Study and development of wireless sensor network architecture tolerant to delays

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Abstract

Transport has become fundamental in the cities to the well functioning of the economy and the welfare of the city population. For several years, transportation faces many issues such as traffic jamming, high accidents rate, unhealthy life due to smoke and dust, air pollution as a result of carbon emission, etc. To deal with these matters, researches integrate digital technologies to ground transportation which is known as Intelligent Transport System (ITS). ITS can sense, analyze, collect, control and communicate different data. This thesis investigates and proposes a new protocol for data collection applications in an urban environment.

We make three main contributions: firstly, we propose a new protocol denoted the "Internet of Bikes" IoB-DTN protocol which applies Delay/Disruption Tolerant Network (DTN) paradigm to the Internet of Things (IoT) applications running a data collection application on urban bike sharing system based sensor network. The protocol is evaluated on a realistic scenario by assessing the buffer management policies, the number of copies sprayed in the network as well as the number of bicycles used. Secondly, a comparative evaluation of the performance of the multi-hop IoB-DTN protocol with a low-power wide-area network (LPWAN) technology, LoRa/LoRaWAN type is investigated. LPWAN have been designed to provide cost-effective wide area connectivity for small throughput IoT applications: multiyear lifetime and multikilometer range for battery-operated mobile devices. This part of our work aims at providing network designers and managers insights on the most relevant technology for their urban applications that could run on bike sharing systems. Finally, we propose an efficient IoB-DTN protocol based on data aggregation mechanism. We propose three variants of IoB-DTN: IoB based on spatial aggregation (IoB-SA), IoB based on temporal aggregation (IoB-TA) and IoB based on spatio-temporal aggregation (IoB-STA). We compare the three variants with the multi-hop IoB-DTN protocol without aggregation and the low-power long-range technology, LoRa type. Comparison results verify that the three variants of IoB-DTN based on data aggregation improve several metrics such as the delivery rate, energy consumption and throughput.

Résumé

Le transport est devenu fondamental dans les villes pour le bon fonctionnement de l'économie et le bien-être de la population urbaine. Depuis plusieurs années, le transport est confronté à de nombreux problèmes tels que l'embouteillage, le taux élevé d'accidents, la vie malsaine due à la fumée et à la poussière, la pollution atmosphérique due aux émissions de carbone, etc. Pour faire face à ces problèmes, les recherches intègrent les technologies numériques au transport terrestre, connu sous le nom de système de transport intelligent (ITS). Les ITS peuvent détecter, analyser, collecter, contrôler et communiquer différentes données. Cette thèse étudie et propose un nouveau protocole pour les applications de collecte de données dans un environnement urbain.

Nous faisons trois contributions principales. Tout d'abord, nous proposons un nouveau protocole dénommé le protocole "Internet of Bikes" IoB-DTN qui applique le paradigme DTN (Réseau tolérant aux délais) aux applications de l'Internet des objets (IoT) exécutant une application de collecte de données sur un système de partage de vélo urbain basé sur un réseau de capteurs. Le protocole est évalué sur un scénario réaliste en évaluant les politiques de gestion des buffers, le nombre de copies pulvérisé dans le réseau ainsi que le nombre des vélos utilisés . Deuxiément, une évaluation comparative des performances du protocole IoB-DTN multi-sauts avec une technologie de réseau étendu à basse consommation (LPWAN), de type LoRa/LoRaWAN est étudiée. LPWAN a été conçu pour fournir une connectivité à grande distance et rentable pour les applications IoT à faible débit: durée de vie de plusieurs années et une portée de multikilomètres pour les appareils mobiles alimentés par des batteries. Cette partie de notre travail vise à fournir aux concepteurs et aux managers de réseaux des idées sur la technologie la plus pertinente pour leurs applications urbaines pouvant fonctionner sur des systèmes de partage de vélos. Enfin, nous proposons un protocole efficace, IoB-DTN basé sur un mécanisme d'agrégation de données. Nous proposons trois variantes de IoB-DTN: IoB basé sur l'agrégation spatiale (IoB-SA), IoB basé sur l'agrégation temporelle (IoB-TA) et IoB basé sur l'agrégation spatio-temporelle (IoB-STA). Nous comparons les trois variantes avec le protocole multi-saut IoB-DTN sans agrégation et la technologie à faible puissance et longue portée, de type LoRa. Les résultats de la comparaison permettent de vérifier que les trois variantes de l'IoB-DTN basées sur l'agrégation de données améliorent plusieurs paramètres tels que le taux de livraison, la consommation d'énergie et le débit.

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Finally, my thanks would not be complete without thanking my parents, for their patience and comprehension by which they surrounded me throughout my studies, my sisters and my family. I would like to extend my special gratitude to my beloved husband, without him this thesis would never have been born, for his moral support, motivation, encouragement, valuable advice and more for the love he has shown me all these years, allowing me to build myself as a researcher.

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List of Abbreviations

DTN	**D**elay **T**olerant **N**etwork
BP	**B**undle **P**rotocol
URL	**U**niform **R**esource **L**ocator
RUNES	**R**econfigurable **U**biquitous **N**etworked **E**mbedded **S**ystems
PRoPHET	**P**robabilistic **Ro**uting **P**rotocol using **H**istory of **E**ncounters and **T**ransitivity
RAPID	**R**esource **A**llocation **P**rotocol for **I**ntentional **D**TN
TTL	**T**ime **T**o **L**ive
IoT	**I**nternet **o**f **T**hings
WSN	**W**ireless **S**ensor **N**etwork
MEs	**M**obile **E**lements
ICT	**I**nformation and **C**ommunication **T**echnologies
ITS	**I**ntelligent **T**ransport **S**ystem
IoT	**I**nternet of **T**hings
LPWAN	**L**ow-**P**ower **W**ide-**A**rea **N**etwork
rssi	**R**eceived **S**ignal **S**trength **I**ndication
snr	**S**ignal to **N**oise **R**atio

Chapter 1

Introduction

1.1 Overview on smart cities

The urban population of the world has grown quickly since 1950, from 746 million to 3.9 billion in 2014. The United Nations Population Division shows that from 1950 to 2050, the part of world's population living in urban areas will grow from 30% to 70% [1]. This migration from rural areas to urban areas has been going on in developing countries, thus increasing the concentration in cities. The large scale urbanization results in enormous negative effects such as unhealthy life by cause of smoke and dust, air pollution by reason of carbon emission, traffic congestion, crowded neighborhoods, transportation issues, dirty streets, noise, etc.

Therefore, there is a need to use information and communication technologies (ICT) to control and improve the urban services quality or to reduce its costs. In such case, we talk about smart cities. A smart city is an urban area that uses different sensors for data collection in order to provide information that can manage effectively the resources. The data can be collected from citizens, mechanical devices, water supply networks, waste management, schools, libraries, hospitals, etc. Indeed, smart city technology allows municipal officials to interact directly with community and urban infrastructures as well as to monitor the city and its evolution. The main functions of smart cities are developed to manage the urban flows and enable real-time responses. Other terms have been used for similar concepts such as digital city, electronic communities, information systems.

1.2 Wireless sensor networks for smart cities

A wireless sensor network (WSN) is a set of hundreds or thousands wireless sensor nodes which are battery-powered tiny devices and can measure several interesting parameters for better city management. It is a specific technology that helps create smart cities. Sensors are able to sense, process, communicate and transmit data, in a certain geographical area, to sink nodes as depicted in Figure A.1.

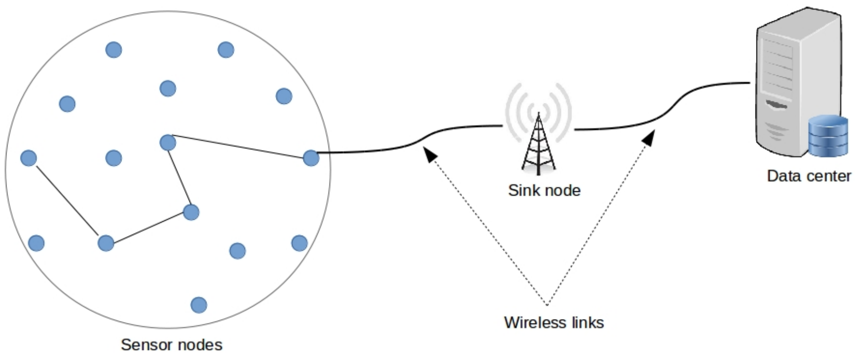


FIGURE 1.1: Wireless Sensor Network architecture.

As shown in Figure 1.2, wireless sensor networks can sense different data related to varieties of applications, as for example smart agriculture [71], environment monitoring [87], transportation issues [8] and military surveillance [85]. All data are forwarded in real time to the concerned citizens or authorities. For example, citizens can monitor the level of air pollution in every street in the city or receive an alert when the level of radiation reached exceeds a certain limit. Garbage cans can also be smarter, sensors can trigger an alarm when they are almost full. Moreover, the road traffic can be controlled to dynamically change urban lighting. Similarly, the traffic can be reduced by using systems which detect the nearest parking space. In such case, the drivers are informed in real time and can quickly reach a free spot, saving time and fuel. All of this helps to reduce air pollution and traffic congestion, thus improving the life quality.

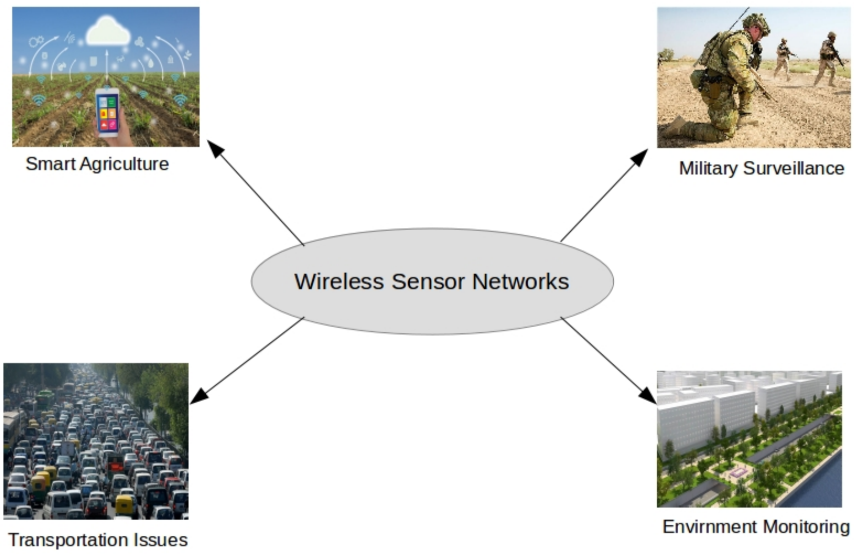


FIGURE 1.2: Some applications based on Wireless Sensor Networks.

In this thesis, we are interested in transportation issues. In fact, transport has become fundamental in the cities to the well functioning of the economy and the welfare of the city population. For several years, transportation faces many issues such as traffic jamming, high accidents rate, unhealthy life due to smoke and dust, air pollution as a result of carbon emission, etc. To deal with these matters, researches integrate digital technologies to ground transportation which is known as Intelligent Transport System (ITS). ITS can sense, analyze, collect, control and communicate different data.

1.3 Global view of data collection

1.3.1 Goals of data collection

Data collection is an approach to gather and measure data on targeted variables in order to get an accurate information of an area of interest [41]. The goal of data collection process is to answer pertinent questions that have been posed at the beginning, make hypotheses, assess results and make predictions about future events. In a wireless sensor network architecture, sensor nodes could be static or mobile densely deployed over a sensing area in order to sense, communicate, collect and forward data to base stations.

In the present thesis, we are interested to investigate a WSN architecture based on mobile elements (MEs) to collect data in an urban environment.

1.3.2 Data collection in smart cities

In the past few years, the accelerated increase of urban population in the world yields critical sustainable development challenges, in particular air pollution and transportation issues. Smart city strategies have been designed to offer solutions for sustainable urban life. In fact, data is collected from various sensor devices placed in the city. There are several mobile objects that can contribute in data gathering. One of the major objects is public transportation system. They have been designed to connect smart devices to the Internet and they have been used to collect data from mobile devices.

In our work, we focus on the use of bicycles as mobile objects in which sensors are mounted to collect data in the city. In effect, the increase number of vehicles causes traffic jam in the city. As well as other urban transportation systems like buses, subways are more suitable for long distance travel. Certainly, biking is emerging as one of the major sustainable transportation modes. Contributing to improve on congestion, accidents, noise, energy consumption, and air pollution, biking has a positive effect on the overall health [2]. It also seems that bicycles are better solution for short distance traveling thanks to its flexibility to save more time, physical power and cost. However, it still has some reluctance for bike users because of poor weather conditions, cycling danger, tiring, etc. There is therefore a worldwide trend to develop urban biking. In particular bike sharing systems are following a tremendous growth for a decade, covering more that 1,000 cities with more than a million bikes [106]. Consequently several digital services have been developed to assist bikers and enhance their urban experience. Most of up and running services are smartphone-based and are comparable to crowdsourcing/geolocalized applications.

This thesis focuses on the use of Internet of Things (IoT) on real networks and in particular on connected bikes. We are interested in opportunistic communications based on converge cast algorithm. Thus, we consider a smart bike sharing system to collect and transfer the data from bikes to a set of sinks.

1.4 Global Overview of Delay Tolerant Networks

In our work, we consider a "smart" bike sharing system in which bikes would have sensing and communicating capabilities, a small amount of memory and computing power, and a weak source of energy. We focus on the networking protocols that could support efficiently the collection of the data sensed by the bikes.

At first sight, wireless sensor networks protocols could be suitable. As discussed above, they are designed for sending data from measurement points to a set of sinks through radio communications. Some protocols support mobility and they run on constrained nodes. However, most of the multi-hop wireless routing protocols assume that the network is fully connected, tolerating short duty cycles for energy saving issues. Roughly, an end-to-end path has to be available, computed a priori or on demand, each time a packet is sent. This assumption is very strong and the signaling cost of most of these protocols rise with the dynamic of the network [96]. Beacon-less protocols have thus be introduced [9].

Delay Tolerant Networking (DTN) is an alternative paradigm. Tightly related to opportunistic communications, it is designed for intermittently connected networks resulting in a lack of instantaneous end-to-end paths between mobile devices [45] and thus facing long duration of partitioning, frequent movement, or limited storage and energy [122]. In this type of network, routing is performed over time to send data by employing long-term storage at the intermediate nodes. Most of DTN routing protocols are based on the store-carry-and-forward method : packets are stored in buffers of relay nodes, carried by the relay nodes, and forwarded as soon as the "next link" is available. Therefore, data will be relayed hop by hop until reaching its destination. However, usual DTN protocols are not suitable out-of-the-box for the context of IoT because of their need for higher computing power or memory storage. Several techniques to create DTN protocols for IoT have been studied, in particular by specializing each protocol to a given application [94].

1.5 Motivations of using DTN

Following the development of connected vehicle innovations, the idea to embed sensors and communication capabilities directly in bikes has emerged. Therefore, we are motivated to propose a "smart bikes" system that could then be able to sense and collect data of great use for municipalities and citizens, e.g. needs for road maintenance, air pollution where people are breathing deeply, ambient noise... Of course, the bikes being human powered and a comparatively cheap vehicle, a practical solution has to be low cost and low power. The forthcoming challenges hare thus closer to the field of IoT devices than traditional gas or electric cars [43, 84].

The first objective of this thesis is to investigate the existing works founded on communication which are based on public transport networks for data collection in an urban environment. The second one is to integrate the DTN paradigm with the Internet of Things in such system for data retention in the case of intermittent connections between mobile devices.

This idea motivates us to study and propose a new protocol which applies DTN paradigm to the IoT applications running a data collection application on urban bike sharing system based sensor network.

1.6 Contributions and organization

1.6.1 Contributions

The main contributions of this thesis are summarized as follows:

- Existing DTN routing protocols are reviewed and classified into three families: flooding, forwarding and coding strategies. A qualitative comparisons of these protocols with regard to four metrics is presented. We also evaluate and compare the performances of six DTN routing protocols in order to determine which is the best to fit in an urban environment.
- The "Internet of Bikes" IoB-DTN protocol which applies DTN paradigm to the Internet of Things applications running a data collection application on urban bike sharing system based sensor network is proposed. The performance of IoB-DTN with regard to two major parameters: buffer management policies and number of copies sprayed in the network.
- A comparative evaluation of the performance of the multi-hop IoB-DTN routing protocol with a low-power wide-area network (LPWAN) technology, LoRa/LoRaWAN type is investigated. Results are discussed to identify the best technology to adapt in IoT data collection applications running on urban bike sharing system.
- In order to improve the performances of IoB-DTN regarding several metrics, an efficient IoB-DTN protocol is proposed based on data aggregation approach. The data packets of different nodes are combined into a single packet before forwarding data. We propose three variants of IoB-DTN: IoB based on spatial aggregation (IoB-SA), IoB based on temporal aggregation (IoB-TA) and IoB based on spatio-temporal aggregation (IoB-STA).

1.6.2 Manuscript organization

This thesis is structured in six main chapters:

We firstly review the state-of-the-art of existing DTN routing protocols in Chapter 2. We mainly classify them into three families based on the property used to find the destination: flooding, forwarding and coding strategies. We give qualitative comparisons of the prominent DTN protocols with regard to four metrics. A performance evaluation of six existing DTN protocols is evaluated in order to determine the best one that can be adapted and applied in an urban environment.

In Chapter 3, we propose the "Internet of Bikes" IoB-DTN protocol being applied to mobile network IoT devices running a data collection application. The performance evaluation of IoB-DTN protocol is presented with regard to two major parameters: buffer management policies and number of copies sprayed in the network.

We give a more detailed performance evaluation of IoB-DTN protocol in Chapter 4. First, we evaluate the performances of the protocol with respect to the transmission power. Performances are measured in terms of delivery rate, delivery delay, throughput and energy cost. Secondly, we compare the multi-hop IoB-DTN protocol to a low-power wide-area network (LPWAN) technology, LoRa/LoRaWAN type.

In Chapter5, we introduce an efficient, "Internet of Bikes", IoB-DTN routing protocol based on data aggregation approach. We propose and assess three variants of IoB-DTN: IoB based on spatial aggregation (IoB-SA), IoB based on temporal aggregation (IoB-TA) and IoB based on spatio-temporal aggregation (IoB-STA).

Chapter 6 summarizes the main contributions of this manuscript as well as we discuss several perspectives to extend the work done in this thesis.

Chapter 2

Delay Tolerant Networking routing protocols

Today's network technologies are based on a set of basic assumptions that are not true in all environments. The first and the most important assumption is that a connection exists from a source to a destination possibly via several intermediates. This assumption can easily be violated because of the mobility, energy saving or unreliable networks. As example, if a wireless device is out of range of other active devices, it can not use any application that requires a communication on this network [56].

A first attempt to cope with these issues in mobile environment was mobile ad-hoc routing in which mobile nodes act as routers. Ad hoc routing protocols can be classified in two categories, proactive and reactive, depending on when and why routes are computed. In proactive routing, routes are calculated independently of traffic arrivals. Most of the Internet routing protocols and some ad hoc protocols such as DSDV (Destination Sequenced Distance Vector) [23, 16, 107, 61] and OLSR (Optimized Link-State Routing) are proactive [23, 12, 53, 88]. In reactive routing, routes are discovered on demand when the traffic must be delivered to an unknown destination. Ad hoc routing protocols such as AODV (Ad-hoc On-demand Distance Vector) [23, 58, 30, 7, 57] and DSR (Dynamic Source Routing) are examples of these protocols [23, 57, 121, 93]. These type of protocols use the route discovery protocol to determine the routes to destinations on demand. The main drawback of such algorithms is a high latency due to route finding. These protocols work best when communication patterns are relatively infrequent. More precisely, they can not provide paths between nodes that are not currently accessible. In such case, reactive protocols will not return a correct path while proactive protocols will determine that the pre-computed path is currently broken.

The Delay Tolerant Network (DTN) paradigm is an attempt to cope with these situations. The Delay Tolerant Networks are designed for low connectivity resulting in the absence of instantaneous end to end path. In these difficult environments, proactive and reactive routing protocols fail to establish routes. A "store, carry and forward" approach is used: data are progressively displaced and stored in buffers of intermediate nodes until they eventually reach their destinations. Several techniques have been proposed to maximize the probability of messages delivery to their destinations: messages replication, estimation of contacts probabilities, prior knowledge of mobility patterns, etc. The term Disruption Tolerant Network is sometimes used instead of Delay Tolerant Networks.

The objective of this chapter is to review existing DTN routing protocols and classify them into three families based on the property used to find the destination: flooding, forwarding and coding strategies. We give qualitative comparisons of the prominent DTN protocols representing each family by looking at the compromise between four criteria: resource consumption, latency, buffer time and delivery ratio. We focus on the application of Delay Tolerant Networking to the Internet of Things, in particular on urban scenarios. The performances of these DTN protocols are evaluated in order to determine the best one to be adapted and can be applied in an urban environment.

2.1 Model of the DTN network

2.1.1 Nodes

A DTN is an end-to-end transmission network that is asynchronous and message-oriented. In this regard, a DTN architecture is different from the Internet architecture [29]. It includes a new layer to the TCP/IP architecture denoted the bundle layer [25] as shown in Figure 2.1. The bundling protocol allows nodes to communicate forming an overlay that enables incessant storage in intermittent networks. Devices implementing the bundle layer are called DTN nodes. These nodes enhance the network path selection by using a naming mechanism based on Uniform Resource Locator (URL) and message encapsulation mechanism. Every node uses the network storage to manage, store and forward packets over multiple paths and longer periods. They have finite storage capacity and energy.

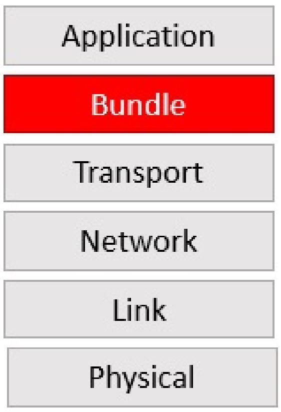


FIGURE 2.1: DTN architecture.

2.1.2 Messages

The communication requests are represented by messages. A message is a tuple (u, v, t, m) where u is the source, v is the destination, t is the time at which the message is injected into the system and m is the size of the message. The set of all messages is called traffic demand [52].

2.1.3 Edges

An edge is the link between two DTN nodes.

In the literature, Jain et al. [52] provide a framework for evaluating several DTN routing protocols with respect to the amount of the knowledge they require about network topology. The DTN graph used is a directed multi-graph in which more than one edge may exist between a pair of nodes as shown in Figure 2.2. So, it may be possible to choose between two physical types of connections to move data between the same pair of nodes. In addition, the capacity of links depends on time. An edge has zero capacity when it is unavailable. Thus the set of edges in the graph should capture time-varying capacity and the propagation delay. Every edge is characterized by the source node (u), the destination node (v), the capacity (c(t)) and the delay function (d(t)).

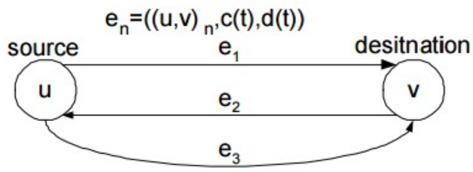


FIGURE 2.2: Links in DTN graph [52].

A contact is an opportunity to forward data over an edge. It represents a time interval, during which every capacity on the edge is able to send a message [52].

2.1.4 Path

A path represents an end-to-end connection between the source and destination nodes. The routing algorithm determines the path in order to forward a message. If there is not an available connection between nodes and as the DTN routing occurs in a store, carry and forward manner, the data are stored in the buffers of intermediate nodes and be assigned to contacts by the routing protocol at a later time [33].

2.2 State-of-the-art of DTN routing protocols

2.2.1 Strategies properties

Routing strategies in DTN are classified according to two properties [56]: replication and knowledge.

The replication property describes how a message is duplicated in each node. Indeed, the components used in DTN are unreliable or unpredictable. Many routing strategies use multiple copies of each message in order to increase the probability that one of them will be transmitted to the destination reducing thus the delivery delay. The most reliable approach is that each node carries a copy of the message. In this case the message is lost only if all nodes carrying this message are unable to deliver it. Nonetheless, the main drawback of this strategy is resources consumption of the bandwidth and the storage in the network.

The knowledge property defines how the strategy uses information on the network status to make routing decisions. The knowledge of information on the network changes from one strategy to another. In some strategies, nodes can make routing decisions without any knowledge on the network. In such case, each node applies the rules configured in the design of the approach. This leads to simple implementations that require minimal configuration and control messages. The drawback of this strategy is that it can not adapt to different networks or different conditions so that it does not make optimal decisions. In other strategies, nodes may need to know all the future schedule of all contacts in the network. If the information is accurate, this results in an efficient message transmission using the best path. Intermediate solutions achieve the trade off between the precision of the Knowledge required and the volume of control traffic.

2.2.2 Strategies families

DTN routing strategies are classified according to three families based on the strategy property used to find the destination. Strategies families are flooding strategies that are characterized by the messages replication, or forwarding strategies that rely on the network knowledge to select the best path to the destination or coding strategies. We first describe each family in general and then describe specific examples in each family.

2.2.2.1 Flooding strategies

Flooding strategies rely mostly on replication. Multiple copies of each message are delivered to a set of nodes called relays. These latter store messages and relay them to other nodes or to destinations at a later time. The first works in the field of DTN routing are included into this family. Traditionally these strategies have been studied in the context of mobile ad-hoc networks where random mobility had a good chance to connect the source with the destination. Message replication is then used to increase the probability of message delivery. The basic protocols of this family do not need to have information about the network however more advanced systems use knowledge to improve performance.

In the following, we classify the flooding strategies with respect to the memory necessary to store the messages in the buffers.

2.2.2.1.1 Memory saving

In the viewpoint of memory saving, only one copy of a message is sprayed in the network avoiding thus a waste of memory.

In the Direct Delivery strategy, the source node stores the data until it becomes in contact with the destination. It represents the depraved case of flooding families as well as for forwarding strategies since it always chooses the direct path between the source node and its destination. Nevertheless, this strategy does not require information about the network and uses only a single hop for data routing, so it is considered as a flood strategy [56, 89]. As a result of its simplicity, the Direct Delivery approach provides low resources consumption.

The First Contact routing strategy allows the source nodes to send the messages to the first contact and then to delete them from their buffers. In this case, messages can be forwarded by multiple nodes [82].

2.2.2.1.2 Limited memory

Some flooding strategies control the number of copies sprayed in the network in order to reduce resource consumption. Here, we present the strategies that require limited memory for data storage.

In Two-Hop Relay strategy, the message is copied to the first n nodes encountered by the source node making the total copies of data in the network to n + 1 [56]. The message is transmitted to the destination through the first contact by any node carrying the message. Hence the transmission occurs in two hops. This strategy consumes more bandwidth and storage capacity but it has a better chance of delivering the message to the destination that direct contact.

The RelayCast routing scheme extends the two-hop relay algorithm in the multicast scenario [68]. It allows multicast scenarios that have been proposed because of the low scalability of unicast networks. For each active cell, the source node transfers a new message to a relay node which is responsible for delivering packets directly to each multicast receiver. The algorithm aims to improve the throughput related to the wireless multicast using the mobile support routing. Scalability is the main feature exploited in this protocol.

The Tree based Flooding strategy extends the Two-Hop Relay algorithm by indicating the number of copies that the relay should make [46].

In RUNES (Reconfigurable Ubiquitous Networked Embedded Systems) strategy, each node keeps the cost in hops from the destination and the source in the form of a vector {m, n}. A message that is near to the source or to the destination is less likely to be deleted [34, 35].

The PRoPHET (Probabilistic Routing Protocol using History of Encounters and Transitivity) protocol calculates a meeting probability between two nodes based on contact history with each other [67, 73, 74]. At each meeting between nodes, the meeting probability value is updated. In this strategy, a message is copied to another node only when the probability of meeting its destination is larger than with the originating node. Therefore, this protocol achieves a high delivery probability allowing a low overhead.

The MaxProp protocol allows a priority in the packet queue [24]. Packets that must be removed and transferred are classified in this priority queue. The priority base may have several methods including the establishments'ratio of good roads or the number of acknowledgments, etc. This protocol increases the rate of messages delivery in general. MaxProp maintains an orderly queue in which the order is based on the destinations associated with each message.

The RAPID (Resource Allocation Protocol for Intentional DTN) protocol considers the DTN routing as a problem of resources allocation [14, 13]. It aims to improve the routing metrics such as the average delivery time, missed deadlines and the maximum delay. During the packet routing, the latter is replicated until a copy reaches the destination. For this, an utility function by packet was derived from the routing metric. This utility is assigned to each packet based on its contribution to this metric. Only packets that result in an increase of the utility function are replicated.

In order to minimize the resources consumption, Spyropoulos et al. have presented a new series of routing strategies that spray a few copies of messages in the network. Each copy is routed independently to the destination. Spray strategies generate only a small number of copies to ensure that the total number of transmissions is small and controlled. One of the famous routing protocols developed by Spyropoulos et al. is Spray-and-Wait protocol [105, 62, 103]. It includes two phases: Spray and Wait phases. For Spray phase, L copies of each message coming from the source node are initially propagated to L distinct relay nodes. For Wait phase, each node carrying a copy of the message switches to direct message forwarding to the destination if the target node is not found in the Spray phase. There is two modes of Spray and Wait protocol: normal and binary modes. In the normal mode, the sender node replicates a message to all encountered nodes. Only n nodes get a copy since there are n messages copies available. An improvement over Spray and Wait is Binary Spray and Wait [105]. The source node of a message initially starts with L copies; any node that has at least two copies and encounters another node having no copies, forwards n/2 stored copies and keeps n/2 for itself. When it is left with only one copy, the last copy is transmitted to final destination.

Spyropoulos et al have proposed a modification of Spray and Wait protocol which is called Spray and Focus [104]. The Wait phase is replaced by the Focus phase in which a single copy of the message is forwarded to a set of relay nodes according to a given sending criteria. This protocol is designed for specific applications where mobility of each node is located .

2.2.2.1.3 Unlimited memory

Some of DTN routing protocols diffuse multiple copies of messages in the network in order to increase the probability to reach destinations. These strategies require a large buffer memory to be able to record all data and have a high delivery rate.

The Epidemic routing protocol allows to distribute messages to nodes called carriers in the network [109]. In this case, all nodes may become carriers of the message. However, upon the contact with other nodes, they only exchange data that they don't have in their buffers. Therefore, this routing protocol is robust to node or network failures ensuring that all nodes eventually receive all messages in minimum time duration during random exchanges. This approach does not require to have information of the network but it requires large amounts of buffer space, bandwidth and power [17].

2.2.2.2 Forwarding strategies

Forwarding strategies use a traditional data routing approach in Delay Tolerant Networks. They require some knowledge about the network topology to select the best path to route the message from the source node to its destination. They do not use replication since they usually send one message across the best path chosen.

Here, we give a classification of forwarding strategies in terms of which node is responsible for routing decisions.

2.2.2.2.1 Source Routing

In Source Routing approach, only the source node should know the whole network topology [112]. It determines the path that messages must be followed by sending control packets to destination nodes.

Routing strategies based on the link metric look like routing protocols of traditional networks. They build a topology graph by assigning weights to each link and then they run the shortest path algorithm to find the best paths [56]. This requires much information about the network since each node must have enough knowledge to run the routing algorithm. The weights of the links are based on certain performance metrics: the highest bandwidth, the lowest latency and the highest delivery rate. In Delay Tolerant Networks, the most important metric is the delivery rate since the network must be able to deliver data reliably. The second metric is the delivery latency. Thus, this approach allows to determine an attribution system for metric links that maximizes the delivery rate and minimizes the delivery latency. Some metrics can also try to minimize the consumption of resources such as buffer space or energy. Jain et al. [52] used link metrics for routing in Delay Tolerant Networks. DTN routing problem depends on several input variables such as the characteristics of the dynamic topology and traffic demand. The complete knowledge of these variables facilitates the calculation of optimal routes. However, with partial knowledge, the ability to calculate optimal paths is low and the routing performance should be lower. Jain et al. created a set of abstractions called "knowledge oracles" to understand the tradeoff between knowledge and performance. These oracles are notations elements used to encapsulate particular knowledge about the network required by different algorithms. In Figure 2.3, the tradeoff between knowledge and performance is presented by indicating the expected performance and requirements of the oracles for each proposed routing algorithm.

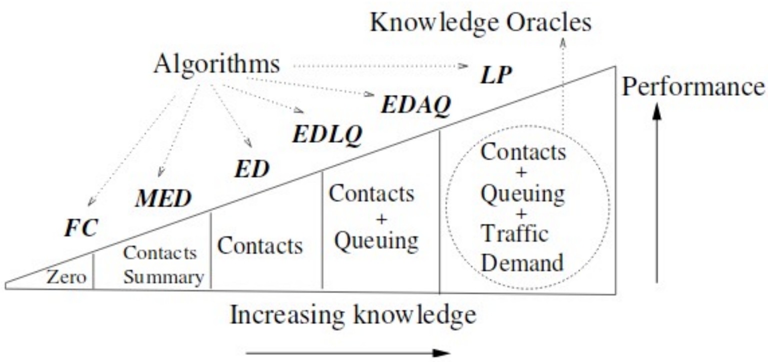


FIGURE 2.3: Tradeoff between knowledge and performance [52].

The contacts summary oracle provides global statistics of contacts and the average waiting time of a node to have the next contact. The second algorithm allows to know contacts between two nodes of the network at any point in the time. The queue oracle provides information about buffers occupation for any node at any time, it can be used also for routing congested nodes. The demand traffic oracle provides information about the current or future traffic demand. It is able to deliver the set of messages into the system at any time.

The authors proposed six transmissions algorithms by increasing the levels of knowledge:

1. First Contact (FC)
2. Minimum Expected Delay (MED)
3. Earliest Delivery (ED)
4. Earliest Delivery with Local Queuing (EDLQ)
5. Earliest Delivery with All Queuing (EDAQ)
6. Linear Program (LP)

The first algorithm (FC) does not use any information about the network to transmit messages. A message is transmitted through a randomly path chosen from the available contacts. MED uses the contacts summary oracle. It uses the Dijkstra algorithm [40] and link costs are invariant in the time. The link cost is the sum of the average waiting time, propagation delay and transmission delay. The ED algorithm uses the Dijkstra algorithm modified with functions which have variant costs over the time based on the waiting time. For EDLQ algorithm, the local queue occupation is taken into account to estimate the links delay. It uses also the Dijkstra algorithm modified with functions that have costs integrating the local queue. The EDAQ algorithm uses the queue oracle to determine sizes of instant queues of the entire topology at any point and time. The last LP algorithm uses all oracles to determine optimal routing minimizing the average delay in the network. As expected Jain et al. showed in their simulations that algorithms which have access to more information have better performance.

2.2.2.2.2 Per-Hop Routing

The intermediate node decides which next hop or next node the message must be sent according to the network topology [18]. It offers better performance than Source Routing approach due to the use of more updated information [27].

The Location based routing approach exploits the geographical coordinates of each node. A distance function is used to estimate the cost of transmitting messages from one node to another. The advantage of this approach is that it requires very little information about the network; it does not need routing tables and it reduces the overhead control. In order to determine the best path, a node needs to know its own coordinates, destination coordinates and those of possible next hops. So a node can easily calculate the distance function from the three informations and thus determine where the message must be forwarded. However this approach has two classic problems [19]. The first problem is that, even if the distance between two nodes is small, there is no guarantee that they are able to communicate. For example, in Figure 2.4, the node A wants to send a message to the node D. It has two possible next hops: the nodes B and C. As the node B is the closest to the node D, the node A sends the message to the node B. Nevertheless the node B can not communicate with the node D due to the obstruction while the node C has a vision to the node D. Therefore the message, may in some cases, does not reach the destination. The second problem is the change of nodes coordinates. If the nodes are moving, their physical coordinates change. Consequently, this complicates the routing of messages because the source node needs to know the coordinates of the destination node. Routing methods based on the location use the previous geographic location to help the packets routing in Delay Tolerant Networks.

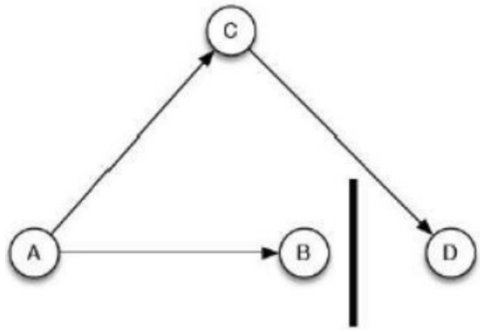


FIGURE 2.4: Location based routing.

Link et al. have proposed a disruption tolerant routing algorithm based on geographic location information called GeoDTN [75]. It codes the information history of geographical movements in a vector in order to predict the possibility that two nodes become neighbors. Then, the packets are forwarded to nodes which are more likely to be neighbors to the destination node.

In [64], Kurhinen et al. have introduced Predictive Graph Relay (PGR) routing scheme. It uses the mobility model of nodes to predict their future movements to transmit packets to a certain geographical destination.

Leontiadis et al. have presented GeoOpps, a geographical opportunistic routing for vehicular networks [70]. It exploits the navigation system to calculate the minimal estimated time of delivery (METD: Mininmal Estimated Time of Delivery). It considers the nearest point of possible routes to the destination and forwards packets to vehicles that drive with the lowest time delivery.

In MobyPoints, meetings probabilities of a node with all possible sites are encoded in vectors. Then, the forwarding decisions are made based on the notion of similarity between vectors of relay nodes and the destination node [69].

In [119], Yuan et al. have proposed an efficient routing algorithm for DTNs called PER (Predict and Relay). In PER, each node determines the future contacts time probability in order to select the best next hop for data forwarding.

In Per-Contact Routing, an update routing table is maintained by every intermediate node. The updated information is done for each contact [55]. Therefore the message is transmitted according to the latest information of the network topology. However the updates can create loops in the network.

The Gradient routing approach allows to assign a weight to each node that represents its ability to deliver messages to a given destination [91]. Upon a contact with a node having a best metric value for the message destination, the message is transmitted to this node. This approach is called Gradient routing because the message follows a degradation of improving the utility function values towards the destination [113]. This requires more knowledge about the network than Location based routing for two reasons. On one hand, each node must store a metric for all possible destinations. On the other hand, sufficient information must be propagated across the network to permit each node to calculate the metric for all destinations.

The metric can be based on many parameters such as the last contact time between the node and the destination, the probability of delivery, residual battery power or mobility.

Sandulescu et al. have introduced ORWAR, a resource-efficient protocol for opportunistic routing in delay tolerant networks [97]. ORWAR exploits the context of mobile nodes (speed, direction of movement and the radio range) to estimate the size of a contact window. This knowledge can make better transmission decisions and minimize the likelihood of partial sending messages. As well as optimizing the use of the bandwidth during overloads, this protocol helps to reduce energy consumption since the partial message transmission is useless. So there is no waste of transmit power. Another feature of this protocol is the use of a differentiation mechanism based on the utility function of the message. This allows more resources allocation for messages that have a high utility value. Their simulations show the benefits of this protocol: it allows to provide a low overhead and a high transmission rate by comparing it with several routing algorithms known as MaxProp and SprayAndWait.

In the past few years, some researches have analyzed the mobility having the same characteristics with the social network and have focused on the study of common social relationships and communications in daily life of people. Therefore the characteristics of social mobility are used to help routing decisions. Routing protocols of the best known social-based forwarding strategies are SimBet and BUBBLE.

In the SimBet routing protocol [38], the social networking model is defined as follows: the whole world is divided into several online communities based on different interests and occupations. Each one has its own community social frequency measured as its social level [78, 120]. Thus the social model has two problems: the division of the community and the social computing degrees. The community division is complemented by the community detection algorithm and the social degree is calculated as the sum of nodes that are directly or indirectly related to the destination node. In addition SimBet introduces the concept of similarity between two nodes as a metric to consider that the probability of meeting of these two nodes in the future is higher if both nodes have more common neighbors. The similarity between two nodes is calculated as the number of the same neighboring nodes. Then the social degree and similarity are synthesized in SimBet utility with an appropriate weight. During the message transfer, the relay nodes are selected based on the higher utility function of SimBet.

In [51], Hui et al. have proposed BUBBLE, a social-based forwarding in delay tolerant networks. This protocol uses a network model similar to SimBet while it calculates the social degree with another manner. It introduces the concept of communities in networks to enhance the data transmission efficiency. It uses information of nodes communities to make decisions for sending the messages. This protocol follows two perceptions: firstly nodes have different popularities in the community, so messages will be transmitted via the most popular nodes instead of the current node; secondly the interaction opportunity of different nodes belonging to the same community is high. Hence the protocol always appreciate the selection of the transmitting node that belongs to the destination community [78]. The message transmission is performed as follows: when the source has a message to a given destination, it builds a hierarchical tree based on the general classification until it reaches a node belonging to the destination community. Subsequently, the message is sent through a local classification tree until it reaches the destination or the lifetime of the message expires. In this approach, each node must be able to compare the classification with neighboring nodes and transmit the message to the most popular nodes.

2.2.2.2.3 Hierarchical Routing

Hierarchical Routing approach introduces the concept of nodes clustering based on communication characteristics and link property. The routing decisions are taken by the cluster head which is selected depending of some criteria. So this makes the traffic location more scalable [50, 66].

2.2.2.3 Coding strategies

Coding strategies use different types of coding techniques to encrypt data. Each data packet is encoded in a unique way using the network coding. Thus, packets leaving the source are generally coded. A node only needs to receive enough packets to decrypt the data which improves the global transmission rate. Among the most known protocols, we mention the EBEC (Estimation based Erasure Coding) and the HEC (Hybrid Erasure coding).

The EBEC protocol uses a fixed overhead for generating a large number of message blocks instead of some copies [72]. This allows the transmission of only one part of the message to the relay node. This ability increases the diversity of routing by combining it with an estimation based approach. When two nodes are in contact, a copy may or may not be generated in the other node based on its ability to be the better or the worse to transmit a message. When a node does not make a copy, this may be a risk in the case where the time between connections is large. The EBEC allows to copy a part of the message in the other node. This part of the message to transmit is calculated by an estimation technique. The contact frequency with the destination is used as a metric to estimate the capacity of a node for message delivery. For each message, the source has a replication factor R and erasing codes $R \times K$ with equal size blocks. The message can be fully decoded at the destination if there are at least K blocks generated that are received successfully. The overhead is simply the factor R.

The HEC protocol combines the erasure codes and an aggressive transmission mechanism [31]. The aggressive transmission mechanism is used to send all packets in a sequential manner during the period of contact nodes. If the battery of a node is dead or a node loses its mobility, it can not transmit data to the destination. This creates a phenomenon called information loss problem 'black hole'. The HEC model uses the contact nodes duration and applies the erasure codes to solve the problem of the black hole caused by the aggressive transmission.

2.3 Classification and comparison of DTN routing protocols

The DTN routing protocols discussed in previous section have advantages as well as drawbacks. Here, we give a classification as well as a comparison between them. The routing protocol selection is prominent and it depends

TABLE 2.1: Names list of DTN routing protocols.

Abbreviations	Protocol names	References
HEC	Hybrid Erasure Coding	[31]
RAPID	Resource Allocation Protocol	[14, 13]
LMR	Link Metric Routing	[56, 52]
ER	Epidemic Routing	[17, 109]
RC	Relay Cast	[68]
TBF	Tree Based Flooding	[46]
EBEC	Estimation based Erasure Coding	[72]
SR	Source Routing	[100]
PHR	Per Hop Routing	[55]
PCR	Per Contact Routing	[55]
HR	Hierarchical Routing	[77, 66]
GR	Gradient Routing	[113, 91]
LBR	Location Based Routing	[19]
THR	Two Hop Routing	[56]
DD	Direct Delivery	[56, 89]
SW	Spray and Wait	[105, 62, 103]
RUNES	Reconfigurable Ubiquitous Networked Embedded Systems	[34, 35]
FC	First Contact	[56, 89]
PRoPHET	Probabilistic Routing Protocol using History of Encounters and Transitivity	[67, 73, 74]

on the network scenario in addition to the application where the network is deployed. Some of these DTN protocols will perform very well but consume more network resources, while some of them give optimal solutions with less resources consumption. We have chosen the most used protocols that represent the three families mentioned in the previous section and we have looked at the compromise between two criteria: resource consumption and latency ; buffer time and delivery ratio. The names list presenting the protocols is given in Table 2.1.

2.3.1 Resource consumption and latency

From Figure 2.5, we notice that most of flooding protocols have low resource utilization and high latency in comparison to forwarding and coding families. More precisely, Epidemic routing protocol, belonging to flooding family, has an overall low performance while RAPID is the best one by giving the optimized performance: low resource consumption and latency. In coding family, Hybrid Erasure Coding protocol requires low latency against moderate resource consumption. It gives better performance than Estimation based Erasure Coding.

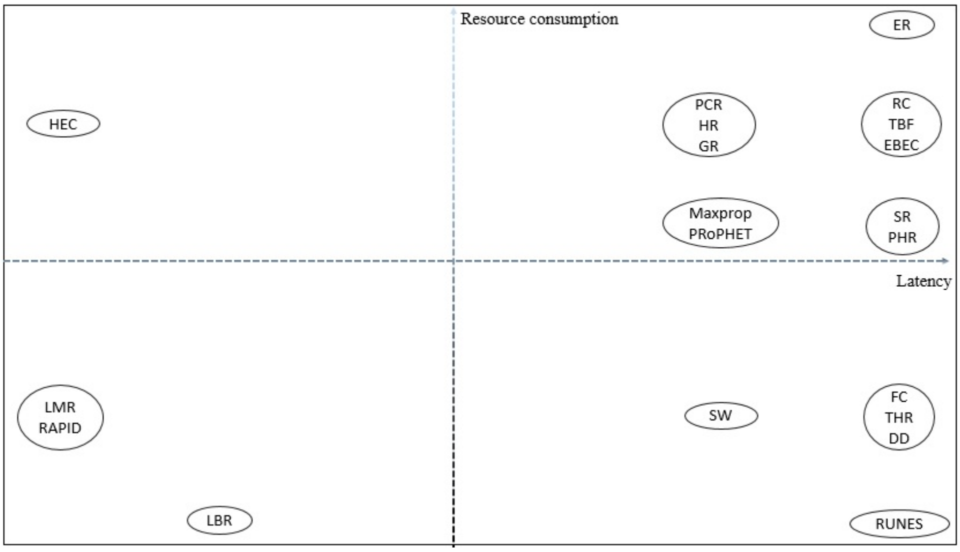


FIGURE 2.5: Comparison of DTN routing protocols with respect to the resource consumption and latency.

2.3.2 Buffer time and delivery ratio

In Delay Tolerant Networks, if the link is not available between two nodes, the packets at the source node will be stored in its buffer waiting the establishment of the link. Therefore, all the nodes should have enough buffer space to store all the packets. Since the memory size of each node is limited, we may have lost packets in the network. Thus, in terms of performance, there are some DTN protocols which require a few time to be stored in buffers of intermediate nodes but having a high delivery ratio whereas some of them demand high buffer time with a low delivery ratio. It is interesting to point out that the buffer time is proportional to the buffer size. In Figure 2.6, we present a comparison of DTN routing protocols with respect to the buffer time and delivery ratio.

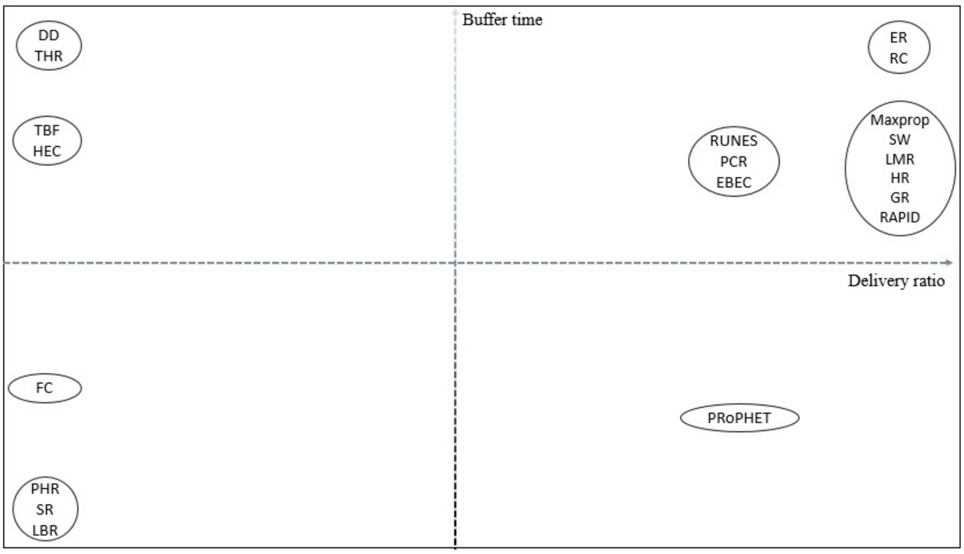


FIGURE 2.6: Comparison of DTN routing protocols with respect to the buffer time and delivery ratio.

The most of flooding based protocols have higher delivery ratio and buffer time than forwarding and coding based families. Per Hop Routing, Source routing and Location based Routing in forwarding based families require low buffer time to be stored and low delivery ratio than others. PRoPHET is the best in terms of performance since it has a high delivery ratio and requires a low buffer time.

From both comparisons presented above, we note that flooding and forwarding protocols require high latency and delivery ratio.

2.4 Related works-Communication based on public transport networks and DTN paradigm with the Internet of Things

As we illustrated in Chapter 1, our work is based on data collection in an urban environment. In particular, it extends a wealth of past works on communication based on two areas: public transport networks and DTN paradigm with the Internet of Things.

Communication based on public transport network has been stressed in a number of recent works. Latora et al. [65] have presented the first studies of networks based on urban transportation systems. They have highlighted the importance of the use of real transportation networks in order to overcome many problems. The DakNet [90] provides low-cost digital communication for remote villages in India and Cambodia. In order to avoid traditional connectivity solutions, buses are used in DakNet to forward data between Internet access points and Internet kiosks in villages. The KioskNet [98] uses buses and cars as "mechanical backhaul" devices for data transfer between remote villages and Internet gateway. The authors have rested on the pioneering lead of Daknet and have extended the DTN Research Group architecture [42] to propose a detailed architecture that addresses the problem of low-cost and reliable connectivity for rural kiosks. Zhao et al. [123] have proposed several vehicle-assisted data delivery (VADD) protocols for vehicular ad hoc networks in order to deliver the packet to the best road with the lowest data-delivery delay. The VADD is based on the carry and forward paradigm [109] where vehicles are used as data carriers and the path to the destination is determined based on the ad hoc connectivity of the vehicles. Their experimental results show that their proposed VADD protocols have better performances than existing solutions in terms of delivery rate, data packet delay and protocol overhead. In particular, the Hybrid Probe (H-VADD) protocol offers the best results. The UMass DieselNet project [24] studies the DTN routing in challenging environments such as power outages or natural disasters. A testbed was deployed, in 2005, to collect data between 40 buses in western Massachusetts. Each bus was equipped with two 802.11 radios, a GPS and 40GB hard drive. The data is forwarded via bus-to-bus communication. The UMass DieselNet has led to the design of the MaxProp routing protocol. The authors in [39] have investigated a public transport based sensor network, called BusNet. It implements a sensor network on top of the transport network to monitor the road surface condition. More specifically, it is designed to supervise environmental pollution using sensors embedded on public transport buses. This network generates and forwards data by using the stable transport infrastructure and it does not rely on the ad hoc connectivity between vehicles.

Bicycles have been also considered as an urban transport system that can collect and forward data. The BikeNet project [43] was the earliest work based on mobile networked sensing system for bikes. It is a mobile sensing system for mapping the cyclist experience. In other words, it uses a variety of sensors embedded into a cyclist's bike to gather quantitative data about the cyclist's rides. BikeNet uses a dual-mode operation to collect data using opportunistically encountered wireless access points in a delay-tolerant manner, and leveraging the cellular data channel of the cyclist's mobile phone for real-time communication in order to deliver the senses data. Nakamura et al. [86] have proposed a web framework for a ubiquitous sensor network (u-framework). It involves bicycles with sensors communication in a Wide Area Ubiquitous Network (WAUN). In experimental field trial, they considered bicycles equipped with small and high-precision NO2 sensors to collect and share information about air pollution in Tokyo, Japan.

In recent years, there are many public bike systems that can collect real-time data. In these schemes, sensors that are mounted on bicycles start collecting data when the bikes leave their bike stations such as schemes in Germany [22] and Netherlands [48]. In the literature, many studies have been focused on analyzing the movement of bicycles in public hire systems such as the public cycle hire system in Lyon [21], Barcelona [47] and London [117].

Over the past few years, applying Delay Tolerant Networking to the Internet of Things (IoT) has been a challenge [10]. In [115], Wirtz et al. have proposed Direct Interaction with Smart Challenged Objects (DISCO) enabling smart objects to define and provide their interaction interfaces immediately to users. They have discussed the notion of the Challenged Internet of Things with regard to both connectivity and interaction interfaces. More precisely, they have pointed out the need to enable interaction between smart objects and mobile users in the Internet of Things. The authors, in [108], have introduced a framework for node deployment and delay-tolerance in RSNs under the IoT paradigm. Moreover, they have proposed DIRSN, an optimized delay-tolerant mechanism for integrated RFID-sensor networks (RSNs). Their framework offers an optimized architecture for integrated RSNs in addition to a delay-tolerant routing scheme. In [44], Elmangoush et al. have addressed the challenges of gathering data from mobile devices characterized with strong energy restrictions in an environment where connectivity is limited. For that, they propose an enhanced architecture to interconnect standard-based machine-to-machine (M2M) platform to opportunistic networks in order to collect data from sensor devices. Many researchers have been focused on investigating DTN with IoT in the domain of delay-tolerant WSN that focus on routing algorithms [60]. Most of the proposal works do not use standard protocols, while they propose approaches dedicated to targeted applications or sensors such as studies on underwater sensor networks [32].

2.5 Performance comparison of existing DTN routing protocols

Here, we evaluate and compare the performances of six DTN routing protocols, presented above, on real networks and in particular in an urban environment. We assess the performances of Epidemic routing, Direct Delivery, First Contact, Spray and Wait, PRoPHET and MaxProp protocols. The choice of these six protocols is based on the variation of their behaviors.

2.5.1 Simulation setup

Our scenarios are evaluated using the Opportunistic Network Environment (ONE) simulator [59]. It offers several functions such as the modeling of node movement, inter-node contacts, application interactions, routing and message handling. Analysis and results in the ONE are generated through visualization, post-processing tools and reports. The overview of the simulator is presented in Figure 2.7. The default map used by the ONE simulator is the Helsinki city map. We used the ONE, which implements an urban mobility for DTN network, to simulate a set of pedestrians, cars and trams that circulate in Helsinki town and exchange messages between them.

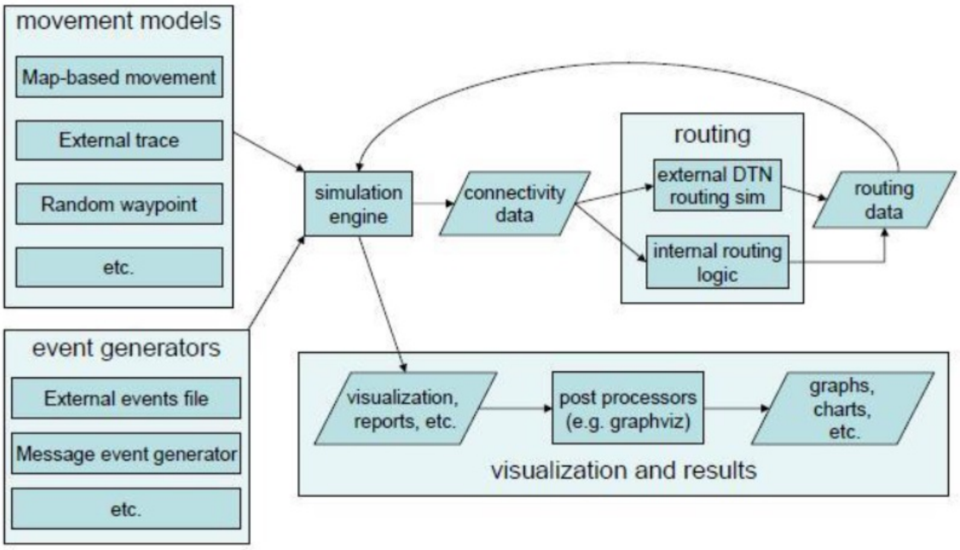


FIGURE 2.7: Overview of the ONE simulator [59].

2.5.2 Simulation parameters

In this part, we describe the simulation settings used for our simulations. Our scenario simulates 6 node groups containing pedestrians, cars and tramways. The total number of nodes is fixed to 126: 80 pedestrians, 40 cars and 6 tramways. The movement model used by cars and pedestrians is the ShortestPathMapBasedMovement while the one used by tramways is the MapRouteMovement. The buffer size used for vehicles and pedestrians is 5M as the one used for tramways is 50M. The lifetime of messages is limited to 5 hours. The minimum value of node movement speed used is 0.5 m/s and the maximum one is 13.9 m/s. The transmit speed interface

TABLE 2.2: Simulation parameters of the variation of the message creation frequency.

Parameters	Values
Message Creation Interval (s)	One message per: 5-10; 10-15; 15-20; 20-25; 25-30; 30-35; 35-40; 40-45; 45-50.
Message Size	500 KB to 1 MB

TABLE 2.3: Simulation parameters of the variation of the message size.

Parameters	Values
Message Creation Interval (s)	One message per 25, 35
Message Size	100 KB - 200 KB; 200 KB - 300 KB; 300 KB - 400 KB; 400 KB - 500 KB; 500 KB - 600 KB; 600 KB - 700 KB; 700 KB - 800 KB; 800 KB - 900 KB; 900 KB - 1 MB.

for vehicles, pedestrians and four tramways is 2Mbps as well as their communication range is 10m; whilst the ones for the remaining tramways are 10Mbps and 1000m respectively. For Spray and wait protocol the number of copies is limited to 6 and the binary mode is applied. The map size is 4500 meters in width and 3400 meters in height. The total simulation time is 12 hours.

We simulate two different scenarios by varying the message creation interval and the message size. Tables 2.2 and 2.3 summarize the configuration used for both scenarios.

2.5.3 Performance metrics

We evaluate the performances of the six protocols according to four metrics:

1. **Average latency:** It represents the message delay from its creation to its delivery to the destination node.

2. **Buffer time:** It is the average time that messages are stored in a buffer at each node.

3. **Delivery probability:** It represents the number of successfully delivered messages to the destination. It is defined as:

   deliveryProb = (1.0 * delivered messages) / created messages.

4. **Overhead ratio:** It is an assessment of the bandwidth efficiency. It is interpreted as the number of created copies per delivered message. That is the amount of replicas necessary to perform a successful delivery.

2.6 Simulation results

In this section, we present our simulation results for both scenarios.

2.6.1 Variation of the message creation frequency

In the first scenario, we vary the message creation interval while keeping a fixed message size.

2.6.1.1 Average latency

From Figure 2.8, we notice that the average latency for most protocols increases respectively. More precisely, Direct Delivery protocol offers the highest value. This is because the created packet will be kept by the source node until it meets its destination. For the remaining protocols, we note that the average latency raises slightly. In such cases, the created packets will be stored in the buffers of intermediate nodes until they arrive to final destinations, thus resulting in a high delivery delay. It is important to point out that the "Spray and Wait" protocol provides the lowest average latency.

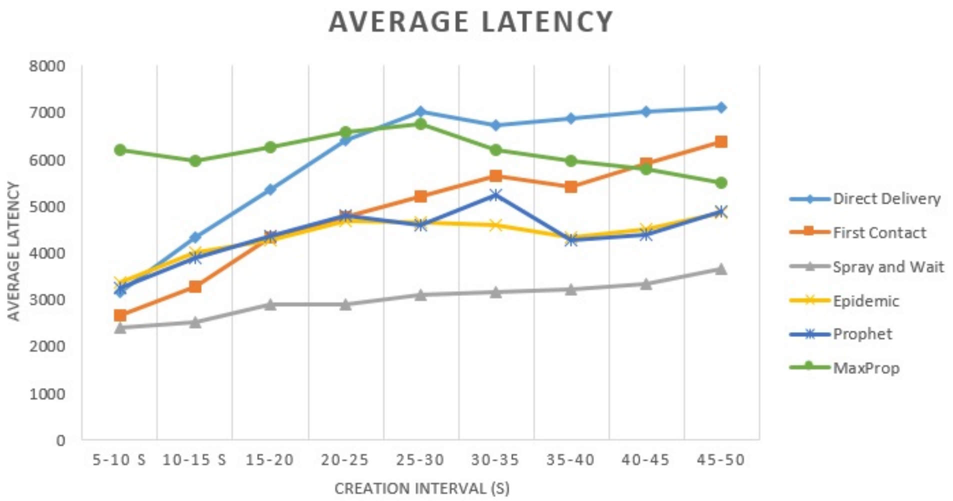


FIGURE 2.8: Average latency of the variation of the message creation frequency.

2.6.1.2 Buffer time

Figure 2.9 shows the average time that messages are stored in buffers of relay nodes. We notice that the buffer time of Direct Delivery and Spray and Wait protocols increases gradually. Indeed, in Direct Delivery protocol, created data packets are stored by the source node until meeting the destination which explains the highest buffer time value. For Spray and Wait protocol, more precisely in the Wait phase, all nodes that receive a copy of a message wait to meet directly the destination to forward it. It is also clear, from Figure 2.9, that First Contact protocol offers the lowest buffer time values. The reason for this is that messages are forwarded to the first encountered nodes and then are deleted from the buffer, thus and so messages are not stored much time in buffers. For the remaining protocols, the buffer time value is almost the same and it increases very slowly. As the aim of our simulation is to ensure reliable data transmission in difficult environments where there is intermittent connected networks facing long duration of partitioning, the reported data by the nodes should be stored for a long time in buffers of intermediate nodes to be transmitted when having an available connection. Thus, we can deduce that the two protocols "Direct Delivery" and "Spray and Wait" are the best protocols ensuring this issue.

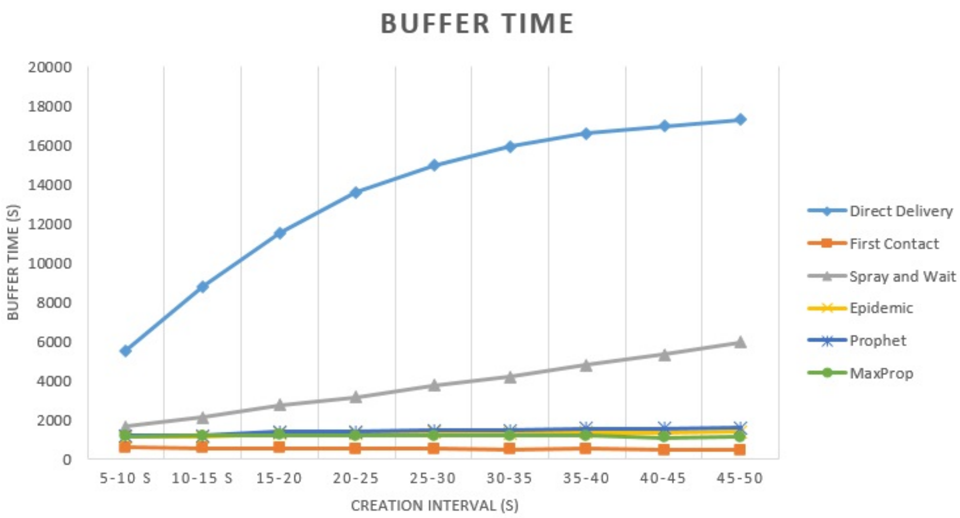


FIGURE 2.9: Buffer time of the variation of the message creation frequency.

2.6.1.3 Delivery probability

From Figure 2.10, we notice that by raising the message creation interval, the delivery probability of messages to their destinations increases regularly. More precisely, MaxProp and Spray and Wait protocols provide the best delivery ratio. Since "MaxProp" protocol allows a priority in the packet queue and "Spray and Wait" protocol secures messages by storing them in buffers, this increases the delivery rate of messages.

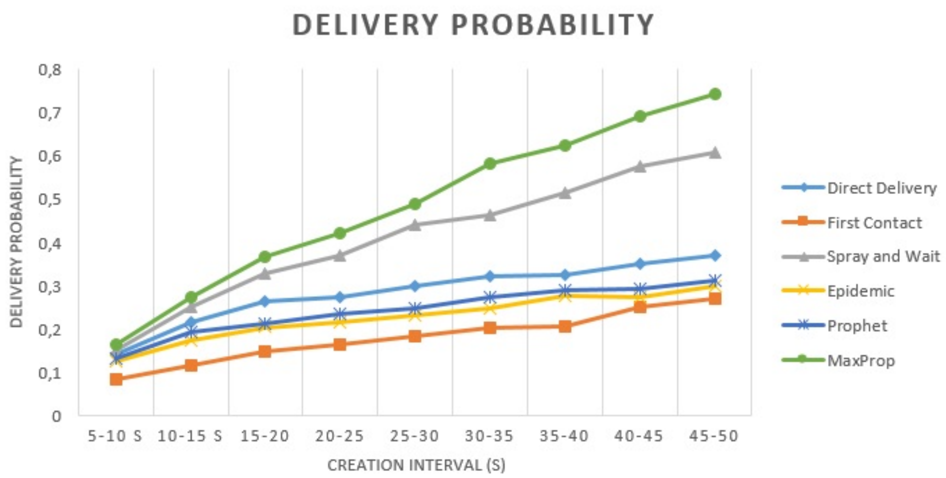


FIGURE 2.10: Delivery probability of the variation of the message creation frequency.

2.6.1.4 Overhead ratio

Figure 2.11 shows the overhead rate with regard to the increase of the message creation interval. It is important to mention that the amount of network resources needed to deliver a packet to its destination for the Direct Delivery protocol is null since a source node keeps the message until it reaches its destination without needing to broadcast multiple copies of the message. The overhead ratio for the Spray and Wait protocol decreases slightly from 20 to approximately 8. In that case, the generated packets saturate very fast the buffer when the creation interval is small. Since the Spray and Wait protocol limits the number of copies sprayed in the network and by increasing the creation interval values, the network resources necessary to deliver packets is smaller. For MaxProp, First Contact, Prophet and Epidemic Routing protocols, the overhead ratio increases respectively by raising the message creation interval. We note that the overhead ratio of Epidemic routing protocol raises instantly by expanding the message creation interval. Since it floods the network, it needs a lot of network resources to reach destinations.

2.6.2 Variation of the message size

In the second scenario, we vary the message size while there is one message creation per [25,35] seconds.

2.6.2.1 Average latency

Figure 2.12 shows the average latency. We notice that it increases gradually by expanding the message size value of most protocols. More in detail, Direct Delivery provides the higher values. As mentioned above, this approach allows the packets to be stored until the meeting of the destination. In other protocols, the packets are stored in buffers of intermediate nodes to be delivered at a later time to final destinations. It is clear from Figure 2.12 that Spray and Wait protocol offers the lower average latency.

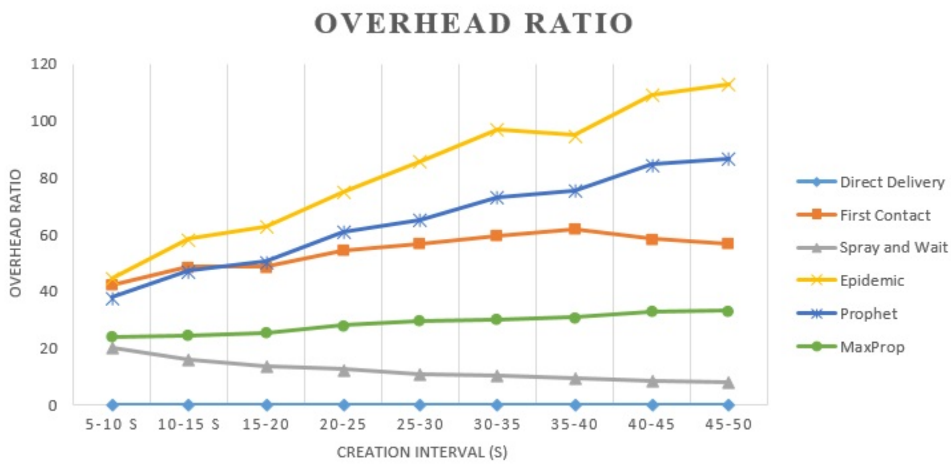


FIGURE 2.11: Overhead ratio of the variation of the message creation frequency.

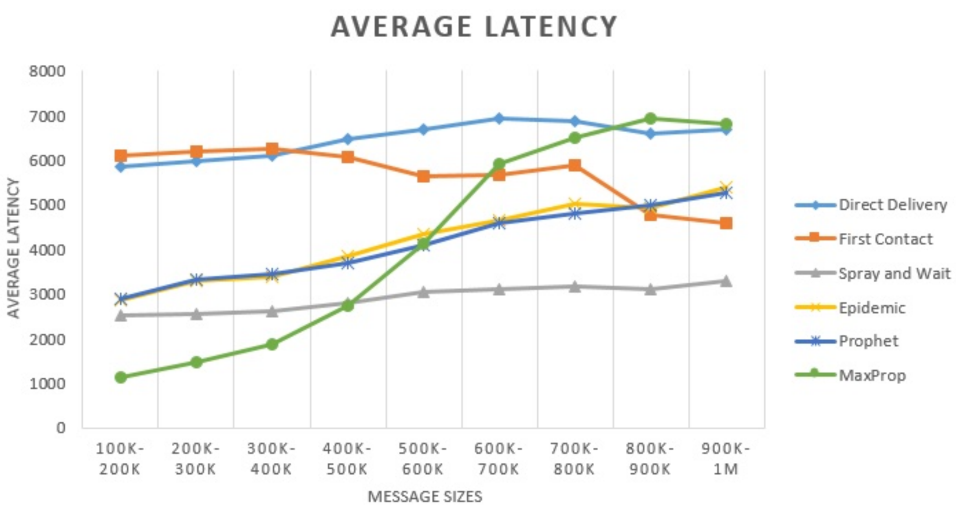


FIGURE 2.12: Average latency of the variation of the message size.

2.6.2.2 Buffer time

From Figure 2.13, we observe that the buffer time of Direct Delivery and Spray and Wait protocols decreases respectively by increasing the message size. This depends on the buffer node size considered in the simulation scenario. For the remaining protocols, the buffer time is almost the same and increases progressively. As mentioned above, the two protocols Direct Delivery and Spray and Wait are the best since they lead the reported data to be stored a long time in the buffers.

2.6.2.3 Delivery probability

Figure 2.14 shows the delivery rate of messages. The first observation we make is that the delivery probability for all routing protocols decreases by increasing the message size. This may depend on two parameters. One is the node buffer size chosen in the simulation, when the buffer is full some

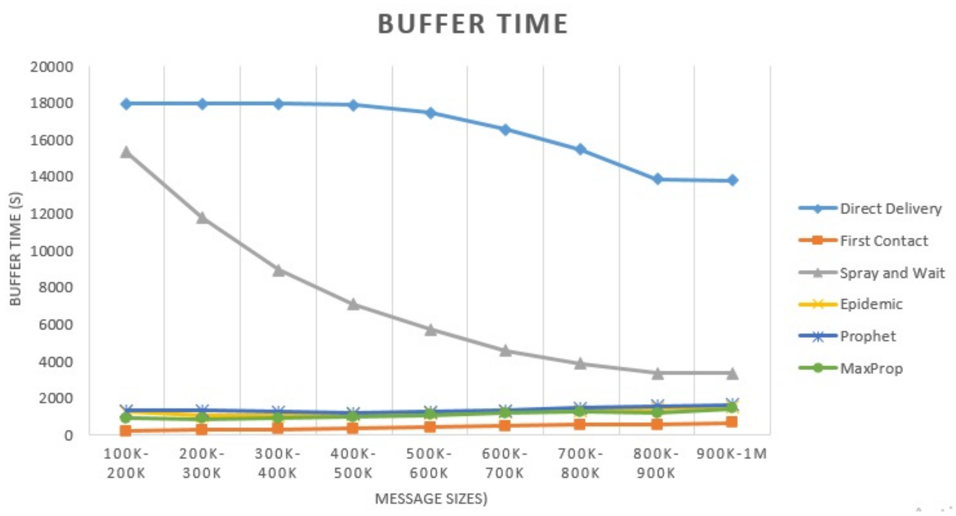


FIGURE 2.13: Buffer time of the variation of the message size.

of messages are dropped according to the protocol and the buffer management policy used. Another reason can be the message lifetime (TTL) defined in the simulation scenario. Thus, for our simulated scenario, MaxProp and Spray and Wait protocols perform better than others protocols.

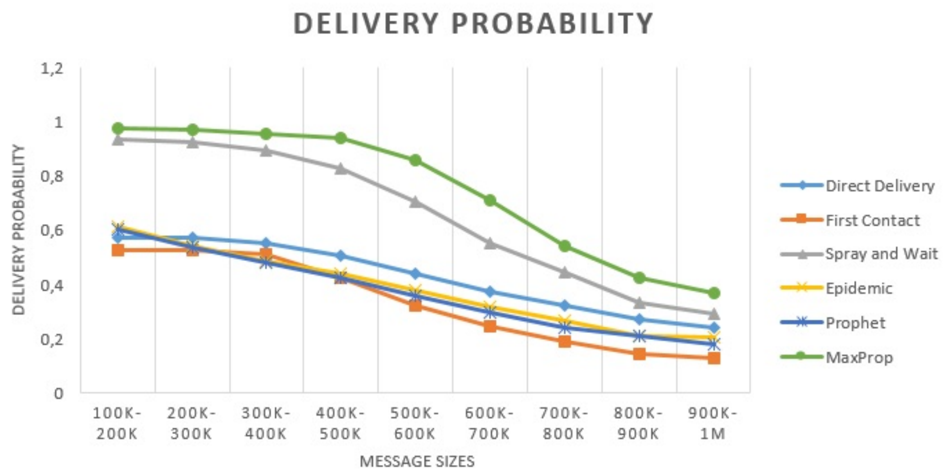


FIGURE 2.14: Delivery probability of the variation of the message size.

2.6.2.4 Overhead ratio

From Figure 2.15, we observe that the overhead ratio of the Direct Delivery protocol is null as in Scenario 1, whereas for Spray and Wait protocol it increases slightly from 5 to approximately 22. Indeed, by increasing the message sizes and limiting the number of copies sprayed in the network, Spray and Wait protocol needs more network resources for forwarding messages to their destinations. For other protocols, the overhead ratio decreases by increasing the message size.

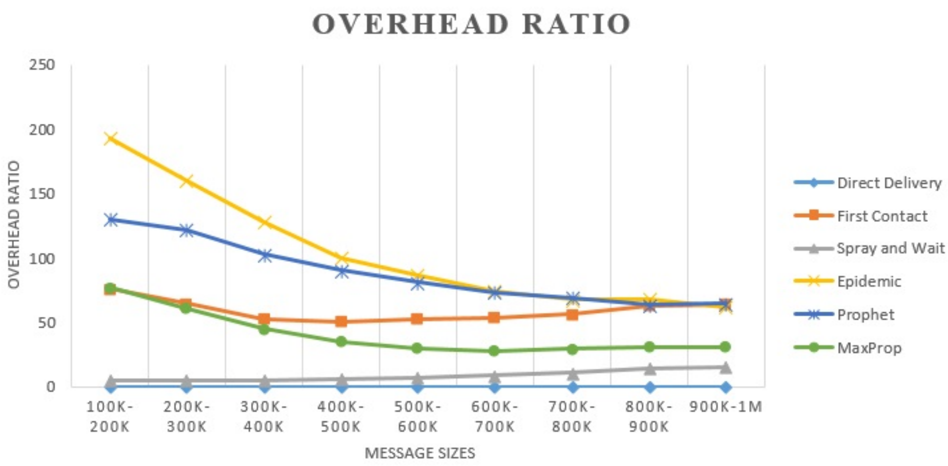


FIGURE 2.15: Overhead ratio of the variation of the message size.

2.6.3 Comparison and discussion

The performance evaluation of routing protocols is very important to figure out their limits before implementing them in any architecture or application.

We present, in Figures 2.16 and 2.17, a comparison of the six protocols simulated in this section with regard to the buffer time and delivery probability; average latency and overhead ratio. These figures illustrate the current location of each simulated routing protocol as well as its previous position given in sections 2.3.1 and 2.3.2. From the comparison presented before, Epidemic Routing requires high latency, resource consumption, buffer time and delivery ratio. Maxprop has moderate latency, resource consumption, buffer time and high delivery ratio. Spray and Wait protocol demands high latency, buffer time, delivery ratio and low resource consumption. Direct Delivery and First Contact protocols require low resource consumption and high latency. PRoPHET has moderate latency, resource consumption and delivery ratio while granting a low buffer time.

Here, it is important to point out that their behaviour, except First Contact protocol, changes. In fact, the comparison given in the state of the art is based on the general description of each protocol while the comparison given here is deduced from our results. We have specified many parameters in our urban scenario such as the mobility model, the movement speed, the interface transmit range, etc. Therefore, we can infer that the behaviour of the most DTN protocols changes in urban environments.

2.7 Conclusion

In this chapter, we review the state-of-the-art of DTN routing protocols.

First, we investigate the DTN routing strategies which are divided into three families: flooding, forwarding and coding strategies based on the strategy property used to find the destination. Flooding strategies are based on messages replication. Forwarding strategies require knowledge about the network topology for data routing. Coding strategies rely on the data

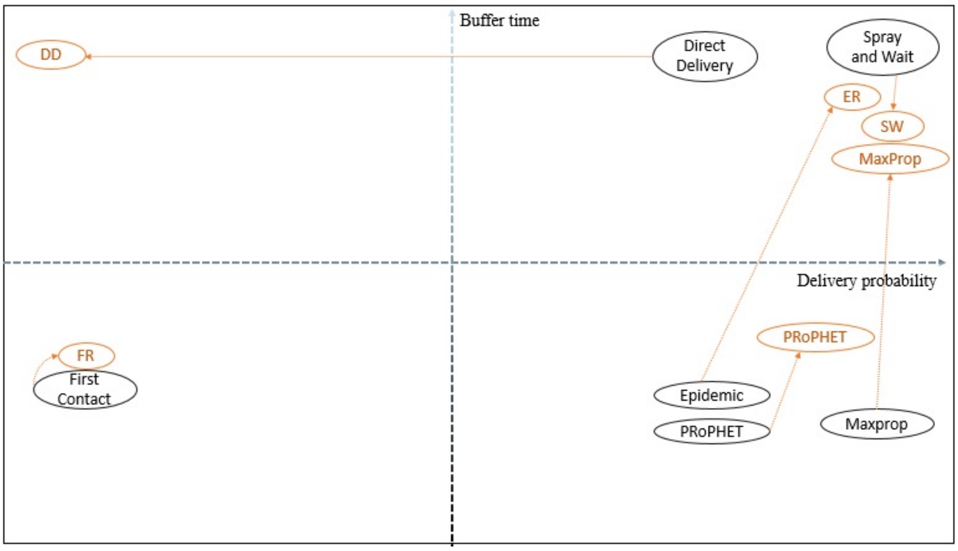


FIGURE 2.16: Comparison with regard to the buffer time and delivery probability.

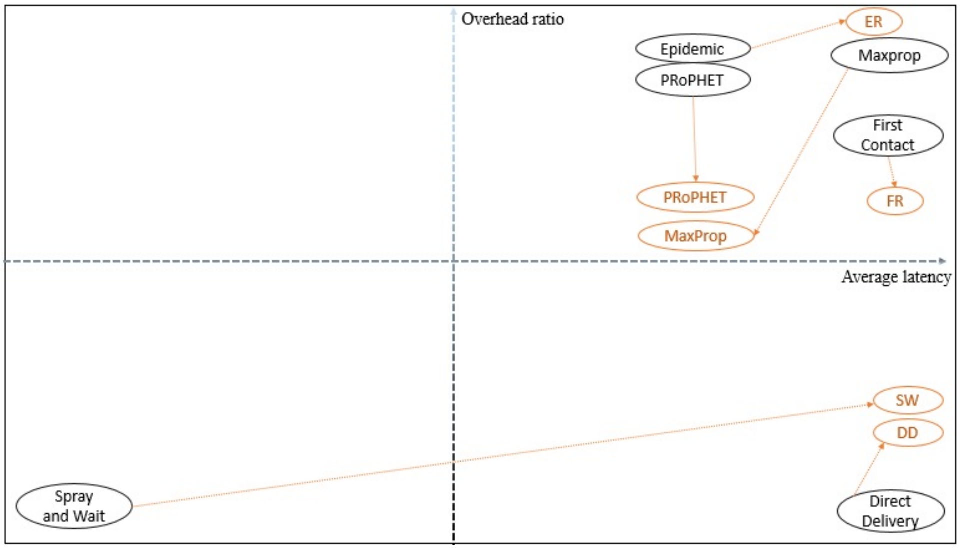


FIGURE 2.17: Comparison with regard to the average latency and overhead ratio.

encryption to transmit data. We present a comparison of some DTN routing protocols with regard to the resource consumption and latency; buffer time and delivery ratio metrics.

Secondly, since our work is based on data collection in an urban environment, we review the state-of-art communication works based on public transport networks and on DTN paradigm with the Internet of Things (IoT). The goal of this chapter is helping researches interesting to apply DTN to the Internet of Things to determine the best DTN routing protocol tailored for being applied to a mobile network IoT devices running a data collection application.

Thirdly, we evaluate the performances of six DTN protocols in an urban environment. The obtained results clearly show that Spray and Wait routing protocol has the best performances as to the average latency, average buffer time, delivery probability and overhead ratio for simulated scenarios.

Based on these results, we inspire our proposal from Spray and Wait protocol which is presented in the following chapter.

Chapter 3

IoB-DTN: a lightweight DTN protocol for mobile IoT Applications to smart bike sharing systems

In this chapter, we introduce "IoB-DTN"[1], a DTN-like protocol dedicated to the following characteristic of the connected bike scenario:

- *converge cast traffic* : the data sensed by the bikes have to be collected on "the Internet" through a given set of equivalent sinks. There is no point-to-point traffic.
- *time bounded disconnection*: at worst, each bike is getting back to a sharing station. All stations are sinks.
- *urban mobility*: mobility patterns are human-generated, hence unpredictable and without known random properties to exploit.
- *energy and computing power constrained*.

In particular, IoB-DTN can be seen as a "lightweight" version of several n-copy DTN protocols, since many features of these protocols are useless and removed, thus decreasing the memory required. No complex computations are performed either (e.g. statistics on the history of neighborhood). We evaluate the performance of several variants of IoB-DTN in a realistic scenario and provide the following engineering insights:

- there is a tradeoff between the loss rate and the energy consumption of the protocols, but gaps are not as large as expected,
- a clever buffer management policy mitigates the need for sending redundant packets but do not improve on the delivery delay,
- redundancy can help to improve performances if the buffer management policy rely on it.

3.1 Our scenario

Public bicycle systems, also known as bicycle-sharing systems have been introduced as part of the urban transportation systems in several cities.

[1] The "Internet of Bikes Delay Tolerant Network protocol"

They have been introduced in European cities in the mid-2000's and have spread worldwide. Such systems are today operating in more than 1,000 cities around the globe, with more than one million bicycles [83, 106]. The present thesis focuses on the use of IoT in connected bicycles. More specifically, we consider a "smart" bike sharing system as follows.

- The bikes have embedded sensors and a 802.11p communication device [124].
- Each bike periodically reads its sensors, generates a packet, and stores it in its buffer.
- Each bike sharing station is connected to the Internet and also have 802.11p device, acting as a fixed sink in the network.
- All sinks are equivalent and our networking protocol is in charge of relaying the packets unless they reach one of the sink.

Figure A.3 depicts a scenario with eight bikes and six base stations. Bicycle 1 leaves Station 2 and starts generating data. When Bikes 1 and 2 are within communication range, they exchange data. The data are stored in the bicycle buffers until a base station comes in range. Bike 4 lies in the area of Station 5, therefore it sends all data stored in its buffer.

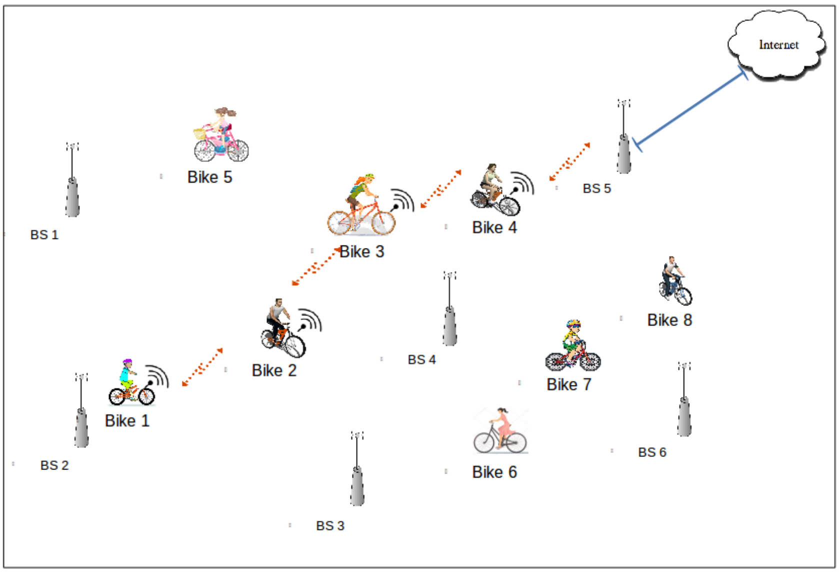


FIGURE 3.1: Illustration of our bike system.

3.2 IoB-DTN : Internet of Bikes-DTN protocol

In this Section, we introduce the IoB-DTN protocol. It is inspired by flooding DTN protocols that do not require any knowledge on the network topology [56]. The mobility of a network of bikes being human generated, it is neither predictable nor periodic in a time frame that would make learning strategies efficient, such as in public transportation. It is also difficult to rely on stochastic properties of the mobility pattern, urban biking mobility being not well understood yet.

Flooding strategies are based on the replication of the messages that are relayed in the network. In some sens, the lack of knowledge is mitigated by an amount of redundancy and extra resource consumption. The description of the protocol is detailed in Algorithm 1. In IoB-DTN, each node generates periodically a packet P with the readings. The packet P and its initial number of copies N are stored in the buffer if the buffer management policy used provides a slot. When the duty cycle is over, each node verifies the existence of a base station in its vicinity. If the node lies in the area of one or more base stations, it forwards all data stored in its buffer to only them. If not, it sends packets having more than one copy, their number of copies and its neighbors list to neighbors nodes. When receiving a packet, each node determines its position in the neighbors list of the source node in order to calculate the new number of copies N' to be kept. The received packet is then stored in the buffer with N', if it is at least equal to one, and an acknowledgement (ACK) is sent to the source node. At the reception of an ACK, each node deletes the corresponding packet if the sender node is a base station, alternatively it updates the number of copies N".

It is worth noting that the copies of a packet stored in a buffer are virtual. It is only a counter and each packet uses only one slot of the buffer. There are actually several copies of a message if and only if they have been sent to another node.

3.2.1 Initial number of copies

The number of copies created when a message is generated is an important parameter of the protocol. As stated in the protocol description, a node replicates and forwards to its neighbors only the packets that have at least two copies in its buffer. Its first neighbor takes half of these copies, the second one takes one fourth, and so on and so forth. This behavior is at the heart of the well known DTN protocol denoted *Binary Spray and Wait* [105]. At worst, each packet is duplicated N^0 times in the network. The larger N^0, the more redundant the protocol is.

In Binary Spray and Wait, N^0 is set to 8. By setting N^0 to 2, IoB-DTN mimics the behavior of another DTN protocol denoted *Two-Hop Relay* [49]. In this variant, each packet is duplicated to the first encountered node then the two nodes carrying the packet wait for their connection to a base station.

Oppositely, one can set $N^0 = \infty$ (or a large enough value) and get the behavior of the *Epidemic Routing* protocol which floods the network [109].

In our simulations, these three variants are compared.

3.2.2 Buffer management policy

Another major parameter of IoB-DTN is the buffer management policies used to find a slot in the buffer when a packet is generated or received.

If the buffer is not full, the buffer management provides the next free slot.

If the buffer is full, it is then necessary to decide which packet has to be discarded, with the risk that no copy of it reaches a base station, and which should be kept.

Algorithm 1 IoB-DTN protocol.

At each sensor reading period
Generate a packet p with the readings
if Buffer management provides a slot **then**
    Store $p \cup N^0$ in the buffer [N^0 copies of p are stored]
end if

When duty cycle is over
$\mathcal{L} \leftarrow$ the list of neighbors
if a base station is in $\mathcal{L}$ **then**
    Send all packets in buffer
else
    for all packet $p \cup N$ in buffer **do**
        if N (number of copies) > 1 **then**
            Send $p \cup N \cup \mathcal{L}$
        end if
    end for
end if
Wait for next duty cycle

On reception of packet $p \cup N \cup \mathcal{L}$
$pos \leftarrow$ self position in $\mathcal{L}$
$N' \leftarrow \frac{N}{2^{pos+1}}$
if Buffer management provides a slot **and** $N' \geq 1$ **then**
    Store $p \cup N'$
    Send ACK for receiving N' copies of p
else
    Packet is rejected, no ACK is sent
end if

On reception of an ACK of p and N'
if sender node is a base station **then**
    Delete p from buffer
else
    Update the number of copies of p : $N'' \leftarrow N - N'$
end if

3.2.2.1 KONP: Keep Oldest No Priority

This policy is an usual "*First In First Served*" buffer, such as in basic network router buffers : if the buffer if full, the new packet is discarded.

3.2.2.2 NP: No Priority

Oppositely, this policy keeps the new packet. It considers that a packet that has spent a long time in the buffer has a higher probability to have been forwarded to another node and to arrive to destination. Hence the oldest packet in the buffer is discarded and replaced by the new one.

3.2.2.3 GPP: Generated Packet Priority

In the buffer, there is two kinds of packet. Those that have been generated by the node and those that have been received from another node. The goal of GPP is to avoid situations in which the received packets take all the place in the buffer and block all the packets generated by the node itself.

Therefore, when a packet is generated, it replaces the oldest received packet. But if there are only generated packets, then it replaces the oldest one.

When a packet is received, it is discarded.

3.2.2.4 LC: Lesser Copy

This policy does not consider the time at which packets have been generated, only the number of copies stored in the buffer. A packet with a small number of copies is more likely to be delivered to a base by another node than one with all its copies. When a packet is received or generated, it thus replaces the packet having the smallest number of copies in the buffer.

3.3 Simulation environment

In this section, we overview the simulation settings used for our simulated scenarios.

3.3.1 Simulation toolchain

The urban environment we used to evaluate our proposal is the city of Lyon, France. Lyon is situated in east-central France, in the Auvergne-Rhône-Alpes region and it is the third-largest city after Paris and Marseille. Lyon is one of the first cities in the world that tested the self-service bicycles called Vélo'v[2]. One of the bike stations in Lyon is presented in Figure 3.3. The system, launched in May 2005, provides more than 4000 bicycles available 24/7 from over 350 stations situated around the cities of Lyon and Villeurbanne. The bicycles can be taken from any station by citizens and returned to any other station. The platform "Data Grand Lyon" [3] provides open data including the description of the Vélo'v system.

[2]Vélo'v: https://velov.grandlyon.com/
[3]Data Grand Lyon: htps://data.grandlyon.com/

These data are integrated with the map of Lyon from OpenStreetMap [4]. Within the area of Lyon city center, depicted in Figure 3.2, 49 bike sharing stations are deployed. The fusion of these two data is then imported in the SUMO open source road traffic simulator [15]. SUMO simulates a realistic mobility of the bikes on the streets of the map. It allows to import and generate road networks, bike routes and obstacles.

The Veins framework[5] connects SUMO to the event-based network simulator OMNeT++ [6] and provides realistic radio propagation and models of 802.11p.

FIGURE 3.2: City area of Lyon.

FIGURE 3.3: Vélo'v bicycle sharing system in Lyon.

3.3.2 Simulation scenario

Our scenario simulates 47 bikes moving across the Lyon city center as depicted in Figure A.4. The histogram of the biking travel times is depicted in

[4]Openstreetmap: https://www.openstreetmap.org
[5]Veins: http://veins.car2x.org/
[6]OMNeT++: https://omnetpp.org

Figure 3.5.

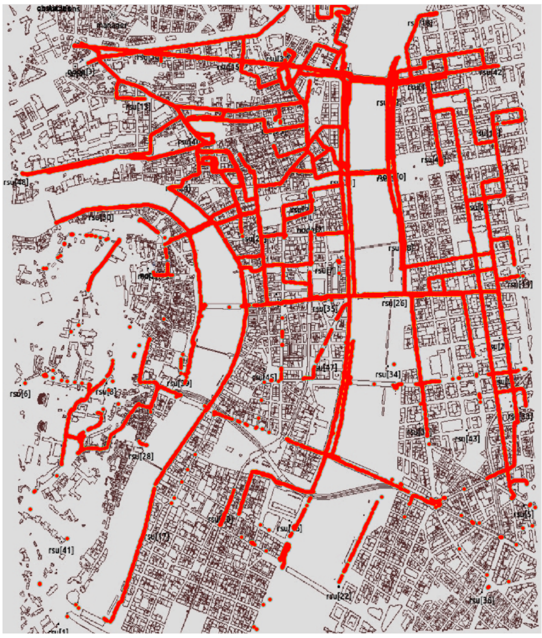


FIGURE 3.4: Mobility traces of bikes.

Each bike reads its sensors and generates a packet each second when it is moving. The mean travel is around $550s$, the longest being $1418s$, with as many packets generated.

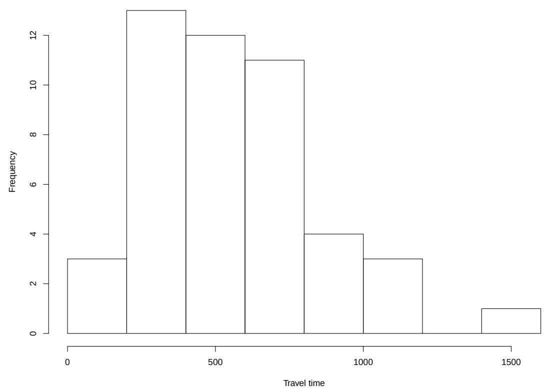


FIGURE 3.5: Bikes travel time.

We simulate four sets of parameters by varying the buffer size and the duty cycle as shown in Table A.1:

- **SB-SDC**: Small Buffer - Short Duty Cycle;
- **SB-LDC**: Small Buffer - Long Duty Cycle;
- **LB-SDC**: Large Buffer - Short Duty Cycle;
- **LB-LDC**: Large Buffer - Long Duty Cycle.

TABLE 3.1: Simulation cases.

	Buffer size	Duty cycle (s)
SB-SDC	250 packets	50
SB-LDC	250 packets	150
LB-SDC	500 packets	50
LB-LDC	500 packets	150

It is interesting to note that the copies of a packet stored in a buffer are virtual. We just increment a counter and each packet occupies only one slot of the buffer. In other words, the buffer size is given as the number of slots. The duty cycle is a period defined in seconds, after which each node forwards the data packets stored in its buffer.

One can remark that it is very likely that packet loss occurs since the buffer sizes are not large enough to store all the packets generated by one bike. This accounts for devices that are constrained in memory.

Table 4.1 summarizes the simulation configuration used for our scenario.

TABLE 3.2: Simulation parameters.

Parameters	Values
Number of bikes	47
Number of bike stations	49
Packet generation frequency	Every second
Number of copies	8
Communication model	802.11p
Transmission power	10 mW
Simulation time	30 minutes

In each simulation, we evaluate the distributions of delivery delays (the time between the generation of a packet and when it is received by a base station) and the loss rate.

3.4 Simulation results

In this part, we evaluate the performance of IoB-DTN protocol. First, we assess four buffer management policies. Secondly, we compare the impact of the number of copies spread in the network. Thirdly, we evaluate the impact of increasing the number of bicycles.

3.4.1 Impact of buffer management policies

We compare the performance of the four buffer management policies cited above with IoB-DTN protocol when the number of copies of a packet is limited to 8.

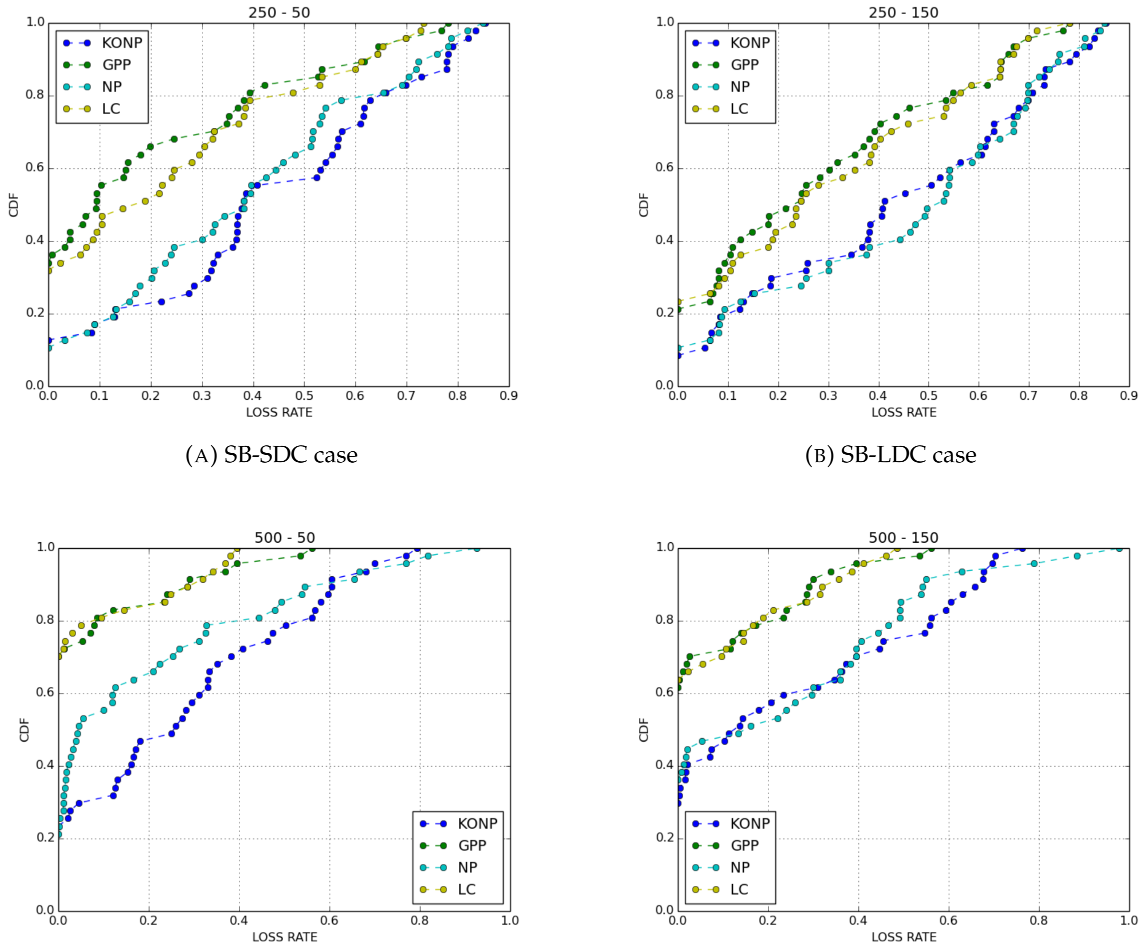
Figure A.6 shows the loss rates obtained for all cases. The first observation we make is that GPP and LC have better performances than KONP and NP buffer management policies.

As expected, KONP performs poorly in particular when the buffer size is small. This is because the generated packets saturate very fast the buffer and all other packets are dropped.

More surprisingly, NP have similar performances in most of the cases. More precisely, it outperforms slightly KONP. It offers bad results comparing to GPP and LC since it drops oldest packets if they are generated or received.

GPP policy provides better performances in all cases. Indeed, forwarding duplicated packets in the network has lesser impact on the loss rate for GPP since it gives priority to the generated packets. However, the fact that the performances are better when the duty cycle is lower shows that the redundancy induced by the mechanisms provides robustness.

LC has similar performances than GPP. Indeed by discarding packets that have less copies in the buffer, it secures packets that have not been shared yet. This increases the redundancy of the packets in the network, hence the robustness. GPP outperforms slightly LC when the buffer size is small. In this case the relative impact of the redundancy is higher.



(A) SB-SDC case

(B) SB-LDC case

(C) LB-SDC case

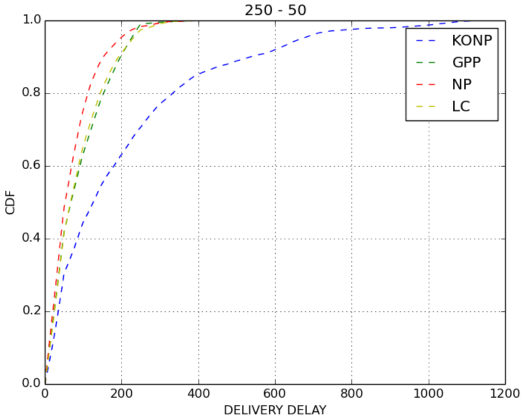
(D) LB-LDC case

FIGURE 3.6: Loss rate.

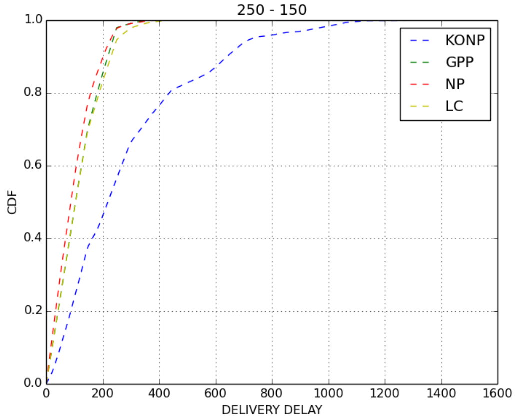
Figure A.7 depicts the delivery delay of the packets that are actually received. These results should then be analyzed with the loss rate in mind.

KONP is the worst policy. This is an obvious consequence of the "keep old" policy: only the oldest packets are delivered. Oppositely, NP offers the best delivery delay in all cases. Here again, it was expected as it drops old packets.

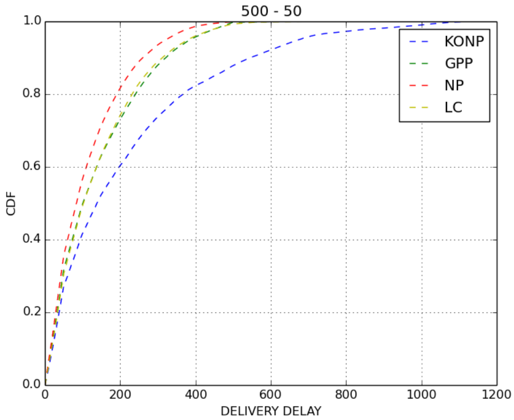
GPP and LC policies have similar performances than NP while granting a better loss rate. There are thus older packets that are delivered. The similar delay distribution shows that there are also delivered faster. This most probably thanks to the redundancy which increases the routing diversity.



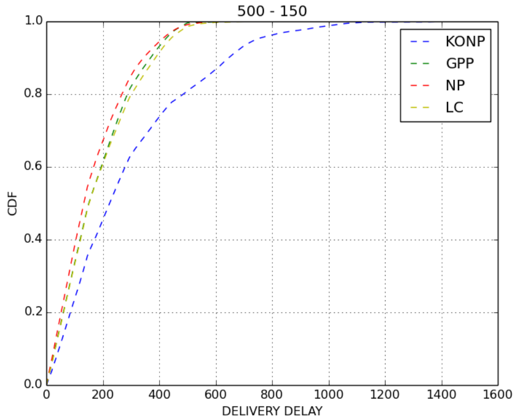
(A) SB-SDC case



(B) SB-LDC case



(C) LB-SDC case

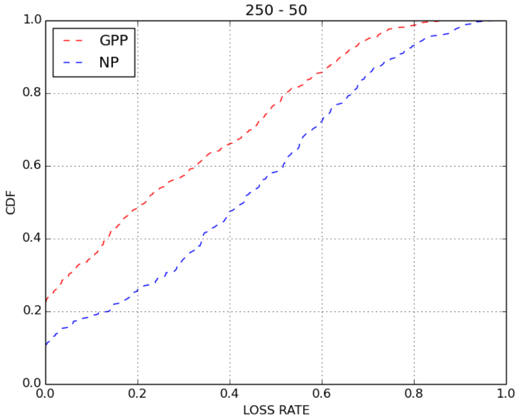


(D) LB-LDC case

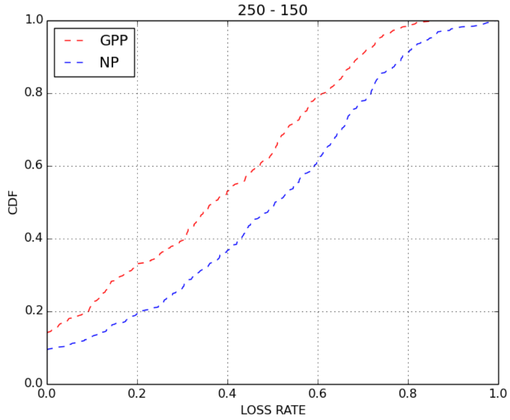
FIGURE 3.7: Delivery delay.

From these results, we can see two class of policies: KONP and NP on one side; GPP and LC on other side. KONP is clearly a bad buffer management policy as it has poor performances both on loss rate and delivery delay. GPP and LC behave quite similarly despite their apparently opposite philosophies: one protects self production against the redundancy while the other rely on redundancy to make place to newer packets. In some sense, we could have expected that NP and LC behave closely since older packets are more likely to have lesser copies.

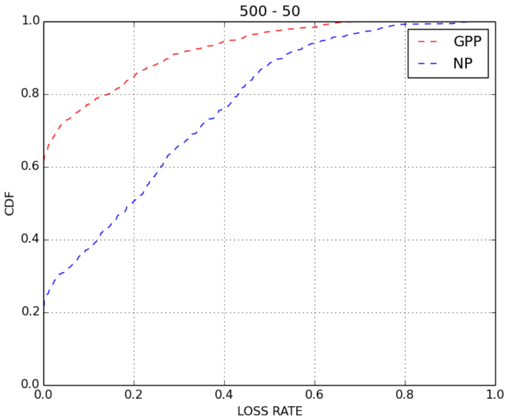
For the purpose of confirmation of our results, we simulated ten scenarios for GPP and NP policies by varying the paths of bikes in each simulated scenario. The average findings obtained on loss rate are depicted in Figure A.8 as well as results on delivery delays are shown in Figure A.9. Clearly, we got results similar to those presented here.



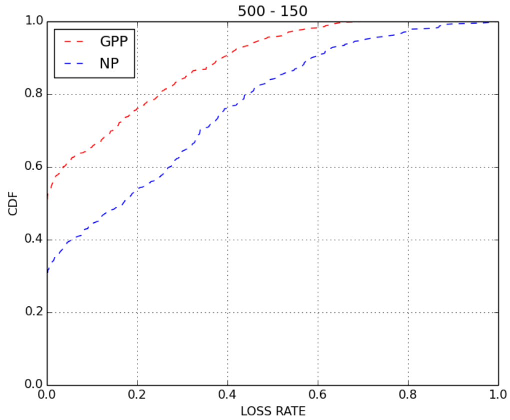
(A) SB-SDC case



(B) SB-LDC case

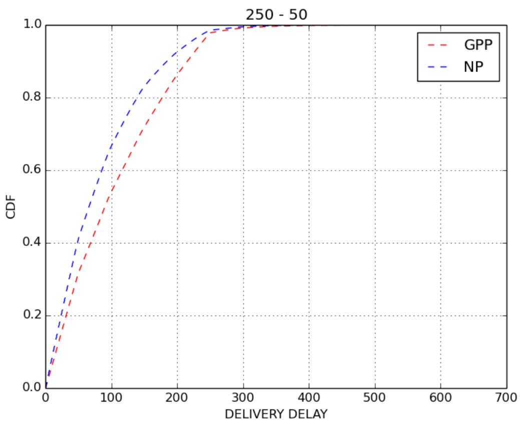


(C) LB-SDC case

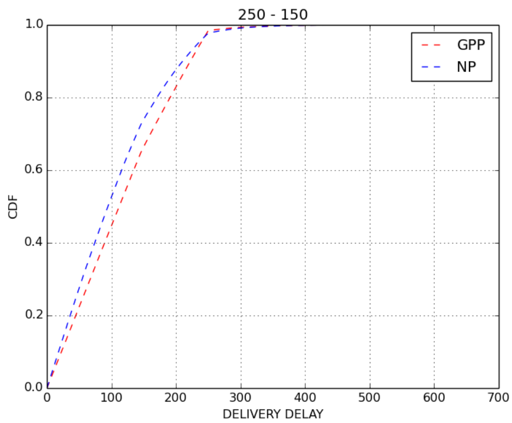


(D) LB-LDC case

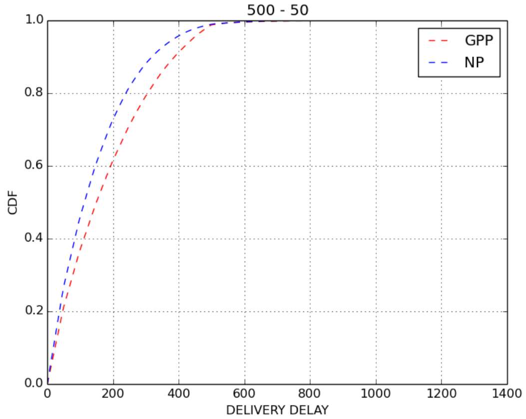
FIGURE 3.8: Average loss rate.



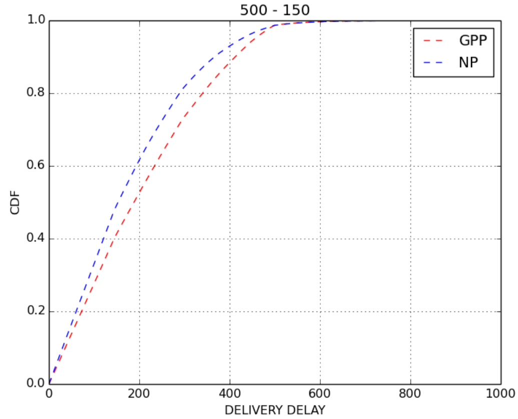
(A) SB-SDC case



(B) SB-LDC case



(C) LB-SDC case



(D) LB-LDC case

FIGURE 3.9: Average delivery delay.

In the following, we evaluate the three variants of IoB-DTN depending on the number of copies sprayed in the network. We only compare the performances of GPP, which gives the best tradeoff between delivery delay and loss rate, and NP, which gives the best delivery delay.

3.4.2 Impact of number of copies

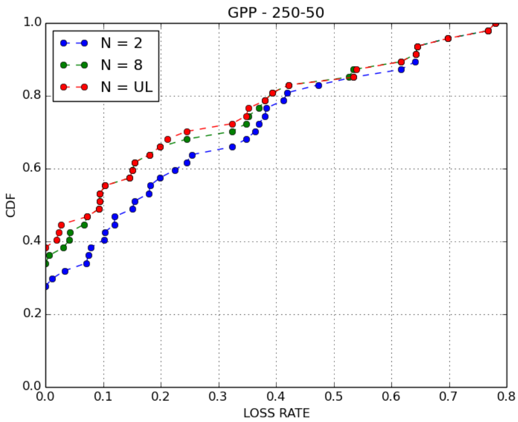
Here, we are interested to compare three variants of IoB-DTN protocol in order to evaluate the impact of the number of copies sprayed in the network. We simulate three cases summarized in Table 4.2. The first case behave like the Two-Hop Relay protocol, the second like Binary Spray and Wait, and the last case like Epidemic Routing.

TABLE 3.3: Number of sprayed copies.

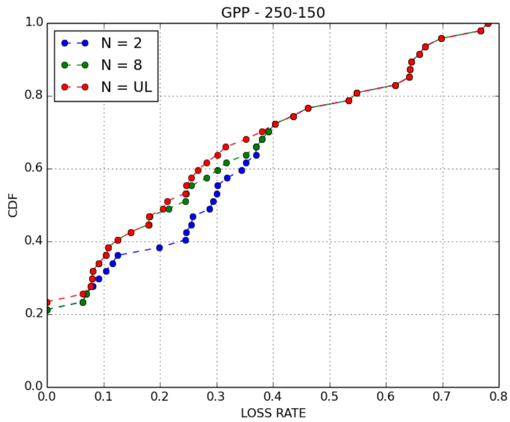
IoB variant	Number of copies
Two-Hop Relay	2
Binary Spray and Wait	8
Epidemic routing	∞

We observe from Figures A.10 and A.11 that Epidemic routing protocol offers the lower loss rate for GPP and NP policies. By disseminating a large number of copies in the network it maximizes the redundancy and the robustness. GPP has a better loss rate comparing to NP in all cases thanks to its protection of self production.

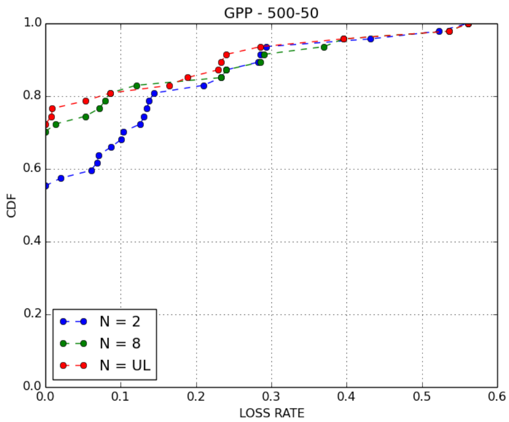
Binary Spray and Wait provide close performances while Two-Hop Relay is significantly below. This may have two explanations. One is that there is not enough diversity and, sometimes, the neighbor chosen as relay is not the good one. Another reason can be that more than two hops are necessary to deliver the redundant packets.



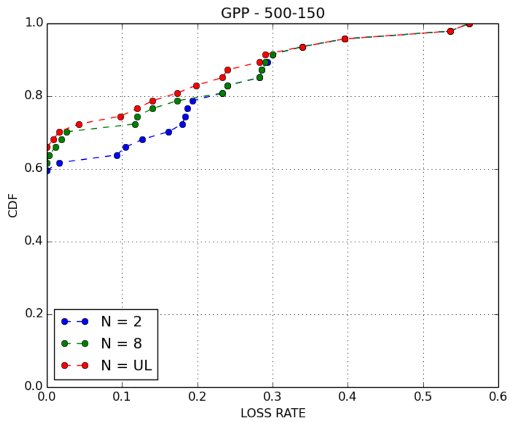
(A) SB-SDC case



(B) SB-LDC case

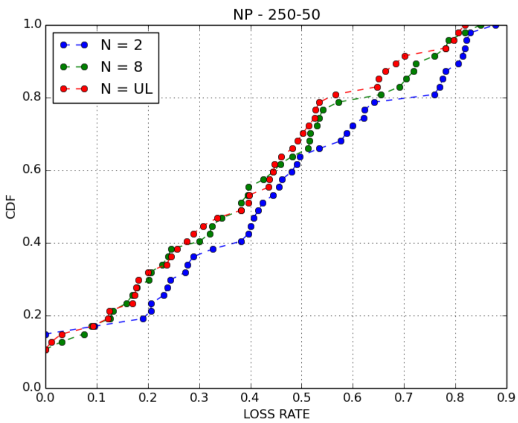


(C) LB-SDC case

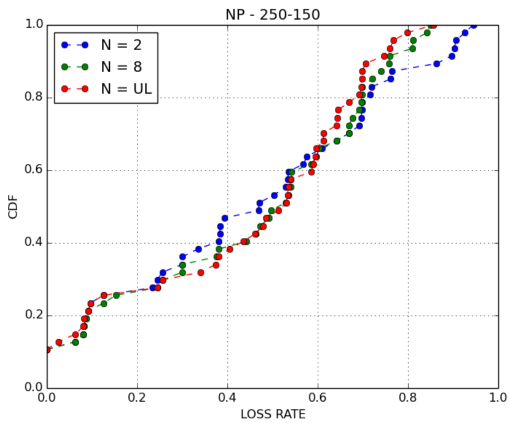


(D) LB-LDC case

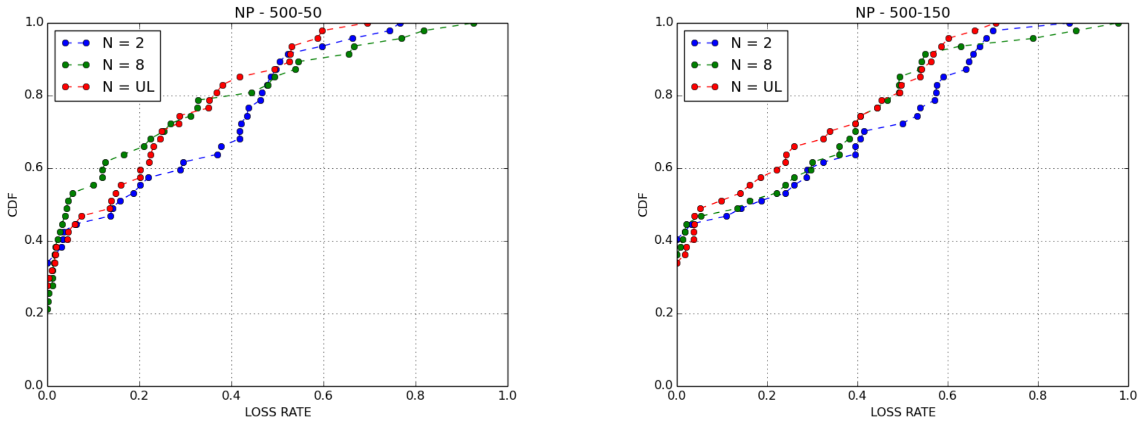
FIGURE 3.10: Loss rate for GPP buffer management policy.



(A) SB-SDC case



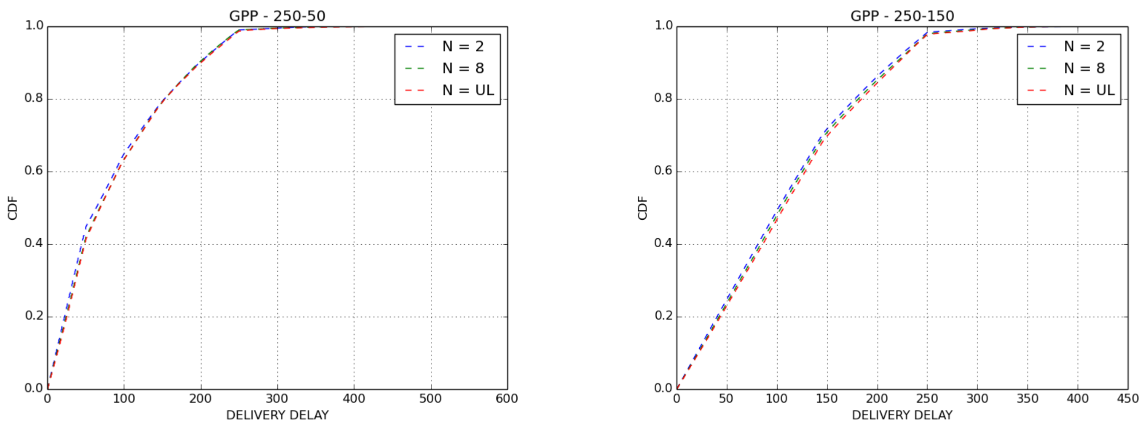
(B) SB-LDC case



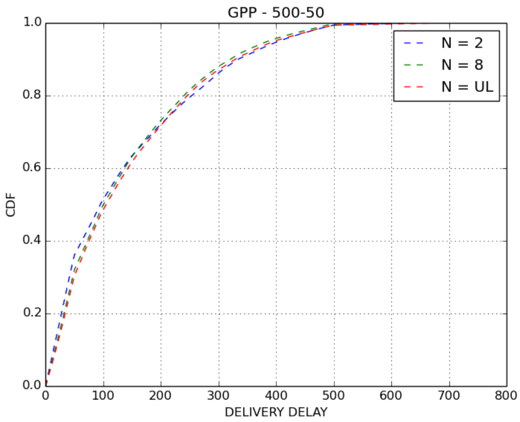
(C) LB-SDC case (D) LB-LDC case

FIGURE 3.11: Loss rate for NP buffer management policy.

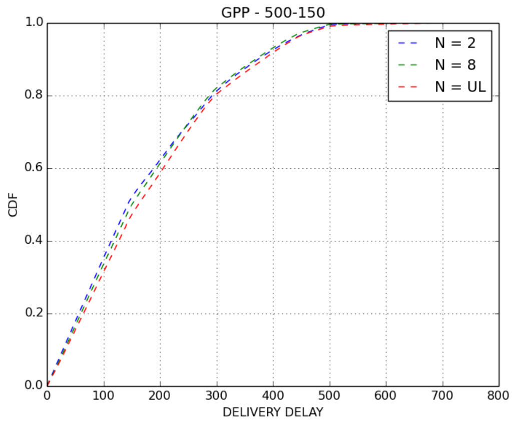
Figures A.12 and A.13 show that the three protocols provide close results in terms of delivery delay. More precisely, Two-Hop Relay protocol offers the best delivery delay while Epidemic routing is the worst. This should however be balanced by the loss rate. Since Epidemic and Binary Spray and Wait deliver more packets, they surely deliver older one, hence degrading the overall delivery delay. The small gap between all performances makes us conclude that Two-Hop relay is not a good trade-off.



(A) SB-SDC case (B) SB-LDC case

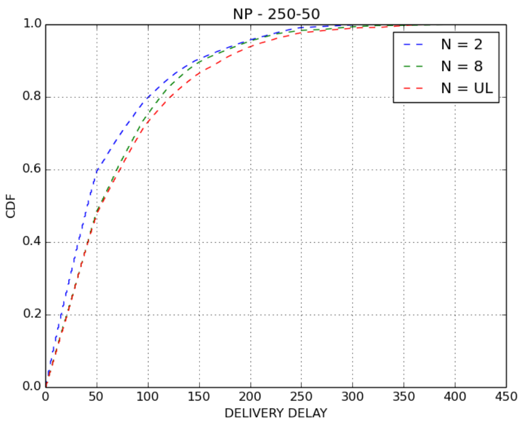


(C) LB-SDC case

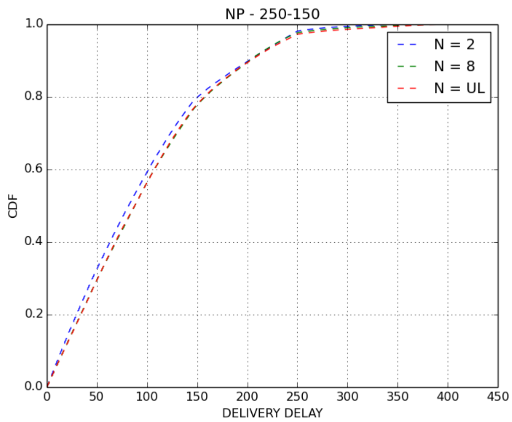


(D) LB-LDC case

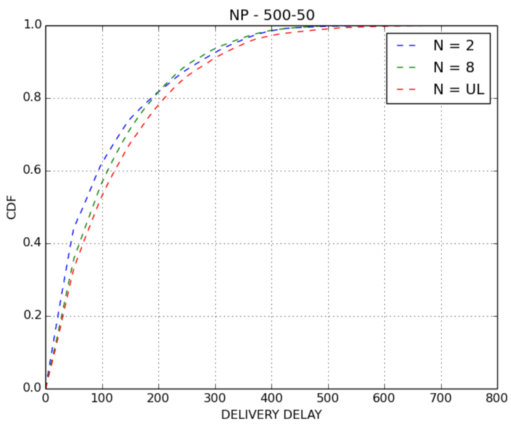
FIGURE 3.12: Delivery delay for GPP buffer management policy.



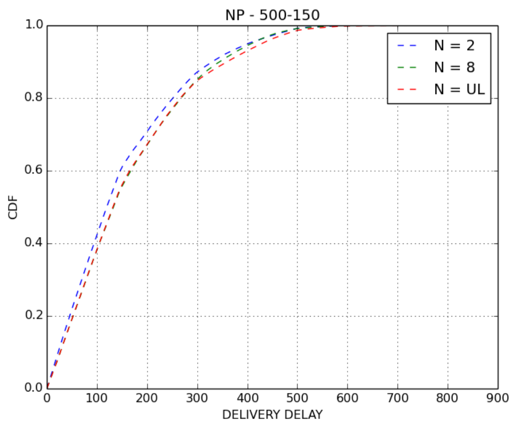
(A) SB-SDC case



(B) SB-LDC case



(C) LB-SDC case



(D) LB-LDC case

FIGURE 3.13: Delivery delay for NP buffer management policy.

Table 3.4 gives the average number of packet actually sent by a node to another in each scenario. This metric is directly linked with the energy consumption of the protocol: at the cost of a small extra storage or extra signaling, a node can send packets to its neighbors only if they don't have a copy of them.

As expected, the more copies sprayed, the more transmissions are needed. It is however not linear with the number of copies and Epidemic consumes only twice as much as Two-Hop relay.

It is more interesting to note that NP generates more transmissions than GPP. Indeed, the mobility of the bike is not uniformly random but constrained by the urban topography. Therefore, the radio neighborhood have phases of stability, e.g. when a group of bikes follow the same street. Since GPP keeps the generated packets in priority, it is more likely that after a while all neighbors of a node have a copy of its packets and no more duplication occurs.

TABLE 3.4: Average number of transmission per node.

		250-50	250-150	500-50	500-150
GPP	N = 2	471	280	738	463
	N = 8	638	317	1113	604
	N = UL	833	329	1437	682
NP	N = 2	600	376	917	562
	N = 8	888	469	1410	762
	N = UL	1265	596	1827	829

3.4.3 Impact of number of bicycles

In this part, we evaluate the impact of the increase in the number of bikes in the network. Figure 3.14 shows the packet delivery ratio when raising the number of bicycles from 50 to 150. We observe that, as expected, the delivery rate increases by raising the number of bikes.

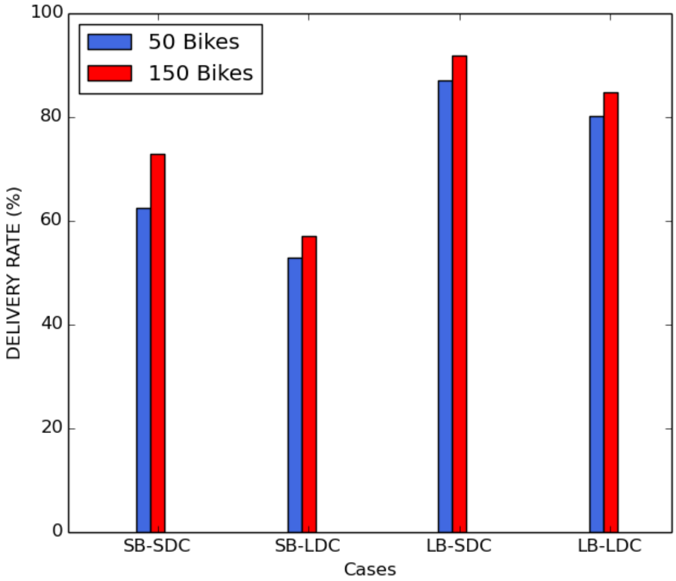


FIGURE 3.14: Impact of the increase in the number of bikes on the delivery rate.

Figures 3.15 and 3.16 confirm this result. They clearly illustrate that the loss rate decreases respectively when rising the number of bicycles.

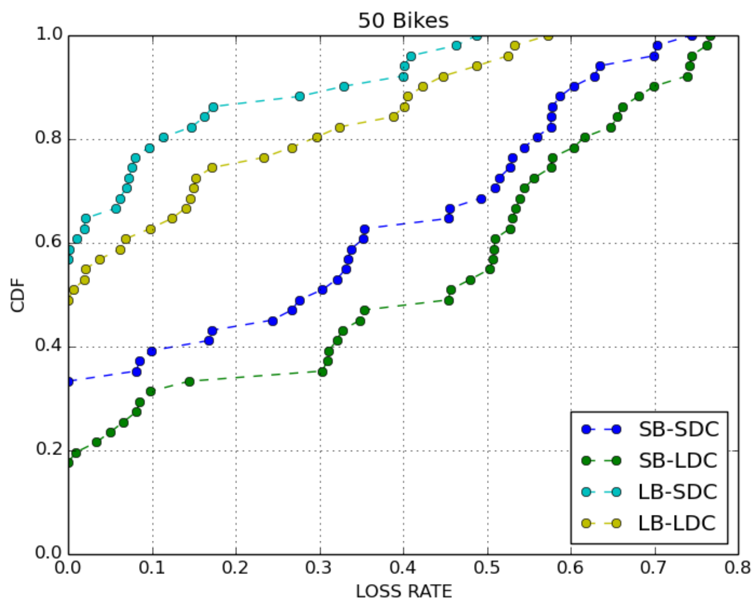


FIGURE 3.15: Loss rate for 50 bikes.

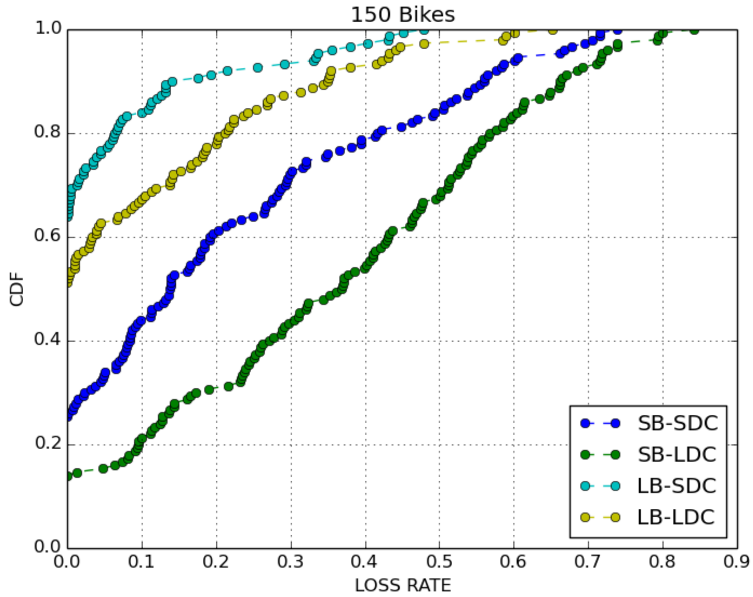


FIGURE 3.16: Loss rate for 150 bikes.

The increase in the number of bikes influences slightly the delivery delay as shown in Figures 3.17 and 3.18. In this situation, more bicycles will circulate in the network allowing more communications with neighbor nodes as well as gateways. Thus, the increase in the number of bicycles offers a better delivery rate and a lower delivery delay.

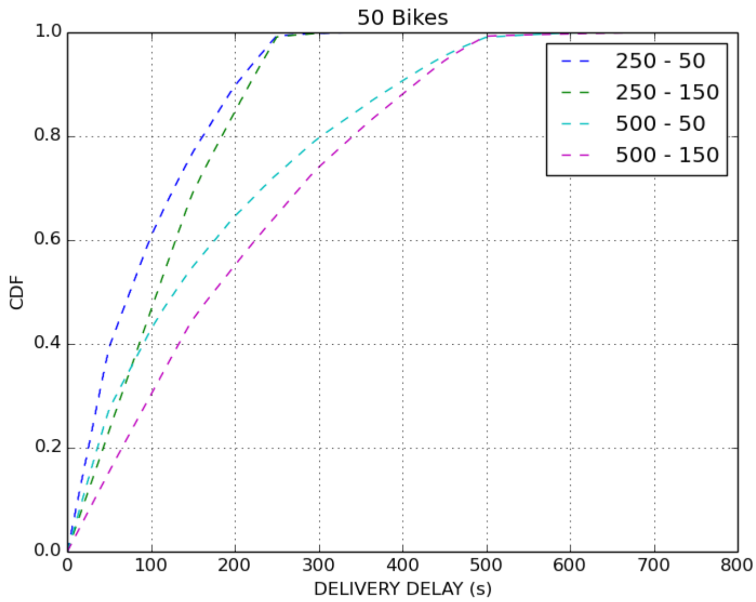


FIGURE 3.17: Delivery delay for 50 bikes.

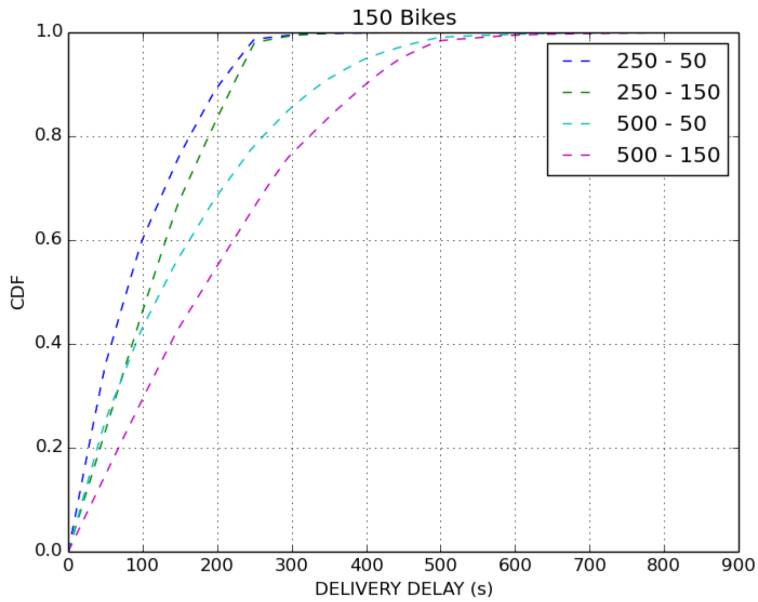


FIGURE 3.18: Delivery delay for 150 bikes.

3.5 Conclusion

In this chapter, we have introduced the IoB-DTN protocol. It is a n-copy protocol closely inspired by Binary Spray and Wait. It is tailored for being applied to mobile network IoT devices running a data collection application. Depending on the parameter settings and the buffer management policies that are implemented, several variants of the protocol can be defined. We evaluate these variants on a realistic scenario of a smart bike-sharing system where each bike embeds sensors and a 802.11p communication device.

Our results highlight the impact of redundancy of packets induced by our protocol and the efficiency to give priority to self generated packets or to already sprayed packets. This redundancy however costs energy as part of packet transmission. This cost can be partially mitigated by exploiting the stability of the radio neighborhood induced by the urban mobility pattern.

In the following chapter, we evaluate IoB-DTN more in details by assessing the impact of the increase of the transmission range of sensors mounted on bikes as well as we give a comparison between the multi-hop IoB-DTN protocol and a long range technology.

Chapter 4

A Comparative Evaluation of the Performance of the multi-hop IoB-DTN routing protocol

In this chapter, we give a more detailed performance evaluation of IoB-DTN protocol. First, we evaluate the performance of the protocol by ranging the transmission power. Performance is measured in terms of delivery rate, delivery delay, throughput and protocol cost resulting in the number of packets transmitted and received in the network. Then, we compare the performance of the multi-hop IoB-DTN protocol with a low-power wide-area network (LPWAN) technology. The performance metrics used for the comparison are the energy consumption and the throughput.

The low power wide area networks represent a novel communication paradigm in the evolution of the wireless communication technologies [95]. They have been designed to provide cost-effective wide area connectivity for the IoT applications: multiyear lifetime and multikilometer range for battery-operated mobile devices. The battery lifetimes can possibly operate up to ten years and the operating range is from over 10 km in rural areas and few tens of kilometers in urban environments. LPWANs consume low power and use a low data rate for data transmission. They are typically seen as cellular networks by connecting end devices (ED) directly to base stations (BS) which relay data packets between the EDs and an application server. An ED communicates only to a BS forming a star-topology network that brings huge energy saving advantages. LPWAN technologies include unlicensed band technologies (e.g. Sigfox, LoRa/LoRaWAN, and Weightless), advanced cellular technologies (e.g. LTEM and NB-IoT) and recent reforms to IEEE standards (e.g. IEEE 802.11ah, IEEE 802.15.4g, and IEEE 802.15.4k).

Here, we compare IoB-DTN protocol to a low-power long-range technology, LoRa/LoRaWAN type [1] which is based on chirp spread spectrum modulation. The use of this modulation provides enhanced performances in terms of range, significantly increasing the robustness of the signal and the sensitivity of the receiver while maintaining low power consumption.

[1] LoRa: https://www.lora-alliance.org/

4.1 Related works - Communication based on long range technologies

Within recent years, many low-power wide-area network (LPWAN) technologies have been deployed. LPWA networks are characterized by having several forms as well as different market approach and technology stack. The most used LPWAN technologies are LoRaWAN, Sigfox and Weightless.

LoRa/LoRaWAN technology [79] was developed by the start-up Cycleo in 2009 in Grenoble city, France and was purchased by Semtech (USA) in 2012. In 2015, LoRa technlogy was standardized by LoRa-Alliance and was deployed in 42 countries. Its architecture is based on chirp spread spectrum modulation which uses the same low power characteristics as FSK modulation, whereas immensely raises the communication range. The LoRa physical layer operates on the 868 in Europe, 433 in Asia or 915 in North Ametica MHz ISM bands.

In 2010, the Sigfox technology [101] was developed by the start-up Sigfox in Toulouse, France. It is characterized by the application of a technique based on ultra-narrowband IoT communications designed to support IoT deployments over long range communications. It operates in the 869 MHz in Europe and 915 MHz in North America bands. The signal of Sigfox is narrowband using channel bandwidths lower than 1 KHz and forwarding a maximum payload size of 12 Bytes.

With regard to Weightless technology [114], the Weightless Special Interest Group has developed three open standards: *Weightless-W*, *Weightless-N* and *Weightless-P*. Weightless-W is based on narrow-band FDMA channels with Time Division Duplex between uplink and downlink. It is designed to be performed in TV white-spaces (470-790 MHz). Weightless-N is based on the ultra-narrow-band technology and it gives only uplink communication. Weightless-P offers ultra-high performance LPWAN connectivity.

4.2 Overview of LoRa technology

Unlike conventional mobile networks, such as 4G or 5G, that can carry large amounts of data, LoRa is tailored to only transport small data packets emitted by sensors mounted on connected objects.

LoRa is the physical layer or the wireless modulation used for long range communication unlike traditional telecom networks [79]. In fact, a single gateway can cover hundreds of square kilometers or even entire cities. More precisely, it can cover few tens of kilometers in urban areas while over 10 Km in rural areas. In LoRa technology, sensors consume low energy to forward data. There is no need for human intervention to change the battery. Indeed, devices can emit for ten years with a small battery.

As mentioned above, LoRa is based on chirp spread spectrum modulation which is dedicated to long communication distances as well as it is robust to interference. Semtech's LoRa chips can send data using the unlicensed frequencies. The widely used band in Europe is 868 MHz, the one in North America is 915 MHz and the frequency used in Asia is 433 MHz. The maximum data rate is 50 kbps as well as the payload of each transmission ranges from 2–255 octets [11]. In LoRa, the bandwidth values that can be occupied by the chirp are 125 kHz, 250 kHz, 500 kHz.

LoRaWAN defines the media access control (MAC) protocol which is responsible for communications [116]. The protocol allows low-powered devices to communicate with applications connected to the Internet over long range distances.

LoRa includes a forward error correction (FEC) code. It is an approach to add redundant bits to the forwarding data in order to be able to recover the errors at the reception. The coding rate (CR) defines the proportion of delivered bits carrying the data. It is defined as follows:

$$CR = \frac{4}{4+n} \tag{4.1}$$

with $n \in \{1, 2, 3, 4\}$.

The spreading factor (SF) represents the length of the code sent. In order to avoid interference, the spread codes are orthogonal, thus several signals can occupy the same channel without interfering. A LoRaWAN network can support up to 6 spreading factors: SF7, SF8, SF9, SF10, SF11 and SF12.

In this chapter, we wish to compare the performance between the multi-hop IoB-DTN protocol and a long range technology. IoB-DTN protocol is a multi-hop protocol since there are bike-to-bike and bike-to-bike station communications. While, in a long range technology, only bike-to-bike station communication is allowed as shown in Figure 4.1.

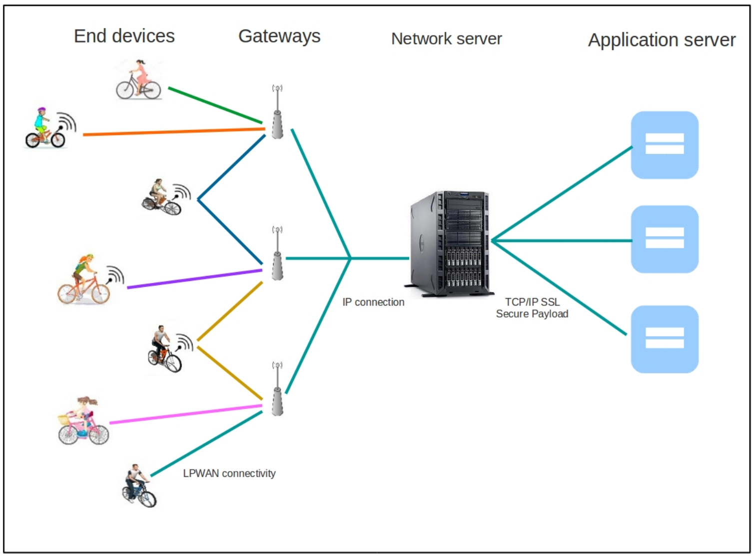


FIGURE 4.1: Illustration of IoB Long-Range.

We consider IoB-DTN protocol with a radio propagation that gives us around 1 kilometer as communication range as denoted IoB-LR. In IoB-LR, each node periodically generates data packets, stores them in its buffer and when the duty cycle is over and whenever a base station comes in range it sends all the data stored in its buffer. Therefore, there is only bike to bike station communication.

4.3 Simulation environment

We consider the same ad-hoc network of bikes presented in Chapter 3. Each bike has embedded sensors, a 802.11p communication device, periodically generates a data packet and stores it in its buffer. All bike stations are equipped with base stations which are connected to the Internet. Each bicycle station has a 802.11p interface and acts as a fixed sink.

In previous chapter, we have proposed and simulated four buffer management policies. From the results obtained, GPP (Generated Packet Priority) policy which protects the self production gives the best results in terms of loss rate and delivery delay. In this chapter, we consider the GPP policy and the number of copies is set to 8 in all our simulations.

For our simulations, we assume 49 bicycle stations deployed in the city center of Lyon as well as 51 bikes moving between those bike stations. We simulate 10 scenarios with different paths of the bikes in each scenario. The simulation time is 30 minutes. We simulate four sets of parameters, as presented in preceding chapter, by varying the buffer size and the duty cycle values.

Since there is not a simulation model for long range technology in OMNeT++ network simulator, we assume that IoB-LR follows the behavior of the LoRa Semtech SX1272 chipset [28]. As in IoB-DTN protocol, the nodes and gateways have a 802.11p communication device, in our theoretical results, we consider the parameters offered by the Qualcomm AR6004 chipset [3], presented in Table 4.1.

TABLE 4.1: Parameters used.

Parameters	**IoB**	**IoB-LR**
Tx	237 mA	26 mA
Rx	66 mA	12 mA
Packet duration	213 μs	250 − 50: 0,2 s 250 − 150:: 0,6 s 500 − 50:: 0,1 s 500 − 150: 0,3 s
ACK duration	213 μs	0.05 s
Packet size	160 Byte	250 − 50: 92 Byte 250 − 150: 260 Byte 500 − 50: 20 Byte 500 − 150: 175 Byte

From Table 4.1, it is important to notice that the packet duration for the long range, LoRa type, varies according to the four considered cases. As an example, considering the SB-SDC scenario: 250 as buffer size and 50s as duty cycle, the 250 packets stored in the buffer have to be forwarded during the 50s time frame of the duty cycle. Therefore, each packet needs to have a maximum airtime of 0.2s.

It is also interesting to point out that the packet size varies for each case for IoB-LR. To well understand that, we refer the reader to Figure 4.2 which shows the airtime in seconds (time to forward a packet) for different spreading factors and payload size given by an operational LoRaWAN namely

The Things Network [20]. For this work, the bandwidth used is 125 KHz and the coding rate is $\frac{4}{5}$. We are based on Figure 4.2 to determine the packet size for each case for IoB-LR. The values of the payload sizes obtained for different spreading factors for each case are presented in Table 4.2.

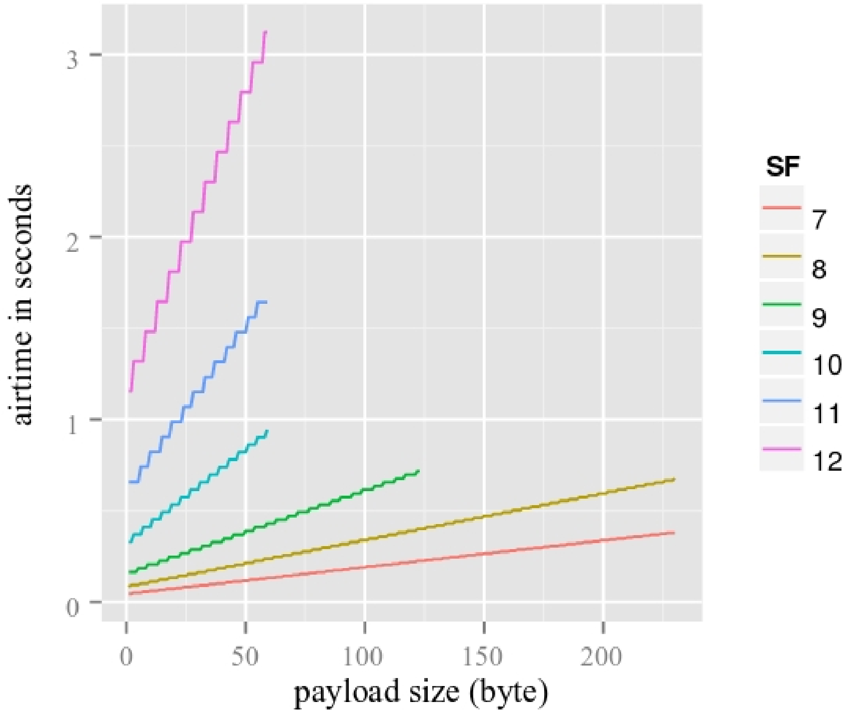


FIGURE 4.2: Airtime for different SF and payloads [20].

Higher chirp rate allows a better reconstruction of the received signal, whereas it delays the time to send a bit. In our simulations, we consider the payload size of IoB-LR using the spreading factor SF7 since it offers the highest values of payload size.

TABLE 4.2: Different payload size (PS) with different SF of IoB-LR.

	Airtime (s)	PS (Byte) SF 7	PS (Byte) SF 8	PS (Byte) SF 9	PS (Byte) SF 10	PS (Byte) SF 11	PS (Byte) SF 12
250 – 50	0.2	92	40	x	x	x	x
250 – 150	0.6	260	220	100	28	x	x
500 – 50	0.1	20	x	x	x	x	x
500 – 150	0.3	175	80	25	x	x	x

4.4 Performance evaluation of IoB by ranging the transmission power

In this section, we evaluate the impact of IoB-DTN protocol on the energy. The transmission power used in our simulations in previous chapter was 10 mW, which gives a communication range ∽ 350 meters. In the present chapter, we focus on the performance evaluation of IoB by assessing four values of the transmission power: 1mW, 5mW, 10mW and 20mW. We present the average results of the ten simulated scenarios.

Figure 4.3 shows the average distances obtained for each transmission power and for each case. We notice that by increasing the value of the transmission power, the communication range of nodes increases respectively.

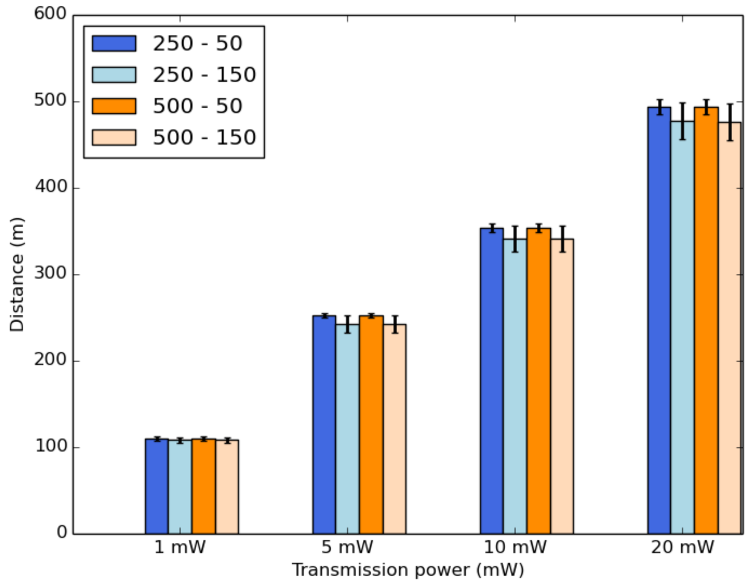


FIGURE 4.3: Average distances.

The average delivery rate obtained is depicted in Figure 4.4. As expected the delivery rate increases by enhancing the transmission power. In this case, the communication range of bikes increases so they encounter more neighbors nodes and more base stations which allows to have a higher delivery rate.

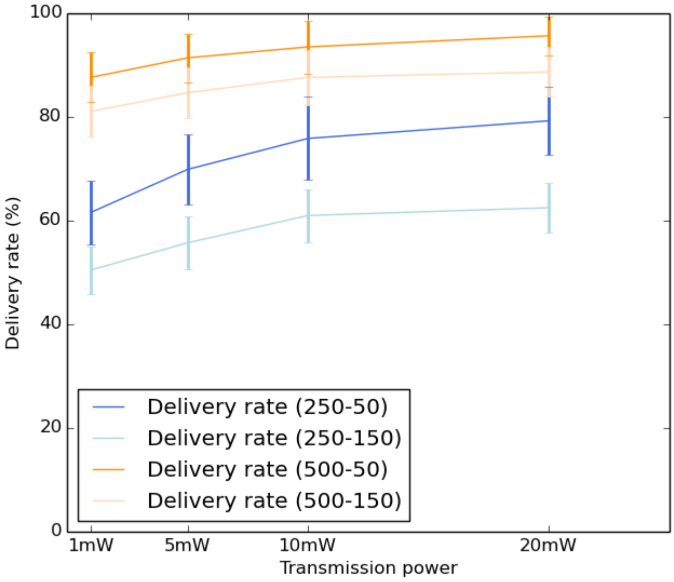


FIGURE 4.4: Average delivery rate.

Figure 4.5 shows the average delivery delays of the received packets. We notice that the impact of the transmission power on the delivery delay is negligible compared to the duty cycle and the size of the buffer. It shows that the connectivity is more impacted by the dynamics of the network than the transmission range. The size of the buffer increases the average delay partly because it prevents more packets to be discarded.

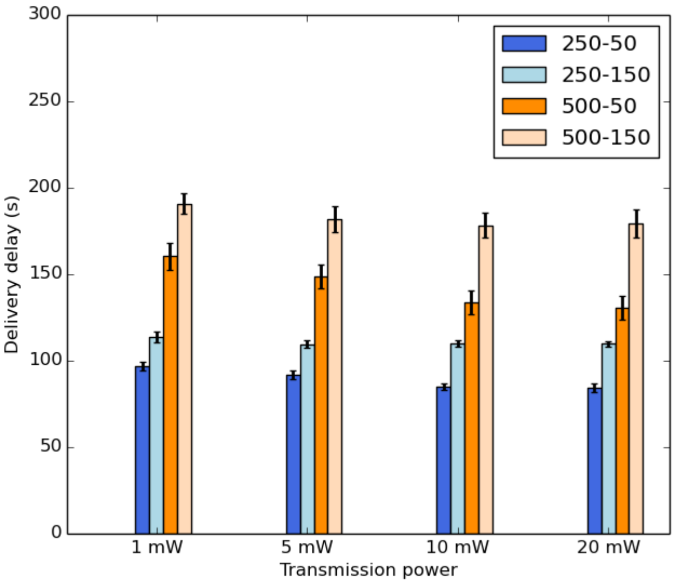


FIGURE 4.5: Average delivery delay.

The transmission range impacts the throughput of the network as depicted in Figure 4.6. The impact of the duty cycle and the buffer size is still very important since the whole buffer is sent at each duty cycle.

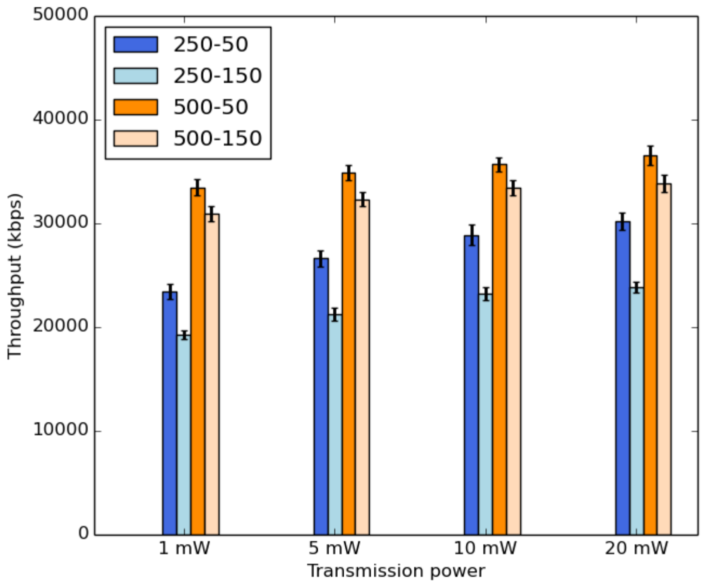


FIGURE 4.6: Average throughput.

We evaluated the average protocol cost of IoB-DTN protocol in terms of the number of transmitted and received packets in all the considered scenarios. The results illustrated in Figure 4.7 present all the communications between bike to bike and bike to bike station. In our setting, each bike finishing its trip forwards all the data packets stored in its buffer to the final bike station that we assume having a very high throughput and we do not consider it in energy consumption assessments. For each case, we can see two columns: the first column represents all the data packets forwarded and the second one depicts all the received data packets. On one hand, the first column contains three fields: NPSN, NASN and NPSG. First, NPSN represents the number of packets sent to nodes. Secondly, NASN is the number of acknowledgments sent to nodes. Finally, NPSG represents the number of packets sent to gateways. On the other hand, the second column has two fields: NPRN and NPRG. The first one corresponds to the number of packets and acknowledgments received by nodes. The last one, NPRG, represents the number of packets received by the gateways.

We notice that the average number of forwarded and received data packets increases by enhancing the transmission power. This is an obvious consequence since the communication range increases allowing more communications with neighbors bicycles or gateways. It is interesting to note that using a higher duty cycle provides a smaller protocol cost. Indeed, in this case, the packets spend more time to be stored in the buffers which decreases the communication with the remaining nodes and gateways in the network.

We notice that the increase in power and the use of a small duty cycle allow for better delivery rate, delivery delay and throughput. Whereas it leads to high energy performance. The choice of this value depends on the needs of the designers of the network.

In the next section, we consider IoB-DTN with 10 mW as transmission power since it gives the compromise between the evaluated metrics.

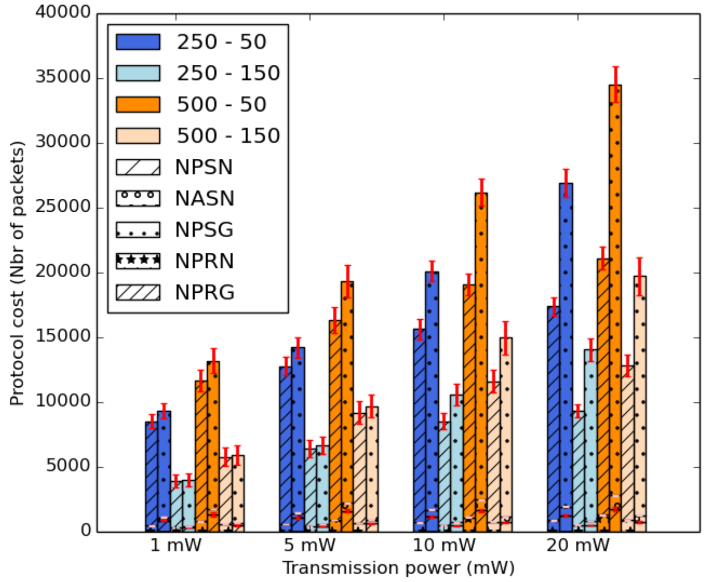


FIGURE 4.7: Average protocol cost of IoB.

4.5 Performance evaluation of IoB and IoB Long-range

In our work, we evaluate the energy consumption and the throughput for IoB and IoB-LR. To evaluate the average energy consumption, we calculate the average transmission cost per bike and the average consumption background per bike. Figure 4.8 shows the average transmission cost per bike. It is measured in mAh and computed as follows:

$$TC = [NPS*Tx*DP]+[NAR*(Tx+Rx)*DA]+\underbrace{[NPR*Rx*DP]}_{\text{for IoB}} \quad (4.2)$$

TC is the transmit cost expressed in mAh. *NPS* corresponds to the number of sent packets. *Tx* and *Rx* represents the transmit and the receive consumption respectively. *DP* and *DA* are the packet and the ACK duration in seconds. *NAR* corresponds to the number of received ACK and *NPR* is the number of received packets from nodes.

We notice that IoB-LR has a higher forwarding cost because bikes send all the data packets only to the gateways. On the other hand, IoB offers a smaller forwarding cost thanks to the bike to bike communication that decreases the transmission cost in the network. In order to respect the duty cycle of radio devices regulated in Europe by section 7.2.3 of the ETSI EN300.220 standard, we consider the maximum theoretical duty cycle allowed which is 10% using the sub-bands (869.4 869.65 MHz) [4]. The duty cycle indicates the real period during which a resource is active. Therefore, we present, in Figure 4.8, the average transmission cost for LoRa, respecting the maximum theoretical duty cycle 10%. In fact, from the four simulated cases, the third case that has a buffer size equal to 500 slots and a time to send all the stored packets equal to 50s represents the real value of the maximum duty cycle allowed by the long range LoRa technology. To fill the $\frac{1}{10}$ of 500 slots in 50s, the duty cycle is then 10%. By following the same concept, the duty cycles for the four simulated cases are:

- **250 − 50**: 20%
- **250 − 150**: 60%
- **500 − 50**: 10%
- **500 − 150**: 30%

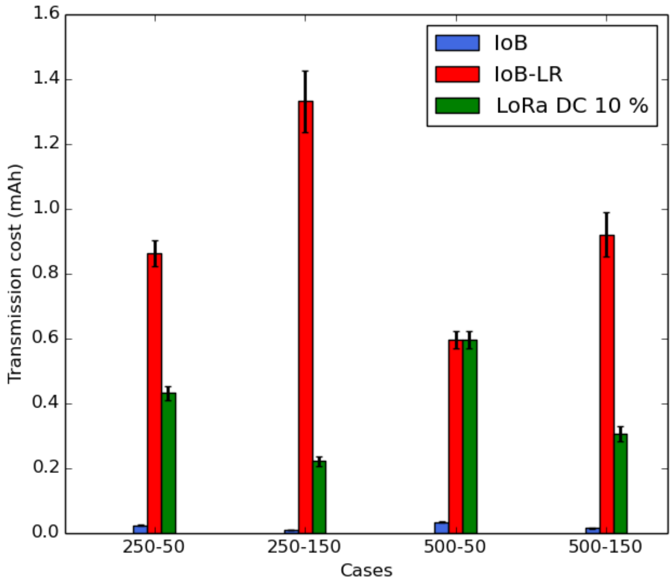


FIGURE 4.8: Average transmission cost per bike.

We note that similar to using the maximum real duty cycle of LoRa technology, IoB gives smaller transmission cost per bike thanks to the bike to bike communication.

Figure 4.9 shows the average consumption background per bicycle. It corresponds to the total consumption per bike and it is measured in mAh. It is computed as follows:

For IoB:

$$BC = \sum(Ta - Td) * Rx \tag{4.3}$$

For IoB-LR:

$$BC = \frac{Rx * BWT}{DC} * \sum(Ta - Td) \tag{4.4}$$

BC is the average background consumption calculated. *Ta* and *Td* represent the arrival and the departure time of the bike expressed in seconds. *DC* is the duty cycle defined in seconds to send all data packets stored in the buffer. It takes as value 50s or 150s depending on the simulated case. *BWT* corresponds to the beacon waiting period defined in seconds. This period is fixed to 10s in all our simulations.

We notice that IoB has higher results in terms of consumption background than IoB-LR since opportunistic communications require the nodes to be always listening for beacons to relay the data packets in the network. Whereas, in long range technology, the nodes enter in sleep mode and they wake up few seconds before starting the packets forwarding.

In Figure 4.9, we also present an optimal average consumption background per bicycle for IoB. In this case, it behaves like IoB-LR. We consider that each bike, having a full buffer, enters in sleep mode. It wakes up a few moments before the packets transmission. From the results obtained in Figure 4.8 and Figure 4.9, we can remark that IoB-LR offers lower energy consumption than the multi-hop IoB protocol.

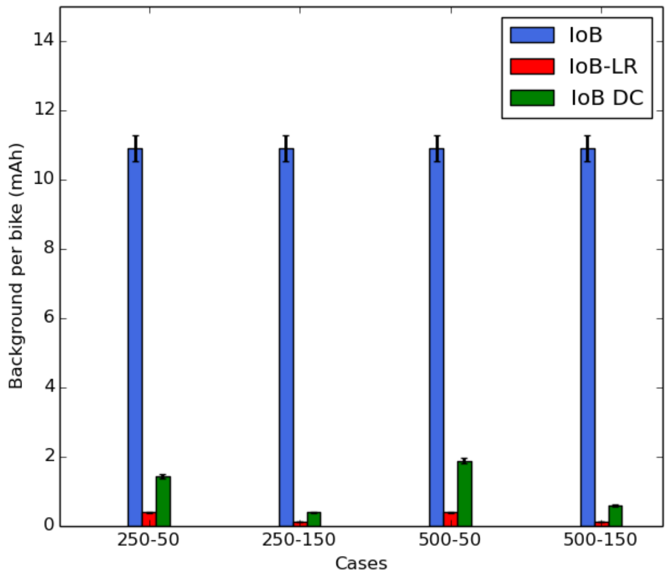


FIGURE 4.9: Average consumption background per bike.

Figure 4.10 shows the average throughput for IoB and IoB-LR. We note that, in all cases, IoB gives better results in terms of throughput by using a smaller duty cycle. While IoB-LR offers better throughput by adopting a higher duty cycle.

This is related to the size of the sent packets in each simulated case. The Figure 4.10 shows also the throughput results for IoB-LR when respecting the maximum theoretical duty cycle allowed by LoRa technology. We remark that IoB has better throughput, in all scenarios, than the long range technology respecting the theoretical duty cycle.

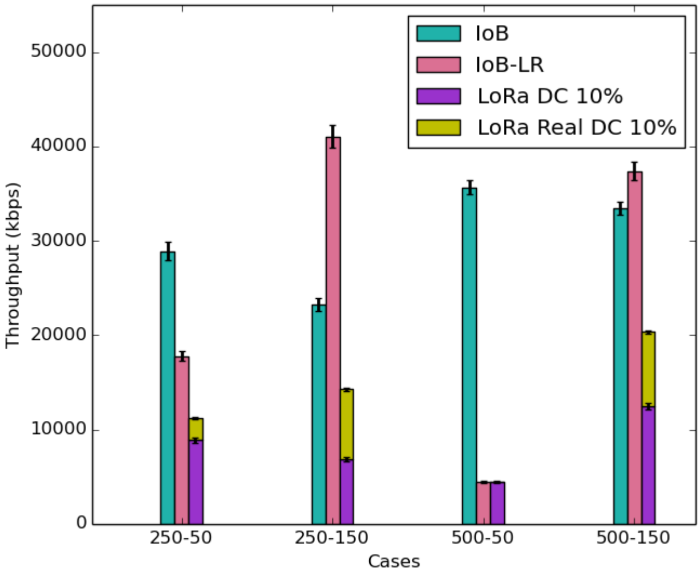


FIGURE 4.10: Average throughput.

In Figure 4.10, we also present the average throughput results for IoB-LR when respecting the effective duty cycle. It represents the real duty cycle for the bikes in each simulation scenario. It is presented in Figure 4.11 and it is measured as follows:

$$EDC = \frac{NPS * Rt}{\sum(Ta - Td)} \tag{4.5}$$

EDC is the effective duty cycle calculated. *NPS* represents the number of sent packets. *Rt* is the airtime defined in seconds.

For example, by respecting the theoretical duty cycle for the first case simulated when having a buffer size equal to 250 slots and the period to send the packets in the buffer equal to 50s, the duty cycle should be 20 %. Whereas in reality, the effective duty cycle for this case is around 16%. It is then interesting to note that IoB protocol offers better throughput, in all cases, than the long range technology respecting the theoretical and the real duty cycle.

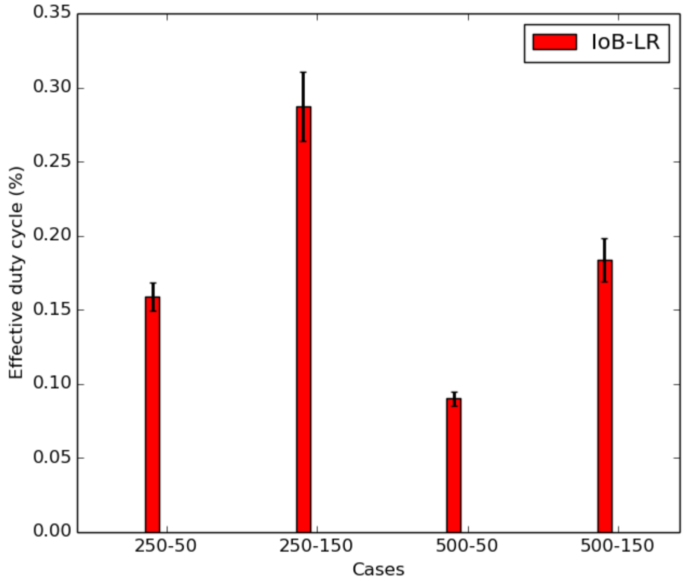


FIGURE 4.11: Average effective duty cycle.

4.6 Conclusion

In this chapter, we provide two performance evaluations of IoB-DTN protocol. First, we give a performance evaluation by varying the transmission power values of sensors. This parameter is important since by increasing the sending power value the communication range of the device raises. In such case, it allows more communications with neighbors nodes and base stations which increases the delivery rate, the throughput and the energy consumption. It is worth to note that using a small duty cycle offers better delivery rate, delivery delay and throughput. Second, we provide a performance comparison of the multi-hop IoB-DTN protocol with a low-power wide-area network (LPWAN) technology, LoRa/LoRaWAN type. Our results show that by using a multi-hop topology, it offers better throughput while by applying a long range technology, where there is only bike to bike station communication, it gives better energy consumption.

In the next chapter, we propose a solution for IoB-DTN protocol based on data aggregation approach to improve its performance on energy consumption.

Chapter 5

For an efficient Internet of Bikes : a DTN routing protocol based on Data Aggregation approach

In the previous chapter, we were interested to compare the multi-hop IoB-DTN protocol to a low-power wide-area network (LPWAN) technology, more precisely LoRa/LoRaWAN type. Our results show that by using a DTN-based multi-hop topology, it gives better throughput while by applying a long range technology, where there is only bike to bike station communication, it provides better energy consumption.

In order to improve the performances of the multi-hop IoB-DTN protocol, data aggregation is performed before forwarding data to destined targets. Data aggregation is a vast research area of wireless sensor networks [54]. It can reduce the energy consumption and network capacity thus achieving a longer network lifetime. In previous studies [111, 110], spatial and temporal aggregations are often based on raw data. With regards to spatial aggregation, data is collected from neighboring sensor nodes, while regarding temporal aggregation data is collected at different time instants.

In this chapter, we investigate an efficient IoB-DTN routing protocol based on data aggregation being applied to mobile network IoT devices running a data collection application. We propose three variants of IoB-DTN: IoB based on spatial aggregation (IoB-SA), IoB based on temporal aggregation (IoB-TA) and IoB based on spatio-temporal aggregation (IoB-STA). We give a comparison evaluation of each variant with IoB-DTN without aggregation and the low-power long-range technology, LoRa type. Performance is measured in terms of delivery rate, delivery delay, throughput and energy consumption.

5.1 Related Works - Communication based on data aggregation mechanism

Over the course of recent years, several works based on data aggregation in wireless sensor networks have been carried out [92]. According studied works in the literature, there are two categories of data aggregation: aggregation structures and aggregation functions.

On one hand, many works have focused on aggregation structures such as tree-based, cluster-based and backbone-based structures. The authors, in [99], have introduced a centralized algorithm and design a distributed protocol for building a tree routing structure with maximum lifetime. Kuo et al. [63] have proposed a data aggregation tree (MECAT) which can minimize the total energy cost of data forwarding and have introduced a 2-approximation algorithm. They have studied two issues: the first one without taking into account relay nodes and the second one with the consider of relay nodes having imperfect link quality. They have proved for the first problem that every shortest path tree has an approximation ratio of 2. According to second case, the problem is proved to be NP-complete and a seven-approximation algorithm is proposed. The authors, in [81], have introduced a spatial clustering algorithm for sensor networks. It can construct a dominating set based on the information description performance of the dominators to perform the data aggregation. In [102], Sinha et al. have proposed an efficient clustering protocol in wireless sensor network that offers significant energy savings. They have performed data aggregation on the basis of entropy of the sensors. The clustering process is distributed and based on the sensed data category, independently of geographic positioning and distance measures. Xu et al. have proposed, in [118], Data Quality Maximization (DQM) protocol based on a backbone that is composed of a set of gateways. The authors have investigated a mobile sink moving along a fixed trajectory without stop to collect data. Their proposal protocol is based on predictability of the sink movement and selects the gateways adjacent to the predicted path of the sink. Cui et al. have proposed, in [37], Similar-evolution Based Aggregation (Simba), a raw data-independent aggregation to consider the evolution of data rather than the raw data. The Simba proposal creates a group of isolated nodes which perform data aggregation, therefore reducing the energy consumption in the network.

On the other hand, several works have focused on aggregation functions. They represent the way to do aggregation. In [76], the authors have presented an experimental study that uses the ARIMA model for the design of an energy efficient data collection in wireless sensor networks. Their proposal avoids sensor nodes to deliver redundant data, this can be predicted by the sink node. Lu et al. have proposed, in [80], an A-ARMA method based on the forecasting by means of an ARMA model over moving average windows. The use of the A-ARMA technique reduces the computation in every sensor node and it does not have a pre-computation phases. In [36], the authors have proposed Agnostic Aggregation (A2), a dynamic forecasting function. Their proposal can predict values with self-tuned model based on temporal aggregation. The authors, in [26], have presented the theory of compressive sampling methods.

5.2 Scenario description

Here, we consider the same smart bicycle sharing system, used in both last two chapters, in which each bike has embedded sensors, a 802.11p communication device, periodically generates a data packet and stores it in its buffer.

The goal of this chapter is to apply the data aggregation mechanism to IoB-DTN in order to enhance its performances regarding several metrics. The idea is to combine data packets of different nodes into a single packet.

It is performed during the generation and the reception phases of a new packet as shown in Algorithms 2 and 3 respectively. We evaluated three variants of IoB with:

- ***Spatial aggregation (IoB-SA)***: packets are aggregated if they were generated in the same area in which its communication range is defined in meters.
- ***Temporal aggregation (IoB-TA)***: packets are aggregated if they were generated less than a variable defined in seconds later or earlier than the reference packet.
- ***Spatio-temporal aggregation (IoB-STA)***: packets are aggregated if they satisfy the two previous aggregations.

Algorithm 2 *Generation phase*: IoB with data aggregation.

At each sensor reading period
Generate a packet p with the readings
if (Δ (p, p') < (Δ area | | Δ period | | (Δ area + Δ period))) **then**
    Aggregate p with the packet p'
else if Buffer management provides a slot **then**
    Store $p \cup N^0$ in the buffer [N^0 copies of p are stored]
end if

Algorithm 3 *Reception phase*: IoB with data aggregation.

On reception of packet $p \cup N \cup L$ (list of neighbors)
$pos \leftarrow$ self position in L
$N' \leftarrow \frac{N}{2^{pos+1}}$
if (Δ (p, p') < (Δ area | | Δ period | | (Δ area + Δ period))) **then**
    Aggregate p with the packet p'
else if Buffer management provides a slot **and** $N' \geq 1$ **then**
    Store $p \cup N'$
    Send ACK for receiving N' copies of p
else
    Packet is rejected, no ACK is sent
end if

In our scenario, we assume that every generated packet has size of 20 byte that could be sent by a long range technology such as LoRa. Since the 802.11p packet size, considered in our previous chapter, was set to 160 byte, we can distinguish two approaches:

- *Aggregation without size reduction*: each node can combine until 7 data packets coming from different intermediate nodes into the same packet without data processing.
- *Aggregation with size reduction*: each node receiving more than 7 data packets to be combined into the same packet, it combines and compresses the readings coming from this different sources. In order to limit the number of data packets aggregated in the same packet, each node applies the basic aggregation functions to process data. The simple operations used are Average, SUM, COUNT, MAX, MIN, etc. The operation used depends on the type of collected data in such application. Our protocols are independent of the aggregation function, we thus do not consider it.

5.3 Simulation settings

As preceding chapters, we consider the same ad-hoc network of bicycles. Here, we simulate 51 bicycles moving between 49 bike stations in the Lyon city. We simulate 5 scenarios by varying the paths of bicycles in each scenario. Each node generates a packet every second. The simulation time is 30 minutes. We consider the Generated Packet Priority (GPP) policy as buffer management policy and the number of packets copies sprayed in the network is set to 8 in all our scenarios. The transmission power of nodes considered is 10mW which gives a communication range $\backsim$ 350 meters. It gives the compromise between the evaluated metrics in our previous chapter. We simulate four sets of parameters, as preceding chapters, by varying the buffer size and the duty cycle values.

5.4 Simulation results and performance evaluation

In this section, we evaluate the performances of IoB-DTN protocol by applying the data aggregation mechanism. More specifically, we compare the three variants of IoB cited above. The performance metrics used for the analysis are the delivery rate, delivery delay, throughput and energy consumption.

5.4.1 Spatial aggregation

The aggregation area is defined where the sensed values by the different sensor nodes are assumed to be generated in the same range. We simulate three values of the aggregation distances: 20m, 50m and 100m.

Figure A.3 shows the average delivery rate for spatial aggregation. We notice that the impact of the aggregation area is negligible. The transmission rate increases slightly by rising the aggregation distance. In the same context, the throughput as illustrated in Figure A.2 is approximately the same. Thus, it shows that the nodes mobility is more impacted than the aggregation area.

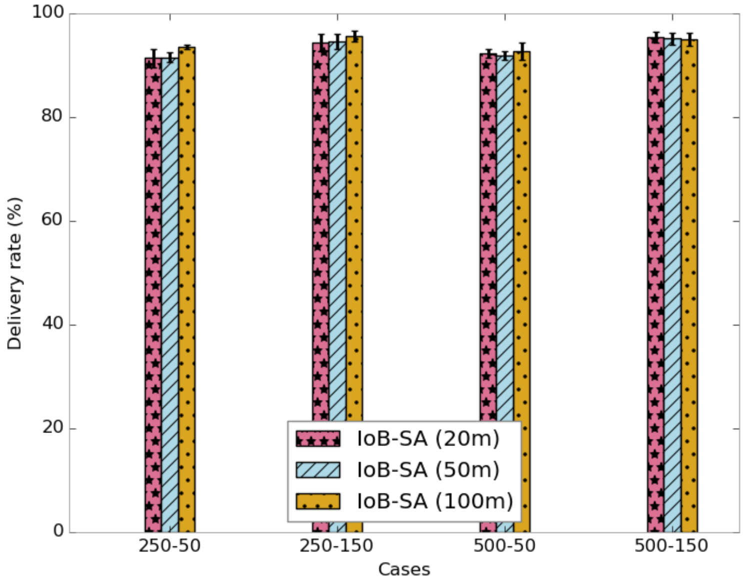


FIGURE 5.1: Average delivery rate for IoB-SA.

The average delivery delays of the received packets are depicted in Figure A.4. By using a small duty cycle, the delays are better, since they are delivered faster, and almost the same for the three parameters.

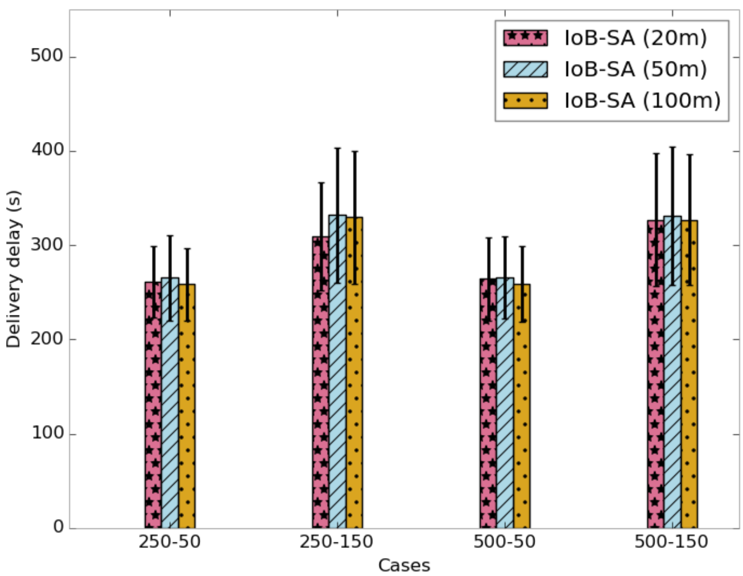


FIGURE 5.2: Average delivery delay for IoB-SA.

In order to evaluate the energy consumption of IoB-DTN protocol with spatial aggregation, we appraise the protocol cost and the number of packets aggregated per packet. Figure A.6 shows the average protocol cost of IoB-SA variant. It is calculated as the number of data packets forwarded in the network and it is depicted in Figure A.6. We can see two fields in each column: *NPSNG* (number of packets sent to nodes and gateways) and *NASN* (number of acknowledgments sent to nodes). It is clear that the increase of the aggregation area reduces the overall protocol cost in the network. This is an obvious consequence since more data packets are aggregated into same packets, thus achieving better communication cost. In addition, the use of a large value of duty cycle reduces the protocol cost since data packets will be stored more time in the buffers.

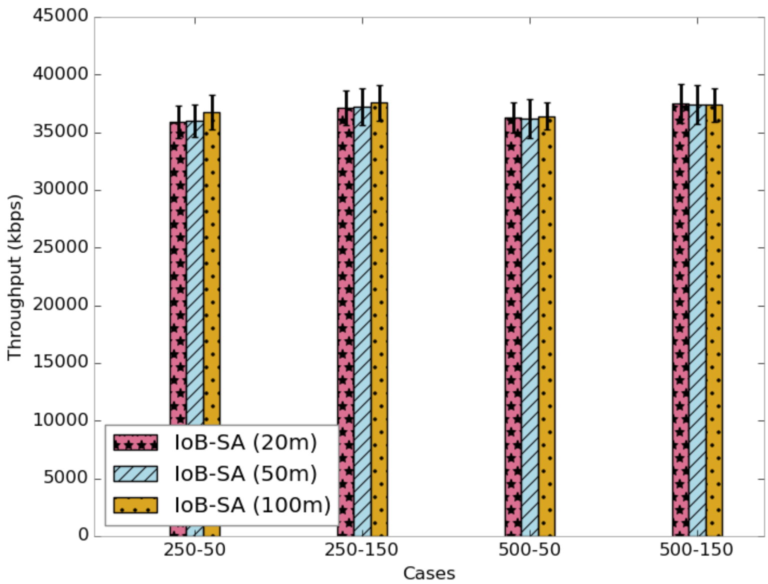


FIGURE 5.3: Average throughput for IoB-SA.

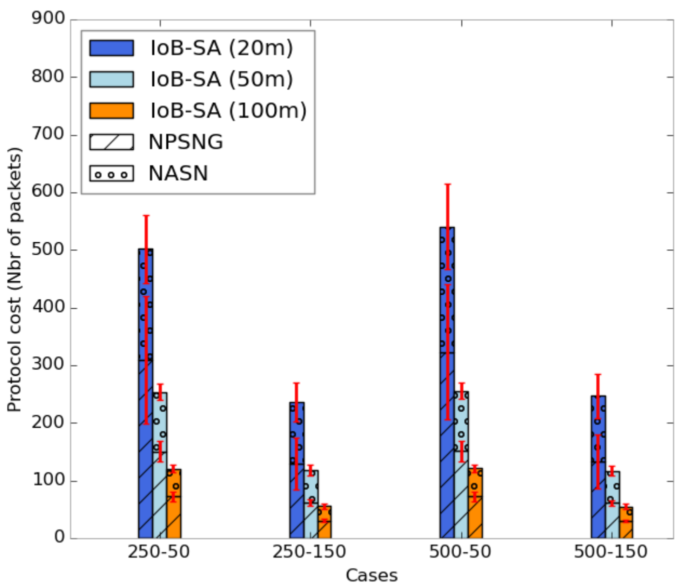
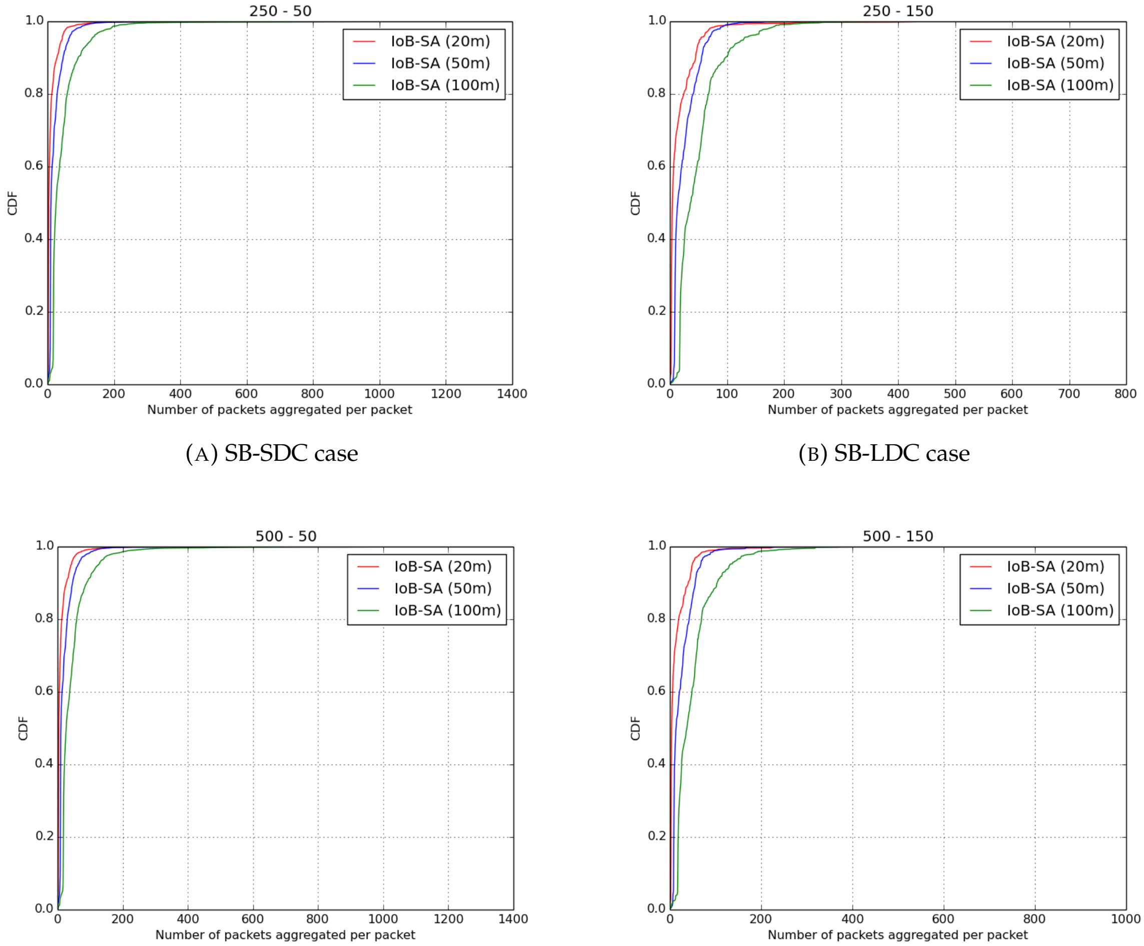


FIGURE 5.4: Protocol cost for IoB-SA.

Moreover the assessment of the communication cost and to well investigate the energy consumption of IoB-SA, we also evaluate the number of aggregated packets into the same packet for the three parameters as illustrated in Figure 5.5. As cited above, when a node receives more than 7 data packets to be aggregated into the same packet, then it applies the aggregation functions. This can influence on the energy consumption of sensor nodes, therefore the overall network lifetime. It is important to notice that using a small aggregation distance (20m) leads to aggregate less data packets into the same packet since the source node meets less neighbors nodes.



(A) SB-SDC case

(B) SB-LDC case

(C) LB-SDC case

(D) LB-LDC case

FIGURE 5.5: Average number of aggregated packets per packet for IoB-SA.

5.4.2 Temporal aggregation

The aggregation period is defined where the sensed values by the different sensor nodes are assumed to be generated less than a variable defined in seconds later or earlier than the reference packet. We evaluate three values of the aggregation period: 2s , 5s and 10s.

The average delivery rate for temporal aggregation is depicted in Figure A.7. It clearly illustrates that by rising the buffer size, the delivery rate reaches 100 % for all cases. We also notice that by increasing the aggregation period, the delivery rate rises respectively. It is fair to note that the transmission rate obtained by using temporal aggregation is better than applying spatial aggregation. Indeed, this impacts the throughput as shown in Figure A.9.

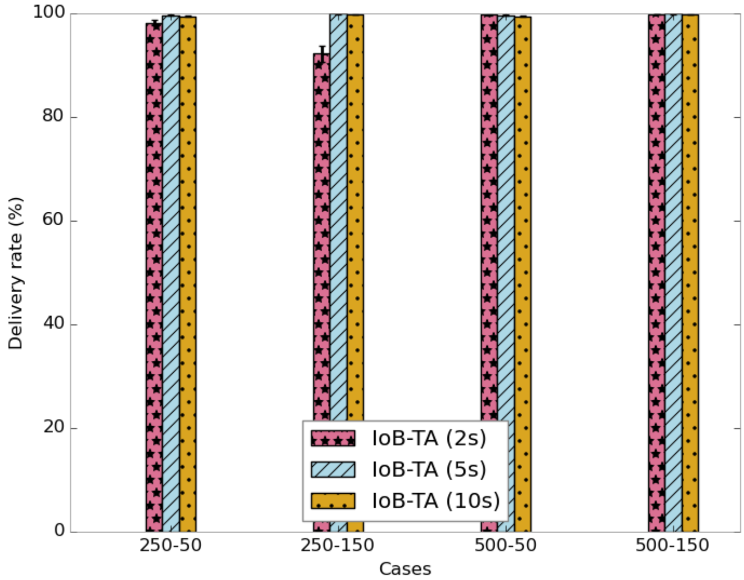


FIGURE 5.6: Average delivery rate for IoB-TA.

Figure A.8 shows the delivery delays. We note that by increasing the aggregation period, the delays rise gradually. As for spatial temporal, using smaller duty cycle gives better performance of delivery delays.

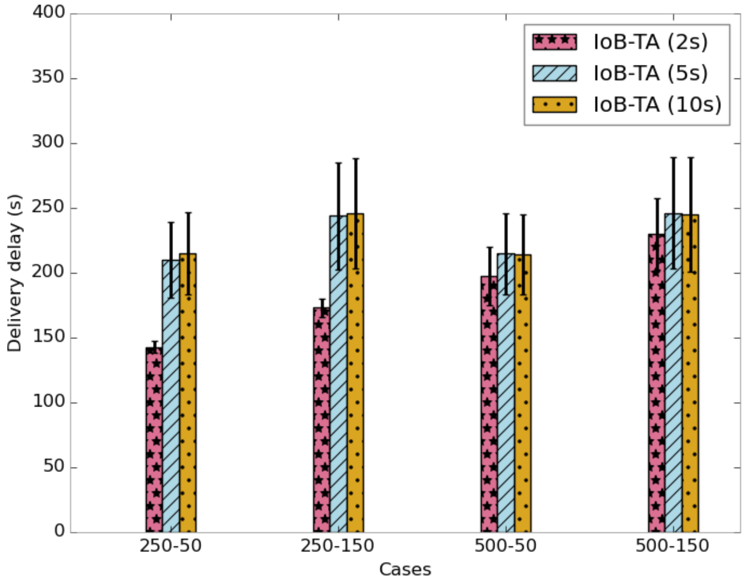


FIGURE 5.7: Average delivery delay for IoB-TA.

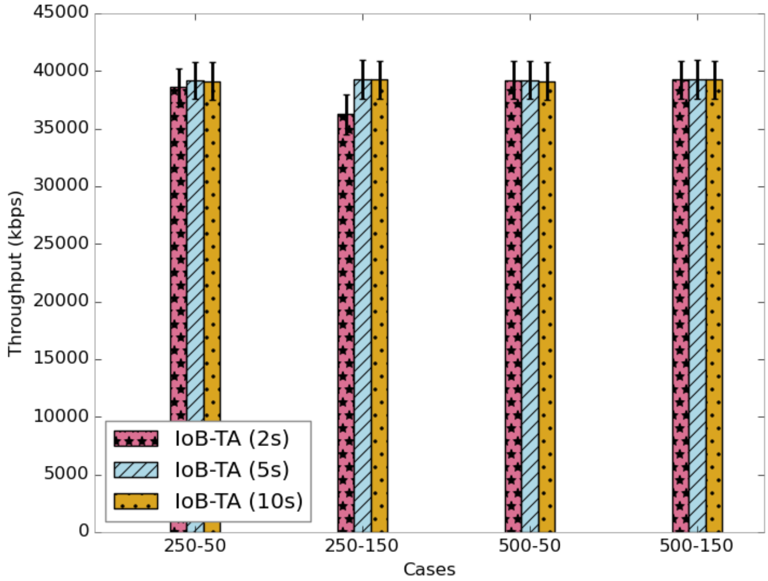


FIGURE 5.8: Average throughput for IoB-TA.

As for the energy consumption of IoB with temporal aggregation, we also evaluate the two parameters cited before. The average protocol cost is illustrated in Figure A.10. We remark that the number of transmitted packets in the network decreases by increasing the aggregation period. As for spatial aggregation, the rise of the aggregation parameter leads to have more packets aggregated which reduces the overall protocol cost in the network. It is important to note that the communication cost for IoB with temporal aggregation is twice than IoB with spatial aggregation.

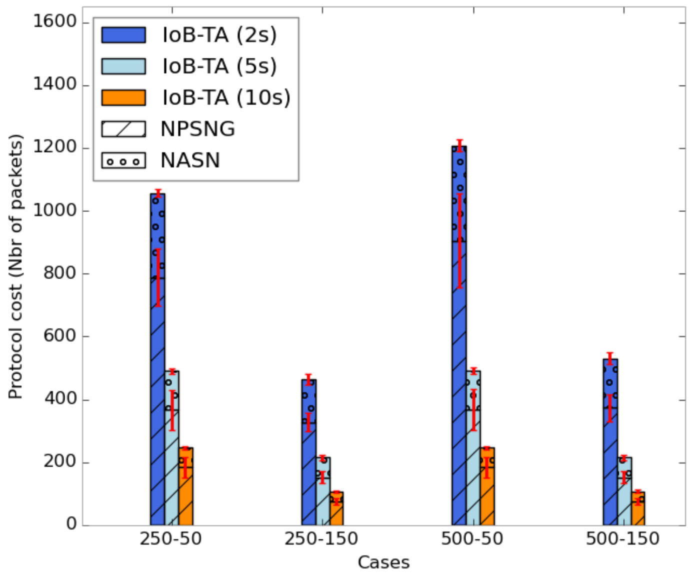
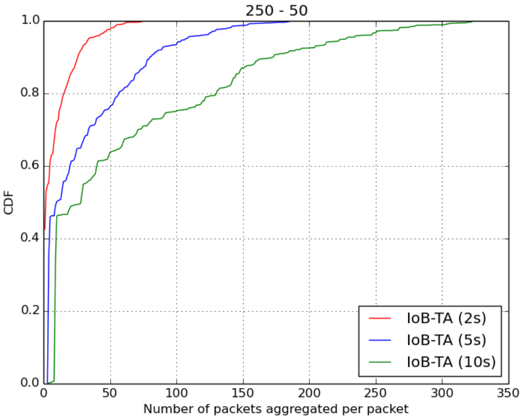
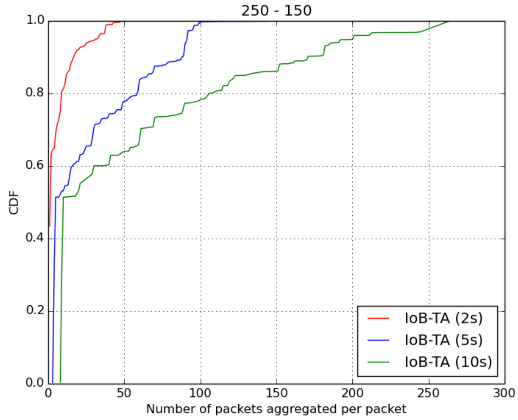


FIGURE 5.9: Protocol cost for IoB-TA.

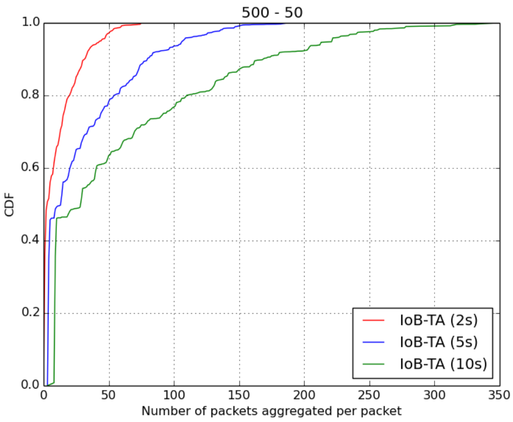
The number of aggregated packets into the same packet for IoB with temporal aggregation is depicted in Figure 5.10. As for spatial aggregation, the use of the smallest period value (2s) gives better performance since it leads to aggregate less data packets into a packet.



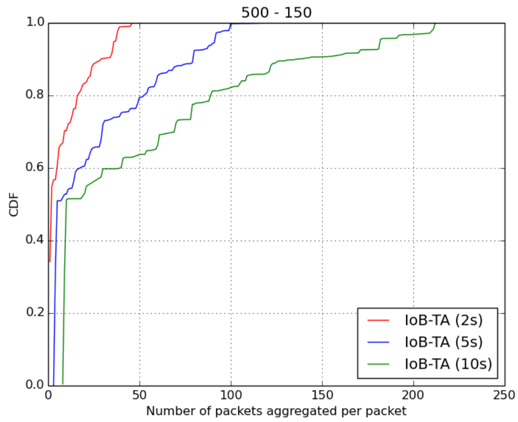
(A) SB-SDC case



(B) SB-LDC case



(C) LB-SDC case



(D) LB-LDC case

FIGURE 5.10: Average number of aggregated packets per packet for IoB-TA.

It is clear to note that temporal aggregation allows to aggregate less than the spatial aggregation. It is also important to point out that using smaller parameters for both aggregations can achieve better performances in terms of energy consumption.

5.4.3 Spatio-temporal aggregation

In spatio-temporal aggregation, the data packets are aggregated if they satisfy the two conditions of the aggregation area and the aggregation period mentioned above. We evaluate four values of IoB-STA variant: 20m-2s, 100m-2s, 20m-5s and 100m-5s.

Figure 5.11 shows the average delivery rate of IoB with spatio-temporal aggregation. As expected, we observe that using higher values of both aggregation parameters offers better performance. In addition, we can notice that using a high value of the aggregation period gives best results than lower one. This indicates the efficiency of temporal aggregation approach. This result impacts the throughput which is presented in Figure 5.13.

The average delivery delays are shown in Figure 5.12. It is clear that the use of small aggregation parameters offer lower delays. It is important to note that using a small buffer size provides the best outcomes in terms of delivery delay.

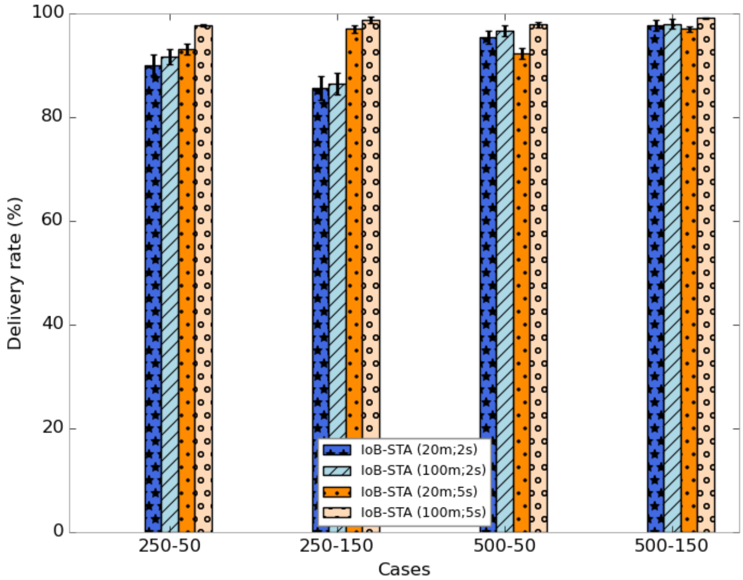


FIGURE 5.11: Average delivery rate for IoB-STA.

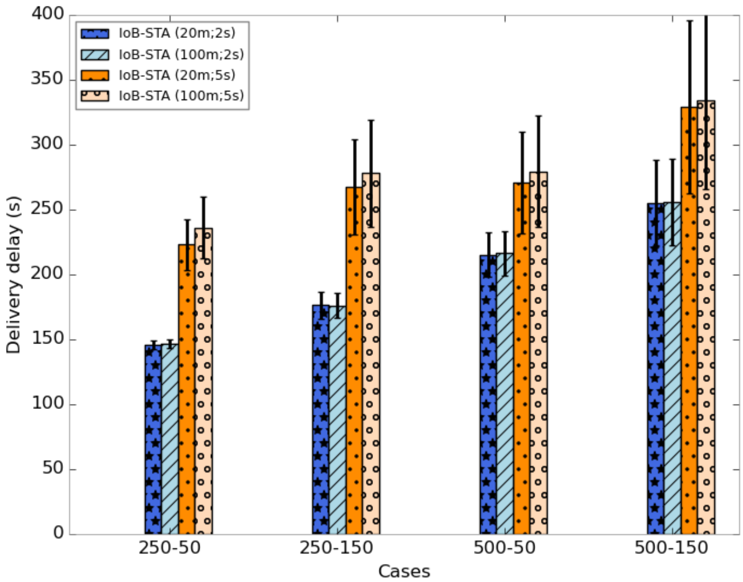


FIGURE 5.12: Average delivery delay for IoB-STA.

Figure 5.14 depicts the average protocol cost of IoB-STA. We notice that more the aggregation parameters values are higher more the protocol cost is better. This is an expected consequence since more data packets will be aggregated into same packets which decreases the communication cost.

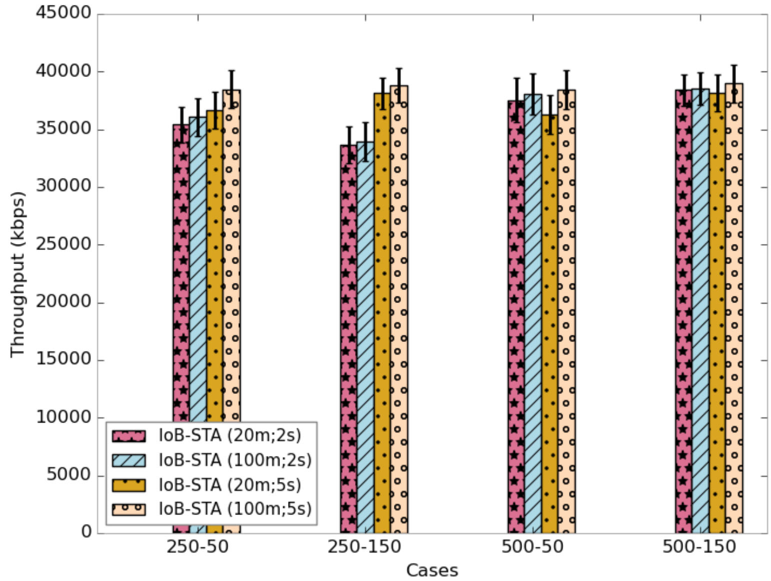


FIGURE 5.13: Average throughput for IoB-STA.

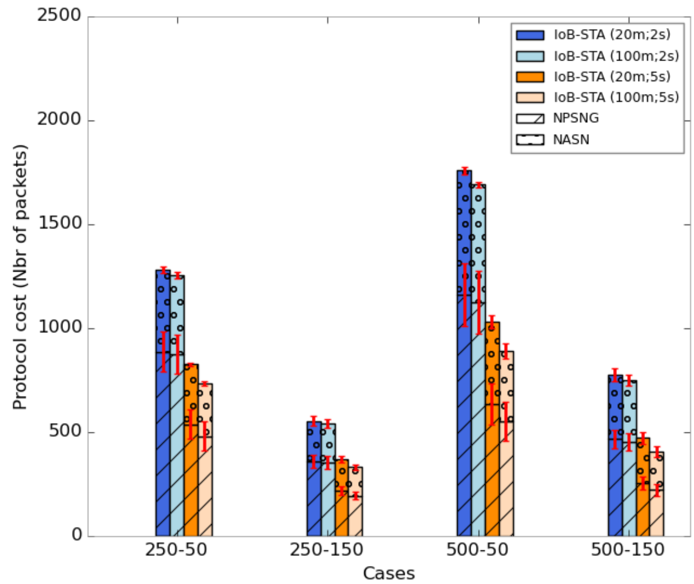
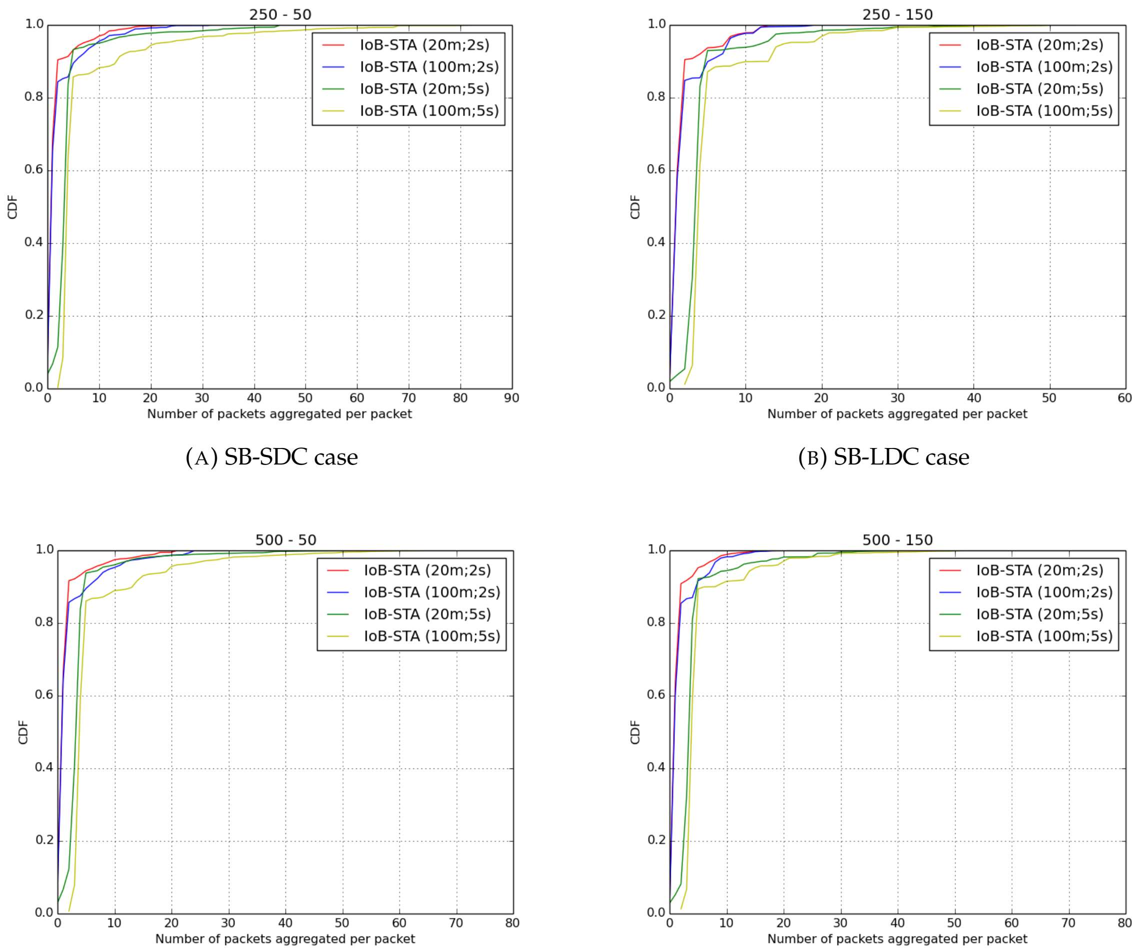


FIGURE 5.14: Average protocol cost for IoB-STA.

As for the number of packets aggregated together, as shown in Figure 5.15, we note that using the smallest aggregation values (20m-2s) offer the best results since they lead to aggregate less packets which improves the energy consumption of sensor nodes.



(A) SB-SDC case

(B) SB-LDC case

(C) LB-SDC case

(D) LB-LDC case

FIGURE 5.15: Average number of aggregated packets per packet for IoB-STA.

5.4.4 Performances comparison

In this section, we give a performance comparison of six protocols: multi-hop IoB-DTN without aggregation , IoB-DTN with one hop, IoB-LR protocol and the three variants cited above by applying data aggregation. The "IoB one hop" has the same behaviour than the multi-hop IoB-DTN without aggregation except there is only bike to bike station communication. IoB-LR operates as a long range technology. It uses a radio propagation that gives around 1 kilometer as communication range and it is characterized by bicycle to gateways communication. The comparative evaluation between IoB-DTN without aggregation and IoB-LR is given in details in the preceding chapter.

From the results obtained before, spatial aggregation with 20m as aggregation area, temporal aggregation with 2s as aggregation period and spatio-temporal with (20m-2s) as aggregation parameters offer the best outcomes in all simulated scenarios. So, we give a comparison of these variants with these aggregation values.

Figure5.16 shows the average delivery rate of the six variants of IoB-DTN protocol. The first observation we make is that the three variants of IoB based on data aggregation mechanism provide better delivery rate. Indeed, by combining data packets into a single packet, it increases the probability to reach destinations. The fact that the delivery rate is higher by using a large buffer size indicates that more data packets are stored in buffers and forwarded later to base stations. This shows that the aggregation mechanism used provides robustness. More precisely, IoB based on temporal aggregation offers better result than other variants and it achieves 100% when the buffer size is large. It is also interesting to note that spatial aggregation gives better performance in terms of forwarding rate than spatio-temporal aggregation when the buffer size is small and inversely by increasing the buffer size.

As for the throughput, as shown in Figure 5.18, the three variants of IoB based on data aggregation provide best performance.

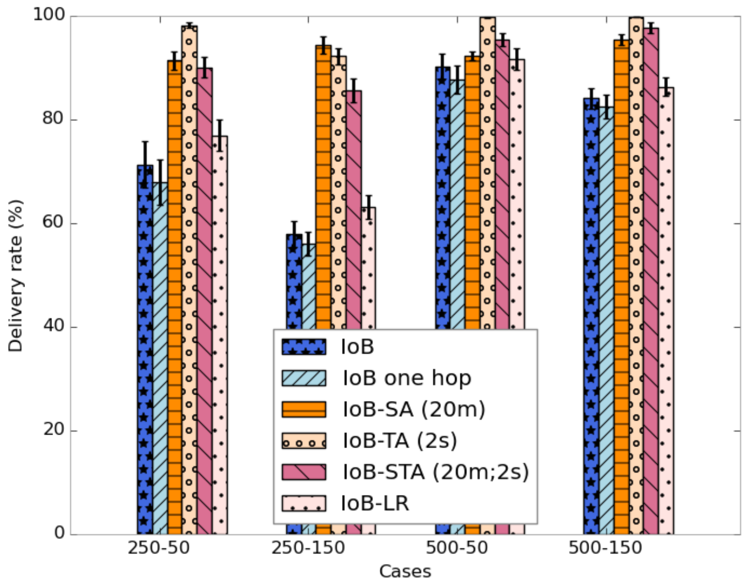


FIGURE 5.16: Average delivery rate comparison.

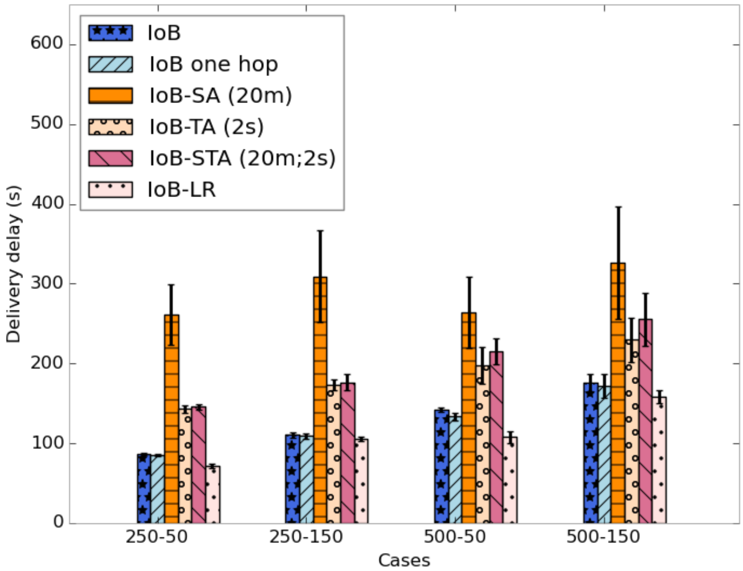


FIGURE 5.17: Average delivery delay comparison.

The average delivery delays are presented in Figure 5.17. Clearly, we notice that the three variants have the highest delays. The fact that data packets are combined generates a significant delay which is an expected result. This may have as an explanation that data packets could be aggregated into packets in the buffers of the nodes having a lower probability to faster meet base stations. More specifically, IoB based on spatial aggregation gives the worst delays.

Figure 5.19 shows the average protocol cost of the six variants of IoB-DTN protocol. It is important to mention that by applying data aggregation mechanism on IoB protocol reduces the communication cost in the network comparing it to other variants. More precisely, IoB with spatial aggregation offers the lower protocol cost.

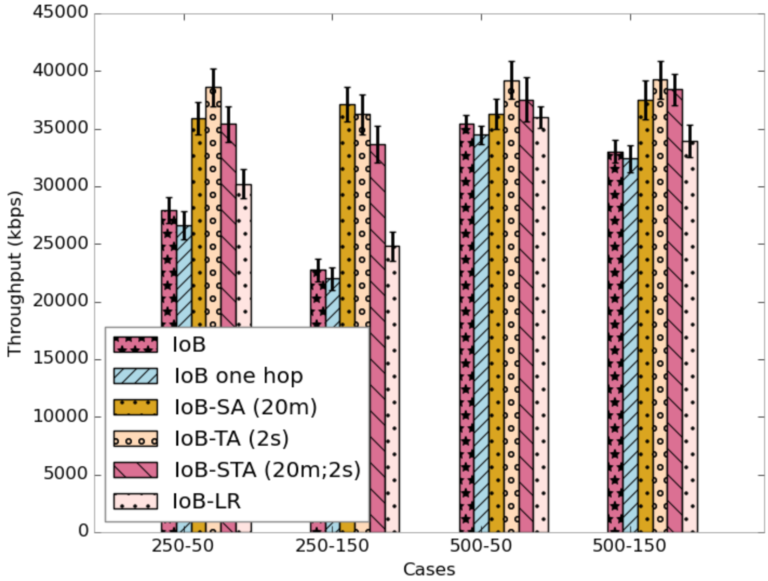


FIGURE 5.18: Average throughput comparison.

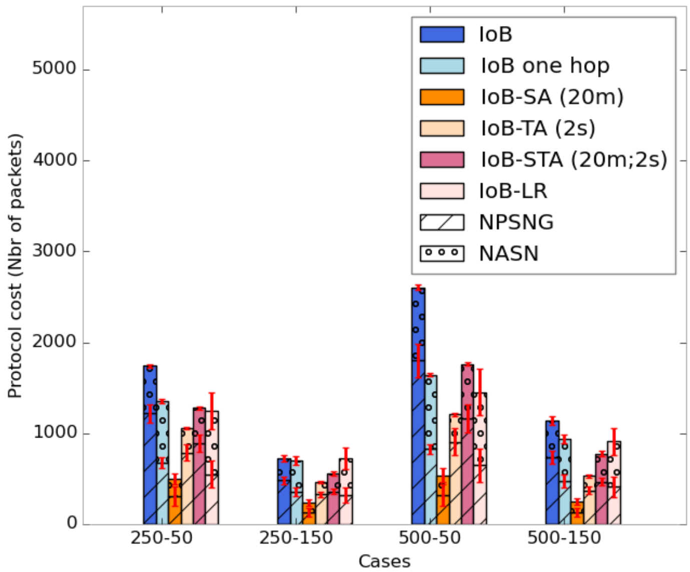
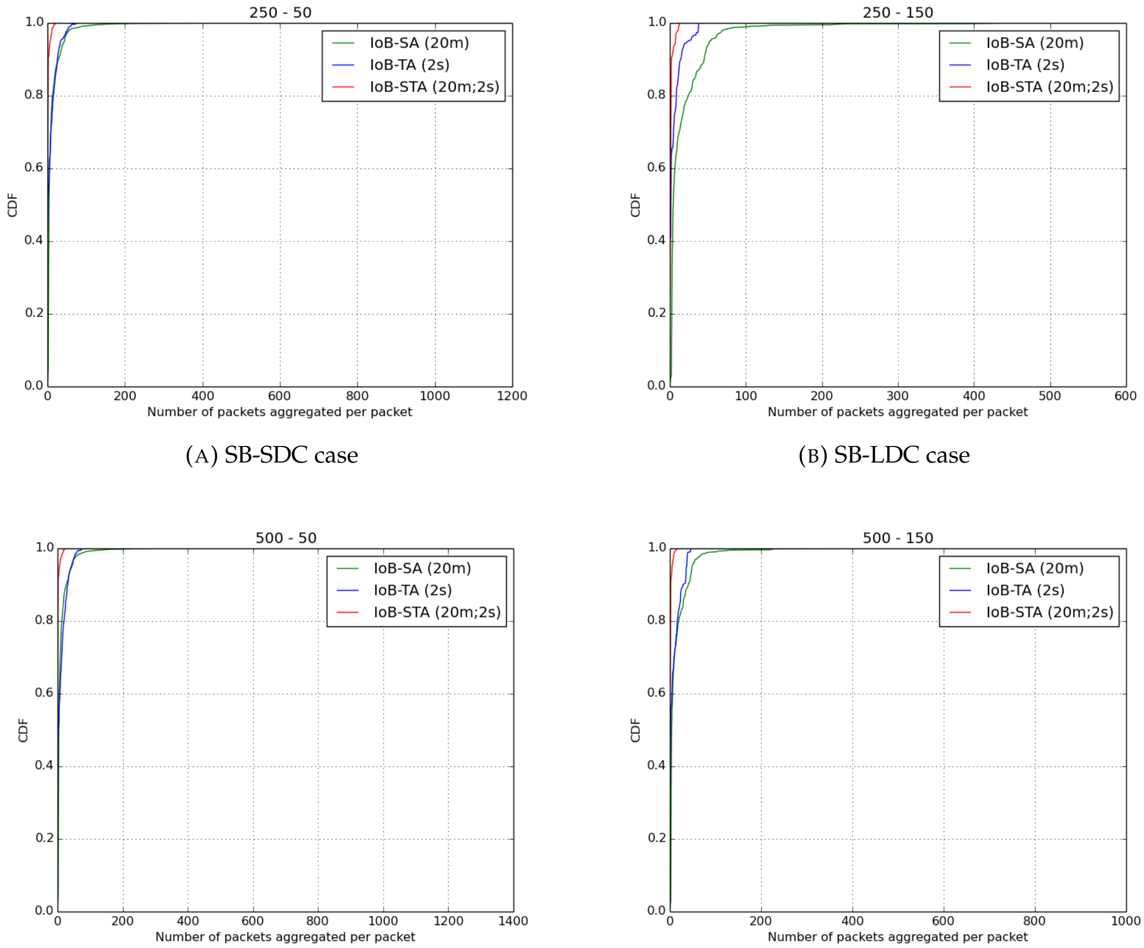


FIGURE 5.19: Average protocol cost comparison.

As for the number of aggregated packets into a single packet which is illustrated in Figure 5.20, we compare the three variants of IoB based on data aggregation with the parameters mentioned at the beginning of this part. We remark that IoB with spatio-temporal aggregation is better than the other variants. It is also worth to fair that IoB with temporal aggregation provides lower number of packets aggregated per packet than IoB with spatial aggregation.



(A) SB-SDC case

(B) SB-LDC case

(C) LB-SDC case

(D) LB-LDC case

FIGURE 5.20: Average number of aggregated packets per packet for IoB-STA.

5.5 Discussion results

We recall the reader that without aggregation the compromise between the delivery ratio and the delivery delay metrics is settled by the buffer size as shown is Figures 5.21 and 5.22. From these Figures, we observe that the buffer size impacts the delivery rate and the delivery delay of received packets more than the duty cycle. More precisely, using small buffer sizes improves the delivery delay as shown in Figure 5.22. In such case, the buffer will be full very fast and oldest packets are always dropped thanks to the GPP buffer management policy that gives priority to the self-generated packets. While, using large buffer sizes enhances the delivery ratio as depicted in Figure 5.21. This is because there is more space to store generated and received packets, resulting in a higher transmission rate.

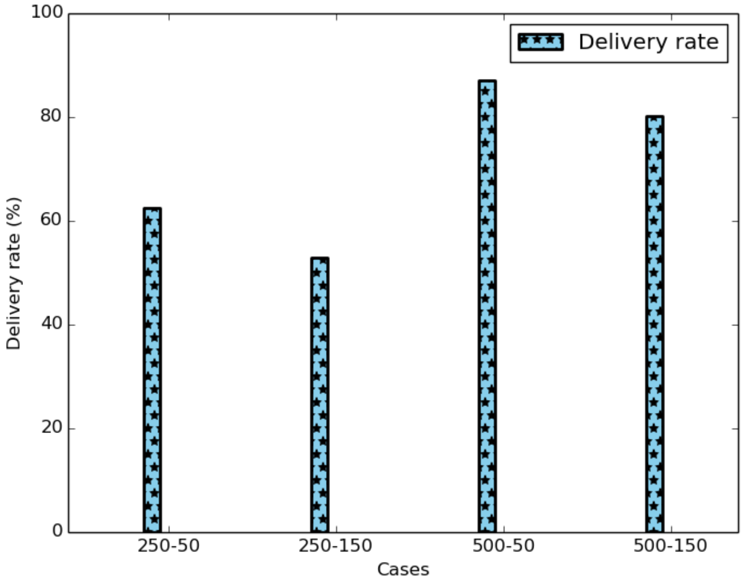


FIGURE 5.21: Loss rate of IoB without aggregation.

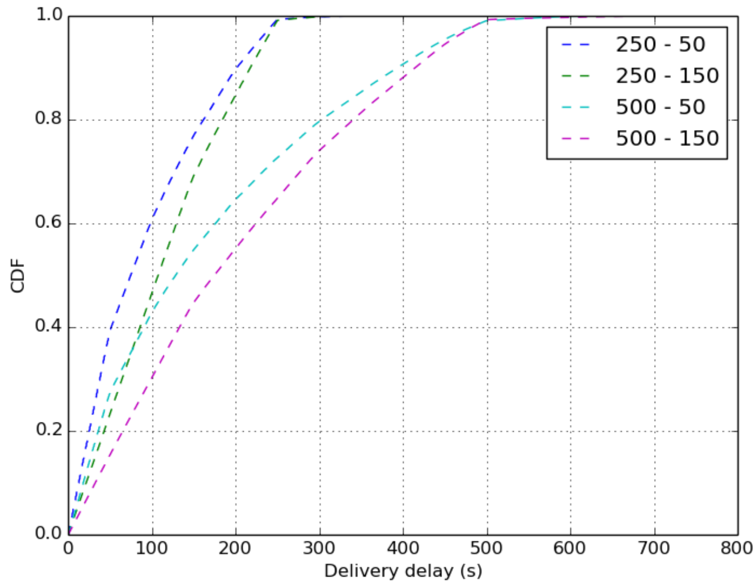


FIGURE 5.22: Delivery delay of IoB without aggregation.

Based on the previous results cited in this section, we can argue that IoB-DTN routing protocol based on data aggregation mechanism can accomplish best performances by saving communication cost and network capacity, achieving better delivery rate and better throughput. Although, it does not impact much the delivery delay. In is interesting to point out that using IoB with aggregation provides less sensitivity to the buffer size regarding to all evaluated metrics.

In an urban application, the choice of the type of which variant of IoB should be used depends on the sensed values. To well understand the limitations of each variant of IoB, we depict in Figures 5.23, 5.24, 5.25 and 5.26 a radar schema summarizing their performances with respect to evaluated metrics. Here, we use a score between 1 and 5 which indicates that the higher score provides the better performance.

As discussed above, each application requires some metrics to be higher than others. For that, we present, as an example in Figure 5.27, another radar schema that indicates the performances required for five proposed applications with regard to temporal aggregation, spatial aggregation, delivery delay and throughput.

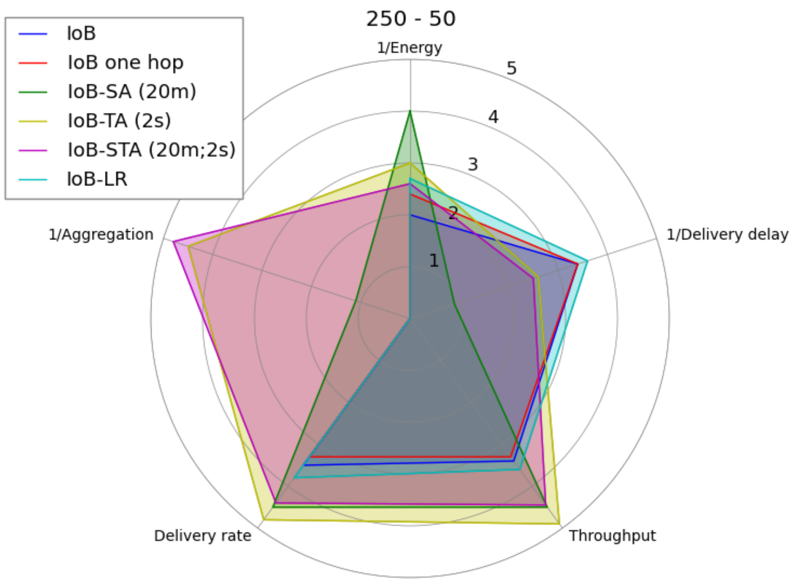


FIGURE 5.23: SB-SDC case.

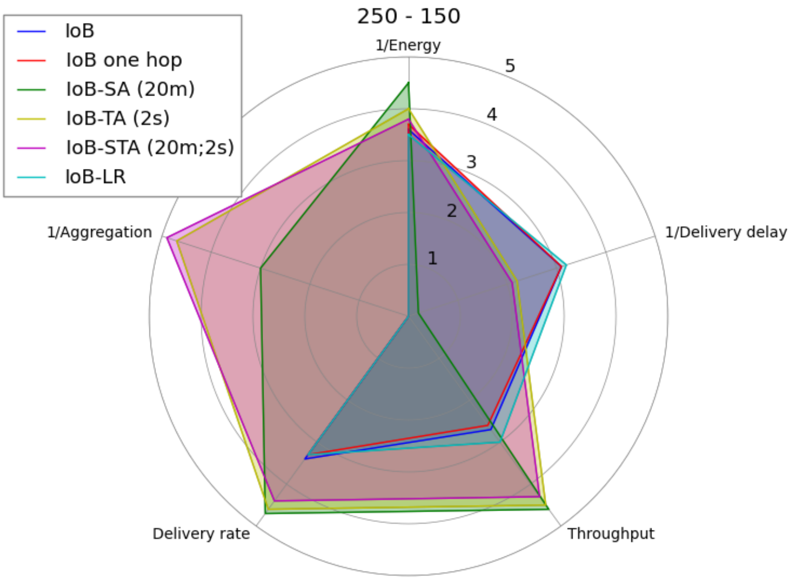


FIGURE 5.24: SB-LDC case.

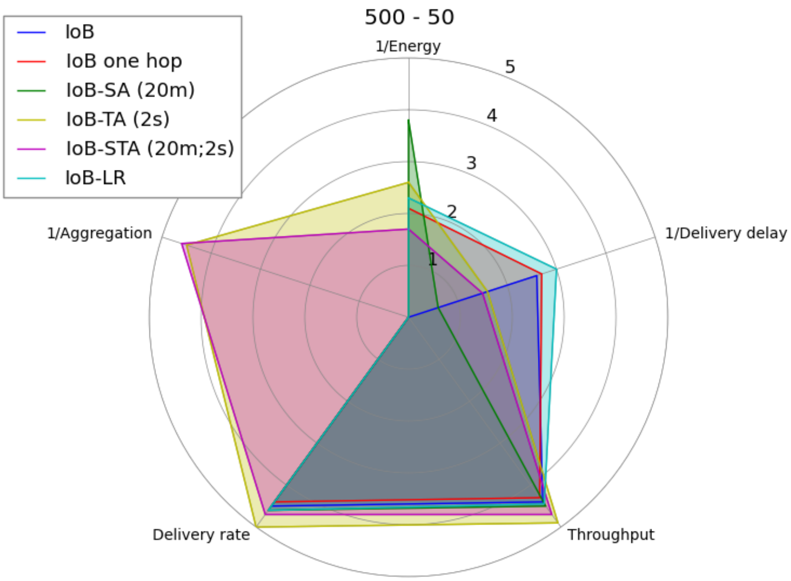


FIGURE 5.25: LB-SDC case.

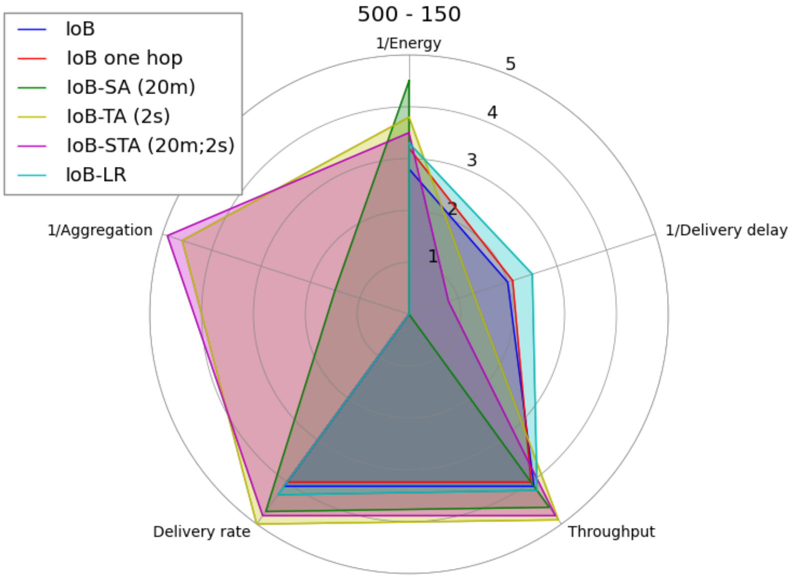


FIGURE 5.26: LB-LDC case.

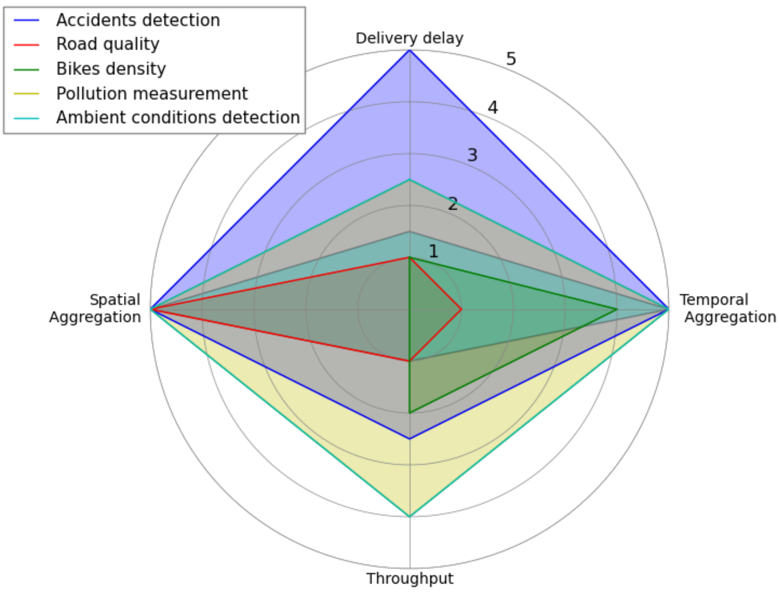


FIGURE 5.27: Performance comparison between five applications.

5.6 Conclusion

In this chapter, we present an efficient multi-hop IoB-DTN routing protocol based on data aggregation mechanism. This approach leads to combine data packets of various sensor nodes into a single packet. We propose three variants: IoB based spatial aggregation (IoB-SA), IoB based temporal aggregation (IoB-TA) and IoB based spatio-temporal aggregation (IoB-STA). Each node generates or receives a new packet verifies the possibility if it can be aggregated according to the aggregation area and/or aggregation period used. Our results show that the three proposed variants give better performances than the multi-hop IoB-DTN protocol without aggregation and the low-power long-range technology, LoRa type. They can save energy, network capacity and upgrade the delivery rate.

Chapter 6

Conclusion and future perspective

In this Chapter, we conclude this manuscript with a summary of our contributions as well as we discuss the open perspectives for future works.

6.1 Conclusions

Nowadays, cities are facing an increasing number of bikes used by citizens therefore the need of monitoring and managing their traffic becomes crucial. Following the trend of the Internet of Thing, public transport systems are seen as an efficient bearer of mobile devices to generate and collect data in urban environments. Bicycle sharing system is one part of the city's larger transport system and could be used as the support of a mobile sensor network. In this manuscript, we propose the "Internet of Bikes" IoB-DTN protocol which applies Delay/Disruption Tolerant Network (DTN) paradigm to the Internet of Things (IoT) applications running on urban bike sharing system based sensor network.

In Chapter 2, we survey DTN routing protocols and classify them into three families based on the strategy property used to find the destination: flooding strategies, forwarding strategies and coding strategies. We study their relevance on urban IoT scenarios where data are forwarded and collected by urban transport systems and sent at a later time to the Internet. The main goal of this chapter is helping researches interesting to apply DTN to the Internet of Things to determine the best DTN routing protocol tailored for being applied to a mobile network IoT devices running a data collection application. Our analysis clearly show that "Spray and Wait" routing protocol has the best results for several metrics such as the average latency, average buffer time, delivery probability and the overhead ratio.

The IoB-DTN protocol is introduced in Chapter 3. It is a n-copy protocol closely inspired by Binary Spray and Wait. It is tailored for being applied to mobile network IoT devices running a data collection application. Depending on the parameter settings and the buffer management policies that are implemented, several variants of the protocol can be defined. We evaluate these variants on a realistic scenario of a smart bike-sharing system where each bike embeds sensors and a 802.11p communication device. Our results highlight the impact of redundancy of packets induced by our protocol and the efficiency to give priority to self generated packets or to already sprayed packets. This redundancy however costs energy as part of packet transmission. This cost can be partially mitigated by exploiting the stability of the radio neighborhood induced by the urban mobility pattern.

A detailed performances evaluation of our proposal IoB-DTN protocol is presented in Chapter 4. First, we give a performance evaluation by varying the transmission power values of sensors. This parameter is important since by increasing the sending power value the communication range of the device raises. In such case, it allows more communications with neighbor nodes and base stations which increases the delivery rate, the throughput and the energy consumption. It is worth to note that using a small duty cycle offers better delivery rate, delivery delay and throughput. Second, we provide a performance comparison of the multi-hop IoB-DTN protocol with a low-power wide-area network (LPWAN) technology, LoRa/LoRaWAN type. LPWAN have been designed to provide cost-effective wide area connectivity for small throughput IoT applications: multiyear lifetime and multikilometer range for battery-operated mobile devices. Our results show that by using a multi-hop topology, it offers better throughput while by applying a long range technology, where there is only bike to bike station communication, it gives better energy consumption. This work aims at providing network designers and managers insights on the most relevant technology for their urban applications that could run on bike sharing systems. To the best of our knowledge, this work is the first to provide a detailed performance comparison between multi-hop and long range DTN-like protocol being applied to mobile network IoT devices running a data collection applications in an urban environment.

In order to upgrade the performance of the multi-hop IoB-DTN protocol, data aggregation is performed before forwarding data to destined targets. Data aggregation is a key mechanism to save energy consumption and network capacity. It can be defined as an approach to combine data of various sensors into a single packet, thus reducing sensor communication costs and achieving a longer network lifetime. In Chapter 5, we introduce an efficient, "Internet of Bikes", IoB-DTN routing protocol based on data aggregation being applied to mobile network IoT devices running a data collection application on urban bike sharing system based sensor network. We propose three variants of IoB-DTN: IoB based on spatial aggregation (IoB-SA), IoB based on temporal aggregation (IoB-TA) and IoB based on spatio-temporal aggregation (IoB-STA). Each node generates or receives a new packet verifies the possibility if it can be aggregated according to the aggregation area and/or aggregation period used. We compare the three variants with the multi-hop IoB-DTN protocol without aggregation and the low-power long-range technology, LoRa type. Comparison results verify that the three variants of IoB-DTN based on data aggregation improve the delivery rate, energy consumption and throughput. In an urban application, the choice of the type of which variant of IoB should be used depends on the sensed values.

6.2 Future perspectives

The works presented in this thesis focus on the proposal of an efficient protocol tailored for being applied to mobile network IoT devices running a data collection application in an urban environment, which can be improved and extended to some areas:

1. Concerning the performance evaluation of our proposal "IoB-DTN" protocol, it can be more deepened. One can think of studying the impact of the increase of the transmission power of gateways while keeping it the same value for all nodes. In such situation, we predict that the communication range of gateways increases, thus allowing more packets reception. Indeed, each sink receives a data packet, it diffuses an acknowledgment to neighbor nodes. Therefore, each node having the packet, deletes it from its buffer. So, buffers will be emptied faster allowing the storage of new packets which can influence the delivery rate metric.

2. In Chapter 4, we put our main concern on the comparison evaluation of the performance of the multi-hop IoB-DTN routing protocol and the low-power long-range technology, LoRa type. We are based on theoretical results to compare both technologies. Thus as an extension, we will further implement a new simulation module for long range technology in OMNeT++ network simulator in order to simulate and compare them by evaluating all the metrics.

3. In this thesis, all our results are simulated or theoretical results. To make sure of the well functioning of our proposal, one can do real experimentation using the same parameters indicated in our simulations. We can implement IoB-DTN with aggregation on 802.11p sensors mounted on bicycles and do the experience for one day in all the city of Lyon. Another real test could be the sport race in which all bikes follow the same path.

4. There is room for improvements in the simulation of our proposal. Due to the limited computing power, our code can be optimized in order to run simulations on a larger scale with a low computing power.

5. Our work focuses on opportunistic communications between bicycles. The data is sensed and collected by the bikes and sent to gateways. Another scenario can be tested in which only the gateways diffuse data to bicycles. In this case, we are talking about the information freshness and not data collection. By way of illustration of this scenario, the gateways can diffuse data to cyclists in a sport race related to the number of kilometers traveled, the time left for the arrival, etc.

6. As discussed in this manuscript, our proposal is based on Delay Tolerant Networking paradigm designed for intermittently connected networks facing long duration of partitioning, frequent movement, or limited storage and energy. Indeed, the data will be stored at intermediate nodes and sent at a later time to destinations. If one is interested in service broadcasting, more precisely if one needs to diffuse a specialized information, DTN can be useless to be applied in such case. As an example, a guidance solution (turn right, turn left, etc) that needs geographic information and different buffer management policies.

7. Our proposal is tailored for being applied to mobile network IoT devices running a data collection application on urban bike sharing system based sensor network. Thus as an extension, one can think of

studying and testing IoB-DTN in other countries where the major public transportation system are the taxis, scouters, buses as for example, the great Maghreb and the Middle East. In such countries, the culture of bikes is not yet well invaded.

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List of publications

Journal Papers

[1] **Y. Zguira**, H. Rivano and A. Meddeb, "Internet of Bikes: a DTN protocol with data aggregation for urban data collection," published in *MDPI, Sensors*, August 2018.

International Conference Papers

- [2] **Y. Zguira**, H. Rivano and A. Meddeb, "IoB-DTN: a lightweight DTN protocol for mobile IoT Applications to smart bike sharing systems," *IEEE Wireless Days Conference (WD)*, pp. 131–136, Duai, UAE, 3-5 April 2018.
- [3] **Y. Zguira**, H. Rivano and A. Meddeb, "A Comparative Evaluation of the Performance of the multi-hop IoB-DTN routing protocol," *International Conference on Ad Hoc Networks and Wireless (AdHoc-Now)*, Saint Malo, France, 5-7 September 2018.
- [4] **Y. Zguira**, H. Rivano and A. Meddeb, "For An Efficient Internet of Bikes : A DTN Routing Protocol Based On Data Aggregation Approach," *ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN)*, Montreal, Canada, 28 October - 2 November 2018.

Research Reports

[5] **Y. Zguira** and H. Rivano, "Evaluation of IoB-DTN protocol for mobile IoT Application," *INRIA Research Report*, RR-9113, December 2017.

[6] **Y. Zguira** and H. Rivano, "Performance evaluation of" Internet-of-Bikes" IoB-DTN routing protocol and IoB-Long range," *INRIA Research Report*, May 2018.

Appendix A

From simulations to experiments

As presented in this thesis, all our results are simulated or theoretical outcomes. Here, we try to go to real world. First, we evaluate the performances of IoB-DTN protocol in real world by using the Z1 motes. Second, we assess the performances of IoB-LR-DTN protocol by using Arduino sensors.

A.1 Experimental results for IoB-DTN

A.1.1 Experimental setup

Our experiments are based on five sensor nodes of type Zolertia Z1 [5] as shown in Figure A.1. They were performed with Contiiki on Z1 sensor hardware that is based on the second generation MSP430F2617 low power microcontroller, 8KB RAM and a 92KB Flash memory. The Z1 provides the CC2420 transceiver, IEEE 802.15.4 compliant, which operates at 2.4GHz with a data rate of 250Kbps.

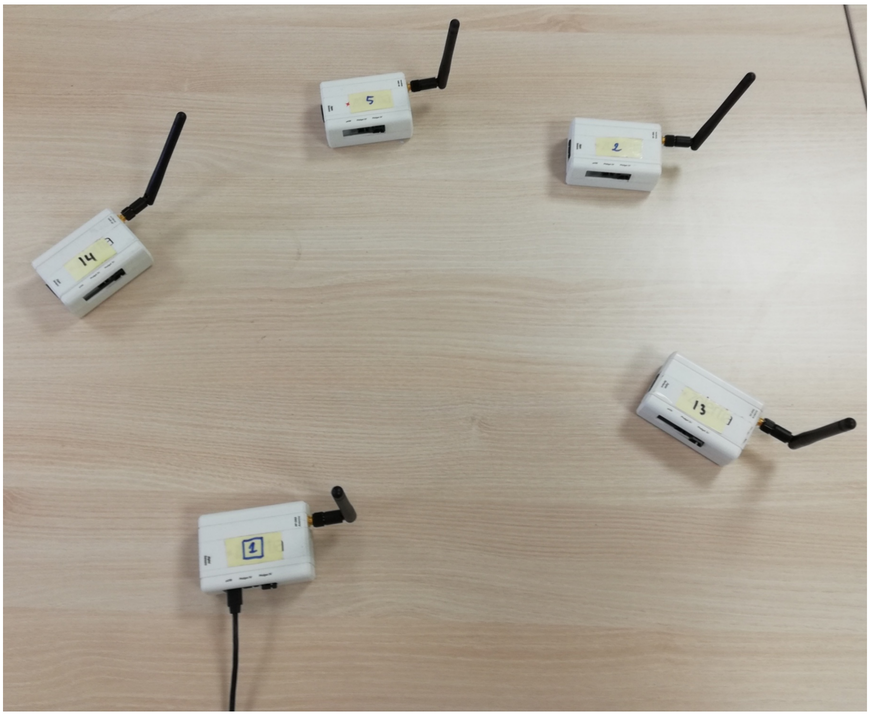

FIGURE A.1: Zolertia Z1 motes considered.

TABLE A.1: Experimental cases.

	Buffer size	Duty cycle (s)
SB-SDC	8	5
SB-LDC	8	10
LB-SDC	18	5
LB-LDC	18	10

We consider the Z1 mote number 1 as the gateway to receive data packets from the remaining sensors. Each mote generates a data packet each second and stores it in its buffer. When the duty cycle is over, each sensor forwards all stored data packets to neighbor nodes. It is important to note that during the experimentation all sensors are static. The positioning of the sensors is presented in Figure A.2. We evaluate four sets of parameters as shown in Table A.1. Due to the low power of Zolertia Z1 motes, we can not assess the same values of the buffer size and the duty cycle as those considered in our simulations. Thus, we consider small values. The experimentation time is 30 minutes.

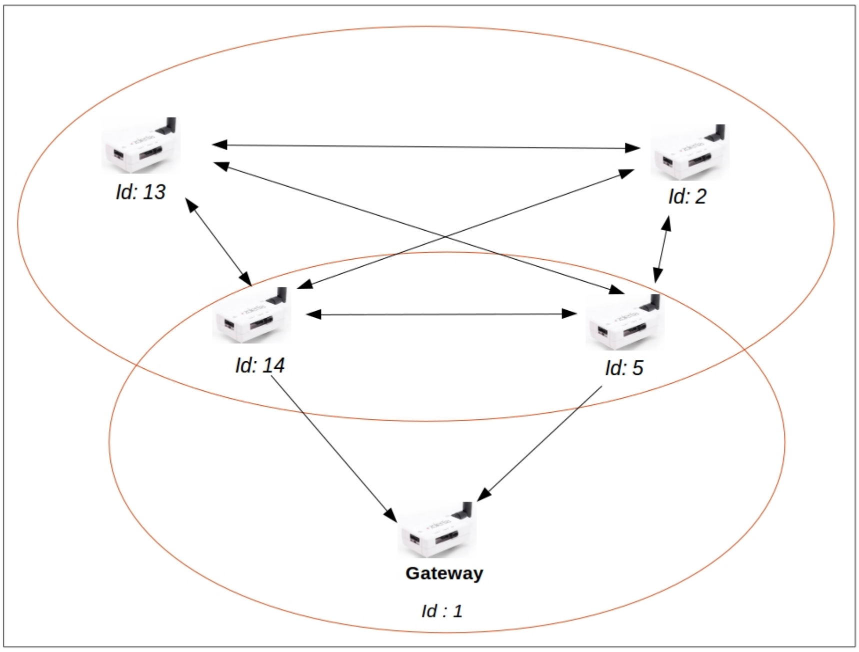

FIGURE A.2: Positioning of Z1 motes.

A.1.2 Results evaluation

In our experiments, we assess the distributions of delivery delays as well as the delivery rate. In order to confirm our results, we do the experimentation five times for each scenario.

From Figure A.3, we notice that using a large value of buffer size as well as a small value of the duty cycle allows for a better delivery rate. This result is expected as obtained in our simulations. In such case, more data packets are stored and sent to gateways. It is also interesting to point out that using a small duty cycle increases the delivery rate.

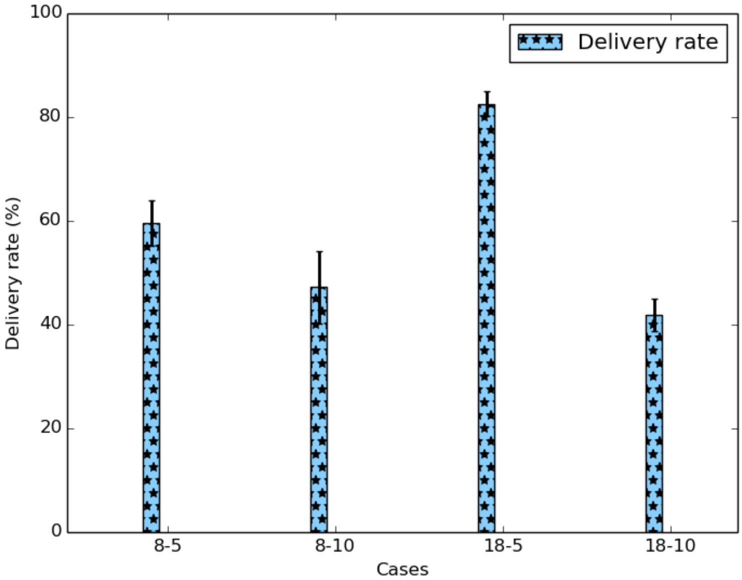

FIGURE A.3: Delivery rate using Zolertia Z1 motes.

The delivery delays of received packets are depicted in Figure A.4. It is clear that the buffer size parameter impacts the delivery delay as presented in our simulations. The use of large buffer size occurs a high delivery delay since more data packets are stored in the buffer for longer time.

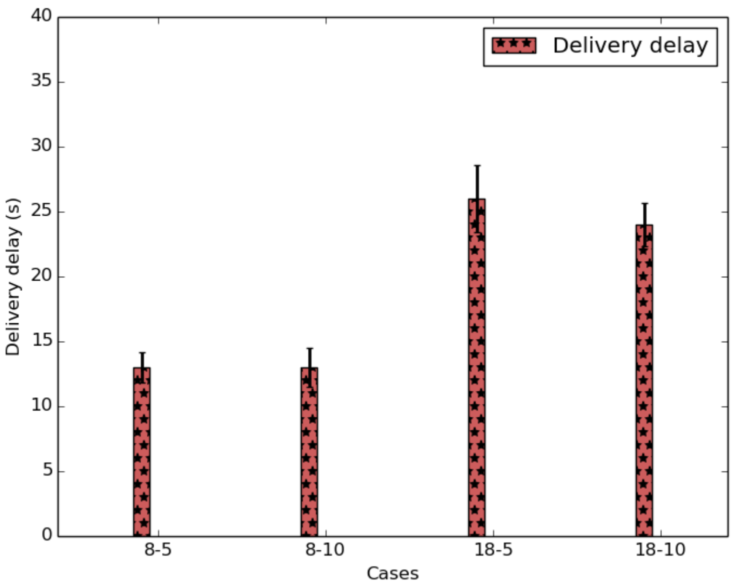

FIGURE A.4: Delivery delay using Zolertia Z1 motes.

In order to really go to real world, we installed the Z1 motes on five bikes and we tested the same scenario presented in this part as shown in

Figure A.5. We got the same results.

FIGURE A.5: Zolertia Z1 mote mounted on Vélo'v bicycle.

A.2 Experimental results for IoB-LR-DTN

A.2.1 Experimental setup

Here, we are interested to evaluate IoB-Long Range (IoB-LR) in which only bike-to-bike station communication is allowed. All our experiments are based on The Things nodes or Uno and two gateways of type The Things Network [6] as shown respectively in Figures A.6 andA.7.

FIGURE A.6: Arduino sensor of type The Things Network.

FIGURE A.7: Gateway of type The Things Network.

The Things Network is the first open source network operator that uses decentralized infrastructure for the Internet of Things. The major objective of The Things Network is enabling low-power devices to forward data to applications using long range gateways. Presently, it supports LoRaWAN for low-power (batteries lifetime from months to years), low bandwidth (51 bytes per packet) and long range (5 to 15km).

Each user registers manually the device on a network as depicted in Figure A.8. After starting the experimentation, all received data packets are shown in the gateway traffic interface as depicted in Figure A.9. We observe that from this interface many parameters values are calculated and presented at the reception phase, as for example the frequency, coding rate, data rate, spreading factor, airtime, payload sizes, etc.

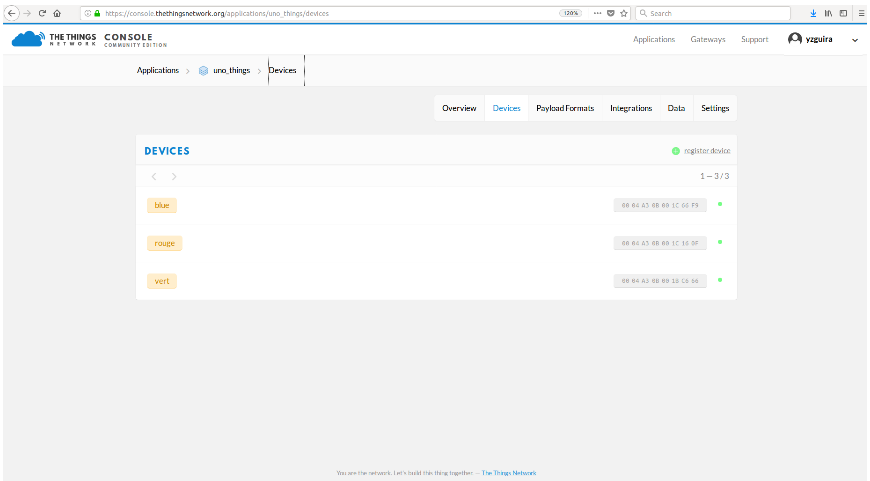

FIGURE A.8: Devices registration in The Things Network.

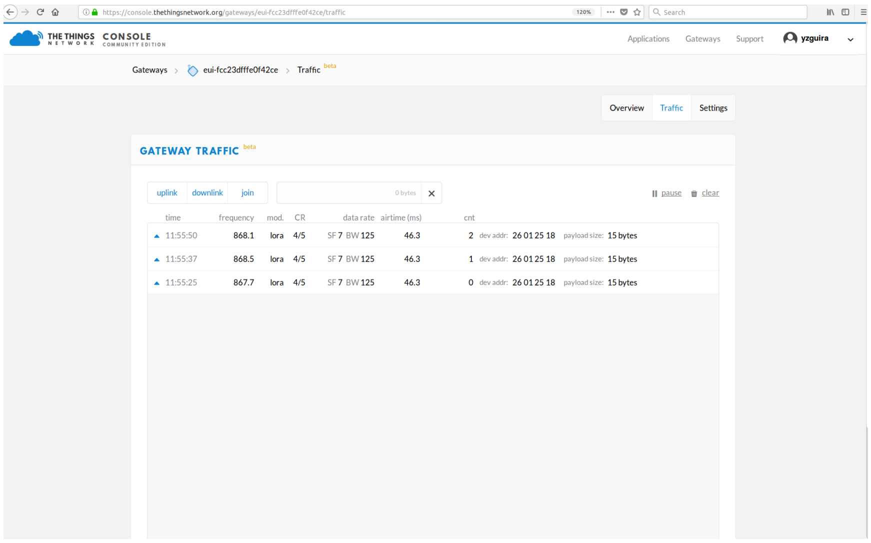

FIGURE A.9: Gateway traffic in The Things Network.

In our experiments, we consider two gateways installed in two different buildings. One of them is installed inside the building, we denote it *gateway A* while the other one is outside the other building, more precisely it is installed on the surface of the building, it is denoted *gateway B*. The distance between both gateways is 750m. It is important to point out that the communication range of *gateway B* is larger than the one of *gateway A*.

In our scenario, each device generates each second a data packet of size 15 bytes. The duty cycle is fixed to 30 seconds and the experimentation time is 15 minutes. The frequency used is 868MHz.

A.2.2 Results evaluation

We assess four metrics: rssi (Received Signal Strength Indication), snr (Signal to Noise Ratio), airtime and delivery rate. The rssi is the power measurement in reception of a received signal, expressed in dBm. This allows to know the reception quality. The signal-to-noise ratio is an indicator of the transmission quality of an information, expressed in dBm. Here, the spreading factor is set to SF7 and the coding rate is 4/5.

A.2.2.1 rssi and snr evaluation

In order to evaluate the rssi and snr metrics, we carry out three different scenarios. First, we do the experimentation where the Things device is inside the building of one of the gateways. Secondly, the device is installed between the two buildings.

From Figure A.10, we notice that the rssi of gateway A is better than gateway B. This result is expected since the Things device is inside the building of gateway A.

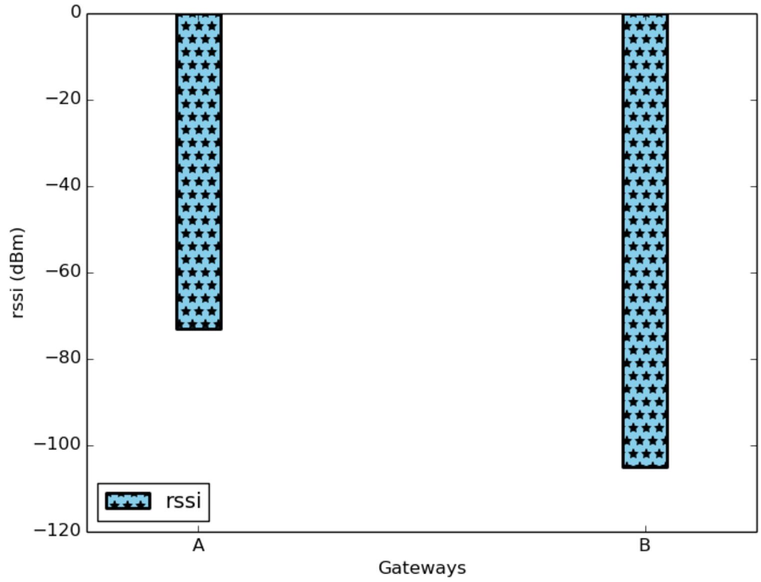

FIGURE A.10: rssi measurement, Indoor - Indoor next to *gateway A*.

Figure A.11 shows the rssi measurement where the device is closer to *gateway B*. The first observation we make is the absence of received signal indication for *gateway A*. As mentioned above, the communication range of *gateway A* is smaller and in this case it can not receive the data packets.

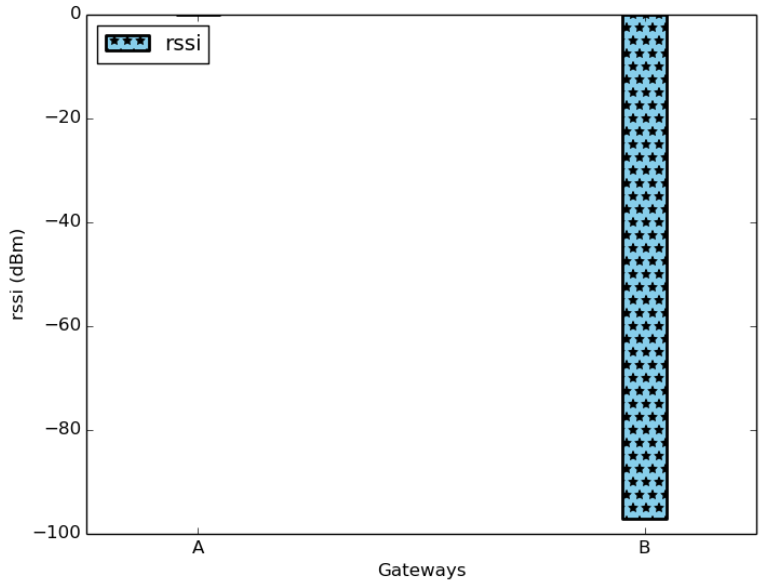

FIGURE A.11: rssi measurement, Indoor - Indoor next to *gateway B*.

In the third scenario, the Things device is placed in the middle of the two gateways. From Figure A.12, we notice that the rssi measurement of *gateway A* is a little better than *gateway B*.

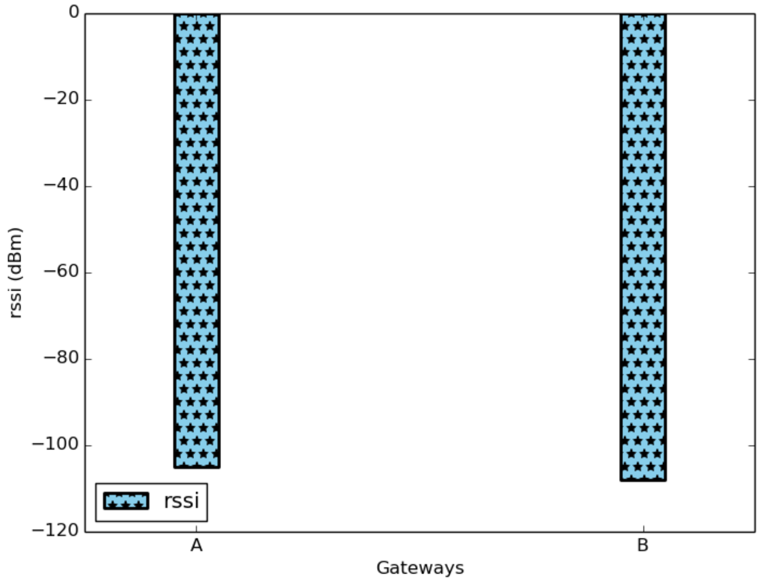

FIGURE A.12: rssi measurement, Indoor - Outdoor.

Now, considering the evaluation of the snr metric, we carry out the same scenarios. It is clear from Figure A.13 that the snr of *gateway A* is better than *gateway B* since the device is closer to *A*.

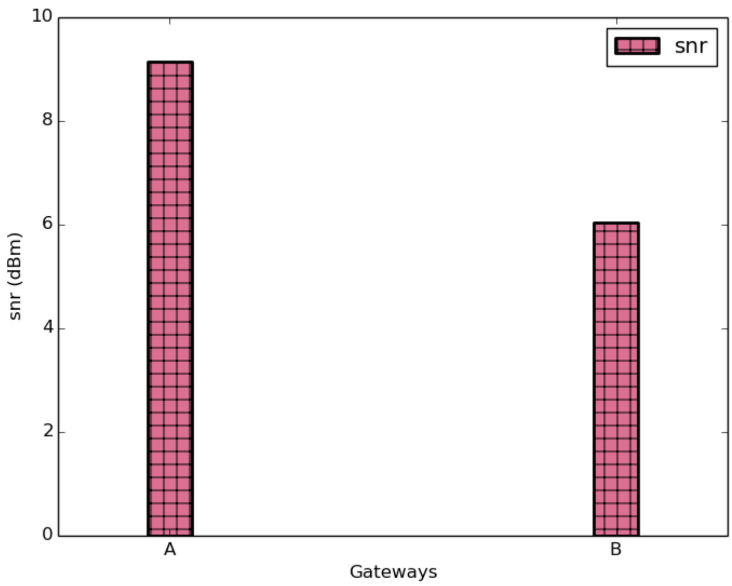

FIGURE A.13: snr measurement, Indoor - Indoor next to *gateway A*.

As for rssi measurement, the snr of *gateway B* is higher while the one of *A* is very small since its communication range is not large enough to receive data packets at 750m.

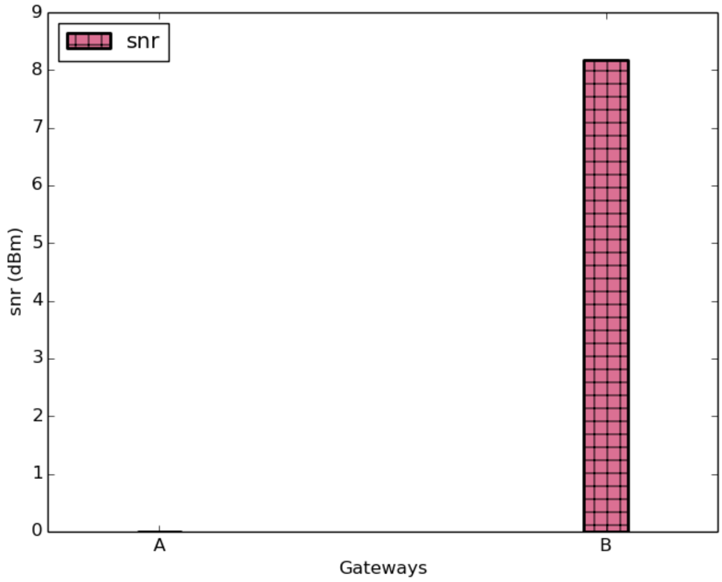

FIGURE A.14: snr measurement, Indoor - Indoor next to *gateway B*.

As for the last scenario of snr measurement, *gateway B* offers the best snr where the device is in the middle of the two buildings.

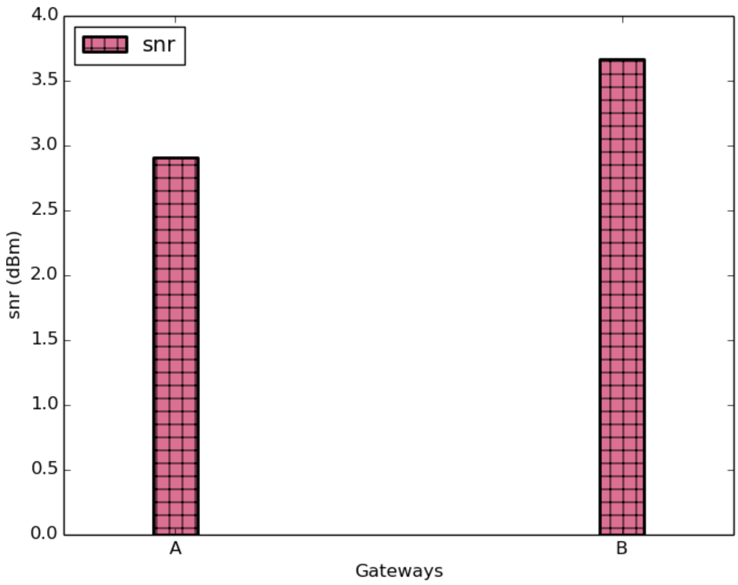

FIGURE A.15: snr measurement, Indoor - Outdoor.

A.2.2.2 Airtime and delivery rate evaluation

In this part, we give the performance evaluation of the airtime and delivery rate metrics. First, the spreading factor is fixed to SF7 and then we assess the packet delivery ratio by varying the spreading factor parameter. It is interesting to point out that all experiments done here include one device and one gateway in which the sensor is close to the sink.

Figure A.16 shows the airtime measurement by varying the packet size. It is clear that the increase of the packet size raises the time to forward a packet.

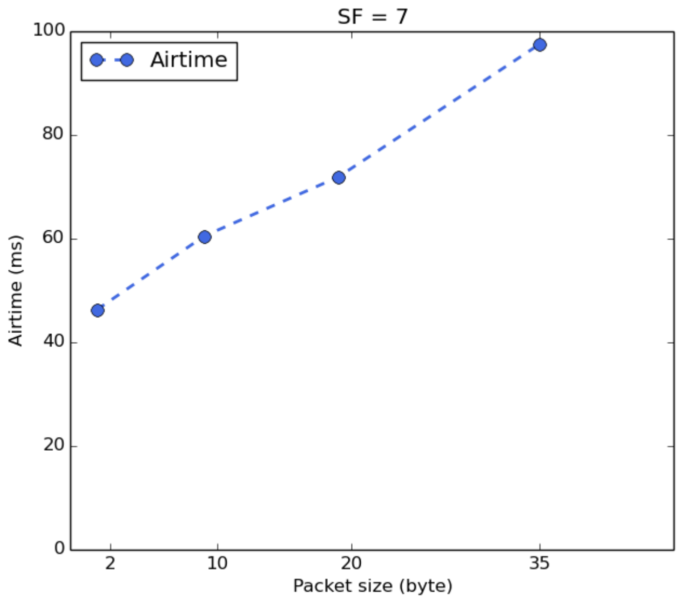

FIGURE A.16: Airtime evaluation using SF7.

From Figure A.17, we notice that by increasing the packet size the packet delivery ratio varies slightly. This depends on the interference of the channel.

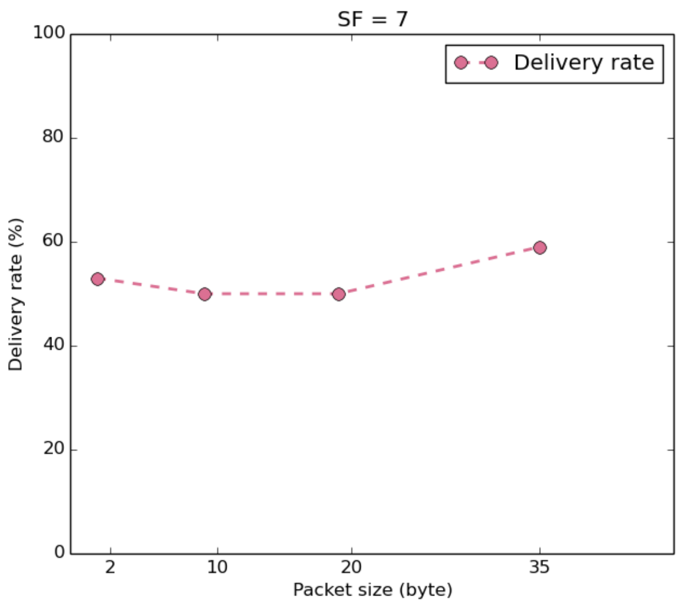

FIGURE A.17: Delivery rate evaluation using SF7.

For the last case, we evaluate the delivery rate by assessing three values of spreading factors: SF7, SF9 and SF12. Here, each device generates a data packet every 3 minutes, the duty cycle is 8 minutes and the experimentation time is 90 minutes. We observe from Figure A.18 that the three values of spreading factors have the same result in term of packet delivery ratio. The fact that they do not reach 100% as delivery rate may have many explanations. One is that there are other data packets that are transmitted on the same frequency 868MHz. Another reason could be that other packets are forwarded using the same spreading factor at the same time causing interference.

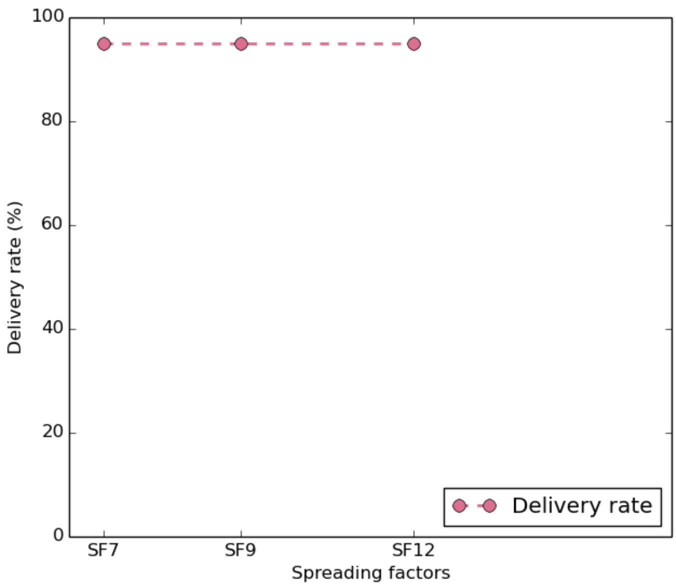

FIGURE A.18: Delivery rate evaluation by varying the spreading factor.

As final experimentation, we installed the Things device on a Vélo'v bicycle and tested the same scenario, presented here, by sending data packets to The Things Network gateway as shown in Figure A.19. We got similar results.

FIGURE A.19: The Things device mounted on Vélo'v bicycle.

FOLIO ADMINISTRATIF

THESE DE L'UNIVERSITE DE LYON OPEREE AU SEIN DE L'INSA LYON

NOM : ZGUIRA BAHRI DATE de SOUTENANCE : 20/12/2018
(avec précision du nom de jeune fille, le cas échéant)

Prénoms : Yosra

TITRE : Study and development of wireless sensor network architecture tolerant to delays

NATURE : Doctorat Numéro d'ordre : 2018LYSEI121

Ecole doctorale : InfoMaths

Spécialité : Informatique

RESUME :
Le transport est devenu fondamental dans les villes pour le bon fonctionnement de l'économie et le bien-être de la population urbaine. Depuis plusieurs années, le transport est confronté à de nombreux problèmes tels que l'embouteillage, le taux élevé d'accidents, la vie malsaine due à la fumée et à la poussière, la pollution atmosphérique due aux émissions de carbone, etc.
Pour faire face à ces problèmes, les recherches intègrent les technologies numériques au transport terrestre, connu sous le nom de système de transport intelligent (ITS). Les ITS peuvent détecter, analyser, collecter, contrôler et communiquer différentes données. Cette thèse étudie et propose un nouveau protocole pour les applications de collecte de données dans un environnement urbain. Nous faisons trois contributions principales. Tout d'abord, nous proposons un nouveau protocole dénommé le protocole "Internet of Bikes" IoB-DTN qui applique le paradigme DTN (Réseau tolérant aux délais) aux applications de l'Internet des objets (IoT) exécutant une application de collecte de données sur un système de partage de vélo urbain basé sur un réseau de capteurs. Le protocole est évalué sur un scénario réaliste en évaluant les politiques de gestion des buffers, le nombre de copies pulvérisé dans le réseau ainsi que le nombre des vélos utilisés. Deuxièment, une évaluation comparative des performances du protocole IoB-DTN multi-sauts avec une technologie de réseau étendu à basse consommation (LPWAN), de type LoRa/LoRaWAN est étudiée. LPWAN a été conçu pour fournir une connectivité à grande distance et rentable pour les applications IoT à faible débit: durée de vie de plusieurs années et une portée de multikilomètres pour les appareils mobiles alimentés par des batteries. Cette partie de notre travail vise à fournir aux concepteurs et aux managers de réseaux des idées sur la technologie la plus pertinente pour leurs applications urbaines pouvant fonctionner sur des systèmes de partage de vélos. Enfin, nous proposons un protocole efficace, IoB-DTN basé sur un mécanisme d'agrégation de données. Nous proposons trois variantes de IoB-DTN: IoB basé sur l'agrégation spatiale (IoB-SA), IoB basé sur l'agrégation temporelle (IoB-TA) et IoB basé sur l'agrégation spatio-temporelle (IoB-STA). Nous comparons les trois variantes avec le protocole multi-saut IoB-DTN sans agrégation et la technologie à faible puissance et longue portée, de type LoRa.
Les résultats de la comparaison permettent de vérifier que les trois variantes de l'IoB-DTN basées sur l'agrégation de données améliorent plusieurs paramètres tels que le taux de livraison, la consommation d'énergie et le débit.

MOTS-CLÉS : Internet des objets, Réseaux tolérants aux délais, Internet des vélos, Réseaux de capteurs, Ville intelligente

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