth k . Each node of the trees¹ is labeled by one bit from $[PRF(x, N_P, N_V)]_{m+1}^{m+\alpha(2^{k+1}-2)}$ (the remaining bits) in a one-to-one way. These labels represent the prover's responses during the fast phase. The challenges are represented by the edges of the trees; left and right edges are labeled with 0 and 1 respectively.

Afterwards, the fast phase begins, for $1 \leq i \leq \alpha$, and $1 \leq j \leq k$, V picks a bit c_j^i at random, starts a timer and sends c_j^i to P . The latter immediately answers a bit $r_j^i = \text{node}(c_1^i, \dots, c_j^i)$, *i.e.* the value of the node located in the i -th tree and reached from the root by taking the sequence of decision bits c_1^i, \dots, c_j^i . Once V receives P 's response, he stops his timer and computes Δt_j^i .

5.1.3.3 Verification

The verifier authenticates the prover if the m bits, sent during the slow phase, are correct. The prover succeeds in the distance-bounding stage, if all his responses are correct and if for all $1 \leq i \leq \alpha$ and $1 \leq j \leq k$, $\Delta t_j^i \leq \Delta t_{\max}$.

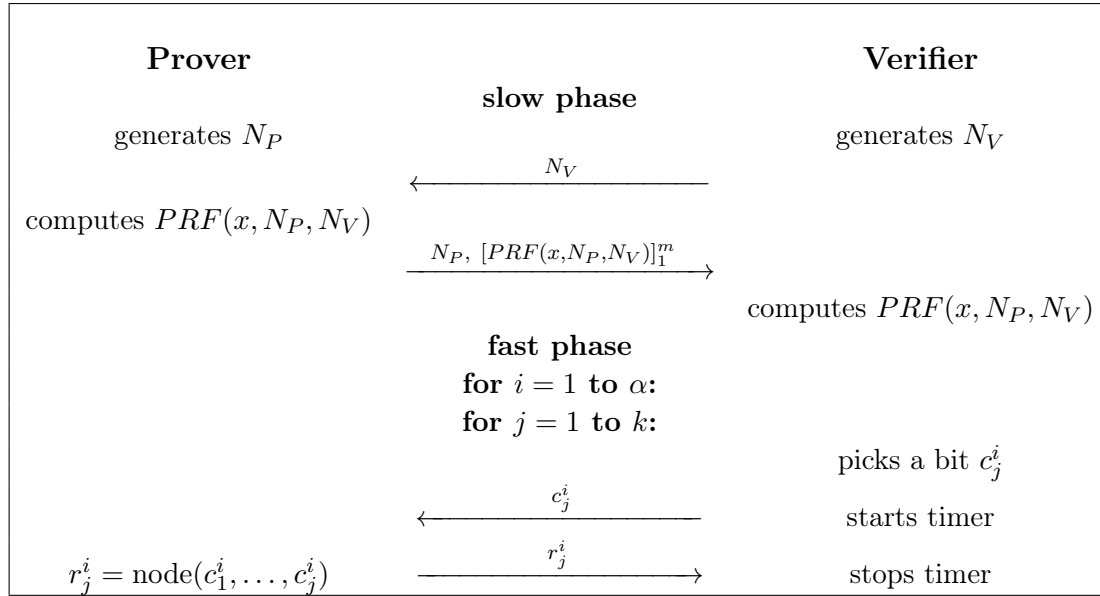


Figure 5.3: Avoine and Tchamkerten protocol

5.2 Graph-based distance-bounding protocol

The ATP protocol [29] in its standard configuration ($\alpha = 1$) relies on a binary tree. The amount of memory needed to build this binary tree is exponential regarding the

¹Except the roots.

number of rounds. Although the authors in [29] proposed to split the binary tree in order to reduce the memory requirements, they pointed out that this procedure leads to a significant decrease in the security level of the protocol. We go a step forward and propose protocols based on graphs rather than trees. The graph-based protocols, as presented below, provide a greater design flexibility, a high security level and a low memory consumption.

5.2.1 Initialisation

5.2.1.1 Parameters

The prover P and the verifier V agree on four public parameters: (i) a security parameter n that represents the number of rounds in the protocol, (ii) a timing bound Δt_{\max} , (iii) a pseudo random function PRF whose output size is $4n$ bits, and (iv) a directed graph G whose characteristics are discussed below. They also agree on a shared secret x .

5.2.1.2 Graph

To achieve n rounds, the proposed graph requires $2n$ nodes $\{q_0, q_1, \dots, q_{2n-1}\}$, and $4n$ edges $\{s_0, s_1, \dots, s_{2n-1}, \ell_0, \ell_1, \dots, \ell_{2n-1}\}$ such that s_i ($0 \leq i \leq 2n-1$) is an edge from q_i to $q_{(i+1) \bmod 2n}$, and ℓ_i ($0 \leq i \leq 2n-1$) is an edge from q_i to $q_{(i+2) \bmod 2n}$. Figure 5.4 depicts the graph when $n = 4$.

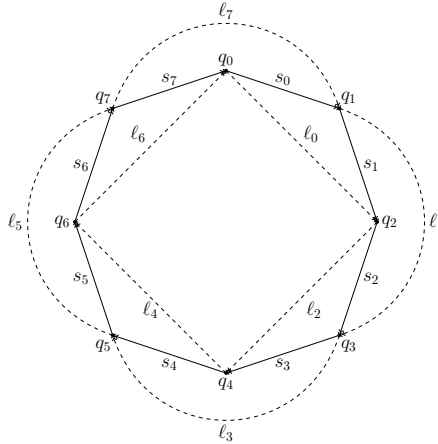


Figure 5.4: Graph when $n = 4$

5.2.2 Exchanges

As described below, the protocol is divided in two phases, a slow one and a fast one. Figure 5.5 summarises the protocol.

Slow phase – P and V generate nonces N_P and N_V , respectively, and exchange them. From these values and the secret x , they compute $H_1 || \dots || H_{4n} = PRF(x, N_P, N_V)$ where H_i denotes the i -th bit of the output of $PRF(x, N_P, N_V)$. The bits H_1, \dots, H_{4n} set up the graph G as follows: the first $2n$ bits are used to value the nodes while the remaining bits are used to value the edges s_i ($0 \leq i \leq 2n - 1$); finally, $\ell_i = s_i \oplus 1$ ($0 \leq i \leq 2n - 1$).

Fast phase – This phase consists of n stateful rounds numbered from 0 to $n - 1$. In the i -th round P 's state and V 's state are represented by the nodes q_{p_i} and q_{v_i} respectively: initially $q_{p_0} = q_{v_0} = q_0$. Upon reception of the i -th challenge c_i , P moves to the node q_{p_i} to $q_{p_{i+1}}$ in the following way: $q_{p_{i+1}} = q_{(p_i+1) \bmod 2n}$ if s_i is labeled with c_i , otherwise $q_{p_{i+1}} = q_{(p_i+2) \bmod 2n}$. Finally, the prover sends as response r_i the bit-value of the node $q_{p_{i+1}}$. Upon reception of the prover's answer r_i , the verifier stops his timer, and computes Δt_i , *i.e.* the round trip time spent for this exchange. Besides, V moves to the node $q_{v_{i+1}}$ using the challenge c_i (as the prover did but from the node q_{v_i}) and checks if $q_{v_{i+1}} = r_i$.

5.2.3 Verification

The authentication succeeds if all the responses are correct, and each round is completed within the time bound Δt_{\max} .

5.3 Security analysis of the graph-based protocol

As stated in the introduction, mafia fraud and distance fraud are the two main security concerns when considering distance bounding protocols. We analyse in this section the graph-based protocol with respect to these frauds.

5.3.1 Mafia fraud

To analyse the mafia fraud we consider the adversary abilities complying with the models provided in [29], [100] and [126]. Below, we define the *head node* and rephrase the well-known pre-ask strategy (see for example [164]) with our terminology.

Definition 15 (Head node). *Given a sequence of challenges $\{c_1, c_2, \dots, c_i\}$ ($1 \leq i \leq n$), the head node is the node that should be used by the prover to send the response*

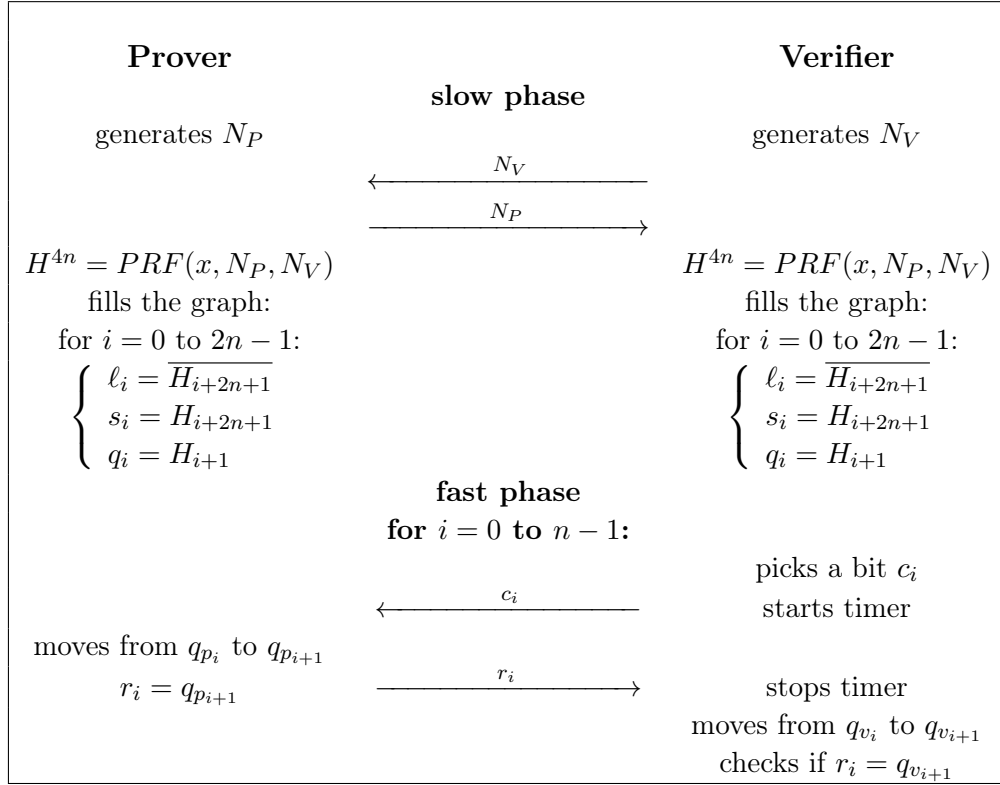


Figure 5.5: The new graph-based proposal

to the verifier according to this sequence of challenges. The head node is denoted as $\Omega(c_1, c_2, \dots, c_i)$.

Definition 16 (Pre-ask strategy). *The pre-ask strategy begins at the end of the slow phase and before the beginning of the fast phase. First, the adversary sends a sequence of challenges $\{\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_n\}$ to the prover and receives a sequence of responses $\{\Omega(\tilde{c}_1), \Omega(\tilde{c}_1, \tilde{c}_2), \dots, \Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_n)\}$.*

Later, during the fast phase, the adversary tries to use the information obtained from the prover in the best way. Let us consider $\{c_1, c_2, \dots, c_i\}$ the challenges sent by the verifier until the i -th round during the fast phase. If $\forall j$ s.t. $1 \leq j \leq i$, we have $c_j = \tilde{c}_j$ then the adversary sends as response $\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_i)$. Otherwise she sends as response the value $\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j)$ where j is selected according to some rule that will be defined later.

Remark 2. *Sending a combination of two or more values as response is completely useless for the adversary because the nodes' values in the graph are independent from each other. Furthermore, in the graph-based protocol one node is never used twice to send a response. Therefore, the adversary can neither obtain nor infer more information than*

the one obtained from the prover. Finally, note that in the security analysis of previous protocols [29], [100] and [126], the best adversary strategy is to pick $j = i$ for every round, i.e. the adversary sends exactly what she received from the prover in the i -th round. However, as we explain below, in the graph-based protocol it makes sense to send a value received in a different round.

While the challenges sent by the adversary match the challenges sent by the verifier, the adversary is able to send the correct response. However, after the first *incorrect* adversary challenge, she can no longer be convinced about the correctness of her response. Consequently, we analyse below the adversary success probability when the adversary sends at least an *incorrect* challenge to the prover during the pre-ask strategy.

Theorem 1. *Let (c_1, c_2, \dots, c_i) be the sequence of verifier challenges until the i -th round, and let $(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_n)$ be the sequence of adversary challenges in the pre-ask strategy. Let F be the random variable representing the first round in which $c_t \neq \tilde{c}_t$ ($1 \leq t \leq n$). Given $\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j)$, the adversary response in the i -th round for some ($1 \leq j \leq n$), we have:*

$$\Pr(\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j) = \Omega(c_1, c_2, \dots, c_i) | F = t) = \begin{cases} 1 & \text{if } i < t \text{ and } i = j, \\ \frac{1}{2} & \text{if } i < t \text{ and } i \neq j, \\ \frac{1}{2} & \text{if } i \geq t \text{ and } j < t, \\ p(t) & \text{if } i \geq t \text{ and } j \geq t, \end{cases}$$

where $p(t) = \frac{1}{2} + \frac{1}{2^{i+j-2t+2}} \sum_{k=0}^{k=2n-1} (A^{i-t}[1, k]A^{j-t}[2, k] + A^{i-t}[2, k]A^{j-t}[1, k])$, and A is the adjacency matrix of the graph which represents the graph-based protocol.

Proof. We analyse the problem by cases:

Case 1 ($i < t$ and $i = j$). As $i < t$ then $\forall 1 \leq k \leq i$, $\tilde{c}_k = c_k$, therefore $\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j) = \Omega(c_1, c_2, \dots, c_i)$.

Case 2 ($i < t$ and $i \neq j$). As $i < t$ then $\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_i) = q_{v_i} = \Omega(c_1, c_2, \dots, c_i)$. On the other hand, as $i \neq j$ then q_{v_i} and $\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j)$ are not the same node in the graph. As the node values in the graph are independent, we conclude that, $\Pr(\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j) = \Omega(c_1, c_2, \dots, c_i)) = \frac{1}{2}$.

Case 3 ($i \geq t$ and $j < t$). This case is analog to Case 2.

Case 4 ($i \geq t$ and $j \geq t$). Let be $q_{v_i} = \Omega(c_1, c_2, \dots, c_i)$ and $q_{a_j} = \Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j)$, so:

$$\Pr(\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j) = \Omega(c_1, c_2, \dots, c_i)) = \Pr(q_{v_i} = q_{a_j}). \quad (5.1)$$

Now, $\Pr(q_{v_i} = q_{a_j}) = \Pr(q_{v_i} = q_{a_j} | v_i = a_j) \Pr(v_i = a_j) + \Pr(q_{v_i} = q_{a_j} | v_i \neq a_j) \Pr(v_i \neq a_j)$ where $\Pr(q_{v_i} = q_{a_j} | v_i = a_j) = 1$ by definition of the graph-based protocol. On the other hand, $\Pr(q_{v_i} = q_{a_j} | v_i \neq a_j) = \frac{1}{2}$ because the node values are selected at random in the protocol. Then

$$\Pr(q_{v_i} = q_{a_j}) = \frac{1}{2} + \frac{\Pr(v_i = a_j)}{2}. \quad (5.2)$$

As $0 \leq v_i, a_j \leq 2n - 1$ then

$$\Pr(v_i = a_j) = \sum_{k=0}^{k=2n-1} \Pr(v_i = k) \Pr(a_j = k). \quad (5.3)$$

As $c_t \neq \tilde{c}_t$ for the first time, then two equally probable cases occur: 1) $\Omega(c_1, \dots, c_t) = q_x$ and $\Omega(\tilde{c}_1, \dots, \tilde{c}_t) = q_{x+1}$, 2) $\Omega(c_1, \dots, c_t) = q_{x+1}$ and $\Omega(\tilde{c}_1, \dots, \tilde{c}_t) = q_x$, where $(0 \leq x \leq 2n - 1)$ and $\forall x, x + 1 = (x + 1) \bmod 2n$. Using these two events in Equation 5.3 we obtain:

$$\begin{aligned} \Pr(v_i = a_j) &= \frac{1}{2} \left(\sum_{k=0}^{k=2n-1} \Pr(v_i = k | \Omega(c_1, \dots, c_t) = q_x) \Pr(a_j = k | \Omega(c_1, \dots, c_t) = q_{x+1}) \right. \\ &\quad \left. + \sum_{k=0}^{k=2n-1} \Pr(v_i = k | \Omega(c_1, \dots, c_t) = q_{x+1}) \Pr(a_j = k | \Omega(c_1, \dots, c_t) = q_x) \right). \end{aligned} \quad (5.4)$$

As $A^y[x, k]$ represents the number of walks of size y between nodes x and k , then $\Pr(v_i = k | \Omega(c_1, \dots, c_t) = q_x) = \frac{A^{i-t}[x, k]}{2^{i-t}}$ and $\Pr(v_i = k | \Omega(c_1, \dots, c_t) = q_{x+1}) = \frac{A^{i-t}[x+1, k]}{2^{i-t}}$; in the same way $\Pr(a_j = k | \Omega(c_1, \dots, c_t) = q_x) = \frac{A^{j-t}[x, k]}{2^{j-t}}$ and $\Pr(a_j = k | \Omega(c_1, \dots, c_t) = q_{x+1}) = \frac{A^{j-t}[x+1, k]}{2^{j-t}}$. Then using Equation 5.4:

$$\Pr(v_i = a_j) = \frac{1}{2^{i+j-2t+2}} \sum_{k=0}^{k=2n-1} (A^{i-t}[x, k] A^{j-t}[x+1, k] + A^{i-t}[x+1, k] A^{j-t}[x, k]). \quad (5.5)$$

Given the graph characteristics, we have $A^y[x, k] = A^y[(x - z) \bmod 2n, (k - z) \bmod 2n]$ for any $z \in \mathbb{N}$. Therefore, $A^{i-t}[x, k] = A^{i-t}[1, (k - x + 1) \bmod 2n]$ and $A^{i-t}[x+1, k] = A^{i-t}[2, (k - x + 1) \bmod 2n]$, in the same way, $A^{j-t}[x, k] = A^{j-t}[1, (k - x + 1) \bmod 2n]$ and $A^{j-t}[x+1, k] = A^{j-t}[2, (k - x + 1) \bmod 2n]$. So:

$$\sum_{k=0}^{2n-1} (A^{i-t}[x, k] A^{j-t}[x+1, k] + A^{i-t}[x+1, k] A^{j-t}[x, k]) =$$

$$\sum_{k=0}^{2n-1} (A^{i-t}[1, k]A^{j-t}[2, k] + A^{i-t}[2, k]A^{j-t}[1, k]). \quad (5.6)$$

Equations 5.1, 5.2, 5.5, and 5.6 yield the expected result.

□

Remark 3. Using Theorem 1, assuming $c_1 \neq \tilde{c}_1$, for $i = 1$ we obtain that $\Pr(\Omega(\tilde{c}_1, \tilde{c}_2) = \Omega(c_1)) = \frac{5}{8} > \Pr(\Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_j) = \Omega(c_1))$ for every $j \neq 2$. This means that in this case it is better for the adversary to send the second response of the prover ($\Omega(\tilde{c}_1, \tilde{c}_2)$). These results only reinforce the ideas shown in Remark 2, that the best adversary strategy is not always to pick $j = i$ in the graph-based protocol.

Corollary 1. Given $r_i = \Omega(\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_i)$ and $c'_i = \Omega(c_1, c_2, \dots, c_i)$ for every $1 \leq i \leq n$, the best adversary success probability in the mafia fraud is:

$$\sum_{t=1}^{t=n} \frac{1}{2^t} \left(\prod_{i=t}^{i=n} \max(\Pr(r_1 = c'_i | F = t), \dots, \Pr(r_n = c'_i | F = t)) \right) + \frac{1}{2^n}$$

where $\Pr(r_j = c'_i | F = t)$ is defined in Theorem 1.

Proof. The adversary success probability in the mafia fraud is:

$$\sum_{t=1}^{t=n} (\Pr(\text{success} | F = t) \Pr(F = t)) + \Pr(c_1 = \tilde{c}_1, c_2 = \tilde{c}_2, \dots, c_n = \tilde{c}_n). \quad (5.7)$$

As the challenges are selected at random, then:

$$\begin{aligned} \Pr(F = t) &= \frac{1}{2^t}. \\ \Pr(c_1 = \tilde{c}_1, c_2 = \tilde{c}_2, \dots, c_n = \tilde{c}_n) &= \frac{1}{2^n}. \end{aligned} \quad (5.8)$$

Considering the pre-ask attack strategy in Definition 16:

$$\Pr(\text{success} | F = t) = \prod_{i=t}^{i=n} \max(\Pr(r_1 = c'_i | F = t), \dots, \Pr(r_n = c'_i | F = t)). \quad (5.9)$$

Equations 5.7, 5.8, and 5.9 yield the expected result.

□

5.3.2 Distance fraud

The distance fraud analysis for most of the distance-bounding protocols is not a hard task. However, for the ATP [29] protocol, to the best of our knowledge, nobody has computed the distance fraud success probability. Unfortunately, in the graph-based protocol which has some similarities with the ATP protocol, distance fraud analysis is also not trivial. Then, in this chapter we provide an upper bound on the distance fraud for a sub-family of the distance-bounding protocols, which will be useful for the ATP protocol and for the graph-based protocol.

Definition 17 (Distance-bounding protocol sub-family). *Let us consider \mathcal{P} a distance bounding protocol. \mathcal{P} belongs to the distance-bounding protocol sub-family if it fulfills the following requirements:*

- *During the fast phase, in each round the verifier sends a bit as challenge and the prover answers with a bit alike.*
- *There is no final phase.*
- *After the slow phase, it should be possible to build a function $f : \{0, 1\}^n \rightarrow \{0, 1\}^n$ such that, given any sequence of challenges $\{c_1, c_2, \dots, c_n\}$, then $f(c_1, c_2, \dots, c_n)$ is the correct response for the verifier. From now on, we are going to call this function “prover function”.*

Definition 18 (Prover function pre-image). *For a sequence $y \in \{0, 1\}^n$ and a prover function f , the prover function pre-image is the set $I_y = \{x \in \{0, 1\}^n \mid f(x) = y\}$.*

Definition 19 (Adversary capability in the distance fraud attack). *The adversary capability in the distance fraud is twofold:*

1. *The adversary has access to the prover function.*
2. *The adversary can send in advance a sequence $y \in \{0, 1\}^n$ to the verifier, trying to maximise $\Pr(f(c_1, c_2, \dots, c_n) = y)$ where $\{c_1, c_2, \dots, c_n\}$ is a random sequence of challenges.*

Proposition 1. *Let y be the sequence sent by the adversary in advance, then the success probability in the distance fraud is $\frac{|I_y|}{2^n}$.*

Undoubtedly, the best adversary strategy is to find and send a sequence $y \in \{0, 1\}^n$ such that for any sequence $x \in \{0, 1\}^n$ it holds that $|I_y| \geq |I_x|$.

Theorem 2. *Given $x, y \in \{0, 1\}^n$ two random sequences, and a prover function f , then, for any sequence $z \in \{0, 1\}^n$ such that $I_z \neq \emptyset$ we have:*

$$\Pr(x \in I_z) \leq \frac{\frac{1}{2^n} + \sqrt{\frac{1}{2^{2n}} - \frac{4}{2^n} + 4 \Pr(f(x) = f(y))}}{2}$$

Proof. Given that $I_z \neq \emptyset$, we have:

$$\begin{aligned} \Pr(f(x) = f(y)) &= \Pr(f(x) = f(y)|y \in I_z) \Pr(y \in I_z) \\ &\quad + \Pr(f(x) = f(y)|y \notin I_z) \Pr(y \notin I_z) \end{aligned} \quad (5.10)$$

But, $\Pr(f(x) = f(y)|y \in I_z) = \Pr(x \in I_z) = \Pr(y \in I_z)$ because x and y are random sequences. On the other hand, $\Pr(f(x) = f(y)|y \notin I_z) \geq \frac{1}{2^n}$ because of the “prover function” definition. Therefore, using these results in Equation 5.10, we obtain:

$$\Pr(f(x) = f(y)) \geq \Pr(x \in I_z)^2 + \frac{1}{2^n}(1 - \Pr(x \in I_z)). \quad (5.11)$$

By calculating the discriminant of this quadratic inequality, and obtaining its solutions, we conclude the proof. Note that, this quadratic inequality has real solutions because $\Pr(f(x) = f(y)) \geq \frac{1}{2^n}$, and in this case, the discriminant value is always positive. \square

Corollary 2. *For every distance-bounding protocol that complies with Definition 17, the adversary success probability in the distance fraud is upper-bounded by:*

$$\frac{\frac{1}{2^n} + \sqrt{\frac{1}{2^{2n}} - \frac{4}{2^n} + 4\Pr(f(x) = f(y))}}{2}.$$

With this result, we are giving a way to compute an upper bound of a sub-family of the distance-bounding protocols. We show below how to apply this result to the graph-based protocol, and later we apply the same result to the ATP protocol.

Theorem 3. *The distance fraud success probability for the graph-based protocol is upper bounded by:*

$$\frac{\frac{1}{2^n} + \sqrt{\frac{1}{2^{2n}} - \frac{4}{2^n} + 4p}}{2}$$

where

$$p = \prod_{i=1}^{i=n} \left(\frac{1}{2} + \frac{1}{2^{2i+1}} \sum_{k=0}^{k=2n-1} (A^i[0, k])^2 \right).$$

Proof. Let us consider two random sequences $x = \{x_1, x_2, \dots, x_n\}$ and $y = \{y_1, y_2, \dots, y_n\}$, then by the definition of the graph-based protocol and the definition of “Prover Function”:

$$\Pr(f(x) = f(y)) = \prod_{i=1}^{i=n} \Pr(\Omega(x_1, \dots, x_i) = \Omega(y_1, \dots, y_i)). \quad (5.12)$$

Let be $q_{x_i} = \Omega(x_1, \dots, x_i)$ and $q_{y_i} = \Omega(y_1, \dots, y_i)$, then, like in Theorem1, we can obtain that

$$\Pr(q_{x_i} = q_{y_i}) = \frac{1}{2} + \frac{\Pr(x_i = y_i)}{2} \quad (5.13)$$

and

$$\Pr(x_i = y_i) = \sum_{k=0}^{k=2n-1} \Pr(x_i = k) \Pr(y_i = k). \quad (5.14)$$

Once again, as $A^i[j, k]$ represents the number of walks of size i between the nodes j and k , where A is the adjacency matrix of the graph, then $\Pr(x_i = k) = \frac{A^i[0, k]}{2^i} = \Pr(y_i = k)$. Therefore, using Equation 5.14:

$$\Pr(x_i = y_i) = \sum_{k=0}^{k=2n-1} \left(\frac{A^i[0, k]}{2^i} \right)^2. \quad (5.15)$$

Equations 5.12, 5.13 and 5.15 yield

$$\Pr(f(x) = f(y)) = \prod_{i=1}^{i=n} \left(\frac{1}{2} + \frac{1}{2^{2i+1}} \sum_{k=0}^{k=2n-1} (A^i[0, k])^2 \right). \quad (5.16)$$

By applying Equation 5.16 to Corollary 2, considering that $p = \Pr(f(x) = f(y))$, we conclude the proof of this theorem. \square

5.4 Experimental results and evaluation

We analyse mafia fraud resistance, distance fraud resistance and memory consumption. Therefore, we need to measure the above features for each of the previous protocols. We have detected that the mafia fraud success probability for the KAP protocol provided in [126] is not correct. Also, as we previously said, the distance fraud success probability of ATP was not presented in [29]. Therefore, we first provide both a correct calculation of the mafia fraud success probability of the KAP protocol and an upper bound for the distance fraud success probability of the ATP protocol.

5.4.1 Mafia fraud success probability for KAP

In the Kim and Avoine protocol, the adversary success probability in the mafia fraud depends on the predefined challenges probability (p_d). Define the following events:

- L_i is the event “the adversary wins the i -th round”;

- D_i is the event “the adversary is detected in the i -th round by the tag for the first time”;
- N_i is the event “the adversary is detected by the tag in the i -th round”;
- N is the event “the adversary is never detected”.

The notation \bar{A} denotes the complement of event A .

By the law of total probability:

$$P(\text{success}) = \sum_{i=1}^{i=n} \Pr(\text{success}|D_i) \Pr(D_i) + \Pr(\text{success}|N) \Pr(N). \quad (5.17)$$

Since $\Pr(N_i) = \frac{p_d}{2}$,

$$\Pr(N) = \left(1 - \frac{p_d}{2}\right)^n. \quad (5.18)$$

The probability of being detected in the i -th round for the first time is:

$$\Pr(D_i) = \prod_{j=1}^{j=i-1} \Pr(\bar{N}_j) \Pr(N_i) = \left(\frac{2-p_d}{2}\right)^{i-1} \left(\frac{p_d}{2}\right). \quad (5.19)$$

On the other hand

$$\Pr(\text{success}|D_i) = \prod_{j=1}^{j=i-1} \Pr(L_j|\bar{N}_j) \prod_{j=i}^{j=n} \Pr(L_j|N_j) \quad (5.20)$$

where $\Pr(L_j|N_j) = \frac{1}{2}$, and

$$\Pr(L_j|\bar{N}_j) = \frac{\Pr(L_j \cap \bar{N}_j)}{\Pr(\bar{N}_j)} \quad (5.21)$$

where $\Pr(L_j \cap \bar{N}_j) = \Pr(L_j \cap \bar{N}_j|p_d)p_d + \Pr(L_j \cap \bar{N}_j|p_r)p_r$. But $\Pr(L_j \cap \bar{N}_j|p_d) = \frac{1}{2}$, because the adversary must send the correct challenges c_j in this round. And $\Pr(L_j \cap \bar{N}_j|p_r) = \frac{3}{4}$, because this is the same case as in the Hancke and Kuhn protocol. Therefore, $\Pr(L_j \cap \bar{N}_j) = \frac{1}{2}p_d + \frac{3}{4}p_r = \frac{3-p_d}{4}$. Using this result in Equation 5.21 we obtain:

$$\Pr(L_j|\bar{N}_j) = \frac{3-p_d}{4-2p_d}. \quad (5.22)$$

Using Equations 5.20 and 5.22 we obtain:

$$\Pr(\text{success}|D_i) = \left(\frac{3-p_d}{4-2p_d}\right)^{i-1} \left(\frac{1}{2}\right)^{n-i+1}, \quad (5.23)$$

and

$$\Pr(\text{success}|N) = \left(\frac{3 - p_d}{4 - 2p_d} \right)^n. \quad (5.24)$$

Using Equations 5.17, 5.18, 5.19, 5.23 and 5.24, we obtain the adversary success probability for the mafia fraud in the Kim and Avoine protocol:

$$P(\text{success}) = \frac{p_d}{2} \sum_{i=1}^{i=n} \left(\frac{3 - p_d}{4} \right)^{i-1} \left(\frac{1}{2} \right)^{n-i+1} + \left(\frac{3 - p_d}{4} \right)^n. \quad (5.25)$$

5.4.2 Distance fraud success probability for ATP

To find an upper bound for the adversary success probability in the distance fraud for the ATP protocol, we use the result of Theorem 3. Indeed, this protocol behaves like the graph-based protocol. The only difference between them is that the ATP protocol creates a full tree as a graph. Therefore, in the ATP protocol the distance fraud success probability is upper bounded by:

$$\frac{\frac{1}{2^n} + \sqrt{\frac{1}{2^{2n}} - \frac{4}{2^n} + 4p}}{2},$$

where

$$p = \prod_{i=1}^{i=n} \left(\frac{1}{2} + \frac{1}{2^{2i+1}} \sum_{k=0}^{k=2n-1} (A^i[0, k])^2 \right).$$

To give a complete equation, we define $A^i[0, k]$ for a tree. For this purpose, we consider that the nodes in the tree are labeled between 0 and $2^n - 1$ using a breadth-first algorithm. Then:

$$A^i[0, k] = \begin{cases} 1 & \text{if } 2^i - 1 \leq k < 2^{i+1} - 1, \\ 0 & \text{otherwise.} \end{cases}$$

Finally we obtain:

$$p = \prod_{i=1}^{i=n} \left(\frac{1}{2} + \frac{1}{2^{i+1}} \right).$$

5.4.3 Comparison

Since memory is a scarce resource in RFID tags and thus it is one of the main concerns in distance-bounding protocols, we relax the ATP protocol to operate with linear memory. As noted in [29], reducing memory in the ATP protocol increases the adversary success probability for both types of fraud. Hence, we pick $\alpha = \frac{n}{3}$, in which case the memory

	Memory	Mafia Fraud	Distance Fraud
HKP	$2n$ [100]	$(\frac{3}{4})^n$ [100]	$(\frac{3}{4})^n$ ²
KAP	$4n$ [126]	Section 5.4.1	$(\frac{3}{4} + \frac{p_d}{4})^n$ [126]
ATP	$2^{n+1} - 2$ [29]	$(\frac{1}{2})^n (\frac{n}{2} + 1)$ [29]	Section 5.4.2
ATP3	$\frac{14n}{3}$ [29]	$(\frac{1}{2})^n (\frac{5}{2})^{\frac{n}{3}}$ [29]	$(0.3999)^{\frac{n}{3}}$ ³
GRAPH	$4n$	Corollary 1	Theorem 3

Table 5.1: Memory consumption, mafia fraud success probability and distance fraud success probability for the HKP protocol, the KAP protocol, the ATP protocols (ATP and ATP3), and the graph-based protocol (GRAPH).

consumption equals $\frac{14n}{3} \approx 5n$, while a sufficient security is still ensured. Note that this memory consumption is in the range of the other studied protocol. This instance of the ATP protocol is named “ATP3”.

Table 5.1 depicts the values of the three parameters for each protocol that we are considering. In terms of memory, the Hancke and Kuhn protocol is, undoubtedly, the best protocol. As can be seen in Figure 5.6, when considering only mafia fraud resistance, the KAP and the ATP protocols are the best ones. Only in terms of distance fraud, the lowest adversary success probability is reached by the ATP protocol (cf. Figure 5.7).

However, our aim is to find the best protocol given a security level in terms of mafia fraud and distance fraud. To that end, Figure 5.8 represents, for each pair of mafia and distance fraud success probabilities, the protocol needing a lowest number of rounds to reach these probabilities. As it can be seen in Figure 5.8, the graph-based protocol is, in general, the best option when considering memory consumption, distance, and mafia fraud at the same time. In particular, if one requires low success probabilities for both mafia and distance fraud, we stress the particularly good behaviour of the graph-based protocol. It should be remarked that in some cases more than one protocol is optimal in terms of number of rounds; in this case, the best one in terms of memory is chosen.

²The distance fraud probability for the HKP protocol is computed using the distance fraud probability for the KAP protocol. Note that the KAP protocol with $p_d = 0$ and the HKP protocol are the same.

³The distance fraud probability for the ATP3 protocol is an accurate value, not an upper bound like in ATP or GRAPH. It was computed by brute force, *i.e.* for a given instance, we computed the adversary success probability. Then, considering all possible instances we deduce the probability in the average case.

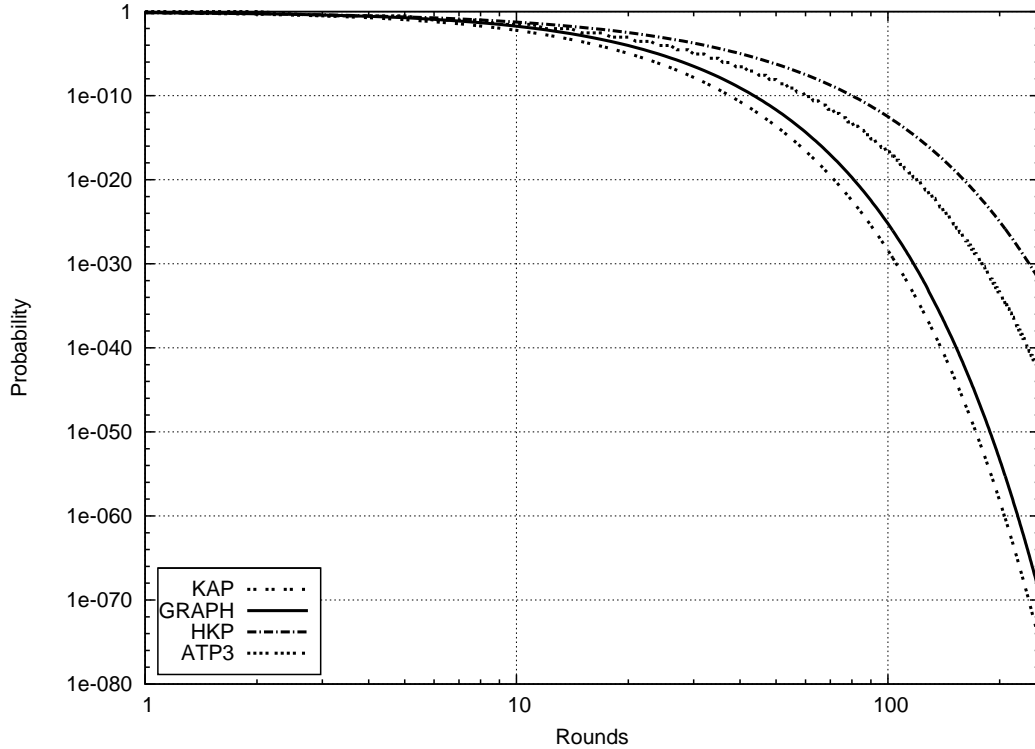


Figure 5.6: Adversary success probability in the mafia fraud against the GRAPH protocol, the HKP protocol and the ATP3 protocol. The ATP protocol in its standard configuration is not represented in this chart because it has the same mafia fraud probability as the KAP protocol.

5.5 Conclusions

In this chapter, we contribute to balancing mafia fraud resistance, distance fraud resistance and memory consumption for distance-bounding protocols. In particular, we provide a way to compute an upper bound on the distance-fraud probability, which is useful for analysing previous protocols and designing future ones. In addition, we propose a new distance-bounding protocol, and we show that the achieved security level is better than all previously published distance-bounding protocols when considering mafia fraud, distance fraud and memory at the same time.

We do not only provide a simple, fast, and flexible protocol, but we also introduce the graph-based protocol concept and several new open questions. An interesting question is to know if there are graph-based protocols that behave still better than the one

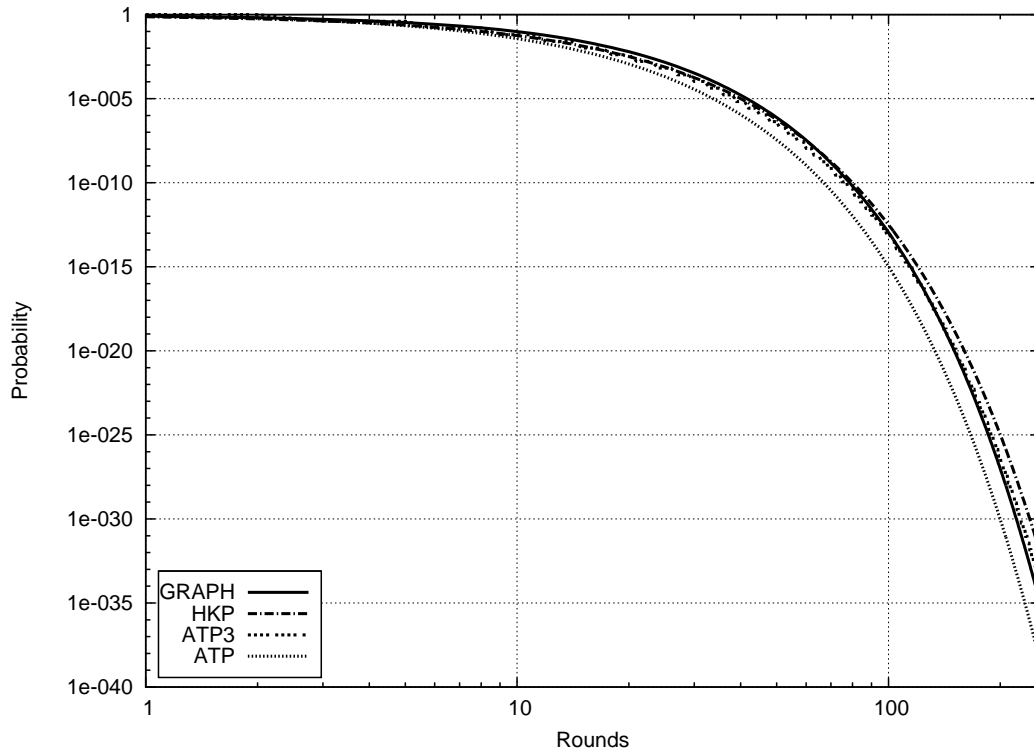


Figure 5.7: Adversary success probability in the distance fraud against the GRAPH protocol, the HKP protocol, and the ATP protocols (ATP and ATP3). The KAP protocol is not represented in this chart because it has the same distance fraud probability as the HKP protocol in the best case.

presented here. In particular, if the number of rounds is not a critical parameter, prover and verifier may be allowed to increase the number of rounds while keeping a $2n$ -node graph. This means that some nodes may be used twice. In such a case, the security analysis provided in this chapter must be refined. On the other hand, although a bound on the distance fraud success probability is provided, calculating the exact probability of success is still cumbersome.

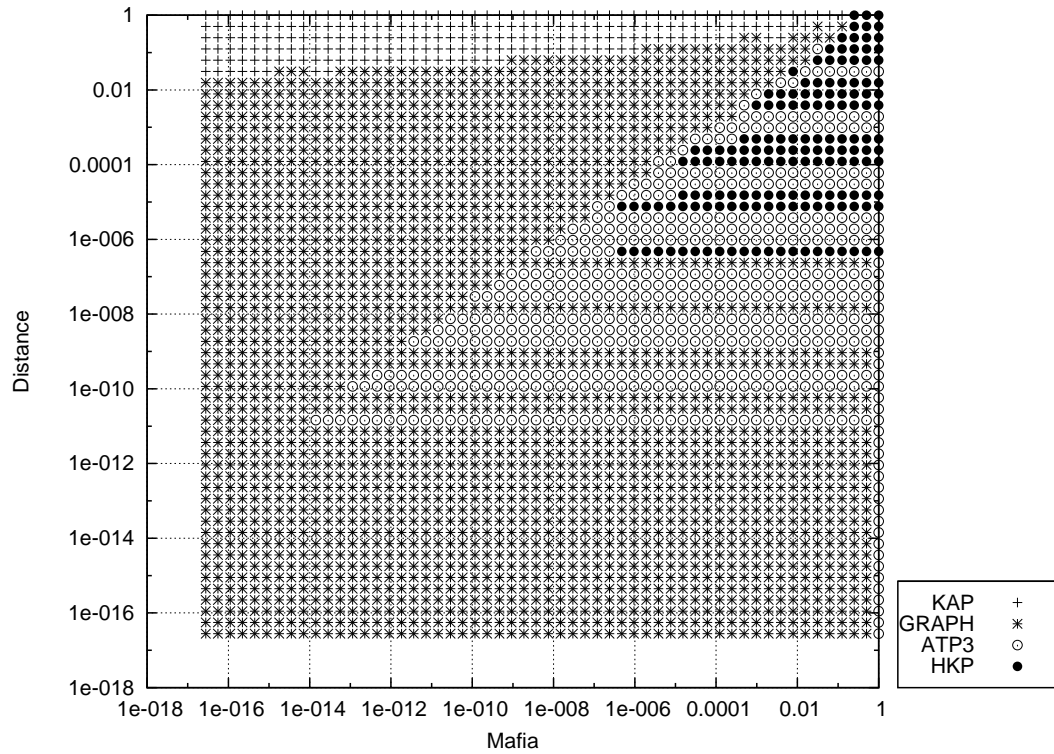


Figure 5.8: Best protocols in terms of number of rounds given different values of mafia fraud probability and distance fraud probability. The considered protocols are: the graph-based protocol (GRAPH), the Hancke and Kuhn protocol (HKP), the Kim and Avoine protocol (KAP), and the Avoine and Tchamkerten protocol (ATP3). The ATP protocol in its standard configuration is not considered in this chart because we are comparing only protocols with linear memory consumption.

Microaggregation- and Permutation-Based Anonymisation of Movement Data

This chapter describes a novel distance measure between trajectories not necessarily defined over the same time span. By using it, two permutation-based trajectory anonymisation algorithms are proposed. Both algorithms preserve the true original locations of trajectories and provide better utility properties than previous algorithms.

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Various technologies such as GPS, RFID, GSM, etc., can sense and track the whereabouts of objects (cars, parcels, people, etc.). In addition, the current storage capacities allow collecting such object movement data in huge spatio-temporal databases. Analysing this kind of databases containing the trajectories of objects can lead to useful and previously unknown knowledge. Therefore, it is beneficial to share and publish such databases and let the analysts derive useful knowledge from them —knowledge that can be applied, for example, to intelligent transportation, traffic monitoring, urban and road planning, supply chain management, sightseeing improvement, etc.

However, the privacy of individuals may be affected by the publication or the outsourcing of databases of trajectories. Several kinds of privacy threats exist. Simple de-identification realised by removing identifying attributes is insufficient to protect the privacy of individuals. The biggest threat with trajectories is the “sensitive location disclosure”. In this scenario, knowing the times at which an individual visited a few locations can help an adversary to identify the individual’s trajectory in the published database, and therefore learn the individual’s other locations at other times. Privacy preservation in this context means that no sensitive location ought to be linkable to an individual.

The risk of sensitive location disclosure is also affected by how much the adversary knows. The adversary may have access to auxiliary information [122], sometimes called side knowledge, background knowledge or external knowledge. The adversary can link such background knowledge obtained from other sources to information in the published database. Estimating the amount and extent of auxiliary information available to the adversary is a challenging task.

There are quite a few differences between spatio-temporal data and microdata, *i.e.* records describing individuals in a standard database with no movement data. One real difference becomes apparent when considering privacy. Unfortunately, the traditional anonymisation and sanitisation methods for microdata [85] cannot be directly applied to spatio-temporal data without considerable expense in computation time and information loss. Hence, there is a need for specific anonymisation methods to thwart privacy attacks and therefore reduce privacy risks associated with publishing trajectories.

Trajectories can be modeled and represented in many ways [81]. Without loss of generality, we consider a trajectory to be a timestamped path in a plane. By assuming movements on the surface of the Earth, the altitude of each location visited by a trajectory stays implicit; it could be explicitly restored if the need arose. More formally, let *timestamped location* be a triple (t, x, y) with t being a timestamp and (x, y) a *location* in \mathbb{R}^2 . Intuitively, the timestamped location denotes that at time t an object is at location (x, y) .

Definition 20 (Trajectory). A trajectory is an ordered set of timestamped locations

$$T = \{(t_1, x_1, y_1), \dots, (t_n, x_n, y_n)\} , \quad (6.1)$$

where $t_i < t_{i+1}$ for all $1 \leq i < n$.

Definition 21 (Sub-trajectory). A trajectory $S = \{(t'_1, x'_1, y'_1), \dots, (t'_m, x'_m, y'_m)\}$ is a sub-trajectory of T in Expression 6.1, denoted $S \preceq T$, if there exist integers $1 \leq i_1 < \dots < i_m \leq n$ such that $(t'_j, x'_j, y'_j) = (t_{i_j}, x_{i_j}, y_{i_j})$ for all $1 \leq j \leq m$.

Hereinafter, we will use *triple* as a synonym for timestamped location. When there is no risk of ambiguity, we also say just “location” to denote a timestamped location.

We present two heuristic methods for preserving the privacy of individuals when releasing trajectories. Both of them exactly preserve original locations in the sense that the anonymised trajectories contain no fake, perturbed or generalised trajectories. The first heuristic is based on microaggregation [68] of trajectories and permutation of locations. Microaggregation has been successfully used in microdata anonymisation to achieve k -anonymity [195, 209, 72]. We use it here for trajectory k -anonymity (whereby an adversary cannot decide which of k anonymised trajectories corresponds to an original trajectory which she partly knows), first by grouping the trajectories into clusters of size at least k based on their similarity and then transforming via location permutation the trajectories inside each cluster to preserve privacy. The second heuristic aims no longer at trajectory k -anonymity, but at location k -diversity (whereby knowing a sub-trajectory S of a certain original trajectory T allows an adversary to discover a location in $T \setminus S$ with probability no greater than $1/k$); this second heuristic is based on location permutation and its strong point is that it takes reachability constraints into account: movement between locations must follow the edges of an underlying graph (*e.g.*, urban pattern) so that not all locations are reachable from any given location. Experimental results show that achieving trajectory k -anonymity with reachability constraints may not be possible without discarding a substantial fraction of locations, typically those which are rather isolated. This is the motivation for our second heuristic: it still considers reachability but it reduces the number of discarded locations by replacing k -anonymity at the trajectory level by k -diversity at the location level.

For clustering purposes, we propose a new distance for trajectories which naturally considers both spatial and temporal coordinates. Our distance is able to compare trajectories that are not defined over the same time span, without resorting to time generalisation. Our distance function can compare trajectories that are timewise overlapping only partially or not at all. It may seem at first sight that the distance computation is exponential in terms of all considered trajectories, but we show that it is in fact computable in polynomial time.

We present empirical results for the two proposed heuristics using synthetic data and also real-life data. We theoretically and experimentally compare our first heuristic with

a recent trajectory anonymisation method called (k, δ) -anonymity [12] also aimed at trajectory k -anonymity without reachability constraints. Theoretical results show that the privacy preservation of our first method is the same as that of (k, δ) -anonymity but dealing with trajectories *not* having the same time span. For the second heuristic involving reachability constraints, no comparable counterparts seem to exist in the literature.

6.1 Trajectory similarity measures

Using microaggregation for trajectory k -anonymisation requires a distance function to measure the similarity between trajectories. Such a distance function must consider both space and time. Although most spatial distances can be extended into spatio-temporal distances by adding a time co-ordinate to spatial points, it is not obvious how to balance the weight of spatial and temporal dimensions. Furthermore, not all similarity measures for trajectories are suitable for comparing trajectories for anonymisation purposes. The requirement for anonymisation is not just similarity regarding shape, but also spatial and temporal closeness. Some typical distances for trajectories include the Euclidean distance, the Hausdorff distance [198], the Fréchet distance [19], the turning point distance [20], and distances based on time series [150] —*e.g.*, dynamic time warping (DTW), short time series (STS)— and on edit distance [57] —*e.g.*, edit distance with real penalty (ERP), longest common sub-sequence (LCSS), and the edit distance on real sequences (EDR) discussed next.

The *edit distance on real sequences* (EDR) [57] is the number of insert, delete, or replace operations that are needed to change one sequence into another. If P and Q are two sequences of m and n triples, respectively, where each triple λ has three attributes — x-position $\lambda.x$, y-position $\lambda.y$ and time $\lambda.t$ — the distance $EDR(P, Q)$ is defined as

$$\begin{cases} \max\{m, n\} & \text{if } m = 0 \text{ or } n = 0 \\ \min\{match(p_1, q_1) + EDR(Rest(P), Rest(Q)), \\ 1 + EDR(Rest(P), Q), 1 + EDR(P, Rest(Q))\} & \text{otherwise} \end{cases}$$

where p_1 and q_1 are the first elements of a given sequence, $Rest(\cdot)$ is a function that returns the input sequence without the first element, and where $match(p, q) := 0$ if p and q are “close”, that is, they satisfy either $|p.x - q.x| \leq \varepsilon$ and $|p.y - q.y| \leq \varepsilon$ for some parameter ε [57] or $|p.x - q.x| \leq \Delta.x$, $|p.y - q.y| \leq \Delta.y$, and $|p.t - q.t| \leq \Delta.t$ for a triple of parameters Δ [13]; otherwise, $match(p, q) := 1$. This definition of $match$ means that the cost for one insert, delete, or replace operation in EDR is 1 if p and q are not “close”.

EDR has been used for anonymisation in [13]. However, the edit distance and variations thereof are not suitable to guide clustering for anonymisation purposes. Indeed, Figure 6.1 shows trajectories with different degrees of “closeness” to trajectory A, but

whose EDR distance from A is the same in all cases. When time-stamps are considered, the situation is even worse.

In Section 6.3, we define a distance measure which is better suited for anonymisation clustering: it can compare trajectories defined over different time spans and even trajectories that are time-wise non-overlapping.

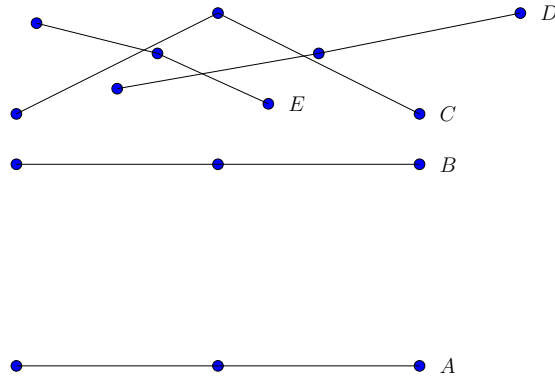


Figure 6.1: Trajectories B, C, D, E are placed at varying “closeness” from A , yet their EDR distance from A is 3 in all cases. We assume that the first point of A matches the first point of each of B, C, D, E ; also, second points are assumed to match each other, and the same for third points.

6.2 Utility and privacy requirements

Every trajectory anonymisation algorithm must combine utility and privacy. However, utility and privacy are two largely antagonistic concepts. What is useful in a set of trajectories is application-dependent, so for each utility feature probably a different anonymisation algorithm is needed.

6.2.1 Desirable utility features

The utility features that are usually considered in trajectory anonymisation are: (i) trajectory length preservation, (ii) trajectory shape preservation, (iii) trajectory time preservation, and (iv) minimisation of the number of discarded locations. We include two additional utility features that are particularly meaningful in urban scenarios:

- *Location preservation.* This essentially means that no fake or inaccurate locations are used to replace original locations; otherwise put, locations in the anonymised trajectories should be locations visited by the original trajectories, without any generalisation or accuracy loss. Preserving original locations helps answering

several queries that may not be responded by generalisation methods [162] or some microaggregation methods [12, 13]: (i) what is the ranking of original (non-removed) locations, from most visited to least visited?; (ii) in which original (non-removed) locations did two or more mobile objects meet?, etc. On the other hand, if trajectory anonymisation rests on replacing true locations with fake locations, an adversary can distinguish the latter from the former and discard fake locations. Hence, location preservation is desirable for both utility and privacy reasons.

- *Reachability.* In the second proposed heuristic, easy reachability between two successive locations in each anonymised trajectory is enforced. This means that the distance from the i -th location to the $i + 1$ -th location on an anonymised location *following the underlying network of streets and/or roads* should be at most R^s , where R^s is a preset parameter. Like location preservation, this is as good for utility as it is for privacy: if the adversary sees that reaching the $i + 1$ -th location from the i -th one takes a long trip across streets and roads, she will guess that the section between those two locations was not present in any original trajectory.

6.2.2 Specific utility measures

Basic utility measures are the number of removed trajectories and the number of removed locations, whether during pre-processing, clustering or cluster anonymisation.

The distortion of the trajectory shape is another utility measure, which can be captured with the space distortion metric [12, Sec.VI.B]. This metric also allows accumulating the total space distortion of all anonymised trajectories from original ones.

Definition 22 (Space distortion metric [12]). *The space distortion of an anonymised trajectory T^* with respect to its original trajectory T at time t when T has triple (t, x, y) and T^* has possible triple (t, x^*, y^*) , is*

$$SD_t(T, T^*) = \begin{cases} \Delta((x, y), (x^*, y^*)) & \text{if } (x^*, y^*) \text{ is defined at } t \\ \Omega & \text{otherwise} \end{cases}$$

where Δ is a distance (e.g. Euclidean), and Ω a constant that penalises for removed locations. The space distortion of an anonymised trajectory T^* from its original T is then

$$SD(T, T^*) = \sum_{t \in TS} SD_t(T, T^*) ,$$

where TS are all the timestamps where T is defined. In particular, if T is discarded during anonymisation, T^* is empty, and so $SD(T, T^*) = n\Omega$, where $n = |TS|$ is the number of locations of T . In this way, the space distortion of a set of trajectories \mathcal{T}

from its anonymised set \mathcal{T}^* is easily defined as

$$TotalSD(\mathcal{T}, \mathcal{T}^*) = \sum_{T \in \mathcal{T}} SD(T, T^*) ,$$

where $T^* \in \mathcal{T}^*$ (which may be empty) corresponds to $T \in \mathcal{T}$.

Another way to measure utility is by comparing the results between queries performed on both the original data set \mathcal{T} and the anonymised data set \mathcal{T}^* . Intuitively, when results on both data sets are similar for a large and diverse number of queries, the anonymised data set can be regarded as preserving the utility of the original data set. The challenge of this utility measure is the selection of queries, which is usually application-dependent or even user-dependent, *i.e.* two different users are likely to perform different queries on the same trajectory data set.

In [213] six types of spatio-temporal range queries were introduced, aimed at evaluating the relative position of a moving object with respect to a region R in a time interval $[t_b, t_e]$. We have used these queries in our experimental work, even though they were designed for use on uncertain trajectories (see Definition 23) rather than synthetic trajectories.

Definition 23 (Uncertain trajectory). *Given a trajectory T and an uncertainty space threshold σ , an uncertain trajectory $U(T, \sigma)$ is defined as the pair $\langle T, \sigma \rangle$, where $(t, x, y) \in U(T, \sigma)$ if and only if $\exists x', y'$ such that $(t, x', y') \in T$ and the Euclidean distance between (x, y) and (x', y') is not greater than σ .*

Definition 24 (Possible motion curve). *A possible motion curve $PMCT$ of an uncertain trajectory $U(T, \sigma)$ is an ordered set of timestamped locations*

$$PMCT = \{(t_1, x_1, y_1), \dots, (t_n, x_n, y_n)\} , \quad (6.2)$$

such that $(t_i, x_i, y_i) \in U(T, \sigma)$ for all $1 \leq i \leq n$.

In short, a possible motion curve defines one of the possible trajectories that an object moving along an uncertain trajectory could follow. Unlike in [213], our anonymised trajectories are not uncertain; hence, we will only use the two spatio-temporal range queries proposed in that paper that can be adapted to non-uncertain trajectories:

- *Sometime_Definitely_Inside*(T, R, t_b, t_e) is true if and only if there exists a time $t \in [t_b, t_e]$ at which every possible motion curve $PMCT$ of an uncertain trajectory $U(T, \sigma)$ is inside region R . For a non-uncertain T , the previous condition can be adapted as: if and only if there exists a time $t \in [t_b, t_e]$ at which T is inside R .
- *Always_Definitely_Inside*(T, R, t_b, t_e) is true if and only if at every time $t \in [t_b, t_e]$, every possible motion curve $PMCT$ of an uncertain trajectory $U(T, \sigma)$ is inside region R . For a non-uncertain T , the previous condition becomes: if and only if at every time $t \in [t_b, t_e]$, trajectory T is inside R .

6.2.3 Adversarial model and target privacy properties

In our adversarial model, the adversary has access to the published anonymised set of trajectories \mathcal{T}^* . Furthermore, the adversary also knows that every location $\lambda \in \mathcal{T}^*$ must be in the original set of trajectories \mathcal{T} . Note that this adversary’s knowledge makes an important difference from previous adversarial models [12, 167, 162, 228], because in our model the linkage of some location with some user reveals the exact location of this user rather than a generalised or perturbed location.

Further, the method used for transforming the original set of trajectories \mathcal{T} into \mathcal{T}^* is assumed known by the adversary. However, this does not include the method parameters or the seeds for pseudo-random number generators, which are considered secret. Indeed, the two methods we are proposing rely on random permutations of locations and random selection of trajectories during the clustering process, and such randomness is in practice implemented using pseudo-random number generators. If an adversary knew the seeds of the generators, she could easily reconstruct the original trajectories from the anonymised trajectories.

Finally, the adversary also knows a sub-trajectory S of some original target trajectory $T \in \mathcal{T}$ ($S \preceq T$) and knows that the anonymised version of T is in \mathcal{T}^* . As in previous works, we consider that every location in \mathcal{T} is sensitive, *i.e.* for any location, learning that a specific user visited it represents useful knowledge for the adversary.

Then, we identify two attacks:

1. Find a trajectory $T^* \in \mathcal{T}^*$ that is the anonymised version of T .
2. Given a location $\lambda \notin S$, determine whether $\lambda \in T$.

If the adversary succeeds in the first attack of linking a trajectory T^* with the target T , the second is not trivial, because in general the locations in T^* will not be those in T , but it is indeed easier. This means that both attacks are not independent. However, the second attack can trivially succeed even if the first attack does not: if all anonymised trajectories cross the same location λ and $\lambda \notin S$, the attacker knows that $\lambda \in T$. As we show below, both attacks are related to the two well-known privacy notions of k -anonymity [195, 209] and ℓ -diversity [154], respectively.

Definition 25 (Trajectory p -privacy). *Let $Pr_{T^*}[T|S]$ denote the probability of the adversary’s correctly linking the anonymised trajectory $T^* \in \mathcal{T}^*$ with T given the adversary’s knowledge $S \preceq T$. Then, trajectory p -privacy is met when $Pr_{T^*}[T|S] \leq p$ for every trajectory $T \in \mathcal{T}$ and every subset $S \preceq T$.*

Definition 26 (Trajectory k -anonymity). *Trajectory k -anonymity is achieved if and only if trajectory $\frac{1}{k}$ -privacy is met.*

Definition 27 (Location p -privacy). *Let $Pr_\lambda[T|S]$ denote the probability of the adversary’s success in correctly determining a location $\lambda \in T \setminus S$, given the adversary’s*

knowledge $S \preceq T$. Then, location p -privacy is met when $\Pr_\lambda[T|S] \leq p$ for every triple (T, S, λ) such that $T \in \mathcal{T}$, $S \preceq T$ and $\lambda \notin S$.

Definition 28 (Location k -diversity). *Location k -diversity is achieved if and only if location $\frac{1}{k}$ -privacy is met.*

6.2.4 Discussion on privacy models

Achieving straightforward trajectory k -anonymity, where each anonymised trajectory would be identical to $k - 1$ other anonymised trajectories, would in general cause a huge information loss. This is why some other trajectory k -anonymity definitions under different assumptions have been proposed.

The (k, δ) -anonymity definition [12, 13] relies on the uncertainty inherent to trajectory data recorded by technologies like GPS. However, it may be hardly applied when accurate data sets of trajectories are needed. Furthermore, in order to achieve (k, δ) -anonymity, the k identical anonymised trajectories should be defined roughly in the same interval of time and they must contain the same number of locations. Such constraints are indeed hard to meet.

According to our privacy model, trajectory k -anonymity is achieved when there are at least k anonymised trajectories in \mathcal{T}^* having an anonymised version of T as a sub-trajectory. Although this definition ignores the time dimension, it does not require the length of the k anonymised trajectories to be equal. However, suppose that the adversary has a trajectory T consisting of only one location, an individual's home; whatever the anonymisation method, the anonymised version of T is likely to be very similar to T . This means that there will be k anonymised trajectories containing the single location of T . However, not all of these anonymised trajectories start at the single location of T . Since an individual's home is likely to be the first location of any individual's original trajectory, those anonymised trajectories that do not start at the single location of T (just pass through it) can be filtered out by an adversary and only the remaining trajectories are considered. The same filtering process can be performed if the adversary knows locations where the individual has never been. In this way, using side knowledge the adversary identifies less than k anonymised trajectories compatible with the original trajectory T . Hence, this definition may not actually guarantee k -anonymity in the sense of Definition 26.

In conclusion, different levels of privacy can be provided according to different assumptions on the original data, the anonymised data, and the adversary's capabilities. We defined above trajectory p -privacy (Definition 25) and location p -privacy (Definition 27) in order to capture two different privacy notions when the original locations are preserved.

6.3 Distance between trajectories

Clustering trajectories requires defining a similarity measure —a distance between two trajectories. Because trajectories are distributed over space and time, a distance that considers both spatial and temporal aspects of trajectories is needed. Many distance measures have been proposed in the past for both trajectories of moving objects and for time series but most of them are ill-suited to compare trajectories for anonymisation purposes. Therefore we define a new distance which can compare trajectories that are only partially or not at all timewise overlapping. We believe this is necessary to cluster trajectories for anonymisation. We need some preliminary notions.

6.3.1 Contemporary and synchronised trajectories

Definition 29 (*p*%-contemporary trajectories). *Two trajectories*

$$T_i = \{(t_1^i, x_1^i, y_1^i), \dots, (t_n^i, x_n^i, y_n^i)\}$$

and

$$T_j = \{(t_1^j, x_1^j, y_1^j), \dots, (t_m^j, x_m^j, y_m^j)\}$$

are said to be *p*%-contemporary if

$$p = 100 \cdot \min\left(\frac{I}{t_n^i - t_1^i}, \frac{I}{t_m^j - t_1^j}\right)$$

with $I = \max(\min(t_n^i, t_m^j) - \max(t_1^i, t_1^j), 0)$.

Intuitively, two trajectories are 100%-contemporary if and only if they start at the same time and end at the same time; two trajectories are 0%-contemporary if and only if they occur during non-overlapping time intervals. Denote the overlap time of two trajectories T_i and T_j as $ot(T_i, T_j)$.

Definition 30 (Synchronised trajectories). *Given two *p*%-contemporary trajectories T_i and T_j for some $p > 0$, both trajectories are said to be synchronised if they have the same number of locations time-stamped within $ot(T_i, T_j)$ and these correspond to the same time-stamps. A set of trajectories is said to be synchronised if all pairs of *p*%-contemporary trajectories in it are synchronised, where $p > 0$ may be different for each pair.*

If we assume that between two locations of a trajectory, the object is moving along a straight line between the locations at a constant speed, then interpolating new locations is straightforward. Trajectories can be then synchronised in the sense that if one trajectory has a location at time t , then other trajectories defined at that time will also have a (possibly interpolated) location at time t . This transformation guarantees that

the set of new locations interpolated in order to synchronise trajectories is of minimum cardinality. Algorithm 4 describes this process. The time complexity of this algorithm is $O(|TS|^2)$ where $|TS|$ is the number of different time-stamps in the data set.

Algorithm 4 Trajectory synchronisation

- 1: **Require:** $\mathcal{T} = \{T_1, \dots, T_N\}$ a set of trajectories to be synchronised, where each $T_i \in \mathcal{T}$ is of the form:

$$T_i = \{(t_1^i, x_1^i, y_1^i), \dots, (t_{n^i}^i, x_{n^i}^i, y_{n^i}^i)\};$$

- 2: Let $TS = \{t_j^i \mid (t_j^i, x_j^i, y_j^i) \in T_i : T_i \in \mathcal{T}\}$ be all time-stamps from all locations of all trajectories;
- 3: **for all** $T_i \in \mathcal{T}$ **do**
- 4: **for all** $ts \in TS$ with $t_1^i < ts < t_{n^i}^i$ **do**
- 5: **if** location having time-stamp ts is not in T_i **then**
- 6: insert new location in T_i having the time-stamp ts and coordinates interpolated from the two timewise-neighboring locations;
- 7: **end if**
- 8: **end for**
- 9: **end for**
-

6.3.2 Definition and computation of the distance

Definition 31 (Distance between trajectories). *Consider a set of synchronised trajectories $\mathcal{T} = \{T_1, \dots, T_N\}$ where each trajectory is written as*

$$T_i = \{(t_1^i, x_1^i, y_1^i), \dots, (t_{n^i}^i, x_{n^i}^i, y_{n^i}^i)\} .$$

The distance between trajectories is defined as follows. If $T_i, T_j \in \mathcal{T}$ are $p\%$ -contemporary with $p > 0$, then

$$d(T_i, T_j) = \frac{1}{p} \sqrt{\sum_{t_\ell \in \text{ot}(T_i, T_j)} \frac{(x_\ell^i - x_\ell^j)^2 + (y_\ell^i - y_\ell^j)^2}{|\text{ot}(T_i, T_j)|^2}} .$$

If $T_i, T_j \in \mathcal{T}$ are 0% -contemporary but there is at least one subset of \mathcal{T}

$$\mathcal{T}^k(ij) = \{T_1^{ijk}, T_2^{ijk}, \dots, T_{n^{ijk}}^{ijk}\} \subseteq \mathcal{T}$$

such that $T_1^{ijk} = T_i$, $T_{n^{ijk}}^{ijk} = T_j$ and T_ℓ^{ijk} and $T_{\ell+1}^{ijk}$ are $p_\ell\%$ -contemporary with $p_\ell > 0$ for $\ell = 1$ to $n^{ijk} - 1$, then

$$d(T_i, T_j) = \min_{\mathcal{T}^k(ij)} \left(\sum_{\ell=1}^{n^{ijk}-1} d(T_\ell^{ijk}, T_{\ell+1}^{ijk}) \right)$$

Otherwise $d(T_i, T_j)$ is not defined.

The computation of the distance between every pair of trajectories is not exponential as it could seem from the definition. Polynomial-time computation of a distance graph containing the distances between all pairs of trajectories can be done as follows.

Definition 32 (Distance graph). *A distance graph is a weighted graph where*

- (i) nodes represent trajectories,
- (ii) two nodes T_i and T_j are adjacent if the corresponding trajectories are $p\%$ -contemporary for some $p > 0$, and
- (iii) the weight of the edge (T_i, T_j) is the distance between the trajectories T_i and T_j .

Now, given the distance graph for $\mathcal{T} = \{T_1, \dots, T_N\}$, the distance $d(T_i, T_j)$ for two trajectories is easily computed as the minimum cost path between the nodes T_i and T_j , if such path exists. The inability to compute the distance for all possible trajectories (the last case of Definition 31) naturally splits the distance graph into connected components. The connected component that has the majority of the trajectories must be kept, while the remaining components represent outlier trajectories that are discarded in order to preserve privacy. Finally, given the connected component of the distance graph having the majority of the trajectories of \mathcal{T} , the distance $d(T_i, T_j)$ for *any two* trajectories on this connected component is easily computed as the minimum cost path between the nodes T_i and T_j . The minimum cost path between every pair of nodes can be computed using the Floyd-Warshall algorithm [80] with computational cost $O(N^3)$, *i.e.* in polynomial time.

6.3.3 Intuition and rationale of the distance

In order to deal with the time dimension, our distance measure applies a linear penalty of $\frac{1}{p}$ to those trajectories that are $p\%$ -contemporary. This means that, the closer in time are two trajectories, the shorter is our distance between both. It should be remarked that we choose a linear penalty because the Euclidean distance is also linear in terms of the spatial coordinates and the Euclidean distance is the spatial distance measure we consider by default. Other distances and other penalties might be chosen, *e.g.* $\frac{1}{p^2}$.

A problem appears when considering 0%-contemporary trajectories. How can two non-overlapping trajectories be penalised? A well-known strategy is to give a weight to the time dimension and another weight to the spatial dimension. By doing so, the time distance and the spatial distance can be computed separately, and later be merged using their weights. However, determining proper values for these weights is a challenging task.

Anyway, the following lemma guarantees that, whenever we consider two trajectories at minimum distance for clustering, they do have some overlap.

Lemma 1. *Any two trajectories in data set \mathcal{T} at minimum distance are $p\%$ -contemporary with $p > 0$.*

Proof. Consider a trajectory $T_i \in \mathcal{T}$ and another trajectory $T_j \in \mathcal{T}$ at minimum distance from T_i . Assume that T_i and T_j are not $p\%$ -contemporary with $p > 0$. Then, since the distance between T_i and T_j is defined, according to Definition 31 a subset of distinct trajectories $\mathcal{T}(ij) = \{T_1^{ij}, T_2^{ij}, \dots, T_{n^{ij}}^{ij}\} \subseteq \mathcal{T}$ must exist such that $T_1^{ij} = T_i$, $T_{n^{ij}}^{ij} = T_j$ and T_ℓ^{ij} and $T_{\ell+1}^{ij}$ are $p_\ell\%$ -contemporary with $p_\ell > 0$ for $\ell = 1$ to $n^{ij} - 1$, and

$$d(T_i, T_j) = \sum_{\ell=1}^{n^{ij}-1} d(T_\ell^{ij}, T_{\ell+1}^{ij}).$$

Then $d(T_i, T_j) > d(T_\ell^{ij}, T_{\ell+1}^{ij})$ for all ℓ from 1 to $n^{ij} - 1$ (strict inequality holds because all trajectories in $\mathcal{T}(ij)$ are distinct). Thus, we reach the contradiction that $d(T_i, T_j)$ is not minimum. Hence, the lemma must hold. \square

6.4 Anonymisation methods

We present two anonymisation methods, called SwapLocations and ReachLocations, respectively, which yield anonymised trajectories consisting of true original locations. The first method is partially based on the microaggregation [68] of trajectories and partially based on the permutation of locations. The second method is based on the permutation of locations only. The main difference between the SwapTriples method [70] and the two new methods we propose here is that the latter effectively guarantees trajectory k -anonymity (SwapLocations) or location k -diversity (ReachLocations). To that end, an original triple is discarded if it cannot be swapped randomly with another triple drawn from a set of $k - 1$ other original triples.

Our two methods differ from each other in several aspects. The first method assumes an unconstrained environment, while the second one considers an environment with mobility constraints, like an underlying street or road network. SwapLocations effectively achieves trajectory k -anonymity. ReachLocations provides higher utility by design, but regarding privacy, it offers location k -diversity instead of trajectory k -anonymity. A common feature of both methods is that locations in the resulting anonymised trajectories are true, fully accurate original locations, *i.e.* no fake, generalised or perturbed locations are given in the anonymised data set of trajectories.

6.4.1 The SwapLocations method

Algorithm 5 describes the process followed by the SwapLocations method in order to anonymise a set of trajectories. First, the set of trajectories is partitioned into several clusters. Then, each cluster is anonymised using the SwapLocations function

in Algorithm 6. We should remark here that we only consider trajectories for which the distance to other trajectories can be computed using the distance in Definition 31. Otherwise said, given the distance graph G (Definition 32), our distance measure can only be used within one of the connected components of G ; obviously, we take the trajectories in the largest connected component of G . It should also be remarked that Algorithm 4 is only used to compute the distance between trajectories. Once a cluster C is created, the anonymisation algorithm works over the original triples of the trajectories in C , and not over the triples created during synchronisation.

We limit ourselves to clustering algorithms which try to minimise the sum of the intra-cluster distances or approximate the minimum and such that the cardinality of each cluster is k , with k an input parameter; if the number of trajectories is not a multiple of k , one or more clusters must absorb the up to $k - 1$ remaining trajectories, hence those clusters will have cardinalities between $k + 1$ and $2k - 1$. This type of clustering is precisely the one used in microaggregation [68]. The purpose of minimising the sum of the intra-cluster distances is to obtain clusters as homogeneous as possible, so that the subsequent independent treatment of clusters does not cause much information loss. The purpose of setting k as the cluster size is to fulfill trajectory k -anonymity, as shown in Section 6.5.1. We might employ any microaggregation heuristic for clustering purposes (see details in Section 6.4.3 below).

Algorithm 5 Cluster-based trajectory anonymisation(\mathcal{T}, R^t, R^s, k)

- 1: **Require:** (i) $\mathcal{T} = \{T_1, \dots, T_N\}$ a set of original trajectories such that $d(T_i, T_j)$ is defined for all $T_i, T_j \in \mathcal{T}$, (ii) R^t a time threshold and R^s a space threshold, both of them public;
 - 2: Use any clustering algorithm to cluster the trajectories of \mathcal{T} , while minimising the sum of intra-cluster distances measured with the distance of Definition 31 and ensuring that minimum cluster size is k ;
 - 3: Let $C_1, C_2, \dots, C_{n_{\mathcal{T}}}$ be the resulting clusters;
 - 4: **for all** clusters C_i **do**
 - 5: $C_i^* = \text{SwapLocations}(C_i, R^t, R^s)$; // Algorithm 6
 - 6: **end for**
 - 7: Let $\mathcal{T}^* = C_1^* \cup \dots \cup C_{n_{\mathcal{T}}}^*$ be the set of anonymised trajectories.
-

The SwapLocations function (Algorithm 6) begins with a random trajectory T in C . The function attempts to cluster each unswapped triple λ in T with another $k - 1$ unswapped triples belonging to different trajectories such that: (i) the time-stamps of these triples differ by no more than a time threshold R^t from the time-stamp of λ ; (ii) the spatial coordinates differ by no more than a space threshold R^s . If no $k - 1$ suitable triples can be found that can be clustered with λ , then λ is removed; otherwise, random swaps of triples are performed within the formed cluster. Randomly swapping

this cluster of triples guarantees that any of these triples has the same probability of remaining in its original trajectory or becoming a new triple in any of the other $k - 1$ trajectories. Note that Algorithm 6 guarantees that every triple λ of every trajectory $T \in C$ will be swapped or removed.

Algorithm 6 SwapLocations(C, R^t, R^s)

- 1: **Require:** (i) C a cluster of trajectories to be transformed, (ii) R^t a time threshold and R^s a space threshold;
- 2: Mark all triples in trajectories in C as “unswapped”;
- 3: Let T be a random trajectory in C ;
- 4: **for all** “unswapped” triples $\lambda = (t_\lambda, x_\lambda, y_\lambda)$ in T **do**
- 5: Let $U = \{\lambda\}$; // Initialise U with $\{\lambda\}$
- 6: **for all** trajectories T' in C with $T' \neq T$ **do**
- 7: Look for an “unswapped” triple $\lambda' = (t_{\lambda'}, x_{\lambda'}, y_{\lambda'})$ in T' minimising the intra-cluster distance in $U \cup \{\lambda'\}$ and such that:

$$|t_{\lambda'} - t_\lambda| \leq R^t$$

$$0 \leq \sqrt{(x_{\lambda'} - x_\lambda)^2 + (y_{\lambda'} - y_\lambda)^2} \leq R^s ;$$

- 8: **if** λ' exists **then**
 - 9: $U \leftarrow U \cup \{\lambda'\}$;
 - 10: **else**
 - 11: Remove λ from T ;
 - 12: Go to line 6 in order to analyse the next triple λ ;
 - 13: **end if**
 - 14: **end for**
 - 15: Randomly swap all triples in U ;
 - 16: Mark all triples in U as “swapped”;
 - 17: **end for**
 - 18: Remove all “unswapped” triples in C ;
 - 19: **Return** C
-

The SwapLocations function specified by Algorithm 6 swaps entire triples, that is, time and space coordinates. The following example illustrates the advantages of swapping time together with space.

Example 1. Imagine John attended one day the political protests in Tahrir Square, Cairo, Egypt, but he would not like his political views to become broadly known. Assume John’s trajectory is anonymised and published. Assume further that an adversary knows the precise time John left his hotel in the morning, say 6:36 AM (*e.g.* because the adversary has bribed the hotel concierge into recording John’s arrival and departure

times). Now:

- If SwapLocations swapped only spatial coordinates, the adversary could re-identify John’s trajectory as one starting with a triple (6:36 AM, x'_h, y'_h). Furthermore, (x'_h, y'_h) must be a location within a distance R^s from the hotel coordinates (x_h, y_h) , although the adversary does not know the precise value of R^s . The re-identified trajectory would contain all true timestamps of John’s original trajectory (because they would not have been swapped), and spatial coordinates within distance R^s of John’s really visited spatial coordinates. Hence, it would be easy to check whether John was near Tahrir Square during that day. Without swapping times, privacy protection can only be obtained by taking R^s large enough so that within distance R^s of the original locations visited by John there are several semantically different spatial coordinates. To explain what we mean by semantic difference, assume (x, y) is Tahrir Square and the trajectory anonymiser guarantees that he has taken R^s large enough so that (x, y) could be swapped with some spatial coordinates (x', y') off Tahrir Square; even if (x', y') turned out to be still within Tahrir Square, John could claim to have been off Tahrir Square; the adversary could not disprove such a claim, because in fact (x, y) could be at a distance R^s from (x', y') and hence outside the Square. However, a large R^s means a large total space distortion.
- If entire triples are swapped, as actually done by SwapLocations, the adversary can indeed locate an anonymised trajectory containing (not necessarily starting with) triple (6:36 AM, x_h, y_h). However, there is only a chance $1/k$ that this triple was not swapped from another of the $k - 1$ original trajectories with which John’s original trajectory was clustered. Similarly, the other triples in the anonymised trajectory containing (6:36 AM, x_h, y_h) have also most likely “landed” in that anonymised trajectory as a result of a swap with some location in some of the $k - 1$ original trajectories clustered with John’s. Hence, John’s trajectory is cloaked with $k - 1$ other trajectories. We will prove in Section 6.5.1 that this guarantees trajectory k -anonymity in the sense of Definition 26. In particular, the triple (t, x, y) corresponding to John at Tahrir Square will appear in one of the k anonymised trajectories, unless that triple has been removed by the SwapLocations function because it was unswappable (the smaller R^t and R^s , the more likely it is for the triple to be removed).

6.4.2 The ReachLocations method

The ReachLocations method, described in Algorithm 7, takes reachability constraints into account: from a given location, only those locations at a distance below a threshold *following a path in an underlying graph* (e.g., urban pattern or road network) are considered to be directly reachable. Enforcing such reachability constraints while requiring

full trajectory k -anonymity would result in a lot of original locations being discarded. To avoid this, trajectory k -anonymity is changed by another useful privacy definition: location k -diversity.

Computationally, this means that trajectories are *not* microaggregated into clusters of size k . Instead, each location is k -anonymised independently using the entire set of locations of all trajectories. To do so, a cluster C_λ of “unswapped” locations is created around a given location λ , *i.e.* $\lambda \in C_\lambda$. The cluster C_λ is constrained as follows: (i) it must have the lowest intra-cluster distance among those clusters of k “unswapped” locations that contain the location λ ; (ii) it must have locations belonging to k different trajectories; and (iii) it must contain only locations at a path from λ at most R^s long and with time-stamps differing from t_λ at most R^t . Then, the spatial coordinates (x_λ, y_λ) are swapped with the spatial coordinates of some random location in C_λ and both locations are marked as “swapped”. If no cluster C_λ can be found, the location λ is removed from the data set and will not be considered anymore in the subsequent anonymisation. This process continues until no more “unswapped” locations appear in the data set.

It should be emphasised that, according to Algorithm 7, two successive locations λ_j^i and λ_{j+1}^i of an original trajectory T_i may be cloaked with respective sets of $k - 1$ locations belonging to different sets of $k - 1$ original trajectories; for this reason we cannot speak of trajectory k -anonymity, see the example below.

Example 2. Consider $k - 1$ trajectories within city A , $k - 1$ trajectories within city B and one trajectory T_{AB} crossing from A to B . When applying ReachLocations, the initial locations of T_{AB} are swapped with locations of trajectories within A , whereas the final locations of T_{AB} are swapped with locations of trajectories within B . Imagine that an adversary knows a sub-trajectory S of T_{AB} containing one location λ_A in A and one location λ_B in B . Assume λ_A and λ_B are not removed by ReachLocations anonymisation. Now, the adversary will know that the anonymised trajectory T_{AB}^* corresponding to T_{AB} is the only anonymised trajectory crossing from A to B . Thus, there is no trajectory k -anonymity, even if the adversary will be unable to determine the exact locations of $T_{AB} \setminus S$, because each of them has been swapped within a set of k locations.

Algorithm 7 swaps only spatial coordinates instead of full triples. We show in the example below that this is enough for ReachLocations to achieve location k -diversity (we have shown above that it cannot achieve trajectory k -anonymity anyway). If swapping time coordinates is not beneficial in terms of privacy guarantees, they should not be swapped, because the fact that anonymised trajectories preserve the original sequence of time-stamps of original trajectories increases their utility.

Example 3. Let us resume Example 1, but now assume that ReachLocations is used instead of SwapLocations to anonymise trajectories. In this case, the adversary will find

Algorithm 7 ReachLocations(\mathcal{T}, R^t, R^s, k)

1: **Require:** (i) $\mathcal{T} = \{T_1, \dots, T_N\}$ a set of original trajectories, (ii) G a graph describing the paths between locations, (iii) R^t is a time threshold and R^s is a space threshold, both of them public;

2: Let $TL = \{\lambda_j^i \in T_i : T_i \in \mathcal{T}\}$ contain all locations from all trajectories, where $\lambda_j^i = (t_j^i, x_j^i, y_j^i)$ and the spatial coordinates (x_j^i, y_j^i) are called a point;

3: Mark all locations in TL as “unswapped”;

4: Let $\mathcal{T}^* = \emptyset$ be an empty set of anonymised trajectories;

5: **while** there exist trajectories in \mathcal{T} **do**

6: Let T_i be a trajectory randomly chosen in \mathcal{T} ;

7: **for** $j = 1$ to $j = |T_i|$ **do**

8: **if** λ_j^i is “unswapped” **then**

9: Let $C_j^i = \{\lambda_1, \dots, \lambda_{k-1}\}$ be a cluster of locations in TL such that:

1. All locations in C_j^i are “unswapped”, with points different from (x_j^i, y_j^i) and no two equal points;
2. Points in C_j^i belong to trajectories in $\mathcal{T} \setminus \{T_i\}$ and no two points belong to the same trajectory;
3. For any $\lambda \in C_j^i$, it holds that:
 - (a) $|t_\lambda - t_j^i| \leq R^t$
 - (b) If $j > 1$ there is a path in G between (x_{j-1}^i, y_{j-1}^i) and (x_λ, y_λ) ;
 - (c) If $j < |T_i|$ there is a path in G between (x_λ, y_λ) and (x_{j+1}^i, y_{j+1}^i) ;
 - (d) The length of each path above is no more than R^s ;
4. The sum of intra-cluster distances in $C_j^i \cup \{\lambda_j^i\}$ is minimum among clusters of cardinality $k - 1$ meeting the previous conditions;

10: **if** such a cluster C_j^i does not exist **then**

11: Remove λ_j^i from T_i ;

12: **else**

13: Mark λ_j^i as “swapped”;

14: With probability $\frac{k-1}{k}$:

1. Pick a random location $\lambda \in C_j^i$ and mark it as “swapped”;
2. Swap the spatial coordinates (x_j^i, y_j^i) of λ_j^i with the spatial coordinates (x_λ, y_λ) of λ ;

15: **end if**

16: **end if**

17: **end for**

18: $\mathcal{T}^* = \mathcal{T}^* \cup \{T_i\}$;

19: Remove T_i from \mathcal{T} ;

20: **end while**

21: **Return** \mathcal{T}^* .

an anonymised trajectory starting with (6:36 AM, x'_h, y'_h). This anonymised trajectory will contain all true timestamps of John’s original trajectory. However, the spatial coordinates appearing in any location of this re-identified trajectory are John’s original spatial coordinates with a probability at most $1/k$. We will prove in Section 6.5.2 below that this guarantees location k -diversity in the sense of Definition 28. If we want to prevent the adversary from making sure that John visited Tahrir Square, we should take R^s large enough (the discussion in Example 1 about the protection afforded by a large R^s when time is not swapped is valid here).

6.4.3 Complexity of SwapLocations and ReachLocations

We first give a complexity assessment of SwapLocations and ReachLocations assuming that the distance graph mentioned in Section 6.3.2 has been precomputed and is available. This is reasonable, because the distance graph needs to be computed only once, while the anonymisation methods may need to be run several times (*e.g.* with different parameters). Regarding SwapLocations, we have:

- Algorithm 5 can use any fixed-size microaggregation heuristic for clustering (*e.g.* MDAV in [72]). Most microaggregation heuristics have quadratic complexity, that is $O(N^2)$, where N is the number of trajectories.
- Algorithm 5 calls the procedure SwapLocations once for each resulting cluster, that is, $O(N/k)$ times.
- In the worst case, the complexity of procedure SwapLocations (Algorithm 6) is proportional to the number of locations of the longest trajectory in C , say $O(n_{max})$. For each location, a search of another location for swapping is performed among the other $k-1$ trajectories. The number of candidates for swapping is $O((k-1)n_{max})$. Hence, the complexity of SwapLocations is $O((k-1)n_{max}^2)$.
- The total complexity of the method is thus

$$O(N^2) + O(N/k) \cdot O((k-1)n_{max}^2) = O(N^2) + O(Nn_{max}^2) \quad (6.3)$$

Regarding the complexity of ReachLocations, we have

- Algorithm 7 has an external loop which is called N times, where N is the number of trajectories in \mathcal{T} . For each trajectory, a swap is attempted for each of its unswapped locations. Hence the algorithm performs $O(Nn_{max})$ swaps, where n_{max} is the number of locations in the longest trajectory.
- Each swap involves forming a cluster which $k-1$ locations selected from TL , which takes time proportional to the total number of locations in TL , that is, $O(Nn_{max})$.

- Hence, the total complexity of the method is $O(N^2 n_{max}^2)$.

By comparing the last expression and Expression 6.3, we see that both SwapLocations and ReachLocations are quadratic in N and quadratic in n_{max} , but ReachLocations is slower. Such complexity motivates the following two comments related to scalability:

- If the number of trajectories N in the original data set is very large, quadratic complexity may be very time consuming. In this case, a good strategy is to use some blocking technique to split the original data set into several subsets of trajectories, each of which should be anonymised separately.
- n_{max} being large may be less problematic than N being large, provided that only a small fraction of trajectories have n_{max} or close to n_{max} locations. If a lot of trajectories are very long, a good strategy would be to split each of these into two or more trajectories and anonymise them independently.

Finally, in case we add the time complexity of the computation of the distance graph mentioned in Section 6.3.2 (which is $O(N^3)$ using the Floyd-Warshall algorithm), the time complexities of both SwapLocations and ReachLocations become $O(N^3) + O(N n_{max}^2)$ and $O(N^3) + O(N^2 n_{max}^2)$, respectively.

6.5 Privacy guarantees

6.5.1 Privacy guarantees of SwapLocations

The main difference between the SwapTriples method in [70] and the SwapLocations method here is that, in the latter, no original location remains unswapped in an anonymised trajectory.

Proposition 2. *Let $S \preceq T_S$ be the adversary's knowledge of a target original trajectory T_S and $\lambda_1, \lambda_2, \dots, \lambda_{|S|}$ be all triples in S . For every trajectory T_i , the probability that the triple λ in S appears in the anonymised version T_i^* of T_i produced by SwapLocations is:*

$$\Pr(\lambda \in T_i^* | \lambda \in S) = \begin{cases} \frac{1}{k} & \text{if } T_S \text{ and } T_i \text{ lie in the same cluster} \\ 0 & \text{otherwise.} \end{cases}$$

Proof. By construction of Algorithm 6, if T_S and T_i do not lie in the same cluster, there is no possibility of swapping triples between them. Hence, in this case, $\Pr(\lambda \in T_i^* | \lambda \in S) = 0$.

Let $T_1, T_2, \dots, T_k \in \mathcal{T}$ be k trajectories that are anonymised together in the same cluster by the SwapLocations method. Without loss of generality, let us assume that

$T_S = T_1$. By construction of Algorithm 6, for every $1 \leq i \leq k$, $\Pr(\lambda \in T_i^* | \lambda \in T_1)$ is 0 if λ was removed, $\frac{1}{k}$ otherwise. Note that a swapping option is to swap a triple with itself, that is, not to swap it. Since it does not make sense to consider removed triples in S , we conclude that $\Pr(\lambda_j \in T_i^* | \lambda_j \in T_1) = \frac{1}{k}$, $\forall 1 \leq j \leq |S|, 1 \leq i \leq k$ and, in consequence, $\Pr(\lambda_j \in T_i^* | \lambda_j \in S) = \frac{1}{k}$, $\forall 1 \leq j \leq |S|, 1 \leq i \leq k$. \square

Theorem 4. *The SwapLocations method achieves trajectory k -anonymity.*

Proof. By Proposition 2, any sub-trajectory $S' \preceq S \preceq T_1$ has the same probability of being a sub-trajectory of T_1^* than of being a sub-trajectory of any of the $k-1$ trajectories T_2^*, \dots, T_k^* . Thus, given S , an adversary is not able to link T_1 with T_1^* with probability higher than $\frac{1}{k}$. Therefore, SwapLocations satisfies $\frac{1}{k}$ -privacy according to Definition 25; according to Definition 26, it also satisfies trajectory k -anonymity. \square

6.5.2 Privacy guarantees of ReachLocations

We show below that ReachLocations provides location k -diversity.

Proposition 3. *Any triple λ in an original trajectory T appears in the anonymised trajectory T^* corresponding to T obtained with ReachLocations if and only if λ was not removed and was swapped with itself, which happens with probability at most $\frac{1}{k}$.*

Proof. Let us prove the necessity implication. By construction of Algorithm 7, any triple λ whose spatial coordinates (point) cannot be swapped within a cluster $C \cup \{\lambda\}$ containing k different points belonging to k different trajectories is removed and does not appear in the set of anonymised trajectories. Further, the only way for a non-removed triple $\lambda \in T$ to remain unaltered in T^* is precisely that its point is swapped with itself, which happens with probability $\frac{1}{k}$. Therefore, to remain unaltered in T^* , a triple in T needs to avoid removal and to have its point swapped with itself, which happens with probability at most $\frac{1}{k}$.

Now let us prove the sufficiency implication. Assume that $\lambda = (t, x, y) \in T$ appears in T^* without having been swapped with itself. Then, by construction of ReachLocations, $\lambda \in T^*$ must have been formed as the result of swapping a triple $(t, x', y') \in T$ with a triple (t', x, y) from another original trajectory, where $(x', y') \neq (x, y)$. Both then T would contain two triples with the same time-stamp t and different spatial locations, which is a contradiction. \square

Theorem 5. *The ReachLocations method achieves location k -diversity.*

Proof. Assume the adversary knows a sub-trajectory S of an original trajectory T . The sequence of time-stamps in S allows the adversary to re-identify the anonymised trajectory T^* corresponding to T (because the time-stamp sequence is preserved). By Proposition 3, any triple $\lambda \in T^* \setminus S$ belongs to $T \setminus S$ with probability at most $\frac{1}{k}$. Now,

consider a triple $\lambda = (t, x, y) \in T^{**} \setminus S$, where T^{**} is an anonymised trajectory different from T^* . The probability that λ came to $T^{**} \setminus S$ from $T \setminus S$ is the probability that λ was swapped and swapping did not alter it. This probability is zero, because swaps preserve time coordinates but take place only between triples having different space coordinates. Hence, in terms of Definition 25, $Pr_\lambda[T|S] \leq \frac{1}{k}$ for every triple (T, S, λ) such that $T \in \mathcal{T}$, $S \preceq T$ and $\lambda \notin S$. \square

Note that the previous proof also implies that, even if a triple $\lambda = (t, x, y) \notin S$ is shared by $M > 1$ anonymised trajectories, the probability of $\lambda \in T \setminus S$ remains at most $\frac{1}{k}$. What can be inferred by the adversary, however, is that M original trajectories (in general not the ones corresponding to the M anonymised trajectories) visited spatial coordinates (x, y) at possibly different times. Indeed, (t, x, y) can be obtained by swapping (t', x, y) and (t, x', y') for any t' such that $|t' - t| \leq R^t$ and for any $(x', y') \neq (x, y)$ at path distance at most R^s . If M is the total number of anonymised trajectories, then the adversary can be sure that original trajectory T visited spatial coordinates (x, y) at some time t' such that $|t' - t| \leq R^t$. Such inference by the adversary does not violate location k -diversity: violation would require guessing *both* the spatial *and* temporal coordinates of a triple in $T \setminus S$. Of course, the time threshold R^t must be taken large enough so that the time coordinate t is sufficiently protected.

6.6 Experimental results and evaluation

We implemented SwapLocations and ReachLocations. SwapLocations performs clustering of trajectories using the partitioning step of the MDAV microaggregation heuristic [72]. We used two data sets in our experiments:

- *Synthetic data set.* We used the Brinkhoff’s generator [47] to generate 1,000 synthetic trajectories which altogether visit 45,505 locations in the German city of Oldenburg. Synthetic trajectories generated with the Brinkhoff’s generator have also been used in [12, 166, 167, 228]. We used this data set mainly for comparing our methods with (k, δ) -anonymity [12]. The number of trajectories being moderate, we were able to run in reasonable time the methods to be compared with a large number of different parameter choices. Another advantage is that the street graph of Oldenburg was available, which is necessary to run ReachLocations. The downside of this data set having a moderate number of trajectories is that these are rather sparse, which causes the relative distortion in the anonymised data set to be substantial, no matter the method used. Anyway, this is not a serious problem to compare methods with each other.
- *Real-life data set.* We also used a real-life data set of cab mobility traces that were collected in the city of San Francisco [188]. This data set consists of 536 files, each

of them containing the GPS coordinates of a cab during a period of time. After a filtering process, we obtained 4582 trajectories and 94 locations per trajectory on average. The advantage of this data set over the synthetic one is that it contains a larger number of trajectories and that these are real ones. Then, we show through a real example how appropriate is our distance metric for trajectory clustering. Also, we present utility measures on the SwapLocations method for this real-life data set using different space thresholds. The weakness of this data set is that it cannot be used for ReachLocations, because it does not include the underlying street graph of San Francisco.

6.6.1 Results on synthetic data

For the sake of reproducibility, we indicate the parameters we used in Brinkhoff’s generator to generate our Oldenburg synthetic data set: 6 moving object classes and 3 external object classes; 10 moving objects and 1 external object generated per timestamp; 100 timestamps; speed 250; and “probability” 1,000. This resulted in 1,000 trajectories containing 45,405 locations. The maximum trajectory length was 100 points, the average length was 45.4 locations, and the median length was 44 locations.

6.6.1.1 Implementation details of our methods

We have introduced a new distance measure between trajectories used by the SwapLocations proposal during the clustering process. As mentioned in Section 6.4.1 above, our distance function can only be used within one of the connected components of the distance graph G . During the construction of the distance graph for the synthetic data we found 11 connected components, 10 of them of size 1. Therefore, we removed these 10 trajectories in order to obtain a new distance graph with just one connected component. In this way, we preserved 99% percent of all trajectories before the anonymisation process. The removed trajectories were in fact trajectories of length one, *i.e.* with just one location in each one.

The SwapLocations method has been implemented using the following simple microaggregation method for trajectories: first, create clusters of size k with minimum intra-cluster distance and then disperse the up to $k - 1$ unclustered trajectories to existing clusters while minimising the intra-cluster distance. This algorithm incurs no additional discarding of trajectories.

On the other hand, the ReachLocations method does not remove trajectories, unlike the SwapLocations method. It does, however, remove non-swappable locations, which causes the removal of any trajectory consisting of non-swappable locations only.

6.6.1.2 Implementing (k, δ) -anonymity for comparison with our method

We compared our proposals with (k, δ) -anonymity [12]. Since (k, δ) -anonymity only works over trajectories having the same time span, first a pre-processing step to partition the trajectories is needed. Superimposing the begin and end times of the trajectories through reduction of the time coordinate modulo a parameter π does not always yield at least k trajectories having the same time span; it may also happen that a trajectory disappears because the new reduced end time lies before the new reduced begin time.

We have used $\pi = 3$ which kept the maximum (and so discarded the minimum) trajectories. From the 1,000 synthetic trajectories, 40 were discarded because the end time was less than the begin time and 187 were discarded because there were at most 4 trajectories having the same time span. In total, 227 (22.7%) trajectories were discarded just in the pre-processing step. The remaining 773 trajectories were in 32 sets having the same time span, each set containing a minimum of 15 trajectories and 24 on average.

We performed (k, δ) -anonymisation for $k = 2, 4, 6, 8, 10,$ and 15 and $\delta = 0, 1000, 2000, 3000, 4000$ and 5000 . Because of the pre-processing step, using a higher k was impossible without causing a significant number of additional trajectories to be discarded.

6.6.1.3 Utility comparison

The performance of our proposals strongly depends on the values of the time and space threshold parameters, denoted as R^t and R^s , respectively. In practice, these values must be chosen to maximise utility while affording sufficient privacy protection. Too large thresholds reduce utility (large space distortion if R^s is too high and large time distortion if R^t is too high), but too small thresholds reduce utility because of removal of many unswappable locations. As a rule of thumb, as illustrated in Example 1, the space threshold R^s must be sufficiently large so that within a radius R^s of any spatial location there are sufficiently distinct locations (*e.g.* if (x, y) lies in Tahrir Square, Cairo, there should be points outside the Square within a radius R^s of (x, y)).

In order to compute the total space distortion, a value for Ω must be chosen and this can be a challenging task. Note that the value of Ω is application-dependent (*e.g.* for applications where the distortion should measure the accuracy of trajectories Ω should be zero so that only non-removed triples contribute to *TotalSD*, while for applications that should avoid removing any triple Ω should be very high). For this reason we propose to compare separately the following three utility properties: (i) total space distortion; (ii) percentage of removed trajectories; and (iii) percentage of removed locations. To do so, we set $\Omega = 0$ when computing the total space distortion. Consequently, the percentage of removed triples as well as the percentage of removed trajectories are considered separately from the total space distortion.

It should be remarked that the computation of the total space distortion of the

ReachLocations method is done using the Euclidean distance between locations rather than the distance defined by the reachability constraints (distance on the underlying network). Note that reachability constraints should be considered during the anonymisation process but not necessarily when computing the total space distortion.

For successive anonymisations aimed at comparing the SwapLocations and ReachLocations methods with (k, δ) -anonymity, we set R^t and R^s in a way to obtain roughly the same total space distortion values as in (k, δ) -anonymity (cf. Table 6.1) with $\Omega = 0$. The idea is that, after assuring that the three methods achieve roughly the same total space distortion, we will be able to focus on other utility properties like the percentage of removed trajectories and the percentage of removed locations. It should be noted that our comparison is not entirely fair for any of the three methods because all of them are aimed at achieving different privacy notions. However, we believe that our results are indicative of the weaknesses and the strengths of our proposals.

$\delta \setminus k$	2	4	6	8	10	15
0	48e6	93e6	120e6	143e6	165e6	199e6
1,000	19e6	60e6	86e6	109e6	131e6	165e6
2,000	4e6	32e6	56e6	78e6	99e6	133e6
3,000	.9e6	14e6	32e6	52e6	71e6	104e6
4,000	.2e6	5e6	16e6	32e6	48e6	79e6
5,000	.03e6	2e6	7e6	18e6	31e6	58e6

Table 6.1: Total space distortion (TotalSD) of (k, δ) -anonymity for several parameter values (e6 stands for $\times 10^6$)

The above principle of equating the space distortions with (k, δ) -anonymity yields a value for the space threshold R^s in each of SwapLocations and ReachLocations; however, it does not constrain the time threshold, which we set at $R^t = 100$. Regarding R^s , we set it to achieve the total space distortions of (k, δ) -anonymity for cluster size $k = \{2, 4, 6, 8, 10, 15\}$ and

$$\delta = \{0, 1000, 2000, 3000, 4000, 5000\}$$

(parameter values considered in Table 6.1). In order to find such space thresholds efficiently, we assume that the total space distortions of our methods define a monotonically increasing function of the space threshold, *i.e.* the higher the space threshold, the higher the total space distortion. Under this assumption, we perform a logarithmic search over the set of space thresholds defined by the interval $[0, 10^6]$. The reason behind defining the maximum value for the space threshold as 10^6 is that it is high enough to achieve low numbers of removed trajectories. Indeed, as shown in Figure 6.2, for both methods there exists a value $R^s_{cutoff} < 10^6$ such that, for every space threshold $R^s > R^s_{cutoff}$, neither the total space distortion nor the percentage of removed locations

and removed trajectories significantly change. Table 6.2 and Table 6.3 show the values of space thresholds used in each configuration of (k, δ) -anonymity for SwapLocations and ReachLocations, respectively.

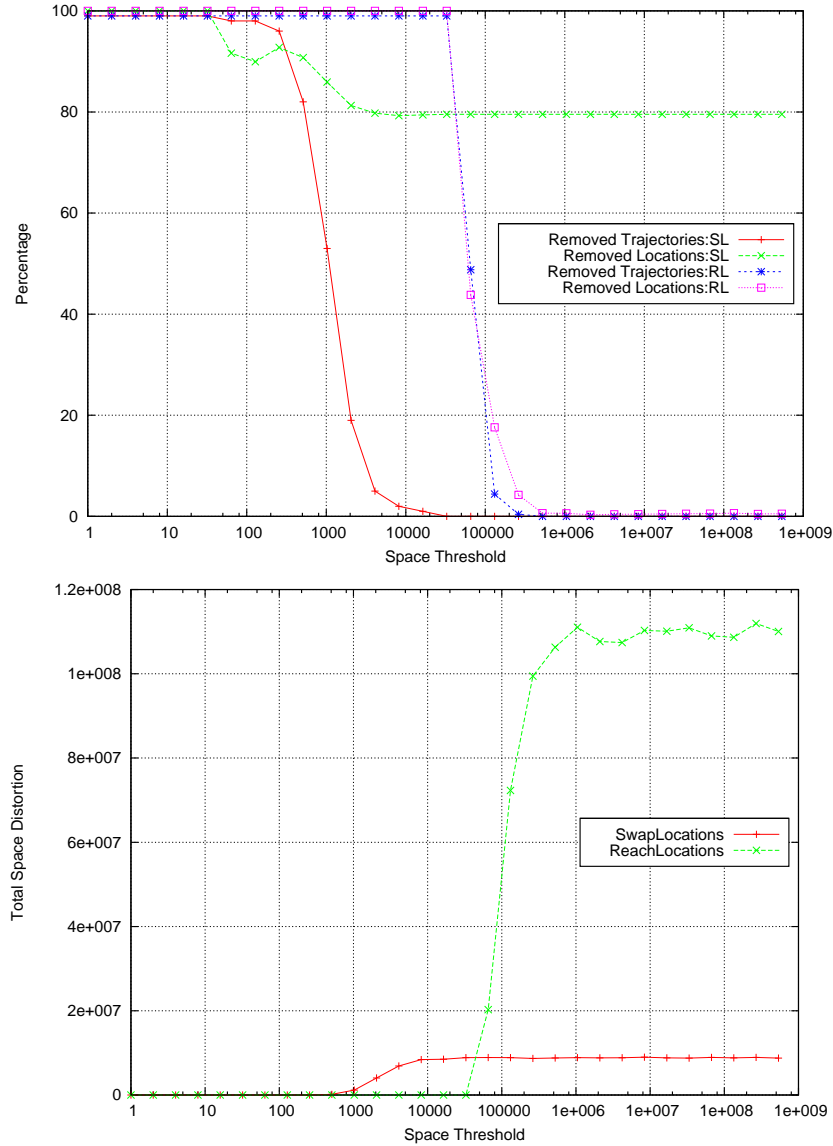


Figure 6.2: Top, percentage of removed trajectories and locations with $k = 10$, $R^t = 100$ and several values of R^s for SwapLocations (SL) and ReachLocations (RL). Bottom, total space distortion with $k = 10$, $R^t = 100$ and several values of R^s for SwapLocations and ReachLocations

As it can be seen in Tables 6.2 and 6.3, we use the maximum value (10^6) of the space

$\delta \setminus k$	2	4	6	8	10	15
0	10^6	10^6	10^6	10^6	10^6	10^6
1,000	10^6	10^6	10^6	10^6	10^6	10^6
2,000	899	10^6	10^6	10^6	10^6	10^6
3,000	257	10^6	10^6	10^6	10^6	10^6
4,000	86	1390	10^6	10^6	10^6	10^6
5,000	19	681	2507	10^6	10^6	10^6

Table 6.2: Space thresholds used in SwapLocations to match the total space distortion of each configuration of (k, δ) -anonymity

$\delta \setminus k$	2	4	6	8	10	15
0	499875	10^6	10^6	10^6	10^6	10^6
1,000	25090	106126	270157	10^6	10^6	10^6
2,000	4780	52468	93717	151915	249999	10^6
3,000	749	37124	64801	95585	132857	238884
4,000	136	25540	51089	73088	94465	152862
5,000	57	18059	39061	58584	79101	113280

Table 6.3: Space thresholds used in ReachLocations to match the total space distortion of each configuration of (k, δ) -anonymity

threshold for several configurations. This is because in those configurations the total space distortion caused by the (k, δ) -anonymity could not be reached by our methods no matter how much we increased the space threshold. Figure 6.3 explains this behaviour by showing the values of total space distortion SwapLocations and ReachLocations minus the total space distortion of (k, δ) -anonymity. With almost every configuration, our methods have a total space distortion lower than the total space distortion of (k, δ) -anonymity. In the case of SwapLocations, the total space distortion is even much lower.

In general, SwapLocations does not reach high values of the total space distortion because it removes more locations than ReachLocations in order to achieve trajectory k -anonymity. Note that removing locations does not increase the total space distortion because we are considering $\Omega = 0$. Tables 6.4 and 6.5 show in detail the percentage of removed trajectories and the percentage of removed locations for different values of $k = \{2, 4, 6, 8, 10, 15\}$ and $\delta = \{0, 1000, 2000, 3000, 4000, 5000\}$, for SwapLocations and ReachLocations, respectively.

As it can be seen in Table 6.4, in general SwapLocations removes less trajectories than (k, δ) -anonymity because SwapLocations can cluster non-overlapping trajectories. Indeed, with (k, δ) -anonymity 227 trajectories were discarded in the pre-processing step alone because their time span could not match the time span of other trajectories, and additional outlier trajectories were discarded during clustering, up to a total 24% of

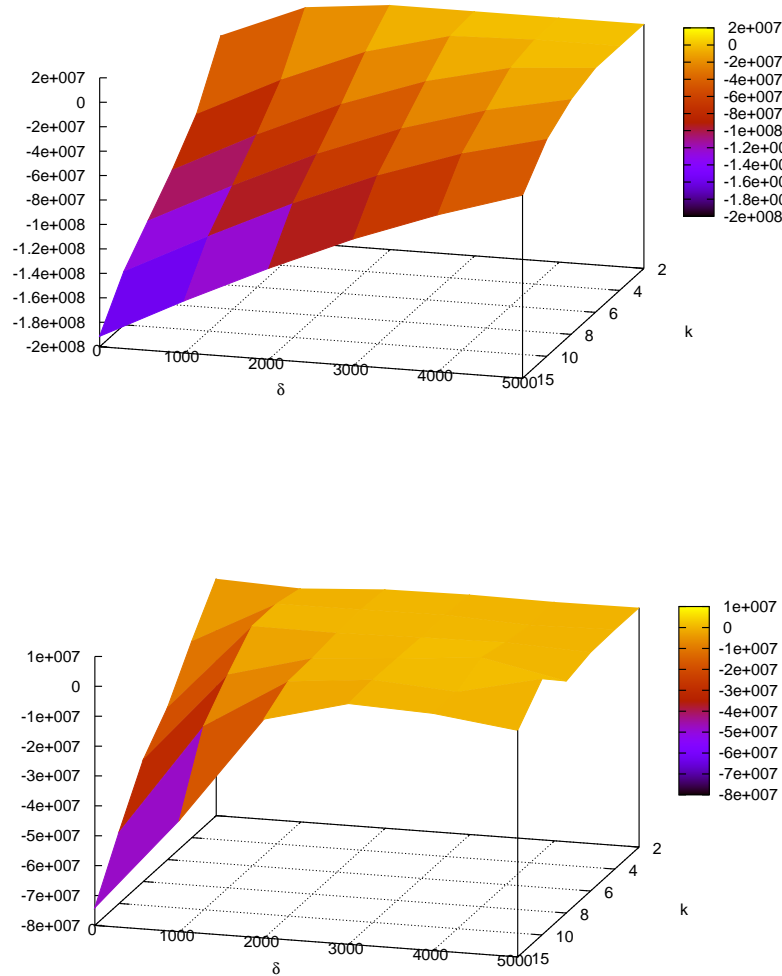


Figure 6.3: Top: total space distortion of SwapLocations minus total space distortion of (k, δ) -anonymity for several parameter configurations. Bottom: total space distortion of ReachLocations minus total space distortion of (k, δ) -anonymity for several parameter configurations. The space thresholds defined in Tables 6.2 and 6.3 have been used, respectively.

discarded trajectories. However, SwapLocations removed up to 84% of all locations in the worst cases and thus, it may not be suitable for applications where preserving the number of locations really matters. SwapLocations removes any location whose

swapping set U contains less than k locations, which is a relatively frequent event when k trajectories with different lengths are clustered together. As the cluster size k increases, the length diversity tends to increase and the removal percentage increases. A simple way around the location removal problem is to create clusters that contain trajectories with roughly the same length, even though this may result in a higher total space distortion; higher space distortion is a natural consequence of clustering based on the trajectory length rather than the trajectory distance.

Table 6.5 shows that ReachLocations removes few trajectories when δ is small and k is large. The reason is that, for those parameterisations, (k, δ) -anonymity introduces so much total space distortion that ReachLocations can afford taking the maximum space threshold $R^s = 10^6$ without reaching that much distortion. Such a high space threshold allows ReachLocations to easily swap spatial coordinates, so that very few locations need to be removed. Furthermore, the trajectories output by ReachLocations are consistent with the underlying city topology. As said above, the only drawback of this method is that in general it does not provide trajectory k -anonymity; rather, it provides location k -diversity.

$\delta \setminus k$	2		4		6		8		10		15	
	T	L	T	L	T	L	T	L	T	L	T	L
0	0	34	0	58	0	69	1	75	0	79	0	84
1000	0	34	0	58	0	69	1	75	0	79	0	84
2000	4	45	0	58	0	69	1	75	0	79	0	84
3000	11	62	0	58	0	69	1	75	0	79	0	84
4000	19	68	5	66	0	69	1	75	0	79	0	84
5000	32	78	20	73	4	72	1	75	0	79	0	84

Table 6.4: Percentage of trajectories (columns labeled with **T**) and locations (columns labeled **L**) removed by SwapLocations when using time threshold 100, $k = \{2, 4, 6, 8, 10, 15\}$ and space thresholds that match the space distortion caused by (k, δ) -anonymity with the previous k 's and $\delta = \{0, 1000, 2000, 3000, 4000, 5000\}$. Percentages have been rounded to integers for compactness.

6.6.1.4 Spatio-temporal range queries

As stated in Section 6.2.2, a typical use of trajectory data is to perform spatio-temporal range queries on them. That is why we report empirical results when performing the two query types described and motivated in Section 6.2.2: *Sometime_Definitely_Inside* (SI) and *Always_Definitely_Inside* (AI). We accumulate the number of trajectories in

$\delta \setminus k$	2		4		6		8		10		15	
	T	L	T	L	T	L	T	L	T	L	T	L
0	0	1	0	3	0	3	0	4	0	4	0	3
1000	0	2	0	3	0	3	0	4	0	5	0	3
2000	36	27	9	18	3	11	0	5	0	6	0	4
3000	74	38	33	39	18	28	6	21	2	13	0	7
4000	82	43	65	49	41	40	20	34	10	27	2	16
5000	84	60	84	53	60	52	40	44	27	35	10	27

Table 6.5: Percentage of trajectories (columns labeled with **T**) and locations (columns labeled **L**) removed by ReachLocations when using time threshold 100, $k = \{2, 4, 6, 8, 10, 15\}$ and space thresholds that match the space distortion caused by (k, δ) -anonymity with the previous k 's and $\delta = \{0, 1000, 2000, 3000, 4000, 5000\}$. Percentages have been rounded to integers for compactness.

a set of trajectories \mathcal{T} that satisfy the SI or AI range queries using the SQL style code below.

- Query $\mathcal{Q}_1(\mathcal{T}, R, t_b, t_e)$:

```
SELECT COUNT (*) FROM  $\mathcal{T}$  WHERE SI( $\mathcal{T}$ .traj, R,  $t_b, t_e$ )
```

- Query $\mathcal{Q}_2(\mathcal{T}, R, t_b, t_e)$:

```
SELECT COUNT (*) FROM  $\mathcal{T}$  WHERE AI( $\mathcal{T}$ .traj, R,  $t_b, t_e$ )
```

Then, we define two different *range query distortions*:

- $SID(\mathcal{T}, \mathcal{T}^*) = \frac{1}{|\xi|} \sum_{\forall \langle R, t_b, t_e \rangle \in \xi} \frac{|\mathcal{Q}_1(\mathcal{T}, R, t_b, t_e) - \mathcal{Q}_1(\mathcal{T}^*, R, t_b, t_e)|}{\max(\mathcal{Q}_1(\mathcal{T}, R, t_b, t_e), \mathcal{Q}_1(\mathcal{T}^*, R, t_b, t_e))}$ where ξ is a set of SI queries as defined in Section 6.2.2 (definition of SI adapted to non-uncertain trajectories).
- $AID(\mathcal{T}, \mathcal{T}^*) = \frac{1}{|\xi|} \sum_{\forall \langle R, t_b, t_e \rangle \in \xi} \frac{|\mathcal{Q}_2(\mathcal{T}, R, t_b, t_e) - \mathcal{Q}_2(\mathcal{T}^*, R, t_b, t_e)|}{\max(\mathcal{Q}_2(\mathcal{T}, R, t_b, t_e), \mathcal{Q}_2(\mathcal{T}^*, R, t_b, t_e))}$ where ξ is a set of AI queries as defined in Section 6.2.2 (definition of AI adapted to non-uncertain trajectories).

For our experiments with the synthetic data set, we chose random time intervals $[t_b, t_e]$ such that $0 \leq t_e - t_b \leq 10$. Also, we chose random uncertain trajectories with a randomly chosen radius $0 \leq \sigma \leq 750$ as regions R . Actually, 10 and 750 are, respectively, roughly a quarter of the average duration and distance of all trajectories. Note that we

used uncertain trajectories *only* as regions R ; however, the methods we are considering in this chapter all release non-uncertain trajectories.

Armed with these settings, we ran 100,000 times both queries \mathcal{Q}_1 and \mathcal{Q}_2 on the original data set and the anonymised data sets provided by SwapLocations, ReachLocations, and (k, δ) -anonymity; that is, we took a set ξ with $|\xi| = 100,000$. The ideal range query distortion would be zero, which means that query \mathcal{Q}_i for $i \in 1, 2$ yields the same result for both the original and the anonymised data sets; in practice, zero distortion is hard to obtain. Therefore, in order to compare our methods against (k, δ) -anonymity, we use the same parameters of the previous experiments (Tables 6.1, 6.2, and 6.3). We show in Tables 6.6 and 6.7 a comparison of SwapLocations, respectively ReachLocations, against (k, δ) -anonymity in terms of SID and AID.

It can be seen from Table 6.6 that SwapLocations performs significantly better than (k, δ) -anonymity for every cluster size and $\delta \leq 3000$. On the other hand, Table 6.7 shows that ReachLocations outperforms (k, δ) -anonymity only for δ up to roughly 2000. Not surprisingly, SwapLocations offers better performance than ReachLocations, because the latter must deal with reachability constraints. It is also remarkable that ReachLocations performs much better in terms of SID than in terms of AID. The explanation is that, while (k, δ) -anonymity and SwapLocations operate at the trajectory level, ReachLocations works at the location level.

We conclude that, according to these experiments, our methods perform better than (k, δ) -anonymity regarding range query distortion for values of δ up to 2000. The performance for larger values of δ is less and less relevant: indeed, when $\delta \rightarrow \infty$, (k, δ) -anonymity means that no trajectory needs to be anonymised and hence the anonymised trajectories are the same as the original ones.

6.6.2 Results on real-life data

The San Francisco cab data set [188] we used consists of several files each of them containing the GPS information of a specific cab during May 2008. Each line within a file contains the space coordinates (latitude and longitude) of the cab at a given time. However, the mobility trace of a cab during an entire month can hardly be considered a single trajectory. We used big time gaps between two consecutive locations in a cab mobility trace to split that trace into several trajectories. All trajectory visualisations shown in this Section were obtained using Google Earth.

For our experiments we considered just one day of the entire month given in the real-life data set, but the empirical methodology described below could be extended to several days. In particular, we chose the day between May 25 at 12:04 hours and May 26 at 12:04 hours because during this 24-hour period there was the highest concentration of locations in the data set. We also defined the maximum time gap in a trajectory as 3 minutes; above 3 minutes, we assumed that the current trajectory ended and that the

$\delta \setminus k$	2		4		6		8		10		15	
	S	A	S	A	S	A	S	A	S	A	S	A
0	34	29	31	14	36	16	36	13	37	13	43	14
1000	24	20	24	8	28	10	27	8	28	9	41	14
2000	18	14	18	4	20	3	20	2	27	6	39	10
3000	8	3	11	-2	13	0	16	-1	21	4	36	10
4000	-6	-7	6	-6	9	-5	11	-4	17	2	30	5
5000	-22	-19	1	-9	3	-9	7	-7	14	-2	27	2

Table 6.6: Range query distortion of SwapLocations compared to (k, δ) -anonymity for SID (columns labeled with **S**) and AID (columns labeled with **A**) when using $k = \{2, 4, 6, 8, 10, 15\}$ and space thresholds that match the space distortion caused by (k, δ) -anonymity with the previous k 's and $\delta = \{0, 1000, 2000, 3000, 4000, 5000\}$. In this table, a range query distortion x obtained with SwapLocations and a range query distortion y obtained with (k, δ) -anonymity are represented as the integer rounding of $(y - x) * 100$. Hence, values in the table are positive if and only if SwapLocations outperforms (k, δ) -anonymity.

$\delta \setminus k$	2		4		6		8		10		15	
	S	A	S	A	S	A	S	A	S	A	S	A
0	34	25	28	12	33	10	32	5	31	5	37	6
1000	25	19	21	6	24	4	23	1	25	2	35	5
2000	10	10	8	-7	17	-3	19	-3	23	-3	33	4
3000	-4	2	0	-12	9	-12	13	-5	19	-4	29	1
4000	-11	-6	-6	-18	-2	-17	3	-16	13	-6	26	-3
5000	-14	-5	-10	-22	-8	-25	-4	-21	8	-14	20	-5

Table 6.7: Range query distortion of ReachLocations compared to (k, δ) -anonymity for SID (columns labeled with **S**) and AID (columns labeled with **A**) when using $k = \{2, 4, 6, 8, 10, 15\}$ and space thresholds that match the space distortion caused by (k, δ) -anonymity with the previous k 's and $\delta = \{0, 1000, 2000, 3000, 4000, 5000\}$. In this table, a range query distortion x obtained with ReachLocations and a range query distortion y obtained with (k, δ) -anonymity are represented as the integer rounding of $(y - x) * 100$. Hence, values in the table are positive if and only if ReachLocations outperforms (k, δ) -anonymity.

next location belonged to a different trajectory. This choice was based on the average time gap between consecutive locations in the data set, which was 88 seconds; hence, 3 minutes was roughly twice the average. In this way, we obtained 4582 trajectories and 94 locations per trajectory on average.

The next step was to filter out trajectories with strange features (outliers). These outliers could be detected based on several aspects like velocity, city topology, etc. We focused on velocity and defined 240 km/h as the maximum speed that could be reached by a cab. Consequently, the distance between two consecutive locations could not be greater than 12 km because the maximum within-trajectory time gap was 3 minutes. This allowed us to detect and remove trajectories containing obviously erroneous locations; Figure 6.4 shows one of these removed outliers where a cab appeared to have jumped far into the sea probably due to some error in recording its GPS coordinates. Altogether, we removed 45 outlier trajectories and we were left with a data set of 4547 trajectories with an average of 93 locations per trajectory. Figure 6.5 shows the ten longest trajectories (in number of locations) in the final data set that we used.

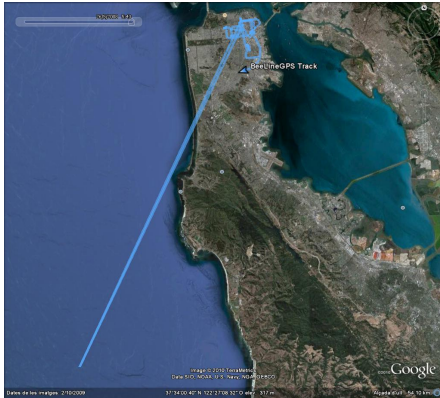


Figure 6.4: Example of an outlier trajectory in the original real-life data set

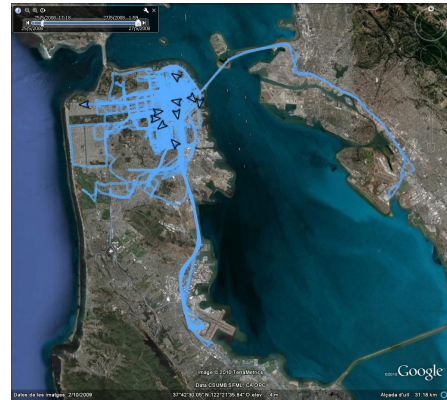


Figure 6.5: Ten longest trajectories in the filtered real-life data set

6.6.2.1 Experiments with the distance metric

We propose in this chapter a new distance metric designed specifically for clustering trajectories. Our distance metric considers both space and time, dealing even with non-overlapping or partially-overlapping trajectories. Contrary to the synthetic data where 10 trajectories had to be removed because the distances to them could not be computed, in this real-life data set our distance function could be computed for every pair of trajectories.

Figure 6.6 shows two trajectories identified by our distance metric as the two closest ones in the data set. The two cabs moved around a parking lot and therefore stayed

very close to one another in space. Also in time both trajectories were very close: one of them was recorded between 12:00:49 hours and 13:50:47 hours, while the other was recorded between 12:00:25 hours and 13:52:30 hours. Therefore, both trajectories were correctly identified by our distance metric as being close in time and space; they could be clustered together with minimum utility loss for anonymisation purposes.

To compare, Figure 6.7 shows two trajectories identified by the Euclidean distance as the two closest ones in the data set. These trajectories are located in a parking lot inside San Francisco Airport and, spatially, they are closer than the two trajectories shown in Figure 6.6. However, one of these trajectories was recorded between 24:42:55 hours and 24:55:59 hours, while the other was recorded between 19:05:29 hours and 19:06:15 hours. Hence, they should not be in the same cluster, because an adversary with time knowledge can easily distinguish them.

6.6.2.2 Experiments with the SwapLocations method

The ReachLocations method cannot be used when the graph of the city is not provided. Hence, in the experiments with the San Francisco real data we just considered the SwapLocations method. As in the experiments with synthetic data, we set $\Omega = 0$ during the computation of the total space distortion. Figure 6.8 shows the values of total space distortion given by the SwapLocations for different space thresholds and different cluster sizes.

Two other utility properties we are considering in this work are: percentage of removed trajectories and percentage of removed locations. Table 6.8 shows the values obtained with the SwapLocations method for both utility properties.

Finally, Table 6.9 reports the performance of SwapLocations regarding spatio-temporal range queries. We picked random time intervals of length at most 20 minutes. Also, random uncertain trajectories with uncertainty threshold of size at most 7 km were chosen as the regions. Analogously to the experiments with the synthetic data set, 20 and 7 are roughly a quarter of the average duration and distance of all trajectories, respectively. It can be seen that the SwapLocations method provides low range query distortion for every value of k when the space threshold is small, *i.e.* when the total space distortion is also small. However, the smaller the space threshold, the larger the number of removed trajectories and locations (see Table 6.8). This illustrates the trade-off between the utility properties considered.

6.7 Conclusions

In this chapter, we have presented two permutation-based heuristic methods to anonymise trajectories with the common features that: (i) places and times in the anonymised trajectories are true original places and times with full accuracy; (ii) both

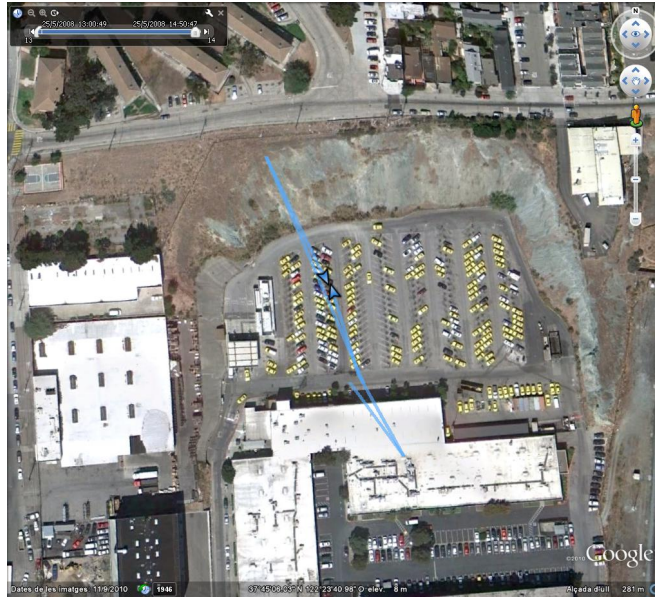


Figure 6.6: The two closest trajectories in the real-life data set according to our distance metric

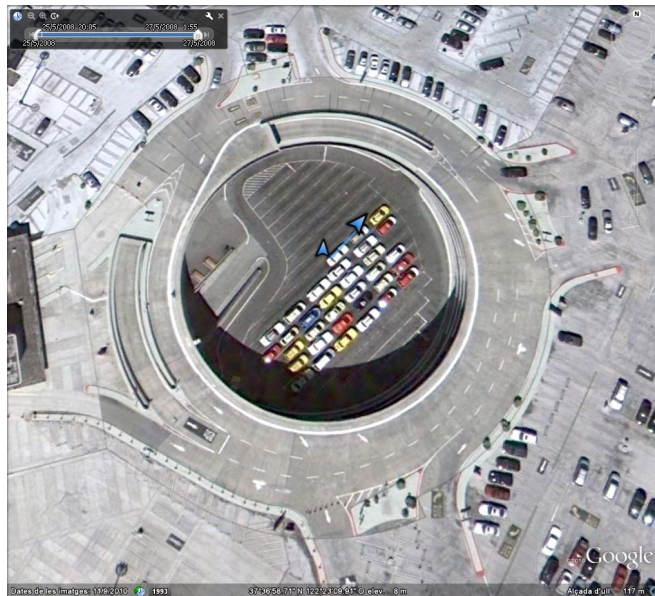


Figure 6.7: The two closest trajectories in the real-life data set according to the Euclidean distance

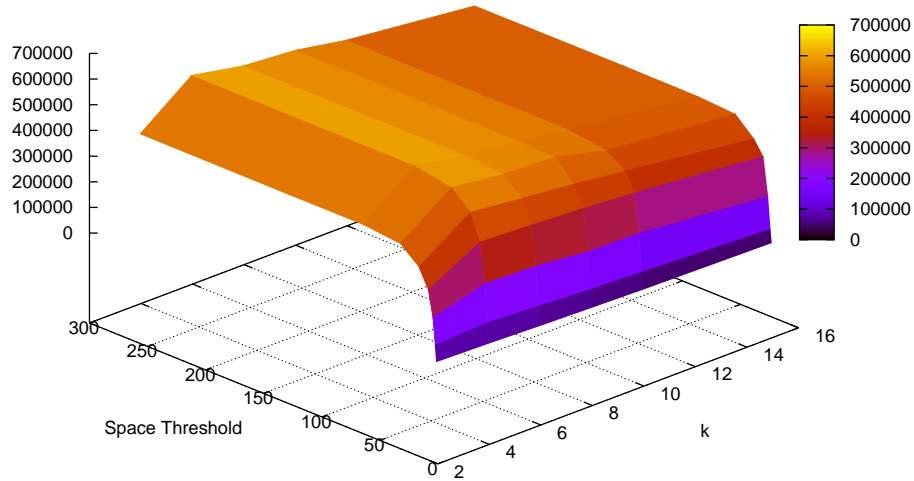


Figure 6.8: Total space distortion (km) for SwapLocations using several different space thresholds and cluster sizes on the real-life data set

$R^s \setminus k$	2		4		6		8		10		15	
	T	L	T	L	T	L	T	L	T	L	T	L
1	23	43	40	64	49	71	58	74	62	77	71	81
2	19	29	34	47	42	54	50	58	54	60	50	66
4	14	17	27	29	35	35	40	40	45	41	54	49
8	9	10	19	19	25	25	31	29	34	31	42	38
16	5	7	11	16	17	22	20	27	23	30	32	38
32	1	7	2	15	3	22	4	27	5	30	8	38
64	0	6	0	15	0	22	0	27	0	30	0	38
128	0	6	0	15	0	22	0	27	0	30	0	38

Table 6.8: Percentage of trajectories (columns labeled with **T**) and locations (columns labeled with **L**) removed by SwapLocations for several values of k and several space thresholds R^s on the real-life data set. Percentages have been rounded to integers for compactness.

methods can deal with trajectories with partial or no time overlap, thanks to a new distance also introduced in this paper. The first method aims at trajectory k -anonymity while the second method takes reachability constraints into account, that is, it assumes a territory constrained by a network of streets or roads; to avoid removing too many locations, the second method changes its privacy ambitions from trajectory k -anonymity to location k -diversity.

Both methods use permutation of locations, and the first method uses also trajectory microaggregation. There are few counterparts in the literature comparable to the first method, and virtually none comparable to the second method. Experimental results show that, for most parameter choices and for similar privacy levels, our methods offer better utility than (k, δ) -anonymity.

$R^s \setminus k$	2		4		6		8		10		15	
	S	A	S	A	S	A	S	A	S	A	S	A
1	13	22	18	27	20	29	19	29	24	31	25	34
2	16	24	25	34	26	35	24	35	27	37	27	37
4	18	25	30	37	33	41	34	42	38	46	38	45
8	21	27	34	40	38	44	40	46	44	50	48	54
16	20	26	36	42	42	47	45	50	50	54	53	58
32	21	26	39	44	45	49	48	53	53	57	58	62
64	20	25	39	44	46	50	51	54	54	57	61	64
128	21	26	39	44	48	50	51	56	54	58	61	64

Table 6.9: Range query distortion caused by SwapLocations on the real-life data set for SID (columns labeled with **S**) and AID (columns labeled with **A**), for several values of k and several space thresholds R^s . In this table, a range query distortion x is represented as the integer rounding of $x * 100$ for compactness.

Conclusions

This chapter summarises the contributions of the present dissertation. In addition, it sketches some lines for future work that arise from either partially reached goals or expected improvements.

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In this thesis we have focussed on security, privacy, and scalability issues in the RFID technology. We have considered RFID identification protocols based on symmetric key cryptography, which seem to be the most suitable for low-cost RFID tags. We have also dealt with the challenges behind measuring the distance between tags and readers in order to improve the security of any RFID identification protocol. Since the RFID technology is becoming more and more popular, we noticed that there is an increasing need for new trajectory anonymisation algorithms. For this reason, the last contribution in this dissertation is devoted to this subject.

7.1 Contributions

In more detail, our contributions are:

1. We have presented a communication-efficient protocol for collaborative RFID readers to privately identify RFID tags. With the presented protocol, the centralised management of tags can be avoided, along with bottlenecks and undesired delays.
2. We have presented a novel protocol that uses location and time of arrival predictors to improve the efficiency of the widely accepted IRHL scheme. We have shown that our protocol outperforms previous proposals in terms of scalability whilst guaranteeing the same level of privacy and security.

3. We have contributed to the design of distance-bounding protocols by: (i) providing a way to compute an upper bound on the distance-fraud probability, which is useful for analysing previous protocols and designing future ones; (ii) re-analysing the mafia fraud probability of the Kim and Avoine protocol [126]; (iii) proposing a new distance-bounding protocol that strikes a better balance than all previously published distance-bounding protocols between memory consumption, distance fraud resistance, and mafia fraud resistance.
4. We have presented two permutation-based heuristic methods to anonymise trajectories with the common features that: (i) places and times in the anonymised trajectories are true original places and times with full accuracy; (ii) both methods can deal with trajectories with partial or no time overlap, thanks to a new distance also introduced in this dissertation. The first method aims at trajectory k -anonymity while the second method takes reachability constraints into account, that is, it assumes a territory constrained by a network of streets or roads; to avoid removing too many locations, this second method changes its privacy ambitions from trajectory k -anonymity to location k -diversity.

7.2 Publications

The main publications supporting the content of this thesis are the following:

- Rolando Trujillo-Rasua, Benjamin Martin, and Gildas Avoine. The Poulidor distance-bounding protocol. In *The 6th Workshop on RFID Security and Privacy - RFIDSEC 2010*, pages 239–257, 2010.
- Josep Domingo-Ferrer, Michal Sramka, and Rolando Trujillo-Rasua. Privacy-preserving publication of trajectories using microaggregation. In *Proceedings of the SIGSPATIAL ACM GIS 2010 International Workshop on Security and Privacy in GIS and LBS, SPRINGL 2010*, San Jose, California, USA, 2 November 2010. ACM, pages 26–33, 2010.
- Rolando Trujillo-Rasua and Agusti Solanas. Efficient probabilistic communication protocol for the private identification of RFID tags by means of collaborative readers. *Computer Networks*, 55(15):3211–3223, 2011.
- Rolando Trujillo-Rasua and Agusti Solanas. Scalable trajectory-based protocol for RFID tags identification. In *The IEEE International Conference on RFID Technologies and Applications - RFID-TA*, pages 279–285, 2011.
- Josep Domingo-Ferrer and Rolando Trujillo-Rasua. Microaggregation- and permutation-based anonymization of movement data. *Information Sciences*, <http://dx.doi.org/10.1016/j.ins.2012.04.015>.

- Rolando Trujillo-Rasua, Agusti Solanas, Pablo A. Pérez-Martínez and Josep Domingo-Ferrer. Predictive protocol for the scalable identification of RFID tags through collaborative readers. *Computers in Industry*, <http://dx.doi.org/10.1016/j.compind.2012.03.005>.
- Josep Domingo-Ferrer and Rolando Trujillo-Rasua. Anonymization of trajectory data. *7th Joint UNECE/Eurostat Work Session on Statistical Data Confidentiality*, Tarragona, Catalonia, 26-28 October 2011. Published at http://www.unece.org/fileadmin/DAM/stats/documents/ece/ces/ge.46/2011/32_Domingo-Trujillo.pdf.

Other publications co-authored by the candidate and related to RFID systems, but not included in this thesis, are listed below:

- Albert Fernández-Mir, Rolando Trujillo-Rasua, Jordi Castellà-Roca and Josep Domingo-Ferrer. Scalable RFID authentication protocol supporting ownership transfer and controlled delegation. In *The 7th Workshop on RFID Security and Privacy - RFIDSEC 2011*, Amherst, Massachusetts (USA), pages 147–162, Jun 2011.
- Rolando Trujillo-Rasua, Antoni Martínez-Ballesté and Agusti Solanas. Revisión de protocolos para la identificación escalable, segura y privada en sistemas RFID. *5as Jornadas Científicas sobre RFID*, Tarragona, Catalonia, 2011. Published at <http://crises2-deim.urv.cat/articles/index/type/conferences#672>.

7.3 Future work

Next, we sketch possible lines for future work in the same order in which we have presented our main contributions.

1. Our first proposal based on collaborative readers (see Chapter 3) opens at least the following research issues: (i) study the effect of the number of neighbours, (ii) propose methods to dynamically vary p so as to adapt it to tag movements, (iii) propose hybrid methods that mix hash-based solutions and tree-based solutions with collaborative readers.
2. In Chapter 4 we partially tackle the second issue explained above by proposing some algorithms aimed at location prediction. However, those predictors may work well in some scenarios, but their performance decreases in others. Although we have provided some practical implementations for the predictors, the definition of our protocol is flexible enough to accept the use of any location predictor. Due to the fact that the efficiency of our proposal highly depends on the accuracy of

the predictors we plan to study and compare a variety of predictors in different scenarios in the future.

3. Chapter 5 introduces the graph-based protocol concept, which in turn suggests lines for further work. First of all, an interesting question is to know if there are graph-based protocols that behave still better than the one presented here. In particular, if the number of rounds is not a critical parameter, prover and verifier may be allowed to increase the number of rounds while keeping a $2n$ -node graph. This means that some nodes may be used twice. In such a case, the security analysis provided in this paper must be refined. On the other hand, although a bound on the distance fraud success probability is provided, calculating the exact probability of success is still cumbersome.
4. Regarding trajectory anonymisation, the future work will be directed towards designing trajectory anonymisation methods aimed at achieving trajectory p -privacy (see Definition 25), but discarding less locations than the SwapLocations method. Also, finding trajectory anonymisation methods for constrained territories with better utility than ReachLocations is an open challenge.

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