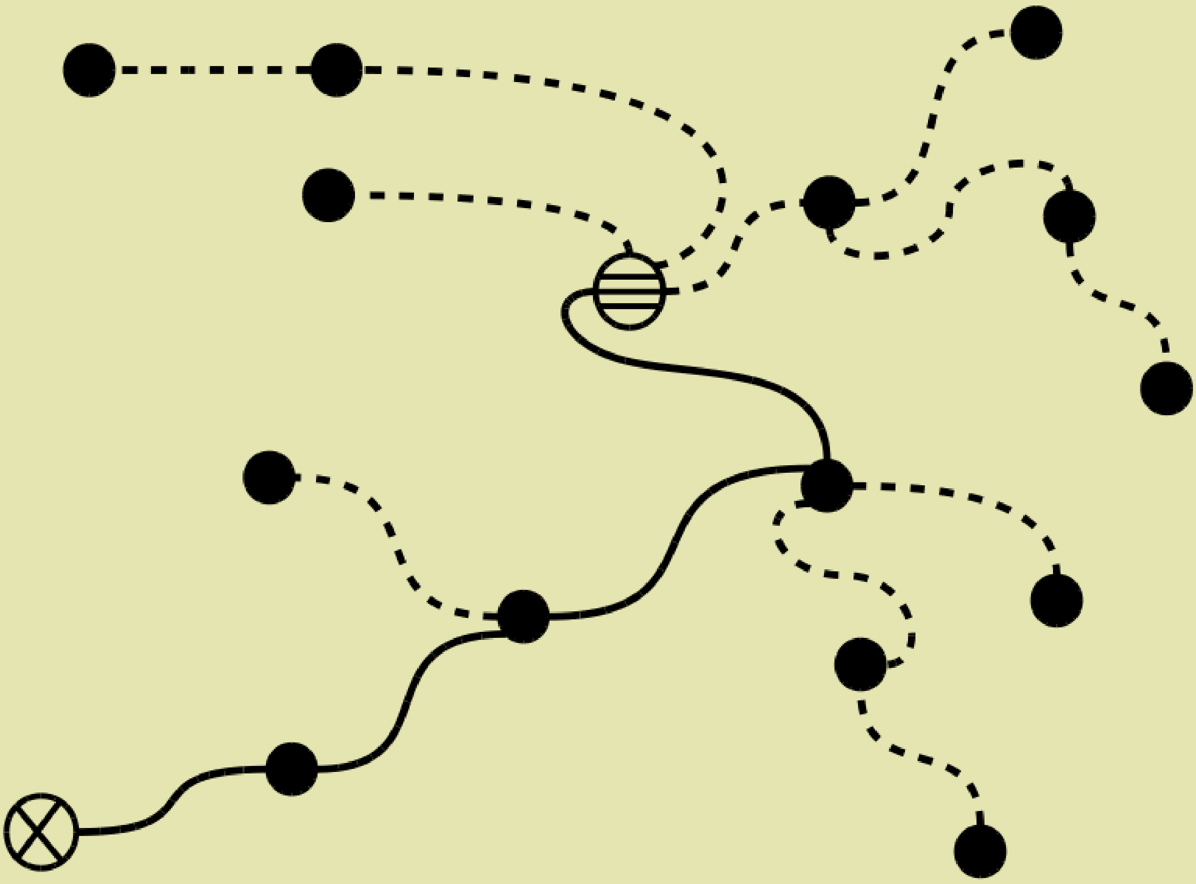

Vitor Guerra Rolla

Enabling Wireless Cooperation in User Provided Networks

Tese de Doutoramento em Ciências e Tecnologias da Informação, orientada pela Professora Doutora Marilia Curado, apresentada ao Departamento de Engenharia Informática da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

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Universidade de Coimbra

Enabling Wireless Cooperation in User Provided Networks

Facilitando a Cooperação Sem-Fios em Redes Facultadas pelos Utilizadores

Vitor Guerra Rolla

Doctoral Thesis in Information Science and Technology
Advised by Prof. Dr. Marilia Curado

Department of Informatics Engineering
Faculty of Sciences and Technology
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11th February 2015

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Abstract

This doctoral thesis investigates user provided networks. Such networks have become important research subjects in the field of informatics engineering due to the recent popularity of smart phones. User provided networks are independent from traditional Internet service providers. Communication and information exchange between users occurs opportunistically, i.e., when the smart phones are close enough to exchange information. Most user provided networks are based on the radio standard IEEE 802.11, popularly known as '*wi-fi*'. However, some networks are based on other low range radio standards, such as Bluetooth and IEEE 802.15.4.

User provided networks are important to the society in general when the traditional Internet service providers become unavailable. For example, this may occur in terrorist attacks, earthquakes, or even cyber attacks. In these emergency situations, when users have a greater interest in common, an efficient system for non-presencial information exchange is necessary. Such networks are also interesting in a social context, when users must be incentivized to share their resources (storage capacity, wireless connectivity and battery) to enable the exchange of information. This doctoral thesis addresses both situations: i) networks whose users have a common interest and ii) networks whose users need to be encouraged to share resources.

Among the various contributions of this doctoral thesis are the *Delay Tolerant Reinforcement-Based* routing solution and the *Messages on oFfer* incentive mechanism. The first is a routing solution for users-provided networks when the users have a prior interest in common. The second is an incentive mechanism to encourage users to exchange information. Both solutions showed excellent results in the simulation environment.

Resumo

Esta tese de doutoramento investiga as redes providas pelos usuários. Com a popularidade do telemóvel esperto (*smart phone*) tais redes se tornaram objeto de pesquisa na área de engenharia informática. Uma característica básica das redes providas pelo usuário é a sua independência em relação aos provedores de serviço tradicionais. A comunicação e troca de informação entre usuários ocorre de forma oportuna, isto é, quando os telemóveis estão próximos o suficiente para se comunicarem. A maioria das redes providas por usuários é baseada no padrão de rádio IEEE 802.11, popularmente conhecido como '*wi-fi*'. No entanto, algumas redes se baseiam em outros padrões de baixo alcance, por exemplo Bluetooth e IEEE 802.15.4.

As redes providas por usuários são importantes para a sociedade no advento dos provedores de serviço tradicionais ficarem indisponíveis. Por exemplo, isso pode ocorrer em ataques terroristas, terremotos, ou mesmo em ataques virtuais. Nessas situações de emergência, quando os usuários têm um interesse maior em comum, é necessário um sistema de troca de mensagens não presencial eficiente. Tais redes também são importantes em um contexto social, quando os usuários precisam ser incentivados a compartilhar os seus recursos (capacidade de armazenamento, conectividade sem-fio e bateria) para que ocorra troca de informação. Essa tese de doutoramento aborda ambas as situações: i) redes cujos usuários têm um interesse em comum e ii) redes cujos usuários precisam ser incentivados a compartilhar recursos.

Dentro das diversas contribuições que esta tese de doutoramento apresenta estão a solução de roteamento *Delay Tolerant Reinforcement-Based* e o mecanismo de incentivo *Messages on oFfer*. A primeira é uma solução de encaminhamento para redes providas por usuários que tenham um interesse em comum prévio. A segunda é um mecanismo de incentivo para estimular que os usuários troquem informação quando não houver o interesse em comum. Ambas as soluções apresentaram excelentes resultados no ambiente de simulação desenvolvido nesta tese.

Preface

This thesis was conducted at the Centre for Informatics and Systems of the University of Coimbra. Throughout this work contributions were made to the following research project: User Centric Routing - UCR (PTDC/EEATEL/103637/2008). The UCR project considers the exchange of data between users according to their interests and expectations, as well as their mobility patterns.

The work that has been published during the development of this thesis is presented next:

- Vitor Rolla, Marilia Curado: Enabling wireless cooperation in delay tolerant networks, Information Sciences, Volume 290, Pages 120-133, January 2015. Impact Factor: 3.893.
- Vitor Rolla, Marilia Curado: A reinforcement learning-based routing for delay tolerant networks, Engineering Applications of Artificial Intelligence, Volume 26, Issue 10, Pages 2243-2250, November 2013. Impact Factor: 1.962.
- Vitor Rolla, Marilia Curado: Time message system for delay tolerant networks, 2nd Baltic Congress on Future Internet Communications, Vilnius, Lithuania, April 25-27, 2012.
- Vitor Rolla, Daniel Silva, Marilia Curado: Intelligent epidemic routing for cooperative IEEE 802.11 networks. 6th IFIP Wireless and Mobile Networking Conference WMNC 2013, United Arab Emirates, 23-25 April, 2013.
- Vitor Rolla, Alexandre Miguel Pinto, Marilia Curado: A simple survey of knowledge plane approaches for future cognitive wireless networks, International Journal of Mobile Network Design and Innovation archive, Inderscience, Volume 4, Issue 4, Pages 179-184, June 2012.

The work that has been submitted for publication before the delivery of this thesis is presented next:

- Vitor Rolla, Marilia Curado: A Simple Survey of Incentive Mechanisms for User Provided Networks. Wireless Personal Communications, Springer, Impact Factor: 0.979.
- Vitor Rolla, Marilia Curado: Enabling Wireless Cooperation in User Provided Networks. IFIP/IEEE Symposium on Integrated Network and Service Management 2015, Ottawa, Canada.

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List of Acronyms

ACK Acknowledgement

ARBR Adaptive Reinforcement-Based Routing

AODV Ad Hoc On demand Distance Vector

AWMN Athens Wireless Metropolitan Network

BGP Border Gate Protocol

BSW Binary Spray and Wait

CNA Complex Network Analysis

CRISP Collusion Resistant Incentive Compatible Routing and Forwarding in Opportunistic Networks

DTRB Delay Tolerant Reinforcement-Based

EBR Encounter-Based Routing

FON FONERA - Spanish Company

FCFS First-Come-First-Serve

FPW First Place Winner

GAR Group Aware Routing

GDP Gain-aware Dissemination Protocol

GPS Global Positioning System

GSM Global System for Mobile

IEEE Institute of Electrical and Electronics Engineers

IOS Iphone Operating System

IAW Incentive-Aware

ISP Internet Service Providers

IWR Intelligent Wireless Router

KAIST Korea Advanced Institute of Science and Technology

KQML Knowledge Query Manipulation Language

MARL Multi-agent Reinforcement Learning

MAC Medium Access Control

MooF Messages on oFfer

OLSR Optimized Link State Routing

OWL Time Ontology in Web Ontology Language

Pi Practical Incentive

PRoPHET Probabilistic Routing Protocol using History of Encounters and Transitivity

P2PWNC Peer-to-peer Wireless Network Confederation

QLAODV Q-Learning AODV

RWP Random Way Point

RADON Reputation-Assisted Data forwarding protocol for Opportunistic Networks

RAPID Resource Allocation Protocol for Intentional Delay Tolerance

REAL Real mobility traces

RL Reinforcement Learning

SANE Social Aware Networking

SIM Subscriber Identity Module

SMART Secure Multilayer

SnW Spray and Wait

TFT Tit-For-Tat

UDEL UdelModels mobility

UPN User Provided Networks

VANET Vehicular Ad hoc Networks

Chapter 1

Introduction

Within the past few years, the Internet has experienced a critical shift. The explosion of wireless mobile computing and the exponential growth of users in densely populated areas enables the general public to become providers of communication services. User Provided Networks (UPN) are revolutionizing wireless communications by allowing users to interact with other users outside of the typical provider infrastructure.

Wireless IEEE 802.11 [Vassis et al., 2005], Bluetooth [Sweeney, 2002], and IEEE 802.15.4 [Karapistoli et al., 2010] technologies have become ubiquitous in densely populated urban areas because of the increasing number of fixed access points and the multitudes of smart phone users. This phenomenon creates a foundation for UPN. When the end-user becomes a provider and shares wireless opportunities based on some form of incentive, a potential alternative radio communication channel becomes available [Sofia and Mendes, 2008].

Incentive mechanisms are fundamental for UPN development, because they encourage user cooperation and prevent selfish behaviour. An effective incentive mechanism motivates users to share, promotes development of new applications for offloading 3G/4G networks, stimulates competition among traditional Internet Service Providers (ISP), and strengthens new UPN communities. However, these new networks depend on the user's willingness to share their wireless connectivity, storage capabilities, and energy resources. Most applications available to the end-user today still depend upon the ISP infrastructure. Incentive mechanisms are important to encourage users to cooperate for effective information sharing [Wang et al., 2014].

This chapter is divided into four sections. The next section introduces different types of UPN Communities. The research questions are presented in Section 1.2.

The contributions of this research are summarized in Section 1.3. Finally, the thesis structure is outlined in Section 1.4.

1.1 UPN Communities
Tethering-based and New Generation UPN

Tethering is the practice of sharing a subscribed Internet (3G/4G or cable) connection through IEEE 802.11 with a smart phone or a fixed home wireless router. Tethering-based UPN communities incentivize the users to cooperate by sharing their wireless resources as well as Internet services. Currently most UPN do not implement multi-hop routing among devices, merely forwarding data from the wireless local area network to the Internet and vice-versa, which limits the coverage of tethering-based UPN communities.

These user networks range from the basic, those with the ability to create a wireless local area network on-the-fly with a simple personal computer or smart phone, to more elaborate cases of commercial success, for example, the Spanish telecommunications company FON [FONERA, 2013]. In order to join the FON UPN community, the user has to acquire a home wireless router. This device creates a private network used by the owner and a public network used/shared by other members of the user provided community. FON members have free Internet access in any FON access point. Figure 1.1 shows how FON access points became ubiquitous in downtown Lisbon, Portugal. OpenSpark [Openspark, 2013] uses the same basic idea, where the community members agree to share cooperatively their extra broadband connection capacity to the Internet, in exchange for receiving free access to other community members access points when in roaming. The Android [Google, 2013] and IOS (iPhone Operating System) [Apple, 2013] have inbuilt software that enables the owner to provide his smart phone as a IEEE 802.11 hotspot to share his 3G/4G subscribed Internet connection.

The new generation of UPN implements multi-hop routing among wireless links. To join the Freifunk UPN community [Freifunk, 2013], one has to set up a home wireless router device with OpenWrt [Openwrt, 2013] using the ad hoc wireless local area network mode, and run the Freifunk routing daemon to implement the Optimized Link State Routing (OLSR) protocol [Clausen et al., 2003]. The OpenWrt is a Linux distribution for embedded devices that frees the end-user from the application selection and configuration provided by the vendor, allowing him to customize

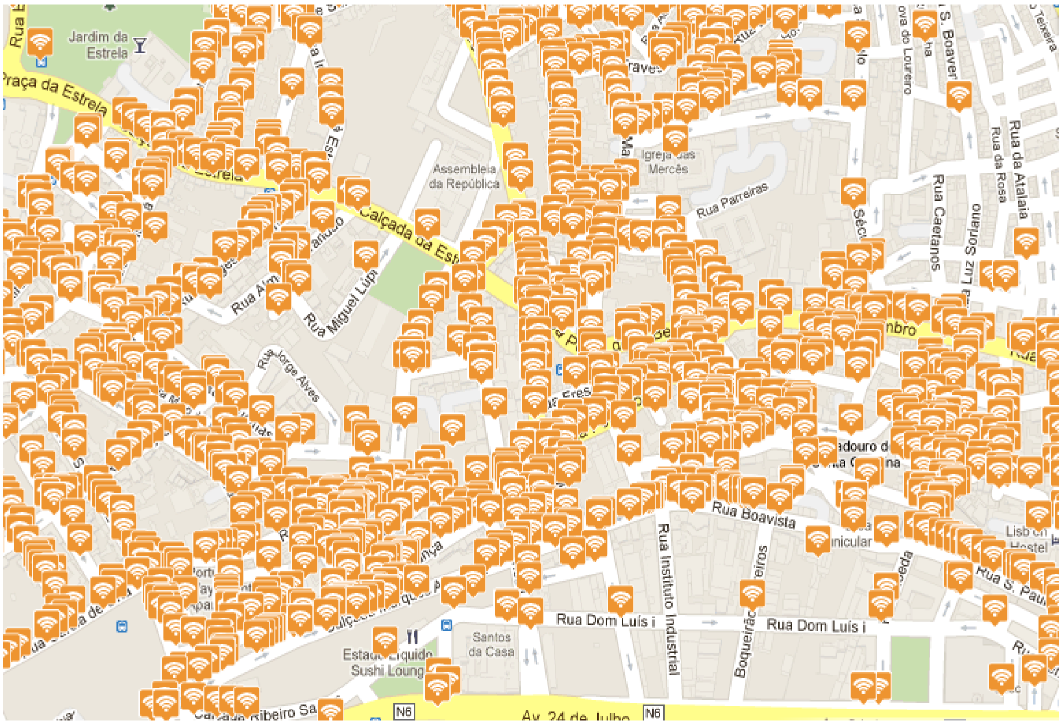

Figure 1.1: FON access points in downtown Lisbon, Portugal [FONERA, 2013].

the device. The Athens Wireless Metropolitan Network (AWMN) UPN community [AWMN, 2013] is also based on OpenWrt, and uses the Border Gate Protocol (BGP) [Claffy, 2012] to forward messages. The Lancaster University in United Kingdom operates a new generation UPN [Ishmael et al., 2008]. The University supplies the nearby village of Wray with Internet access running Ad Hoc On demand Distance Vector (AODV) protocol [Perkins et al., 2003].

Bytewalla [Ntareme and Domancich, 2011] is a new generation UPN community that implements the idea that people travelling from villages to cities and vice-versa shall carry data on their smart phones. In the village a user downloads data from a IEEE 802.11 access point (without Internet connectivity). Then, he carries the data to the city, where he can connect to another IEEE 802.11 access point to upload the data to the Internet. Emails downloaded at the village will finally be delivered in the city. This data-mule operation is transparent to the user, who is able to use his mobile phone as usual. Bytewalla uses the Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) [Lindgren et al., 2003] on Android smart phones.

At first, the tethering-based UPN emerged with the aim of providing Internet access to roaming users by sharing subscribed Internet connections using home wireless routers with members of the same UPN community. Because of smart phones popularization a new generation of UPN communication that could be ISP independent arises. Here are some examples of applications based on delay tolerant routing solutions that can be executed in UPN: urban transport system control [Doering et al., 2010], 3G/4G offloading [Chen and Wu, 2010], driver to driver content sharing [Gerla and Kleinrock, 2011], epidemic text message exchange [Rolla and Curado, 2013a], rural villages content delivery [Ntareme and Domancich, 2011], conference systems [Hui et al., 2011], advertising [Leontiadis et al., 2009], and dissemination of weather and tourist information.

Two key aspects for the development and wide adoption of the UPN paradigm are: i) delay tolerant routing solutions and ii) incentive mechanisms. These two aspects are the main objects of this research.

i) Since UPN do not have predefined infrastructure (like traditional ISP), and wireless IEEE 802.11, Bluetooth, and IEEE 802.15.4 technologies have limited transmission ranges, delay tolerant routing solutions play an important role to provide end-to-end data delivery in UPN. Delay tolerant routing solutions can deal with the lack of instantaneous end-to-end paths and ISP infrastructure. These routing solutions use a store-carry-forward approach to adeptly deliver the message to the destination. Examples of distinguished delay tolerant routing solutions are: PRoPHET [Lindgren et al., 2003], Delay Tolerant Reinforcement-Based (DTRB) [Rolla and Curado, 2013b], and Spray and Wait (SnW) [Spyropoulos et al., 2005].

ii) Users may have conflicting interests in UPN, especially when limited resources are crucial, for instance battery and storage capacity. Thus, the development of incentive mechanisms, which promote sharing and are compatible with delay tolerant routing solutions is necessary. Examples of distinguished incentive mechanisms for UPN are: Messages on oFfer (MooF) [Rolla and Curado, 2014], Gain-aware Dissemination Protocol (GDP) [Hajiaghajani et al., 2014], and the Practical incentive (Pi) [Lu et al., 2010].

1.2 Research Questions

This work investigates the use of delay tolerant routing solutions in UPN based on IEEE (Institute of Electrical and Electronics Engineers) wireless technologies.

First, it is considered that nodes (users) are willing to cooperate. This is true when the nodes have a common interest, for example during natural disasters or virtual terrorism. Citizens, teams of firefighters and doctors need to act in an environment without communication infrastructure. UPN are important during emergency situations due to the possible absence of ISP infrastructure. An important question that arises when the nodes have a common interest is:

1 - Is it possible to have a high delivery rate of text messages with a tolerable delay in IEEE 802.11 (or IEEE 802.15.4) user provided networks?

Typically nodes do not belong to the same domain, which may lead to conflicting interests among users, especially when they have limited resources, such as battery and storage capacity. Taking into account the possibility of user cooperation and the level of user selfishness in a UPN, the following question arises:

2 - Is there an incentive mechanism to encourage users to cooperate, given the amount of smart phones in urban centers today and their limited resources?

The answers to the research questions here presented are given in the conclusion of this thesis. In the next subsection, the contributions are described.

1.3 Contributions

In order to address the aforementioned research questions, an in-depth analysis of related works in the state of the art of delay tolerant routing solutions and incentive mechanisms was conducted. This analysis revealed three important aspects: i) UPN can have a minimal fixed wireless infrastructure in urban areas, ii) a lack of efficient delay tolerant routing solutions for UPN, and iii) a lack of efficient incentive mechanisms compatible with delay tolerant routing solutions for UPN. Such aspects lead to the following first three contributions of this thesis. Finally, the fourth contribution is related to the reliable simulation environment, where the results were obtained.

Contibution 1, Internet as a backbone. The home wireless routers within the same UPN community can communicate through the wired network (Internet) to guarantee delay tolerant message delivery and enhance the UPN coverage. The messages from a particular source mobile node to another particular destination mobile node may be delivered using the Internet as a backbone. This practice provides a minimal fixed wireless infrastructure for UPN in urban centres.

Contibution 2, Delay Tolerant Reinforcement-Based (DTRB). This delay tolerant routing solution for UPN utilizes artificial intelligence techniques to learn about routes in the network and forward the delay tolerant messages. A learning algorithm is executed to calculate the distances between the nodes as a function of time from the last meetings.

Contibution 3, Messages on oFfer (MooF). This credit-based incentive mechanism for UPN utilizes a utility function that represents the monetary value of a given data message during its journey in the network, and a buffer management optimization algorithm to prevent selfish behaviour among nodes.

Contibution 4, Performance Evaluation. A realistic urban mobility simulator was used to model the UPN. The simulator emulates pedestrian nodes interacting directly with vehicular nodes and home wireless routers. Mobility traces were also utilized. Various delay tolerant routing solutions were simulated and evaluated. The simulation results provide important insights on how existing and future delay tolerant solutions and incentive mechanisms for UPN can be correctly assessed.

The source code for both solutions (DTRB and MooF) can be downloaded from: *http://eden.dei.uc.pt/∼vitorgr/*. In the next subsection, the thesis structure is presented.

1.4 Thesis Structure

The shortcuts to read this thesis are depicted in Figure 1.2.

The rest of the document is organized as follows:

- **Chapter 2 - Related Work:** existing research on delay tolerant routing solutions and incentive mechanisms.
- **Chapter 3 - Intelligent Wireless Router:** using the Internet as a backbone.
- **Chapter 4 - Delay Tolerant Reinforcement-Based (DTRB)**: a delay

tolerant routing solution for UPN.

- **Chapter 5 - Messages on oFfer (MooF)**: a credit-based incentive mechanism for UPN.
- **Chapter 6 - Conclusions and The Future:** answers to the research questions, the concluding remarks, as well as future steps to further research in the area addressed in this thesis.

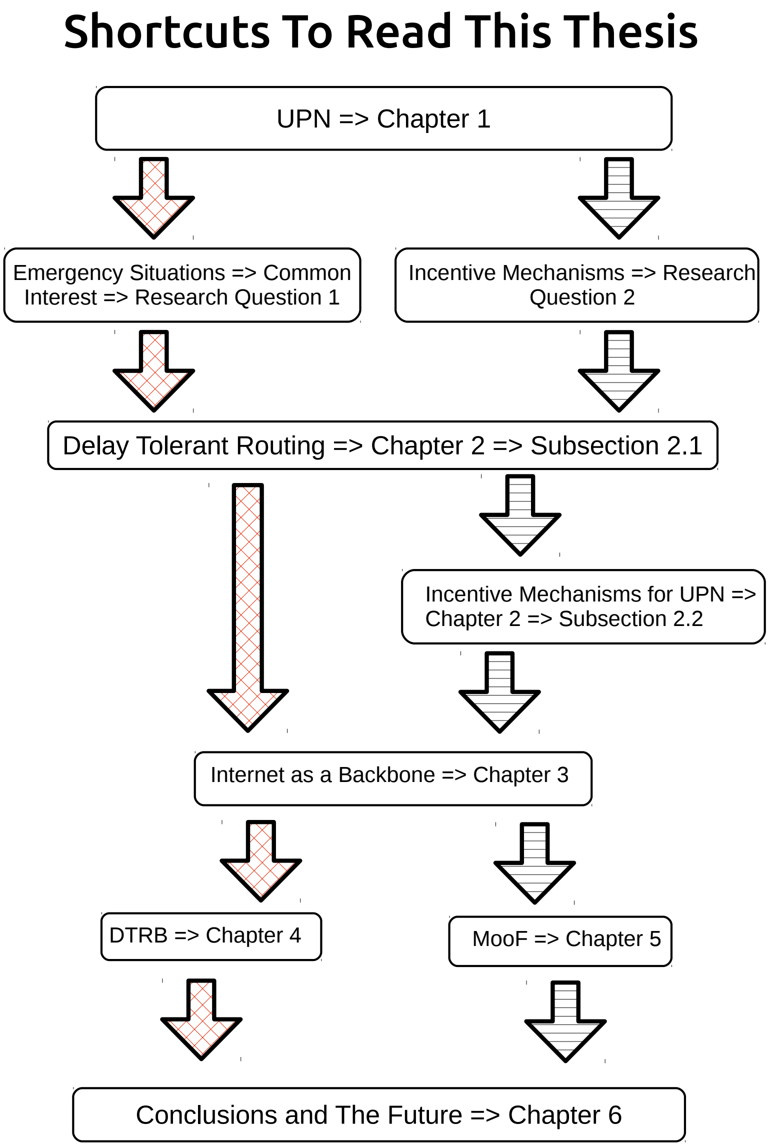

Figure 1.2: Shortcuts to read this thesis.

Chapter 2

Related Work

Lack of instantaneous end-to-end paths occurs in UPN. Routing solutions for these types of networks must use a store-carry-forward approach to opportunistically deliver the message to the destination. Currently, single-copy and multi-copy delay tolerant routing solutions are known. The multi-copy class allows multiple copies of the same message in the network, while the single-copy class does not allow message replication. Multi-copy delay tolerant routing solutions, for instance PRoPHET [Lindgren et al., 2003] and Spray and Wait [Spyropoulos et al., 2005], receive more attention from the research community because of their high delivery rates and low end-to-end delays. These routing solutions are known to suffer from waste of network resources. Applications based on single-copy routing solutions [Spyropoulos et al., 2008c] have limitations, such as long delays and low delivery rates. Section 2.1 presents existing research on delay tolerant routing for UPN. Such routing solutions are important when the nodes have a common interest, for example during natural disasters (e.g. earthquake). Consequently, emergency teams (doctors) need to act and communicate in an environment without communication infrastructure [Saha et al., 2014].

Incentive mechanisms for UPN are a novel theme among wireless research circles because they potentially solve the problem of selfish behaviour among nodes. Incentive mechanisms encourage the end-user to share his opportunistic connectivity, storage capabilities and energy resources. Wireless cooperation is a trend topic in the computer networks field [de Moraes et al., 2013]. Currently, credit- and reputation-based incentive mechanisms are known. Credit-based mechanisms use the notion of virtual currency to guide the data exchange in UPN. Cooperation rewards virtual payment whenever the node acts as a forwarder, and such monetary value (credit) can later be used to encourage others to cooperate with them.

Reputation-based mechanisms evaluate the cooperation levels of nodes and provide better services to nodes with a higher reputation. Selfish behaviour is not condoned resulting in partial or total network disconnection. Section 2.2 presents existing research on incentive mechanisms for UPN.

2.1 Delay Tolerant Routing Solutions

Delay tolerant routing solutions have evolved from space communication networks to terrestrial networks geared toward use in extreme situations where traditional coverage does not or can not exist. For example, in military environments, after natural disasters or terrorist attacks, in developing regions, or as an alternative for congested network resources. Delay tolerant routing solutions, as the name suggests, do come with their challenges and can result in bandwidth limitations, continuous network partitions, unexpected delays, restricted energy sources, and limited transmission ranges due to obstructions (e.g. walls, buildings, and mountains). These routing solutions aim to solve technical problems which exist in the absence of instantaneous end-to-end paths between any source and destination nodes.

A basic classification for delay tolerant routing solutions is: single-copy and multi-copy [Balasubramanian et al., 2010]. Single-copy routing solutions conserve resources because only one copy of a message exists in the network, but experience lower message delivery rates and longer delays. A common single-copy issue concerns predicting the next opportunity of connectivity (next meeting between two nodes). This single-copy application can be observed in low orbit satellites with 90 minute intermittent coverage cycles. An interesting study about the limitations of single-copy routing solutions can be found in [Spyropoulos et al., 2008a].

In multi-copy routing solutions, multiple message copies exist in the network. An epidemic solution replicates a message whenever two nodes meet with the idea that one of these copies shall reach the destination [Vahdat et al., 2000]. Multi-copy routing solutions can be sub-classified in flooding-based and quota-based solutions [Nelson et al., 2009]. In flooding-based solutions, if storage resources and mobility allow, it is possible for every node in the network to have a replica of the message. The quota-based solutions intentionally limit the number of replicas. Because of successful delivery rates, multi-copy routing solutions are favored by the research community. Waste of network resources, scalability, and congestion are common issues of these types of routing solutions. Epidemic information spreading amongst

IEEE 802.11 mobile nodes (e.g. advertisements and traffic conditions) is a result of multi-copy routing.

Subsection 2.1.1 presents traditional delay tolerant routing solutions for UPN. Subsection 2.1.2 presents delay tolerant routing solutions that utilize multi-agent reinforcement learning techniques. A discussion is presented in the last subsection.

2.1.1 Traditional Delay Tolerant Routing

The PRoPHET [Lindgren et al., 2003] is a flooding-based delay tolerant routing solution that relies on the calculation of delivery predictability to forward messages to the reliable node. Probability is used to decide if one node is reliable to forward a message to. A node that is often encountered has a higher delivery predictability than the others. If two nodes do not encounter each other during an interval, they are less likely to exchange messages, thus the delivery predictability values must be reduced. PRoPHET utilizes a rather simple forwarding strategy: when two nodes meet, a data message is replicated to the other node, only if the delivery predictability of the destination of the message is higher at the encountered node. Predictabilities between nodes are exchanged and updated using a transitive property. This property is based on the observation that if node O frequently encounters node D, and node D frequently encounters node X, node X probably is a good node to forward messages destined for node O. In another version of PRoPHET [Sok et al., 2013], the authors introduce and solve a delivery dilemma when two or more neighbour nodes carry equal delivery predictabilities.

Spray and wait [Spyropoulos et al., 2005] is a quota-based delay tolerant routing solution that attempts to limit the number of possible replicas of a given message. The protocol restricts the number of message copies, improving network resource efficiency. A number L represents the upperbound maximum number of message copies in the network. The source of a new message “spray” (delivers) L copies to distinct delay tolerant nodes. When a node receives one of the L copies, the “wait” phase begins, and continues until the destination is encountered. There are different routing decisions in the Spray and Wait family protocol. One of them consists in the source node transmitting a single-copy of the message to the first L distinct nodes it encounters after the message is created. In another one, called binary spray and wait, the source node transfers half of its copies to nodes it encounters. Then, each of these nodes transfers half of the total number of copies they have to future nodes they meet. When a node eventually gives away all of its copies, except for one, it switches into the waiting phase, where it waits for a direct transmission opportunity with the destination. The second routing decision has the advantage of disseminating the messages faster than the first routing decision. In another version, the authors propose an improved spray and wait routing solution based on delivery probabilities [Kim et al., 2014].

The Group Aware Routing (GAR) [Chen and Lou, 2014] argues that in emergency situations (e.g. earthquakes) the mobile nodes with common interests or close relationship will form groups and move together. The routing solution maximizes the message delivery probability with the consideration of this group feature under the constraints of bandwidth and buffer space. GAR is composed by a cooperative message transfer scheme and a buffer management strategy. In the cooperative message transfer scheme, the limited bandwidth is considered and the message transfer priorities are designed to maximize the delivery probability. The buffer management strategy proposes a cooperative message caching scheme, where the dropping order of messages is also designed to maximize the delivery probability. GAR is quota-based.

Resource Allocation Protocol for Intentional Delay Tolerance (RAPID) [Balasubramanian et al., 2010] is a flooding-based delay tolerant routing solution. The authors show that the delay tolerant routing problem in terrestrial networks is NP-hard using a polynomial-time reduction from the edge-disjoint path problem for a directed acyclic graph [Aharoni and Berger, 2008]. RAPID is executed when two nodes are within range and have discovered one another. The protocol arranges the messages in order to choose a feasible schedule for transfers, and also assumes constraints on both storage capacity and available bandwidth. The protocol was deployed in a real vehicular network and simulated in a custom event-driven simulator.

SimBet [Daly and Haahr, 2007] uses Complex Network Analysis (CNA) [Newman, 2003] metrics for delay tolerant routing. This single-copy delay tolerant routing solution uses social similarity to detect nodes that are part of the same community, and *betweenness* centrality to identify the nodes that could carry a message from one community to another. Bubble Rap [Hui et al., 2011] is a single-copy protocol which also utilizes CNA and is focused on two specific aspects of society, namely community and centrality. The routing decision is based on the popularity of each node.

Encounter-based routing (EBR) [Nelson et al., 2009] argues that nodes with more encounters are more likely to successfully pass data along to the final destination than the nodes who only infrequently meet others. Every node running EBR is responsible for maintaining two pieces of information: an encounter value and a current window counter for the calculation of past rate of encounter average. EBR is quota-based. When a new message is created in the system, a number L is attached to that message indicating the maximum allowable copies of the message in the network. When two nodes meet, the relative ratio of their respective rates of encounter determines the appropriate fraction of message replicas the nodes should exchange. A similar approach is used in [Abdelkader et al., 2010], however, the authors explore the idea that more encounters between two nodes means the more these nodes are expected to meet. Consequently, less is the benefit that they carry the same messages.

Social Aware Networking (SANE) [Mei et al., 2010] is a quota-based delay tolerant routing solution. The solution is based on the idea that individuals with similar interests tend to meet more often and that individuals movements are guided by their interests. Interests can be understood in a very broad sense, for instance, the fact that an individual belongs to certain physical or virtual communities or the degree of interest in a certain specific topic can be considered in the forwarding decision. Each message has a fixed number of copies in the network and each message has a header with its target interest profile. When two nodes are within range, they exchange their interest profile (a vector of interests) and calculate the cosine similarity [Tan et al., 2005] between them. Based on the similarity, each node starts scanning its buffer for messages to relay. A message should be relayed if and only if the number of replicas is higher than one and the cosine similarity between the relevance of the message and the interest profile is higher than a given threshold p.

2.1.2 Routing with Multi-agent Reinforcement Learning

Multi-agent Reinforcement Learning (MARL) systems are dedicated to the development of autonomous agents which can solve distributed problems or control complex systems. An introduction to MARL is available in the beginning of Chapter 4. Currently only a few delay tolerant routing solutions utilize MARL techniques.
Q-Learning AODV (QLAODV) [Wu et al., 2010] proposes integration of delay tolerant mechanisms on the original AODV routing protocol [Perkins et al., 2003]. It uses a Q-Learning algorithm [Watkins, 1989] to achieve whole network link status

information, changing routes preemptively using the learned information. In order to make Q-Learning work efficiently, a new route request/reply mechanism is proposed, which periodically verifies the correctness of the route information obtained allowing rapid reaction to network topology changes. QLAODV is a multi-copy routing solution proposed for Vehicular Ad hoc Networks (VANET) and tested in network simulator 2 [Issariyakul and Hossain, 2008] with the Freeway and Manhattan mobility models [Bai et al., 2003]. QLAODV uses a simple rewarding process: $true$ for neighbor nodes and $false$ for non-neighbor nodes.

Adaptive Reinforcement-Based Routing (ARBR) [Elwhishi et al., 2010] uses cooperative groups of nodes to make forwarding decisions based on a cost function at each contact with another node. The protocol considers node mobility statistics, congestion, and buffer occupancy, which are taken as feedback in the cost function. The feedback is based on sampling channel availability and buffer space during node contact. In the ARBR environment, each node maintains the network status within fixed consecutive time windows. Because of node mobility, the solution must adopt an algorithm to represent smooth transfer of the cost function values between the consecutive time windows. ARBR is a quota-based routing solution. The authors propose a custom simulator which uses a Community Based mobility model [Spyropoulos and Turletti, 2009]. ARBR also uses a simple rewarding process: $true$ for neighbor nodes and $false$ for non-neighbor nodes.

The Q-routing algorithm [Boyan and Littman, 1994] was the first attempt to use MARL to solve network problems, but the solution was designed for wired networks and is not useful for UPN. SAMPLE [Dowling et al., 2005] was proposed to enable RL agents to solve optimization problems in MANET. The protocol attempts to maximize overall network throughput and delivery rate while minimizing the number of transmissions required per message sent. Although SAMPLE performs well in high node density scenarios, it assumes that an end-to-end connection always exists from the origin to the destination, not considering link breakage due to node mobility.

2.1.3 Discussion

Table 2.1 presents a summary of the traditional delay tolerant routing solutions and the delay tolerant routing solutions that use MARL. Chapter 4 includes an introduction to MARL techniques. Computer network research on delay tolerance is vast and the academic community addresses the issue from different perspectives. It is important to note that the general delay tolerant routing problem is NP-hard, thus the majority of routing solutions are heuristic-based and therefore non-optimal. The routing solutions in this section do not consider incentive mechanisms, i.e., the users already have a common interest in communicating.

Traditional Delay Tolerant Routing Solutions			
Protocol	**Classification**	**Functionality**	**Compared to**
Epidemic [Vahdat et al., 2000]	Multi-copy (Flooding-based)	Replicates a message whenever two nodes meet	None
PRoPHET [Lindgren et al., 2003]	Multi-copy (Flooding-based)	Calculates delivery predictability	Epidemic
Spray and wait [Spyropoulos et al., 2005]	Multi-copy (Quota-based)	Limits number of possible messages in the network	Epidemic, Random and Spray and wait variations
GAR [Chen and Lou, 2014]	Multi-copy (Quota-based)	Composed by a cooperative message transfer scheme and a buffer management strategy	EBR, Spray and wait, PRoPHET and Epidemic
RAPID [Balasubramanian et al., 2010]	Multi-copy (Flooding-based)	Arranges messages and assumes constraints	MaxProp, Spray and wait and Random
SimBet [Daly and Haahr, 2007]	Single-copy	CNA metrics using social similarity	PRoPHET
Bubble Rap [Hui et al., 2011]	Single-copy	CNA metrics focus on community and centrality	PRoPHET
EBR [Nelson et al., 2009]	Flooding-based	Nodes with more number of encounters are more likely to delivery data to destination.	Epidemic, PRoPHET and Spray and wait
SANE [Mei et al., 2010]	Quota-based	Individuals with similar interests tend to meet often.	Epidemic, Spray and wait and Bubble Rap.
Delay Tolerant Routing Solutions based on MARL			
QLAODV [Wu et al., 2010]	Forwarding-based	Uses Q-Learning algorithm to change routes preemptively using the learned information	AODV
ARBR [Elwhishi et al., 2010]	Quota-based	Groups of nodes cooperate and make forwarding decisions based on a Reinforcement Learning (RL) cost function	Epidemic and Spray and wait
DTRB [Rolla and Curado, 2013b]	Flooding-based	The nodes that recently *gossip* about the destination of a given UPN data message are more likely to deliver the message	PRoPHET

Table 2.1: Summary of delay tolerant routing solutions.

Although the Delay Tolerant Reinforcement-Based (DTRB) [Rolla and Curado, 2013b] routing solution is explained in detail in Chapter 4, an introduction to this routing solution is given here for the sake of comparison with the routing solutions presented in Subsection 2.1.2. DTRB enables device to device data exchange without the support of any pre-existing network infrastructure. The solution utilizes Multi-Agent Reinforcement Learning techniques to learn about routes in the network and replicate the messages that produce the best reward.

DTRB is the first delay tolerant flooding-based routing solution that uses MARL techniques. The solution differs from QLAODV because it does not need the support of an underlying MANET routing solution for end-to-end routing. DTRB does not need an algorithm to represent smooth transfer of the cost function values between consecutive time windows due to node mobility as seen in ARBR. In addition, DTRB also utilizes an innovative calculation method which uses the relative distance between nodes as a function of time, to calculate the value of the reward offered for a given message exchange.

Next section presents existing research on incentive mechanisms for UPN.

2.2 Incentive Mechanisms for UPN

Incentive mechanisms for user provided networks are attracting much attention from the research community. Various incentive mechanisms encourage user cooperation and aim to avoid selfish behaviour among nodes. Incentive mechanisms are important to UPN, because they encourage the end-user to share his connectivity, storage capabilities and energy resources. Currently, credit- and reputation-based incentive mechanisms exist.

Credit-based incentive mechanisms use the notion of virtual currency to regulate the data exchange in UPN. Virtual payment incentivizes user cooperation each time the node acts as a router, and these credits can later be used by these nodes to encourage others to cooperate with them. Security is an intrinsic issue in credit-based incentive mechanisms. To avoid fake payments some strategies assume the use of hardware to store the virtual credit (tamper-proof devices). In practice, tamper-proof incentive mechanisms assume a hard code secure module that is part of the Medium Access Control (MAC) hardware or implemented in the Subscriber Identity Module (SIM) cards in Global System for Mobile (GSM) smart phones. Other strategies rely on the use of an off-line central trusted authority for virtual banking. A practical example of delay tolerant virtual banking is given in Section 5.2. Whenever a source node creates a message, it reserves the monetary value to pay the virtual bank the next time it comes in contact with the central authority. Intermediate nodes involved in successful message delivery receive extra credits when they come in contact with the central authority.

Reputation-based incentive mechanisms evaluate the cooperation levels of nodes and provide better services to nodes with a higher reputation. The more a node cooperates in the system, the more access it will have to network resources. The more selfish a node behaves, the less that node will take part in the network. Partial or total network disconnection are punishments towards selfish nodes. Usually, reputation-based incentive mechanisms use Tit-For-Tat (TFT) [Asher et al., 2012] schemes. A tit-for-tat node may decrease data exchange with a neighbour if it detects that the neighbour is misleading.

This Section is focused on incentive mechanisms that have the potential to enable new applications in UPN. Table 2.2 presents a classification for incentive mechanisms, in the context of UPN.

i)	**Incentive mechanisms for vehicular applications**
ii)	**Incentive mechanisms for 3G/4G offloading**
iii)	**Incentive mechanisms for social applications**

Table 2.2: Classification of incentive mechanisms for UPN.

The following Subsections present credit- and reputation-based incentive mechanisms that encourage UPN cooperation. The incentive mechanisms are presented according to the following features: functionalities, typical end-to-end delays and the potential to enable different applications in UPN.

2.2.1 Incentive Mechanisms for Vehicular Applications

Vehicular applications which use incentive mechanisms have the potential to enable location dependent information sharing and provide local advertising, traffic reports, and parking information. Research related to these incentive mechanisms relies on the use of a Global Positioning System (GPS) network and the IEEE 802.11p [Ibanez et al., 2011] standard. Usually, the expected end-to-end delay for vehicular networks ranges from few minutes to couple of hours, and no energy constraints exist.

The Secure Multilayer (SMART) [Zhu et al., 2009] credit-based incentive mechanism assumes the existence of an off-line central trusted authority. The intermediate nodes involved in successful message delivery receive a dividend of the total credit provided by the source node. The payment, the remuneration conditions, the class of service and the reward policies are information attached to a new message. Based on such information, the intermediate nodes agree (or not) to provide forwarding service under the predefined class of service. If the provided forwarding service satisfies the remuneration conditions defined in the reward policy, each forwarding node along one or multiple paths shall share the credit, when in contact with the virtual bank. SMART is compatible with two delay tolerant routing solutions: PRoPHET and Spray and Wait.

The Practical Incentive (Pi) [Lu et al., 2010] mechanism combines reputation-based and credit-based incentive schemes. The intermediate nodes can get credit from the source node, only if the message arrives at the destination. In the case of message forwarding failure, the intermediate nodes get good reputation scores from the off-line central trusted authority. The credit-based part follows the same idea of SMART. The reputation-based part rewards the effort of a node that participates in the forwarding process, even if the node was not able to deliver the message. Pi is also compatible with several delay tolerant routing solutions, such as spray and wait and PRoPHET. The end-to-end delay observed in the simulations ranges from 5 minutes to 45 minutes.

MobiGame [Wei et al., 2011] is a reputation-based incentive mechanism that uses game theory to design reasonable cost and reward parameters in the forwarding process. The game model assumes the existence of an off-line central trusted authority responsible for security key distribution. In the simulations, nodes behave selfishly and try to maximize their own utility function without considering global network performance. At the same time, the nodes must avoid being on the blacklist. The local buffer stores the reputation information for each node. The incentive mechanism is compatible with several delay tolerant routing solutions. MobiGame uses Spray and Wait delay tolerant routing in a vehicular mobility scenario. The end-to-end delay was not reported in the paper, but the message time-to-live used in simulations was 12 hours.

Reputation-Assisted Data forwarding protocol for Opportunistic Networks (RADON) [Li and Das, 2010] is a reputation-based incentive mechanism to evaluate an encounter's competency of delivering data. RADON integrates with a large family of existing delay tolerant routing solutions. In particular, a special message, called *positive feedback message*, monitors the forwarding behaviour of a node. RADON utilizes the number of previous encounters as the metric to select the next qualified node to forward the message, more encounters between two nodes denotes more competency of delivering data. The maximum end-to-end delay observed in simulations was 4 hours.

2.2.2 Incentive Mechanisms for 3G/4G Offloading

Incentive mechanisms for 3G/4G offloading potentially lower Internet costs for cooperative users. Research related to these incentive mechanisms relies on the use of home wireless router (access points) to avoid the use of 3G/4G networks for Internet access. For instance, users of the same UPN community could exchange multi-copy, tweet size text messages, in a urban space relying on their shared subscribed Internet connections as a backbone infrastructure [Rolla and Curado, 2013a]. The average end-to-end delay observed during 3G/4G offloading ranges from 3 to 24 hours, but it depends on the user demand for data.

Win-coupon [Zhuo et al., 2011] focuses on investigating the trade off between the amount of traffic being offloaded and the user's satisfaction. This credit-based solution proposes a tamper-proof incentive mechanism to motivate users to trade their delay tolerance for 3G/4G offloading. Users receive service charge discounts if they agree to wait longer for data. High delay tolerance and large offloading potential have priority in the mechanism. A justified pricing scale uses reverse auction techniques [Pal et al., 2007]. The optimal auction outcome considers both the delay tolerance and the offloading potential of the users to find the minimum incentive cost, given an offloading target. The auction winners setup contracts with the 3G operator for the delay and the coupon they earn, while the other users directly download data via 3G at the original price. The end-to-end delay observed in the simulations ranges from 3 to 24 hours.

MobiCent [Chen and Wu, 2010] is a credit-based incentive mechanism to lower Internet costs for cooperative users. The solution utilizes the 3G network for small data exchanges, and IEEE 802.11 links for larger amounts of data exchange. For example, a control message will arrive using the 3G network, but, when the user once again connects to an IEEE 802.11 access point, larger data file exchange occurs. MobiCent assumes usage-based pricing [Sen et al., 2012] and the willingness of the end-user to share his subscribed Internet connection with a home wireless router. The maximum end-to-end delay observed in simulations was 8 hours.

The Peer-to-peer Wireless Network Confederation (P2PWNC) [Efstathiou et al., 2006] is a reputation-based incentive mechanism that uses team formation combined with a reciprocity (tit-for-tat) scheme to encourage users to have consumption and contribution ratios near 1 : 1. The users sign digital receipts when they consume service from another team. A receipt graph aggregates the receipts, a reciprocity algorithm identifies contributing teams using network flow techniques. The algorithm provides a yes/no answer to the question: should team p provide service to team c? The authors argue that UPN should complement 3G networks in metropolitan areas, and the growth of IEEE 802.11 deployments make the reciprocity scheme relevant.

2.2.3 Incentive Mechanisms for Social Applications

Social applications which use incentive mechanisms have the potential to facilitate different services in a UPN, such as rural village content delivery, conference systems, local advertising, and dissemination of weather and tourist information. Research related to these incentive mechanisms presents high energy constraints, because the network nodes are often smart phones. Usually, the expected end-to-end delay for UPN social applications ranges from few minutes to several days.

Gini [Guan et al., 2011] is a credit-based incentive mechanism to solve the issue of internal threats using the Gini coefficient (the measure of inequality in a population [Ceriani and Verme, 2012]). The coefficient measures the social distribution in a UPN, and to adopt the correct strategy to re-distribute the social virtual money avoiding the appearance of *poor* nodes. Popular nodes, with more social relations, are frequently used to help other nodes, and consequently these types of nodes obtain more rewards. On the other hand, the nodes that have less social relations are under utilized and therefore have difficulties obtaining rewards. As time passes by, the nodes with less social relationship ties fall into the *poor* status, then a re-distribution of the virtual money is necessary. The authors argue that users prefer to exchange messages with those who have more social ties. The incentive mechanism evaluates a text message exchange application, where each node generates one message per day and assigns to it a random destination. The message time-to-live is 100 days.

The Incentive-Aware (IAW) routing solution [Shevade and Zhang, 2008] proposes a reputation-based tit-for-tat scheme that allows selfish nodes to maximize their individual utilities conforming TFT constraints. The approach focuses on detecting good behaviour. Message acknowledgements are proof of work done by a neighbour. All nodes check if they have delivered enough packets in the previous network interval to satisfy their predicted demand for the upcoming network interval. If the predicted demand is not satisfied, the node has to forward more in order to get increased service in the next network interval. Human mobility traces (extracted from bluetooth devices, and collected during the IEEE INFOCOM 2006 conference) test the incentive mechanism. The end-to-end delay reported in the simulations range from 2 to 20 minutes.

RELICS [Uddin et al., 2010] is a reputation-based tit-for-tat incentive mechanism that considers the battery as the main reason of selfishness. The mechanism considers the fact that a node needs to spend more battery if it wants to raise its delivery ratio. A third node observes if a particular node forwards messages originated from nodes other than itself, and the rank of the node represents the level of cooperation on the network by the node. The solution proposes the following convergence idea. The user is responsible to set the shared energy rate that limits the rate of exchanged messages, and the rank of a node defines the priority of message exchange, thus affecting delivery ratio. The protocol is compatible with any delay tolerant routing solution. The end-to-end delay reported in the simulations range from 2 to 48 hours.

First Place Winner (FPW) [El-Azouzi et al., 2013] is a reputation-based incentive mechanism that employs two-hop routing [Liu et al., 2012] and evolutionary game theory [Altman et al., 2009] to elaborate conditions for the existence of stable strategies depending on energy expenditure and delivery probability. Each node can adopt two types of strategies: full or partial activation depending on their level of battery. Strategies played by nodes evolve with time, due to periodic revision. The main contribution of the paper is a competition game model where the forwarding process determines strategies played by connected nodes with the objective of increasing their reputation. For each message generated by a source node, only the first relay node to deliver the message to the destination node shall increase its reputation.

The Collusion Resistant Incentive Compatible Routing and Forwarding in Opportunistic Networks (CRISP) [Sadiq et al., 2012] is a credit-based incentive mechanism, where the data transfer and data loss are a model of a non-linear generalized flow network. Optimality conditions for flow maximization describe the optimal behaviour of a relay. This optimal behaviour requires a forwarding node to make a specific payment upon receiving the data. Real traces collected from people walking in a state fair test the incentive mechanism. The maximum end-to-end delay reported was 30 minutes.

2.2.4 Discussion

Table 2.3 summarizes the incentive mechanisms described in this Section. Incentive mechanisms for vehicular networks can provide information such as nearby business advertising, relevant traffic reports, and site specific parking information. Vehicular networks are not exposed to energy constraints and delays range from minutes to hours. Incentive mechanisms for social applications enable services, such as epidemic text message exchange and nearby business advertising in UPN. Since the network nodes are often smart phones, energy constraints are unavoidable. Social applications have expected end-to-end delay that ranges from few minutes to days. Incentive mechanisms for 3G/4G offloading play a different role in UPN. Incentive mechanisms for vehicular and social applications encourage users carrying messages for other users, while incentive mechanisms for 3G/4G offloading encourage the end-user to share Internet access with a home wireless router to potentially lower their costs, avoiding the use of 3G/4G contracted services. User demand for data varies, affecting the end-to-end delays. The stark difference between the end-to-end delays observed in Table 2.3 is due to different network scenarios in which each incentive mechanism was evaluated. The number of pedestrian nodes, cars, and access points are not equivalent, as well as the playground area and the application message size.

Although the MooF (Messages on oFfer) [Rolla and Curado, 2014] incentive mechanism is explained in detail in Chapter 5, an introduction to this incentive mechanism is given here for the sake of comparison with the incentive mechanisms presented in this section. MooF enables device to device data exchange without the support of any pre-existing network infrastructure. The incentive mechanism utilizes buffer management techniques to prevent selfish behaviour among nodes.

MooF differs in three main aspects from the solutions presented in this section. First, it considers a two-hop credit model (only the intermediate node gets credit when delivering a message). SMART, Pi, and Gini mechanisms redistribute the virtual money to all intermediate nodes which participate in successful message delivery. Thus, such incentive mechanisms must keep track of the entire path crossed by the message during its journey in the UPN. CRISP obligates the source to pay to the forwarder during the message exchange process. Reputation-based incentive mechanisms, such as RADON, MobiGame, and Pi, are known to suffer from *sybil* attack [Xiao et al., 2009] (alternative egos) and collusion attack [Xiao et al., 2012]. The last one is related to malicious nodes interacting only to raise their profit. Reputation-based incentive mechanisms are more susceptible to fraud, because they do not use an off-line central trusted authority. An example of the off-line central trusted authority is provided in Chapter 5.

Second, MooF is built upon a very specific feature observed during the spray phase of the binary spray and wait delay tolerant routing solution. This feature is called isotropic delivery and is described in Chapter 5. The related work does not take into account specific features of the under layer routing solution, consequently the majority of incentive mechanisms presented in this Section is compatible with different delay tolerant routing solutions. MooF is compatible only with binary spray and wait, because it takes into account a specific feature of the under layer routing solution. In one hand, the related work is flexible because it supports more than one routing solution. On the other hand, MooF is more robust against failures because it is integrated into the routing protocol.

Third, MooF is the first incentive mechanism based on buffer management. When two nodes opportunistically meet, the mechanism exchanges the messages that maximize the monetary value, i.e., the mechanism guarantees that each node will store the set of messages that produce a buffer with the largest monetary value. The incentive mechanisms presented above utilize basic (or infinite) buffer management schemes, such as DropTail [Krifa et al., 2008a] or DropOldest [Pan et al., 2013], which do not depict realistic scenarios.

Important research shows that buffer management affects the performance of delay tolerant routing significantly [Zhang et al., 2007] and [Krifa et al., 2008b]. Buffer limitations in multi-copy delay tolerant routing solutions can be overcome with the use of intelligent buffer management schemes [Spyropoulos et al., 2008b]. Indeed, buffer management is one of the constraints that make the delay tolerant routing problem NP-hard [Balasubramanian et al., 2010]. Mahendran et al. [Mahendran and Murthy, 2013] show that buffer dimensioning is essential to design an efficient multi-copy delay tolerant routing solution, and propose an analytical model to systematically quantify the overall UPN buffer size. The adaptive optimal buffer management scheme [Li et al., 2009] shows that when there are buffer space limitations, selecting the appropriate messages to drop is critical under multi-copy routing solutions. Thus, basic message dropping policies maximize the average delivery rate or minimize the average delivery delay. Zhang et al. [Zhang et al., 2011] present a simple message prioritization scheme for multi-copy routing solutions based on First-Come-First-Serve (FCFS) [Chan et al., 1973].

The buffer management schemes presented assume a cooperative network, where nodes are cooperative in optimizing network performance (e.g. military network). This is true when the nodes belong to the same domain. However, nodes do not always belong to the same domain, which may lead to conflicting interests among users, especially when they have limited resources, such as battery and storage capacity. Incentive mechanisms are necessary when the nodes do not belong to the same domain. The incentive mechanism presented in Chapter 5 is buffer management based. MooF is compared to other traditional and widely used delay tolerant buffer management schemes: DropTail and DropOldest. When using DropTail a node only requests message replications if the buffer is not full. If the buffer becomes full, the node must deliver one of the messages stored in its buffer to make room for new message replications. Thus, if the buffer is filled to its maximum capacity, the newly arriving messages are dropped until the queue has enough room to accept new replications. When using DropOldest and the buffer becomes full, a node discards the oldest message in the buffer to make room for new message replications. The idea of dropping the oldest message in the buffer is used because it has the highest probability to have been previously delivered [Rashid et al., 2013].

Mechanism	**Type**	**Functionality**	**End-to-end delay**
Incentive Mechanisms for Vehicular Applications			
SMART [Zhu et al., 2009]	Credit-based	Intermediate nodes involved in successful message delivery	Minutes/hours
Pi [Lu et al., 2010]	Credit- and Reputation-based	SMART + Reputation-based	Minutes
MobiGame [Wei et al., 2011]	Reputation-based	Game theory to design reasonable cost and reward	None
RADON [Li and Das, 2010]	Reputation-based	More encounters between = more competency of delivering data	Minutes/hours
Incentive Mechanisms for 3G/4G Offloading			
Win-Coupon [Zhuo et al., 2011]	Credit-based	Trade off between the amount of traffic being offloaded and the user's satisfaction	Hours
MobiCent [Chen and Wu, 2010]	Credit-based	3G network for small data exchanges, and IEEE 802.11 links for larger amounts of data exchange	Minutes/hours
P2PWNC [Efstathiou et al., 2006]	Reputation-based	Team formation combined with a reciprocity (tit-for-tat) scheme	None
Incentive Mechanisms for Social Applications			
Gini Coefficient [Guan et al., 2011]	Credit-based	Nodes with less social relationship ties fall into the *poor* status	Days
IAW [Shevade and Zhang, 2008]	Reputation-based	Individual utilities conforming TFT constraints	Minutes
RELICS [Uddin et al., 2010]	Reputation-based	Considers the battery as the main reason of selfishness	Hours
FPW [El-Azouzi et al., 2013]	Reputation-based	Two-hop routing and evolutionary game theory	None
CRISP [Sadiq et al., 2012]	Credit-based	Optimality conditions for flow maximization describe the optimal behaviour of a relay	Minutes
MooF [Rolla and Curado, 2014]	Credit-based	Isotropic deliveries, buffer Management	Minutes

Table 2.3: Incentive mechanisms for UPN.

2.3 Summary

This chapter presented the related work on delay tolerant routing solutions (Section 2.1) and the related work on incentive mechanisms compatible with UPN (Section 2.2). Delay tolerant routing solutions are important to UPN, because they aim to solve technical problems which exist in the absence of instantaneous end-to-end paths between any source and destination nodes. Incentive mechanisms are important to UPN when there is no intrinsically common interest. Consequently, such mechanisms have the properties to encourage the end user to share his connectivity, storage capabilities and energy resources.

The related work necessary to understand Chapter 3 was presented in the first part of Chapter 2: the basic epidemic routing and the spray and wait routing. The related work necessary to understand Chapter 4 was presented in Section 2.1. The discussion in Subsection 2.1.3 is fundamental to go further and read Chapter 4. The related work necessary to understand Chapter 5 was presented in Section 2.2. The discussion in Subsection 2.2.4 is fundamental to go further and read Chapter 5.

Chapter 3

Internet as a Backbone

Intelligent Wireless Router

UPN are an alternative for message exchange in terrestrial wireless networks. The IEEE 802.11 technology became ubiquitous due to the proliferation of smart phones and wireless access points. A complete epidemic delay tolerant routing solution replicates a message whenever two nodes are within wireless range with the idea that one of these copies shall reach the destination. Epidemic routing enables message dissemination between smart phones in a UPN.

The Intelligent Wireless Router (IWR) protocol is proposed for the fixed nodes (IEEE 802.11 home wireless routers) of a UPN community. IWR's goal is to deliver messages from a particular source mobile node to another particular destination mobile node using the Internet as a backbone to control the network overhead, and consequently lowering overall energy consumption.

The main motivation of this chapter is to investigate a different UPN scenario where the user's wired subscribed Internet connections are used as a backbone to diminish the delay and control the network overhead of traditional UPN epidemic routing [Vahdat et al., 2000]. Combined with a knowledge base, this protocol aims to select the best fixed node to initiate an *epidemy* among the mobile nodes (laptops and smart phones) that belong to a wireless cooperative community.

The Time Ontology in Web Ontology Language (OWL) [Hobbs and Pan, 2006] was used to model the knowledge acquired by the agents (home wireless routers) when within wireless range of mobile nodes (smart phones and notebooks). Such knowledge is stored in a central entity in the Internet, the Knowledge Base server. The Knowledge Query Manipulation Language (KQML) [Labrou and Finin, 1997] was used to model the knowledge exchange between the agents and the central entity. These languages provide nodes with high flexibility of expression. Though, in a dialogue, the nodes can argue of what to utter in each step of the conversation [Heras et al., 2014].

The IWR protocol differs from traditional UPN routing proposals in two aspects: i) it uses an ontology knowledge base compatible with a proper knowledge manipulation language to support routing, and ii) it uses the Internet to improve performance, and consequently lowers overall mobile device energy consumption. Simulation results show that the IWR protocol can deliver the same number of messages of traditional epidemic routing causing less network overhead with a tolerable end-to-end delay.

The IWR solution uses an ontology knowledge base compatible with a proper knowledge manipulation language to select the best fixed node to initiate an IEEE 802.11 *epidemy* among the mobile nodes. Together with spray and wait, the IWR protocol uses the Internet as a backbone to diminish the delay and control the network overhead on the wireless network. Beside the IWR routing solution, which is presented in this chapter, the epidemic delay tolerant routing solution and the spray and wait delay tolerant routing solution were already discussed in the first part of the last chapter.

Next section describes the network environment. The IWR protocol is presented in Section 3.2. Simulation setup and results are described in Section 3.3. Finally, Section 3.4 presents a summary about IWR.

3.1 Network Environment

The network scenario considered in this work relates to a regular user roaming in a metropolitan area covered by a specific wireless cooperative community. The users registered in the system agree to forward data to other registered users epidemically by IEEE 802.11 technologies. Though, users of the same community share storage capabilities, energy resources and wireless connectivity. The users may also agree to share their subscribed Internet wired connection using their home wireless router, as depicted in Figure 3.1. A video illustration of the network scenario (and consequently, the simulation scenario) is available at [VIMEO, 2013].

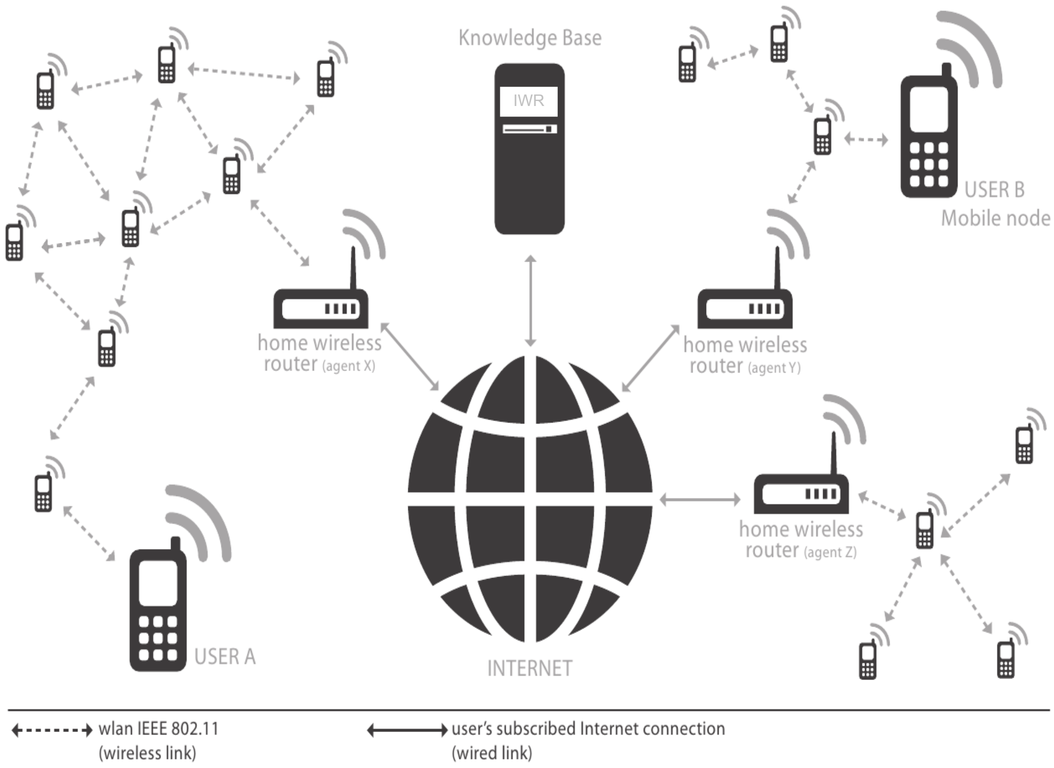

Figure 3.1: Network environment.

The epidemic routing only occurs in the wireless part of the network. It is modeled as a proactive ad hoc routing solution, which means that each node periodically announces its presence on the network through a *control_message*. When two nodes are within wireless range, they replicate the UPN data messages properly, according to the spray and wait UPN routing solution.

Such new spontaneous communication networks are based on the idea that the dissemination of information may augment the user life experience. For instance, by means of such spontaneous setting, the members of the wireless community can get news, traffic information, or even exchange messages independently of their location and terminal, increasing the pervasiveness of the community, and consequently the Internet itself.

3.2 The IWR Protocol

The Intelligent Wireless Router protocol's goal is to deliver delay-tolerant data messages from a particular source mobile node to another particular destination mobile node using the Internet as a backbone to diminish the delay and cause less network overhead among the members of a wireless IEEE 802.11 community.

The Time Ontology is used to model the knowledge acquired by the agent (home wireless routers) when within wireless range of mobile nodes (smart phones and notebooks). This knowledge is forwarded to and stored by the Knowledge Base server. The KQML is used to model the knowledge exchange between the agents and the Knowledge Base server.

3.2.1 Knowledge Base

The Time Ontology provides a vocabulary for expressing facts about topological relations among *Instants* and *Intervals*. Such relations can be further represented together to convey *Durations* and *Date-time* information. This vocabulary allows the expression of two temporal entries concerning the meetings between an agent (home wireless router) and a mobile node (smart phone or notebook). Such temporal entries are presented as follows: i) The last time that the agent heard about a specific mobile node. Whenever an agent receives a *control_message* from a mobile node, it updates this knowledge base entry. The entry is expressed in Table 3.1. ii) A meeting between the agent and a mobile node always has a *Beginning*, an *End*, and a *Duration*. The entry is expressed in Table 3.2.

```
:last
    a                      :Instant;
    :inXSDDateTime         (e.g 2011-06-24T16:29:00).
```

Table 3.1: The last time that the agent heard about a specific mobile node.

In Tables 3.1 and 3.2, the Knowledge Base states that: the last time that a specific agent (home wireless router) heard about the mobile node was at 2011-06-24T16:29:00, there was a total of two meetings between both in the current window period, and the nodes were connected so far 235 seconds, the sum of all meetings duration.

The window period is the only parameter in IWR. It determines how important the meeting is at the time of best agent selection. If the meeting took place during the current window period, it is more important to the best agent selection process.

:meeting#0	
a	:Interval;
:hasBeginning	:meetingStart#0;
:hasEnd	:meetingEnd#0;
:hasDuration	:meetingDuration#0.
:meetingStart#0	
a	:Instant;
:inXSDDateTime	(e.g. 2011-06-24T16:21:03).
:meetingEnd#0	
a	:Instant;
:inXSDDateTime	(e.g. 2011-06-24T16:21:58).
:meetingDuration#0	
a	:DurationDescription;
:seconds	(e.g. 55).
:meeting#1	
a	:Interval;
:hasBeginning	:meetingStart#1;
:hasEnd	:meetingEnd#1;
:hasDuration	:meetingDuration#1.
:meetingStart#1	
a	:Instant;
:inXSDDateTime	(e.g. 2011-06-24T16:26:00).
:meetingEnd#1	
a	:Instant;
:inXSDDateTime	(e.g. 2011-06-24T16:29:00).
:meetingDuration#1	
a	:DurationDescription;
:seconds	(e.g. 180).

Table 3.2: A meeting between the agent and a mobile node.

3.2.2 Knowledge Exchange

The KQML was used to model the knowledge query between the agents (home wireless routers) and the Knowledge Base server. Such communication protocol is designed to support run-time interaction and knowledge exchange among intelligent agent systems. Whenever an agent needs to start an *epidemy* in the wireless community, it may ask the following question to the Knowledge Base server: what is the home wireless router (agent) that is more likely to be within wireless range of the UPN data message destination mobile node? The query and the possible agents answers are expressed in Table 3.3.

Here, *ask*, *tell* and *deny* are the performatives. The point of this utterance is that the speaker, agent-y, is asking the Knowledge Base server for a response to the query contained in the message :content. The :language indicates that the :content is expressed in Prolog [Bratko, 2001], and the :ontology used to express the knowledge is the Time Ontology in OWL. In this particular answer, the Knowledge Base server *tells* agent-y that agent-z has an open connection (is in a meeting) with the mobile node x. In this case, the *epidemy* has not even started. Agent-y simply forwards

Query:	
(ask	
:sender	:(e.g. agent-y);
:receiver	:knowledge_base_server;
:language	:prolog;
:ontology	:time ontology in owl;
:content	:“?-bestAgent(’mobilenode_x’, *any*)”.)
Answers:	
(tell	
:sender	:(knowledge_base_server);
:receiver	:agent-y;
:language	:prolog;
:ontology	:time ontology in owl;
:content	:“[bestAgent(’mobilenode_x’, ’agent-z’)”.)
(deny	
:sender	:(knowledge_base_server);
:receiver	:agent-y.)

Table 3.3: The query and the possible answers in KQML.

the UPN data message to agent-z, because the last one is connected to the message destination (mobile node x). A *deny* answer is issued when the Knowledge Base server has no entries about the message destination (mobile node x).

The Knowledge Base server answers the question after running the proposed Algorithm 1, where:

A: is the vector of known agents;

x: is the UPN data message destination address;

$meet(a, x)$: is a meeting between an agent a and a mobile node x.

3.3 Simulation Setup and Results

The simulations were performed using the Omnet++ network simulator version 4.1 with the INETMANET framework [Varga and Hornig, 2008]. The IEEE 802.11 Layer in ad-hoc mode was used with Nakagami-m [Kuntz et al., 2008] propagation model on the physical layer. The playground size used was 2000m x 2000m. All nodes have synchronized clocks [Choi and Shen, 2010]. The data was collected over 30 simulation runs for each scenario. UPN data messages of 140 characters, a ”tweet” [Predd, 2011], were generated in each mobile node using random mobile destination addresses. The parameters used in the simulations are given in Table 3.4.

Algorithm 1: What is the home wireless router (a) that is more likely to be within wireless range of the UPN data message destination (x)?

```
forall the known agent in A do
    if $a.isConnectedTo(x)$ then return;
    ($a$);
    forall the $meet(a, x)$ do
        Calculate $sum(meet(a, x).meetingDuration)$ in the current window period;
        return ($a.maxMeetingDuration$);
    if ($a.maxMeetingDuration$) == 0; then
        forall the $meet(a, x)$ do
            Calculate $sum(meet(a, x).meetingDuration)$ total meetings duration;
            return ($a.maxMeetingDuration$);
    if ($a.maxMeetingDuration$) == 0; then
        return (deny);
```

3.3.1 Setup

UDelModels [Kim et al., 2009] is a suite of tools for simulating urban mesh networks that includes a simulator of realistic urban mobility. The mobility simulator is able to simulate daily life pedestrian dynamics (e.g. arrival times at work, lunch time, breaks) and vehicle traffic dynamics (e.g. traffic lights). Most of the related work presented here were evaluated in simple mobility models, especially Random Way Point or vehicular mobility (e.g. Manhattan mobility). IWR was evaluated in a complex urban mobility model, where the pedestrian nodes interact directly with vehicular nodes in an urban area. UDelModels default simulation parameters were utilized.

The application layer on mobile nodes generates UPN data messages to random destination nodes every 30 seconds. To simulate Internet delay, the wired channels were setup accordingly[1]. Whenever a UPN data message is replicated to one of the agents the IWR protocol starts. It is responsible for deciding which agent shall best improve the UPN message *epidemy* among the mobile nodes.

---

[1] According to Verizon Co., the mean ping delay on the Internet nowadays is less than 500 (ms).

Simulation Parameters	
General	
Simulation time	4000s
UPN data message size	140 bytes
UPN buffer size	7500 bytes
Playground size	2000m x 2000m
Nakagami-m Propagation model	$m = 1$
Wired Channel delay (Internet delay[1])	uniform(1s,2s)
ctrl_message period (proactive ad-hoc parameter)	uniform(5s,10s)
Scenario - 1	
N°of pedestrian	15
N°of cars	10
N°of home wireless routers (agents)	10
Scenario - 2	
N°of pedestrian	30
N°of cars	10
N°of home wireless routers (agents)	10
Urban Mobility Model Parameters	
City	RealisticCitiesV1.2 - Chicago2000m
Pedestrian Speed (min/max)	0.7-3 m/s (considering cyclists)
Car Speed (min/max)	6-18 m/s
Fraction where pedestrian appear (Room)	0.5
Fraction where pedestrian appear (Parking lot)	0.5
Fraction of nonworkers	0.5
Traffic Lights	On
IWR Parameter	
Window Period	100s
Spray and wait Parameter	
N°replicated msgs allowed in the network(L)	10

Table 3.4: Simulation parameters - IWR.

3.3.2 Results

The IWR routing solution was compared to three other approaches: i) Full epidemic routing: this uses the Internet as a backbone, when two nodes are within wireless range (or are wired connected, in the case of home wireless routers) they replicate the UPN data messages properly, avoiding duplications; ii) Traditional epidemic routing: without the use of the Internet as a backbone; iii) Traditional UPN spray and wait routing: without the use of the Internet as a backbone.

Table 3.5 shows the average delivery rate for both scenarios. As expected, the solutions that make use of the Internet as a backbone, namely, Full epidemic and IWR, can deliver more messages compared to both other solutions. No significant increase was observed in delivery rates of the denser scenario, possibly due to higher interference present in the link layer.

The histogram for end-to-end delay in the sparse and dense network scenarios is

Delivery Rate				
	F. Epidemic	IWR	Tr. Epidemic	Tr. SnW
Scenario-1	92.67%	91.58%	84.12%	81.13%
Scenario-2	92.71%	91.56%	84.44%	80.01%

Table 3.5: Average delivery rate.

presented in Figures 3.2 and 3.3, respectively. The Full epidemic solution delivers faster than all the other solutions in both scenarios. The IWR and the Traditional epidemic solutions can deliver the same number of messages almost in the same period of time. An interesting observation concerning these two solutions shows that in the dense scenario IWR delivers 42 seconds on average faster than Traditional epidemic routing, while in the sparse scenario Traditional epidemic routing delivers 3 seconds on average faster than the IWR solution. Thus, the strategy of utilizing the Internet as a backbone is even more efficient when the network density is increased, reducing the overall IWR end-to-end delay. As expected, the Traditional spray and wait takes longer to deliver its messages in both scenarios.

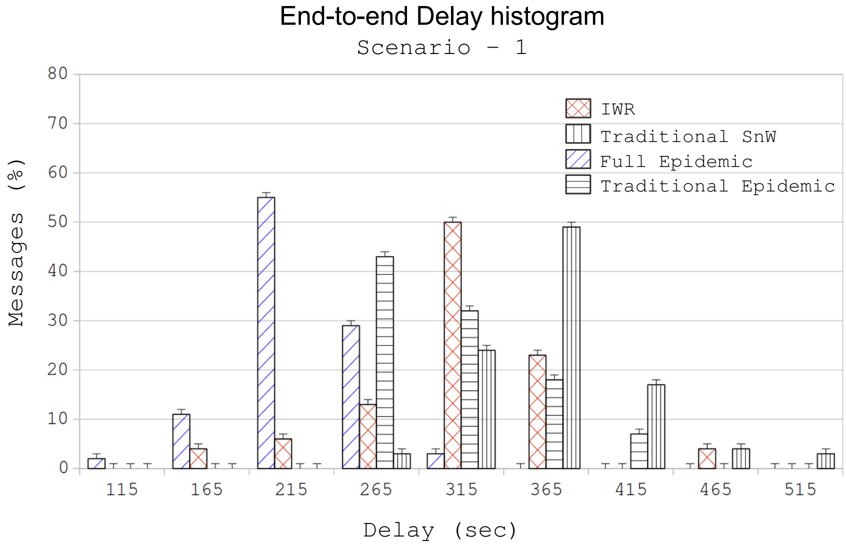

Figure 3.2: End-to-end delay histogram - scenario 1.

In delay tolerant systems, the overhead can be measured by the amount of unnecessarily replicated messages. In the simulation, unwanted messages were the messages that arrived late to the destination; plus, the messages that were too old to be stored by a custodian node during a contact, due to flooding. IWR is able to overload almost 50 percent less than both epidemic solutions, keeping the delivery rate up within a tolerable end-to-end delay. Table 3.6 shows the unwanted messages rate for both scenarios.

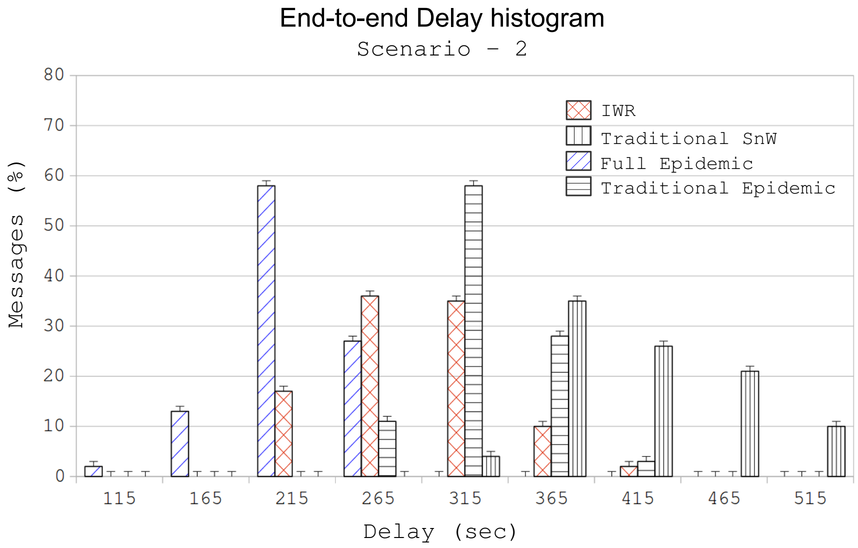

Figure 3.3: End-to-end delay histogram - scenario 2.

Unwanted Messages				
	F. Epidemic	IWR	Tr. Epidemic	Tr. SnW
Scenario-1	36.14%	17.97%	29.13%	16.74%
Scenario-2	38.28%	23.93%	27.82%	9.94%

Table 3.6: Network overhead - unwanted messages.

3.4 Summary

This chapter proposes the Intelligent Wireless Router protocol [Rolla and Curado, 2013a] for the fixed nodes (home wireless routers) of a cooperative IEEE 802.11 community network. This algorithm selects the best fixed node (agent) to initiate an *epidemy* among the mobile nodes (laptops and smart phones). The IWR algorithm proposes the use of Artificial Intelligence tools (Time Ontology in OWL and KQML) to improve UPN routing in a urban scenario.

Energy consumption (battery life) is crucial for pedestrian nodes in IEEE 802.11 urban environments and routing solutions that produce low overhead are extremely important. Simulation results on realistic urban mobility models show that IWR can deliver almost the same number of messages as the Full epidemic solution, within a similar end-to-end delay when compared to the Traditional epidemic solution causing half of the network overhead. IWR's proposed network environment, where the user's wired subscribed Internet connection is used as a backbone, is by design, fundamental.

Chapter 4

Delay Tolerant Reinforcement Based Routing

Delay Tolerant Reinforcement-Based is a delay tolerant routing solution for IEEE 802.11 wireless networks which enables device to device data exchange without the support of any pre-existing network infrastructure. The solution utilizes Multi-Agent Reinforcement Learning techniques to learn about routes in the network and forward/replicate the messages that produce the best reward. The rewarding process is executed by a learning algorithm based on the distances between the nodes, which are calculated as a function of time from the last meetings. DTRB [Rolla and Curado, 2013b] is a flooding-based delay tolerant routing solution. The simulation results show that DTRB can deliver more messages than a traditional delay tolerant routing solution does in densely populated areas, with similar end-to-end delay and lower network overhead.

Multi-agent reinforcement learning systems are dedicated to the development of autonomous agents which can solve distributed problems or control complex systems. Multi-agent systems have engineering applications in a variety of domains, such as: robotic teams [Balch and Arkin, 1997], intelligent transportation systems [Mhr et al., 2010], games [Niekum et al., 2011], collaborative decision support systems [Bowling and Veloso, 2002], and resource and network management [Elwhishi et al., 2010]. The methodology is based on a set of algorithms and protocols that enable the design of agents which learn the solutions to non-linear stochastic tasks about which the agent has limited prior knowledge. MARL is the next generation of Reinforcement Learning (RL). RL algorithms have reliable convergence when solving the single-agent task, but are ineffective in a multi-agent system. Several new challenges exist in MARL, mostly because of the *non-stationary* (because of simultaneous multi-agent learning the best policy is continually changing [Busoniu et al., 2008]) behavior that invalidates the convergence properties of single-agent algorithms, such as multi-agent unexpected communication delays. Convergence to an optimal equilibrium or a stationary global state is improbable because the objective function is constantly shifting and consequently continuous simulation is essential while evaluating and implementing MARL algorithms.

In UPN, data messages are forwarded during opportune contacts and connectivity is only sporadic. In the absence of infrastructure, only ad-hoc communication exists. For example, during emergency situations (e.g. natural disasters or virtual terrorism). MARL techniques are used in DTRB to learn about routes in the network and replicate the data messages that produce the best reward.

DTRB differs from the solutions presented in Chapter 2, Subsection 2.1.2 because it is the first delay tolerant flooding-based routing solution that uses MARL techniques. DTRB also utilizes an innovative calculation method which uses the relative distance between nodes as a function of time, to calculate the value of the reward offered for a given message exchange.

Section 4.1 describes the DTRB routing solution in detail. Section 4.2 evaluates simulation results. Conclusions and future works are presented in Section 4.3.

4.1 DTRB

DTRB nodes exchange knowledge through regularly broadcast $ControlMessages$ that carry two pieces of information: the distance-table and the rewards offered for a given data message exchange. The distance-table algorithm is a *gossip* style algorithm that calculates the distances between nodes as a function of time from the last meetings. The learning algorithm takes into account such distances between the nodes and creates a reward-table that is used to offer the best rewards to the neighbor nodes. In this work, x's neighbor nodes are the nodes that are inside the transmission range of x. The nodes that recently exchange *gossip* about the destination of a given data message are more likely to deliver the message, and consequently receive better rewards.

4.1.1 MARL Model and Assumptions

In DTRB the MARL model consists of: i) A discrete set S of environment states. Each node $s \in S$ in the network is considered a state of the agent. The set of all nodes in the network is the state space. ii) A discrete set A of agent actions. In DTRB, each data message is an agent indexed by its source and destination nodes. The state transitions (an action taken by an agent) are equivalent to a message being delivered from one node to one of its neighbors. The possible set of actions allowed at a node is the set of its neighbors in a given time. iii) A set of scalar reinforcement rewards R subjected to an exponential decay function.

Each node has a buffer to store data messages and all data messages are timestamped. When the buffer is full, the oldest data message is discarded. All *Control-Messages* are also timestamped to allow the distance-table algorithm to calculate the distance as a function of time.

4.1.2 Distance-Table Algorithm

Each node has a distance-table that indicates the distance as a function of time from the source node to all known nodes. Theoretically prior recent encounters with a destination node of a given data message are prioritized to bring the message “closer” to the destination node. Since we are dealing with a flooding-based algorithm, DTRB only replicates a message to neighbor nodes that exchanged *gossip* recently about the destination. The distance-table has three entries: the known node address, the last time a node exchanged *gossip*, and the node distance at that particular time.

When a node x receives a *ControlMessage* from node y, it uses the *Control-Message* timestamp to update its temporal distance *D(x,y)*. This calculation is shown in Eq. 4.1:

$$D_{(x,y)} \leftarrow t_{now} - t_{cmts} \tag{4.1}$$

where t_{now} is the time when node x processes the *ControlMessage* and t_{cmts} is the *Control-Message* timestamp. Then, x compares the received distance-table from node y with its own distance-table:

- Any distinct node known by node y and unknown by node x is created in x’s distance-table. This update is shown in Eq. 4.2 and Eq. 4.3, where $t_{last}(x, z)$

is the last (updated) time that node x exchanged *gossip* about the distinct node z.

$$t_{last}(x, z) \leftarrow t_{now} \tag{4.2}$$

$$D_{(x,z)} \leftarrow t_{now} - t_{last}(y, z) + D_{(y,z)} \tag{4.3}$$

- Distinct nodes known by node y that are also known by node x, shall be updated in x's distance-table if and only if, Eq. 4.4:

$$t_{now} - t_{last}(x, z) + D_{(x,z)} > t_{now} - t_{last}(y, z) + D_{(y,z)} \tag{4.4}$$

4.1.3 Learning Algorithm and Reward Process

Q-learning [Watkins, 1989] is a Reinforcement Learning technique that works by estimating the values of state-action pairs, without requiring a model of the environment. An agent learns an action-value function that rewards a given action in a given state following a fixed policy. The Q-value $Q(s, a)(s \in S, a \in A)$ is an estimate of the value of future rewards if the agent takes a particular action a when in a particular state s.

DTRB learning algorithm is inspired by Q-Learning. Every node maintains a reward-table which consists of Q-values $Q(d, x)$, where d is the destination node and x is the next hop to the destination. The node reward-table size is determined by the number of destination nodes (for buffered data messages) and the number of neighbor nodes. Exploration is achieved through $ControlMessages$. At the start of communication, agents know nothing about the rest of the network, thus elements of the reward-table are initialized to zero. The reward-table represents the knowledge of each node in the network at that specific time. $Q_s(d, x)$ is the value that node s estimates as the practicability of delivery of a data message bound for node d by way of neighbor node x. When node s receives a $ControlMessage$ from node x, then s revises its estimate as:

$$Q_s(d, x) \leftarrow (1 - \delta)Q_s(d, x) + \delta\{R + MF_x[max_{(y \in N_x)} Q_x(d, y)]\} \tag{4.5}$$

where N_x denotes the set of neighbors of node x and R denotes the reward. In Eq.(5.1), $\{R+MF_x[max_{(y \in N_x)} Q_x(d, y)]\}$ is calculated by the $ControlMessage$ sender node, in this case node x. This calculation represents the best rewards that node x can offer, and such information is attached in its $ControlMessages$. The reward R

is subjected to exponential decay as a function of $D_{(x,y)}$, and it is defined in Eq.(5.2) as:

$$R = \begin{cases} e^{-k}, & \text{if } 0 < D_{(x,y)} < k \\ 0, & \text{if } D_{(x,y)} > k, \quad \text{where } y \in N_x. \end{cases} \tag{4.6}$$

The system only rewards the nodes that replicate data messages addressed to nodes that are less than k seconds away from the $ControlMessage$ source node. The greater the distance $D_{(x,y)}$, the smaller is the reward offered by x with respect to y. Messages are only replicated to nodes that are "closer" to the destination node. Distances greater than k are not rewarded, because this work assumes a given node has no knowledge about a destination node if their distance as a function of time is greater than k. The exponential decay constant k is the parameter which controls the number of replications on the system. Some insights on its behaviour are given in Subsection 4.2.3.

4.1.4 Learning Rate and Discount Factor

The learning rate parameter δ limits how fast learning can occur. In DTRB, it governs how quickly the Q-values can change with a network topology change. If the learning rate is too low, the learning will not adapt readily to network mobility. Otherwise, the algorithm cannot reflect the network mobility because agents may receive incorrect rewards.

The discount factor is also an important parameter of MARL algorithms, because it controls the value placed on future rewards. If the value is low, immediate rewards are optimized, otherwise it causes the learning algorithm to count future rewards more strongly. The discount factor is modeled by a mobility factor, as seen in [Wu et al., 2010]:

$$MF_x = \begin{cases} \sqrt{\frac{|N_x \cap N_x^p|}{|N_x \cup N_x^p|}}, & \text{if } N_x \cup N_x^p \neq 0 \\ 0, & \text{otherwise.} \end{cases} \tag{4.7}$$

where N_x is the current neighbor set of node x and N_x^p denotes the neighbor set of node x at the time that the previous $ControlMessage$ was sent. Every node needs to maintain a N_x^p. When the $ControlMessage$ timer expires a node uses these values to calculate MF_x. In case of a static connected network, $MF_x = 1$ for every node, denoting reliable rewards.

4.1.5 Practicability Ageing and Forwarding Strategy

The practicability of delivery $Q_s(d,x)$ must age. This process is based on a constant aging and the number of time units (sec) that have elapsed since the last time s exchanged *gossip* about x. If a pair of nodes does not exchange *gossip* over a certain period of time, $Q_s(d,x)$ decreases, resulting in lost learned knowledge. The aging calculation is shown in Eq.(4.8), where $\omega \in [0,1)$ is the aging constant, and μ is the number of time units that have elapsed since the last time the metric was aged.

$$Q_s(d,x) \leftarrow Q_s(d,x)_{old} * \omega^{\mu} \tag{4.8}$$

In DTRB, the agent forwarding strategy is greedy, taking the actions with the highest Q-value (practicability of delivery). For instance in Figure 4.1, when node d approaches node x, x is able to compute the new distance to d, and then x advertises better rewards for his other neighbors in its $ControlMessages$, as seen in Algorithm 2. If s has a data message addressed to d then s can compute the reward when replicating the message to x, as seen in Algorithm 3.

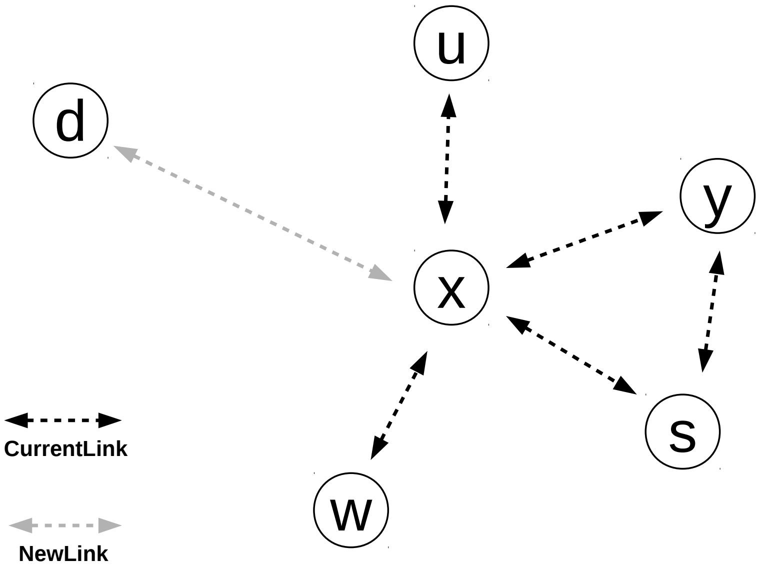

Figure 4.1: Learning through distance as a function of time rewards.

DTRB was compared to PRoPHET, because it is well-known by the research community and can achieve fair delivery rates in heterogeneous network scenarios.

Algorithm 2: New *ControlMessage* on node x.

```
new_ctrl_msg = new $ControlMessage$;
new_ctrl_msg.$addDistanceTable()$;
$x.calculateMF()$;
forall the neighbor $y$ in $N_x$ do
    $x.calculateR(D_{(x,y)})$;
    bestReward = $(R + MF_x(max_{(y \in N_x)} Q_x(d, y)))$;
    new_ctrl_msg.$addBestReward$(bestReward);
new_ctrl_msg.$setTimestamp()$;
$x.sendCtrlMsg$(new_ctrl_msg, $broadcast$);
```

Algorithm 3: *ControlMessage* reception in node s.

```
rcvd_ctrl_msg.$update(D_{(s,x)})$;
rcvd_ctrl_msg.$updateDistanceTable()$;
forall the buffered data msgs do
    if (data_msg.$getDestination()$ == $d$) then
    $Q_s(d, x) \leftarrow (1 - \delta)Q_s(d, x) + \delta*$ rcvd_ctrl_msg.$getBestReward()$;
    $s.sendDataMsg$(data_msg, $x$);
```

PRoPHET reference implementation is maintained by the Internet Research Task Force. Both solutions are flooding-based. While PRoPHET utilizes a rather simple replication/forwarding strategy: when two nodes meet, a data message is replicated to the encountered node, only if the delivery predictability of the destination of the message is higher at the encountered node, DTRB evaluates the distance as a function of time between two nodes to decide whether a message replication is necessary. Consequently, DTRB only replicates a data message to an encountered node, if the encountered node is "closer" to the destination of the message. This idea justifies the lower network overhead reported by DTRB in the next section, because it does not replicate data messages unnecessarily.

4.2 Evaluation

The evaluation was made using the Omnet++ network simulator version 4.1 with the INETMANET framework [Varga and Hornig, 2008]. DTRB and PRoPHET were implemented as network layer modules on the INETMANET. The goal of the simulation is to verify if the evaluated solutions can achieve a reasonable level of delivery rate with a tolerable delay and less overhead on the network.

4.2.1 Setup

The IEEE 802.11 layer in ad-hoc mode was used with a TwoRayGround propagation model on the physical layer. The application layer generates data messages to random destination nodes uniformely distributed between 45 and 90 seconds, after an initial phase of 10 min for proper PRoPHET delivery predictabilities setup. Different transmission ranges were applied in order to simulate sparse (125m, 150m, 175m) and dense networks (200m, 225m, 250m). The simulation data was collected over 60 simulation runs, 10 runs for each network density. All nodes have synchronized clocks [Choi et al., 2012]. Table 4.1 presents a summary of the simulation parameters. The parameters were inspired by the simulation setups observed in the related work, in this case Subsections 2.1.1 and 2.1.2.

Simulation Parameters	
General	
Simulation time	2000s
Data message size	140 bytes
Buffer size	7000 bytes
Playground size	600m x 600m
Propagation model	TwoRayGroundModel[Rappaport, 1996]
Scenario: Random Way Point Mobility RWP	
N^{o}of pedestrian nodes	20
Pedestrian mobility model	Random Way Point
Pedestrian speed (min/max)	1-2 m/s
Pause time	0s
N^{o}of car nodes	5
Car mobility model	Rectangle mobility
Car speed (min/max)	6-11 m/s
N^{o}of POI	5
Scenario: Urban Mobility UDEL	
City	RealisticCitiesV1.2 - Chicago9Blk
N^{o}of pedestrian	20
N^{o}of cars	10
Pedestrian Speed (min/max)	0.7-3 m/s (considering cyclists)
Car Speed (min/max)	6-18 m/s
Fraction where pedestrian appear (Room)	0.5
Fraction where pedestrian appear (Parking lot)	0.5
Fraction of nonworkers	0.5
Traffic Lights	On
DTRB	
$ControlMessage$ period	3 s
Learning rate (δ)	0.85
Practicability ageing (ω)	0.95
k	35 s
PRoPHET	
Init. predictability (P_{init})	0.75
Ageing (γ)	0.7
Predic. scaling factor (β)	0.25
Hello Interval	3s

Table 4.1: Simulation parameters - DTRB.

Recent research in urban wireless networks has demonstrated the lack of accurate results obtained from widely used network simulators when compared to real-life implementations. This lack of accuracy while simulating urban wireless environments can be attributed to the utilization of simple mobility models. UDelModels [Kim et al., 2009] is a suite of tools for simulating urban mesh networks that includes a simulator of realistic urban mobility. The mobility simulator is able to simulate daily life pedestrian dynamics (e.g. arrival times at work, lunch time, breaks) and vehicle traffic dynamics (e.g. traffic lights). DTRB and PRoPHET were executed in two scenarios:

1. Scenario RWP: pedestrian nodes were placed randomly and start moving continuously according to the random way point mobility model without pause time. Car nodes move in rectangular mobility and the points of interests (POI) do not move.
2. Scenario UDEL: using UDelModels the pedestrian nodes interact directly with vehicular nodes in an urban area, simulating a real life environment scenario.

The data message size was set at 140 characters, using the maximum “tweet” message standard [Predd, 2011]. The buffer for each node was set at 7000 bytes (50 data messages).

4.2.2 Results

Each graph contains both network scenarios. Figure 4.2 shows the delivery rate for different transmission ranges (network densities). As expected, in sparse networks with a transmission range of less than 150m, DTRB delivers fewer messages than PRoPHET. Sparse networks lead to longer distances and less knowledge of the network neighbours for DTRB, consequently less rewards R are offered in the network. With increasing density, DTRB achieves on average higher delivery rates than PRoPHET.

Figure 4.3 shows the cumulative distribution functions for end-to-end delay in a dense network of 250m transmission range and Figure 4.4 shows the cumulative distribution functions for end-to-end delay in a sparse network of 125m transmission range. PRoPHET delivers faster than DTRB in both scenarios, although the difference is smaller in denser scenarios.

Table 4.2 shows average end-to-end delay. When the network density is higher (transmission range = 250m), PRoPHET delivers 23 seconds faster than DTRB in

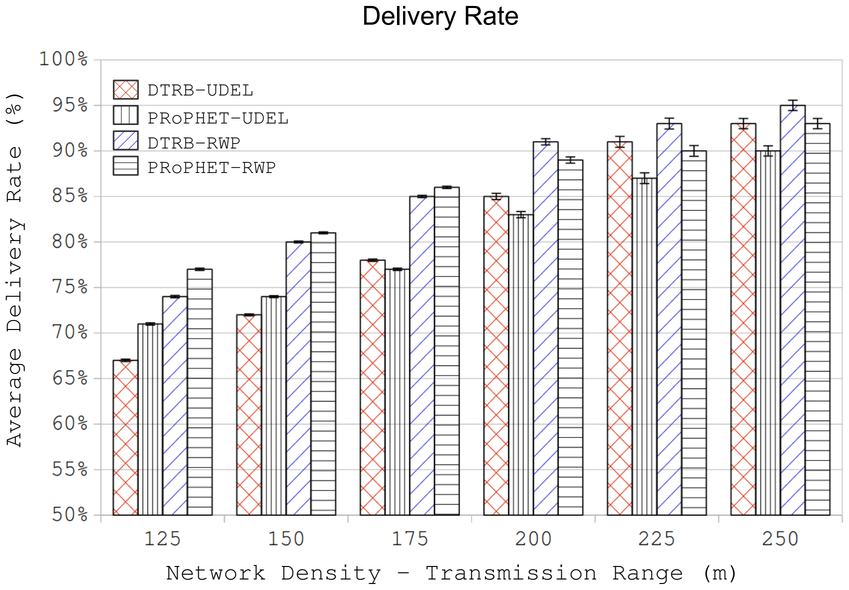

Figure 4.2: Delivery rate with different network densities.

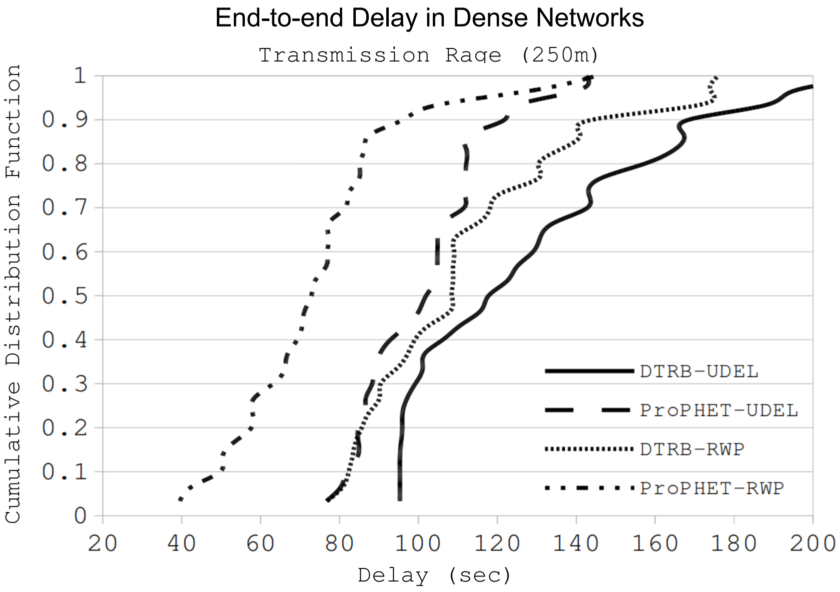

Figure 4.3: End-to-end delay in dense mobile networks.

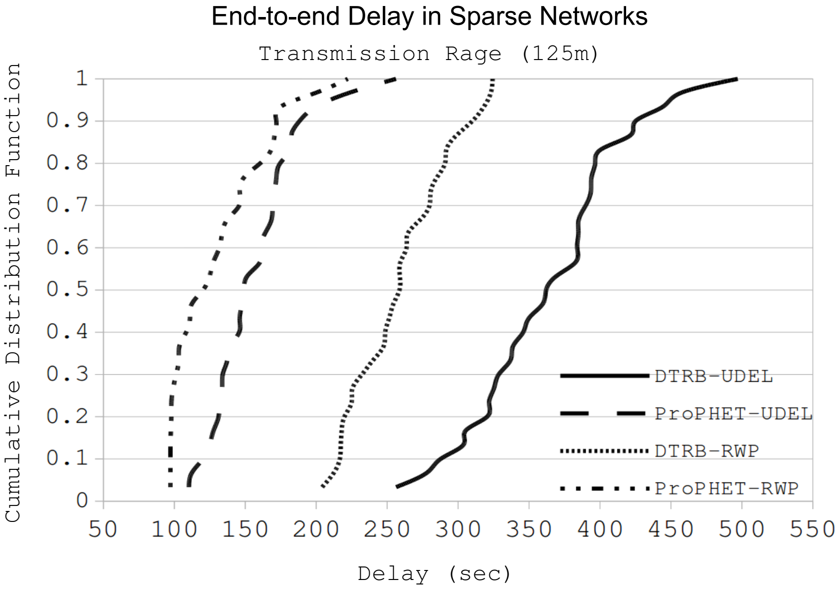

Figure 4.4: End-to-end delay in sparse mobile networks.

the realistic network scenario (UDEL), and in the random way point scenario (RWP) the difference is 33 seconds. When the network density is lower (transmission range = 125m), PRoPHET delivers 167 seconds faster than DTRB in the realistic network scenario and 126 seconds faster in the random way point scenario. An interesting observation about the random way point scenario is that both protocols deliver faster compared to the realistic scenario. Most likely the delay decreases in the random way point scenario because the nodes have a tendency to migrate towards the center [Yoon et al., 2003].

Average End-to-end Delay

	DTRB-UDEL	PRoPHET-UDEL	DTRB-RWP	PRoPHET-RWP
Dense Network (transmission range = 250m)	124s	101s	108s	75s
Sparse Network (transmission range = 125m)	324s	157s	256s	130s

Table 4.2: Average end-to-end delay in sparse and dense networks.

DTRB routing achieves better delivery rates than PRoPHET, with a tolerable average end-to-end delay, which demonstrates the potential of reinforcement learning techniques to solve network routing problems. Since we are referring to UPN, the average 23 seconds end-to-end delay difference is not significant compared to PRoPHET in dense realistic network environments.

In delay tolerant systems, the overhead can be measured by the amount of un-

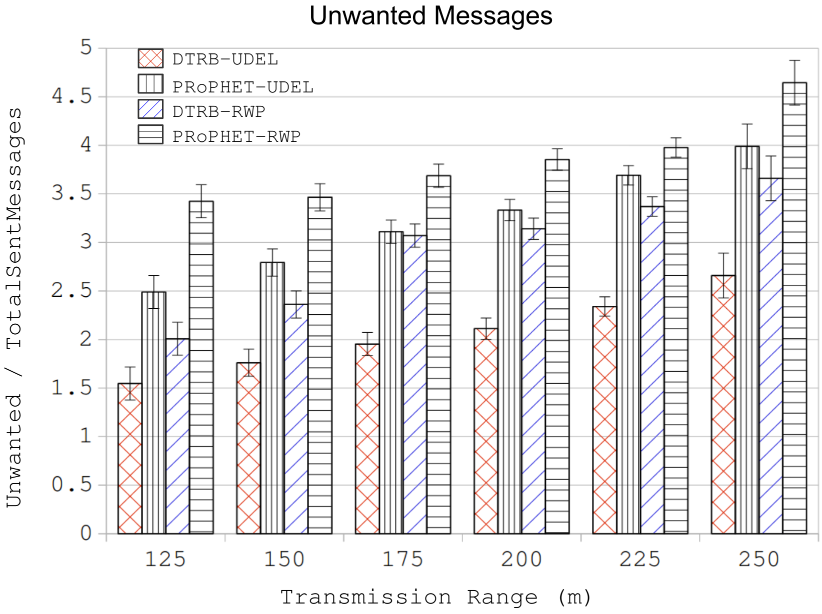

Figure 4.5: Unnecessary replicated messages with different network densities.

necessarily replicated messages, as depicted in Figure 4.5. Unwanted messages were messages that arrived late to the destination plus the messages that were too old to be stored by a custodian node during a contact, due to buffer overload and flooding. Using Multi-Agent Reinforcement Learning, DTRB is able to overload 33% less than PRoPHET in both scenarios yielding more available bandwidth in the network. PRoPHET's faster end-to-end delay is derived from its higher network overhead, i.e., its higher data messages replications.

4.2.3 Notes on k

The exponential decay constant k is the major parameter in the proposed delay tolerant routing solution. In the simulations presented in this work $k = 35$ seconds. The parameter controls the number of replications on the system. Future works suggest further studies on the k parameter, although some insights are given here. When k increases, DTRB replicates more data messages. Consequently, the end-to-end delay decreases, the network overhead increases, and the delivery rate increases. From a certain point, DTRB behaves like PRoPHET in terms of end-to-end delay and the network overhead. When k decreases, DTRB replicates fewer data messages. Consequently, the end-to-end delay increases, the network overhead decreases and the delivery rate decreases. From a certain point, DTRB becomes unable to deliver data messages.

4.2.4 DTRB and IWR

In this subsection, the IWR protocol (presented in Chapter 3) is employed in conjunction with DTRB. The goal is to assess the idea of using the Internet as a backbone and to evaluate how it contributes to the overall system performance. Thus, five home wireless routers (which employ IWR) were strategically positioned in the UDEL scenario to enhance the delivery rate.

Figure 4.6 shows the improvement on delivey rates when DTRB is employed with IWR. The combined approach is on average 3% better than DTRB alone. IWR enables DTRB to deliver 5% more messages in the sparse scenario (125m) and 2% more messages in the dense scenario (250m).

Figure 4.7 shows the improvement on end-to-end delay when DTRB is employed with IWR. While the first and the last messages are delivered within 70 and 120 seconds in the combined approach, DTRB alone delivers the first and last messages within 95 and 200 seconds. IWR enables DTRB to start delivering the fisrt messages on average 25 seconds before DTRB alone. Since DTRB is flooding-based, there was no difference on the observed network overhead when comparing DTRB + IWR and DTRB employed alone.

4.3 Summary

UPN are networks which lack continuous end-to-end connectivity enabling data message exchange between mobile devices without the support of any pre-existing network infrastructure. Multi-Agent Reinforcement Learning can solve and control distributed problems using autonomous agents with limited prior knowledge to learn solutions to complex network systems. Delay Tolerant Reinforcement-Based [Rolla and Curado, 2013b] routing utilizes Multi-Agent Reinforcement Learning techniques to predict the practicability of data message delivery. In the DTRB system, rewards are determined using a distance-table algorithm which calculates the distance between nodes as a function of time from the last encounter. The nodes that recently exchanged *gossip* about the destination of a given data message are more likely to deliver the message and consequently receive better reinforcement learning rewards.

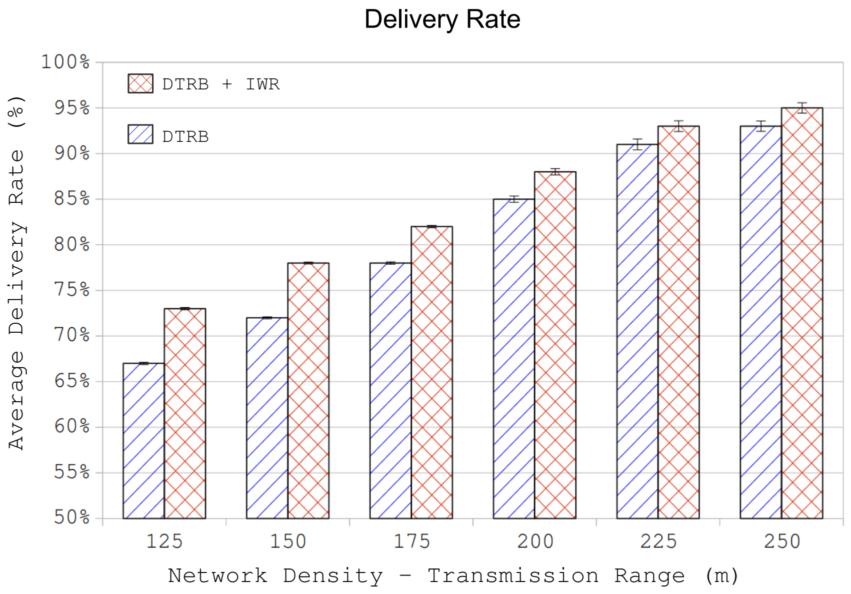

Figure 4.6: Delivery rates (DTRB vs. DTRB + IWR).

Routing solutions that produce low overhead are extremely important because they contribute to the overall available bandwidth and overall energy output. Both are important resources for pedestrian nodes in UPN.

Simulations were performed using a "tweet" sized data message on realistic urban mobility models which imitate daily life pedestrian and vehicular dynamic patterns. Results show that DTRB can deliver on average more messages than PRoPHET, in densely populated areas within a similar end-to-end delay. In both scenarios, (UDEL and RWP), DTRB is able to overload 33% less than PRoPHET, resulting in more available bandwidth, more available overall buffer, and theoretically less overall energy output. IWR enables DTRB start to deliver the first messages earlier then DTRB employed alone.

This work utilizes three novel concepts: i) the distance-table algorithm to calculate the distance as a function of time between nodes, ii) the Multi-Agent Reinforcement Learning algorithm based on Q-Learning, including the exponential decay reward calculation, and iii) the use of realistic daily pattern simulation results in urban scenarios.

Artificial Intelligence techniques such as MARL have the potential to solve wireless routing issues in UPN. DTRB "thinks" based upon a reward learning process before replicating a message and because of this "thinking" it causes less network

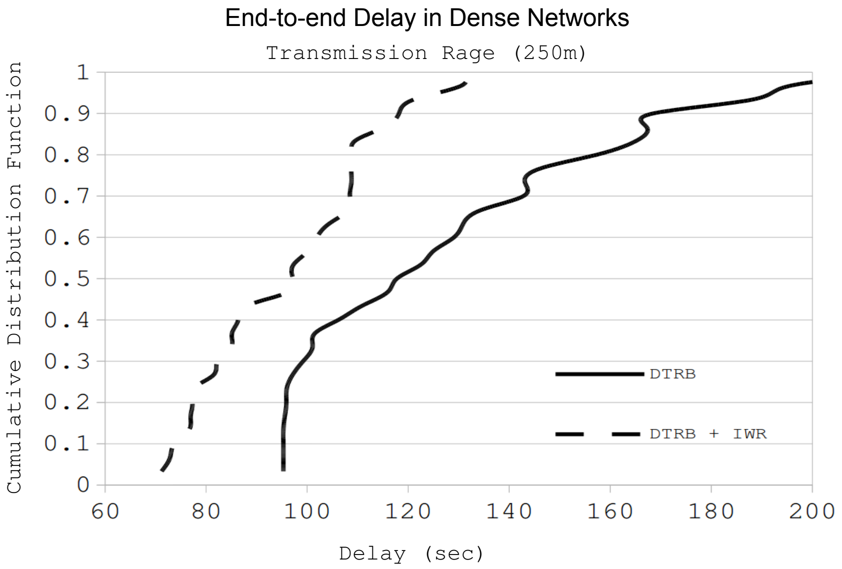

Figure 4.7: End-to-end delay (DTRB vs. DTRB + IWR).

overhead. The proposed DTRB routing approach has been designed for urban areas with very dense environments and targets users of mobile devices. Artificial Intelligence solutions such as DTRB could contribute to a new paradigm in network routing solutions which think before they react.

Chapter 5

Messages on oFfer?

This chapter presents a credit-based incentive mechanism for UPN which enables device to device data exchange without the support of traditional ISP. Incentive mechanisms increase the likelihood of a user to share his resources (opportunistic connectivity, storage capabilities, and energy resources) to help another user [Mota et al., 2014]. The solution uses a utility function that represents the monetary value of a given data message during its journey in the network, and a buffer management optimization algorithm to prevent selfish behaviour among nodes. Virtual banking relies on an off-line central trusted authority. The chapter introduces the concept of isotropic deliveries in UPN which uses Binary Spray and Wait (BSW) forwarding strategy. Simulations with the IEEE 802.15.4 standard show the proposed incentive mechanism preventing selfish behaviour and guaranteeing more extra credits to the end-user.

MooF (Messages on oFfer) [Rolla and Curado, 2014] differs from the solutions presented in Chapter 2, Section 2.2 in three main aspects. First, it considers a two-hop credit model (only the intermediate node gets credit when delivering a message). Second, MooF is built upon a very specific feature observed during the spray phase of the binary spray and wait delay tolerant routing solution. This feature is called isotropic delivery. Third, MooF is the first incentive mechanism based on buffer management.

This chapter presents a credit-based incentive mechanism called MooF (Messages on oFfer). Section 5.1 describes the BSW forwarding strategy implementation and the delay tolerant routing solution utilized in this chapter. Section 5.2 presents the interaction between the user's device and the off-line central trusted authority. Section 5.3 explains the concept of isotropic deliveries. Section 5.4 introduces MooF.

Section 5.5 describes the simulation and shows the results. Section 5.6 summarizes the chapter.

5.1 Delay Tolerant Routing

The delay tolerant routing solution utilized in this chapter is BSW [Spyropoulos et al., 2005]. BSW is part of the spray and wait family. The protocol restricts the number of message copies in the UPN, improving network resource efficiency. Each message created in the system has a maximum replication number c attached to it. The number c represents the upper bound number of replicas of the same message in the network. Any node with $c > 1$ message copies, forwards $c/2$ and keeps $c/2$ copies when in contact with another node without a copy (*spray* phase). When a node has only one copy of the message, it switches to direct transmission, i.e., the node will store the message with hope to meet its destination (*wait* phase). BSW is a multi-copy quota-based delay tolerant routing solution, thus replications of the same data message occur in the UPN.

Figure 5.1 presents the basic network layer protocol utilized in this chapter. This protocol works as a network layer module in the Omnet++ simulator [Varga and Hornig, 2008]. It is the base to support the BSW forwarding strategy and the buffer management implementations. According to Figure 5.1, when two nodes are within each others transmission ranges they are able to exchange control messages. The control messages are periodically broadcast and contain a list with the data messages that the source node is willing to replicate, i.e. $c > 1$. As soon as a node receives a control message, the data delivery process starts and the data messages delivery happens. When the data delivery process is over, a node sends a replication request message that contains a list with the data messages that should replicate. As soon as a node receives a data replication request message, the data replication process starts. The node sets $c/2$ in its own copy of the data message and replicates a copy with $c/2$.

5.2 Off-line Central Trusted Authority

Whenever a source node creates a message, it reserves the monetary value for future payment to the virtual bank the next time it comes in contact with the central

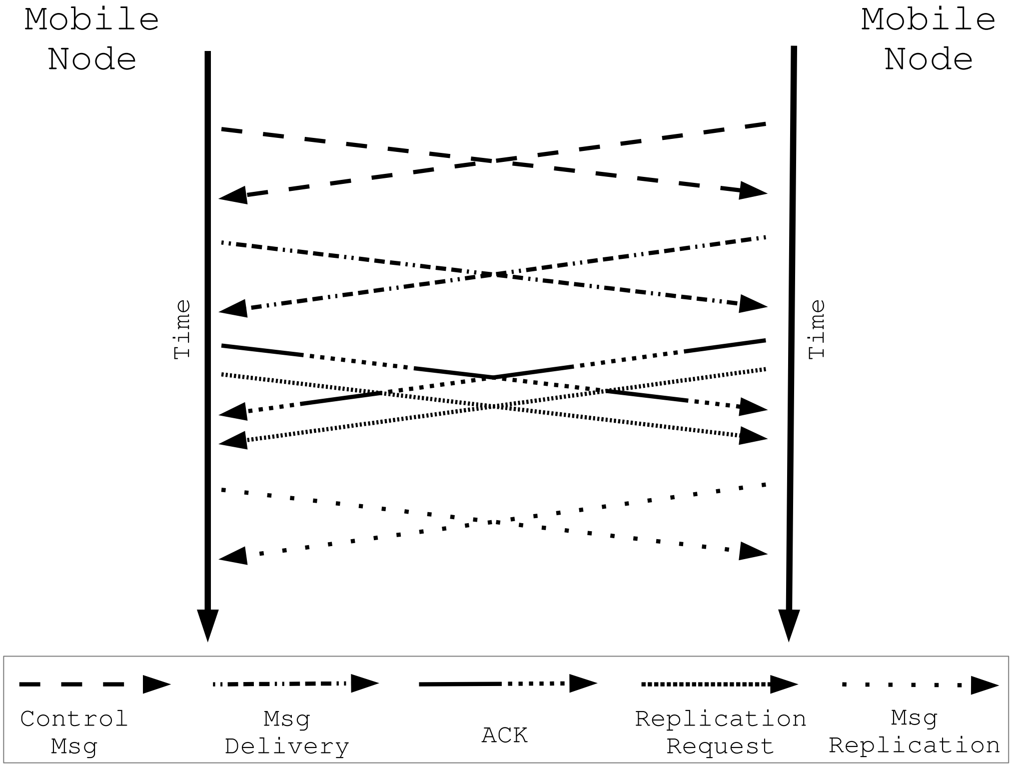

Figure 5.1: An encounter between two mobile nodes.

authority. For security reasons, a tamper proof hardware device to avoid fraudulent activity stores this reserved monetary value. The source node also attaches a number c of message copies to each forwarded copy so the intermediate nodes can calculate the monetary value of each message. When an intermediate node delivers a message to a destination, it receives an acknowledgement (ACK) as a delivery certificate. The next time the intermediate node is in contact with the central authority it receives the monetary value credit when presenting the ACK. This work is only interested in the extra credits that a user can earn from delivering data messages. Thus, it is assumed that users can buy the necessary credits from the virtual bank to send their own data messages.

5.3 Isotropic Delivery

Multi-copy delay tolerant routing solutions, such as BSW, replicate a message with hope that one of this replicas shall meet the destination. An isotropic delivery happens in the UPN when the isotropic node delivers a message to its destination, before any other copy of the same message has been delivered. The isotropic node has the only replica of the message that has traveled the maximum number of hops.

In a delay tolerant network, which uses a binary spray and wait forwarding strategy along with a limited buffer, an isotropic delivery occurs using the maximum number of hops, i.e., within longest paths. The following theorem states that for each message sent in a delay tolerant network which uses BSW forwarding strategy and a limited buffer, only one isotropic node exists. To observe a data message delivery by an isotropic node, the following conditions must arise. First, the data message's end-to-end delay must be greater than the total replication delay time (time it takes to replicate the maximum number of hops). Second, the data message's end-to-end delay must be shorter than the time-to-live in the isotropic node buffer.

Theorem 5.3.1. *In a delay tolerant network which uses BSW forwarding strategy and limited buffer, an isotropic delivery occurs, if and only if, the end-to-end delivery delay is longer than the replication time to the isotropic node and shorter than the elimination time from the isotropic node buffer.*

Proof. Consider a node "active" when it has more than one copy of a data message. Consider, also, a spray and wait algorithm in terms of a function $f : c \to c$ as follows: when an active node with c data message copies encounters another node, it hands over to the encountered node $f(c)/2$ copies, and keeps the remaining $f(c)/2$ copies. The following binary tree represents the algorithm: assign the root a value of c; if the current node has a value $c > 1$ create a right child with a value of $f(c)/2$ and a left one with a value of $f(c)/2$; continue until all leaf nodes have a value of 1. A complete spraying corresponds to a data message being replicated to all nodes of the tree before any copy has been delivered to the destination. Since the total number of tree nodes is $log(c)$, it is easy to see from the tree structure that there is only one isotropic node, and this node is the last descendent from the first source node replication. The isotropic node has a replica of a data message that has the maximum number of hops. Therefore, to observe an isotropic delivery, the message must stay in the isotropic node buffer until it encounters the destination of the message.

□

Figure 5.2 shows the binary spray and wait algorithm replication and the isotropic node. The numbers in the figure illustrate the replication process. All nodes in the

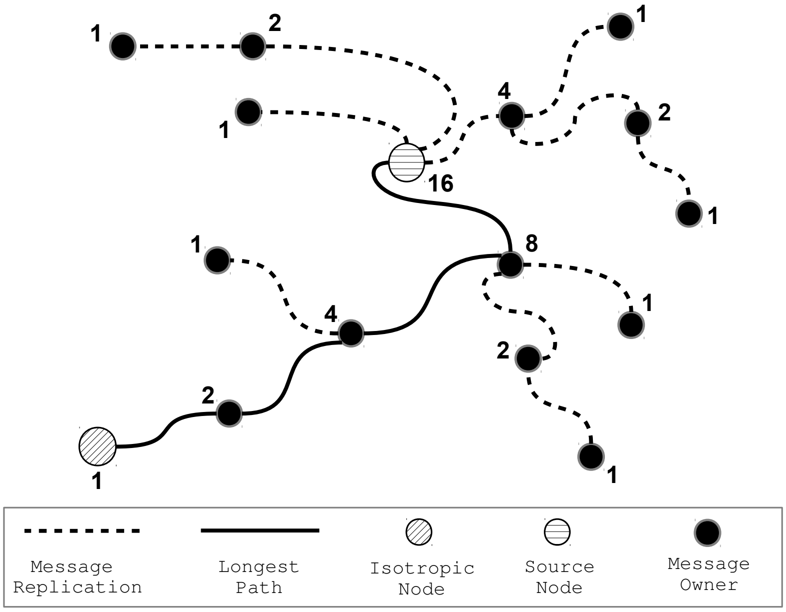

Figure 5.2: Binary spray and wait algorithm and the isotropic node ($c = 16$).

figure have a copy of the same message. Such message was sent by the source node using $c = 16$. When a data message is first delivered to the destination by the isotropic node, a delay tolerant network which uses BSW forwarding strategy is isotropic. Which means that a data message had time to replicate totally, and stayed in the isotropic node buffer until its delivery to the destination, and before any other copy of the same message has been delivered. Thus, in UPN where isotropic deliveries happen, there is a tendency for higher end-to-end delays. The probability of observing a data message being delivered by the isotropic node is $1/c$. The maximum number of hops depends on c, and can be easily computed using: $log(c) + 1$.

Figure 5.3 shows the isotropic delivery observation in a $c = 16$ network simulation. In this preliminary simulation, 100 nodes generate new messages to random destinations with an interval departure time of 30 to 180 seconds uniformly distributed. BSW is the forwarding strategy, and no incentive mechanism is employed. Each point in the figure represents a message delivered to its destination during the simulation, and the number of hops used to deliver such message. It is easy to see that the minority of the deliveries occurred within maximum number of hops. This figure shows that isotropic deliveries occur rarely when compared to non-isotropic deliveries. All network simulations in this chapter had isotropic deliveries. The isotropic delivery observation is this chapter's first contribution.

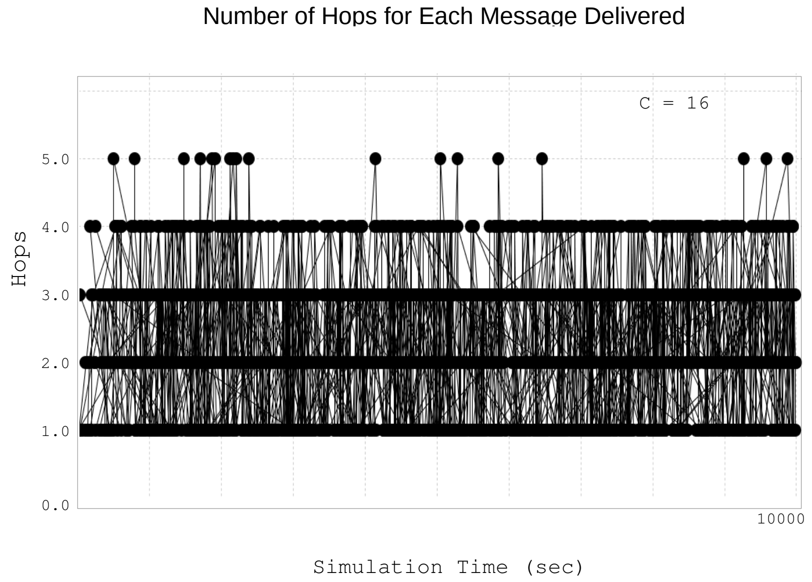

Figure 5.3: Number of hops ($c = 16$).

5.4 An Incentive Mechanism for UPN

The proposed credit-based incentive mechanism for UPN uses an off-line central trusted authority for virtual banking, and a two-hop credit model: the node which forwards (delivers) the first copy of a data message to the destination receives credits when in contact with the virtual bank.

The proposed credit-based incentive mechanism guarantees that each node has (is carrying) a buffer that has the largest monetary value. In Subsection 5.4.1, the utility function represents how much the delivery of a specific message is worth (monetary value) in a given time in the UPN. Subsection 5.4.2 describes the credit-based incentive mechanism as a buffer management optimization problem.

5.4.1 The Utility Function

Multi-copy delay tolerant routing solutions replicate a message with hope that one of this replicas shall meet the destination. BSW is a multi-copy quota-based routing solution. The protocol can be configured to restrict the number of message replicas, improving network resource efficiency. Consequently, the monetary value of a data message in the network can be given according to the following ideas:

(i) - The more copies of a data message a source node sprays into the network, the greater the overall network resources utilization: storage capacity, energy consumption, and overhead. Thus, the more copies of the message, the lower the value of the message in the system, i.e., the intermediate node shall receive less credits (monetary value) for delivering messages with a high number of copies.

(ii) - The delivery of a message in the must also be related to its end-to-end delay. The faster the intermediate node delivers the message, the greater the monetary value of the message. Thus, the monetary value must decay with time [Xiao et al., 2013].

The monetary value represents how much the delivery of a specific message is worth in a given time in the UPN. The monetary value can be characterized by the following utility function (5.1):

$$f(x) = \frac{x \cdot exp^{-\lambda t}}{log_2(c)} \tag{5.1}$$

where, x is the value charged by the system for each data message sent, c is the total number of copies of the same message allowed in the system, t is the delay, and λ is the exponential decay constant.

In the simulations presented in this work, x is equal to 1 (e.g. *dollar* or *euro*). The equation (5.1) represents the monetary value of a given data message during its journey in the network. Therefore, at the time of a $c = 4$ message creation, $f(x) = 0.5$. When the message delivery occurs (for the first time) to the destination, the node issues an ACK containing the credit that the intermediate node shall receive when in contact with the off-line central trusted authority. Such credit is calculated using equation (5.1). The exponential decay constant λ is the only parameter in this proposed credit-based incentive mechanism for UPN. Some insights on its behaviour will be given in Subsection 5.5.3.

5.4.2 Optimization Problem

The credit-based incentive mechanism is buffer management based. MooF objective is to guarantee that each node is carrying the maximum monetary value given all its encounters and data messages exchanges (replications). When two nodes are within each other's transmission ranges, they will exchange the data messages that maximize their total buffer monetary value, according to:

$$\max \quad \sum_{m \in (M \cup O)} f(x) \tag{5.2}$$

$$\text{s.t.}$$

$$b \geq \sum m_p \tag{5.3}$$

$$x \geq 0 \tag{5.4}$$

where, M is the set of messages already in the buffer, O is the set of messages offered by the encountered node, b is the size of the buffer, and m_p is the message payload. MooF's worst-case complexity is $|M|^2$, because two nodes can meet and have no data messages in common and these messages could have all $c > 1$ copies. Consequently, all the messages already in one buffer may replicate to the other node's buffer.

The following two user behaviours characterize selfishness: i) the number c of data message copies that a user wants to replicate in the network; and, ii) the amount of buffer that a user is willing to share to carry (store) other users data messages. Respectively, the greater c is, the more selfish a user is. The less storage capacity offered by a user, the more selfish a user is.

Figure 5.4 shows a preliminary result in a 100 node UPN, considering 20400 bytes of storage capacity[2] shared by all users participating in the network to carry other users data messages cooperatively. This work considers selfishness as the number c of data messages a user wants to replicate in the network to guarantee delivery. Selfish users utilize $c = 16$ and unselfish users utilize $c = 8$. The selfishness rate[3] for this simulation was 50%. It is clear that the users store more unselfish data messages when using the MooF buffer mechanism.

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[2] Storage capacity = 100 data messages of 140 characters (a *tweet* [Predd, 2011]) plus 64 bits for source and destination addresses.

[3] Selfishness rate = $(NumberOfSelfishNodes/NumberOfTotalNodes)$.

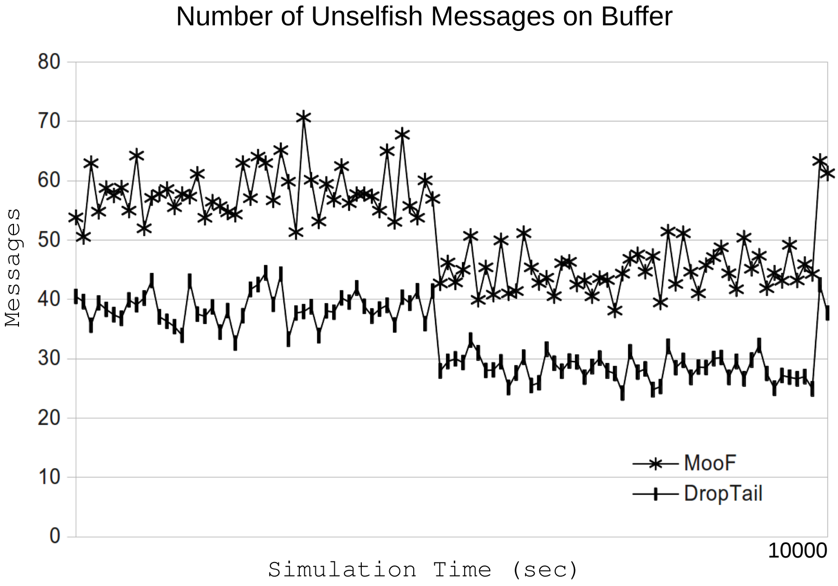

Figure 5.4: MooF in action.

5.5 Simulation Setup and Results

The Omnet++ network simulator version 4.1 with the INETMANET version 2.0 framework [Varga and Hornig, 2008] were used in conjunction with the IEEE 802.15.4 [Karapistoli et al., 2010] standard link layer in ad hoc mode. The IEEE 802.15.4 standard is a low-cost, low-rate, ubiquitous communication designed for wireless personal area networks and pocket switched networks. The application layer on mobile devices generates data messages to random destinations, with an interval departure time of 30 to 180 seconds uniformly distributed. The remainder of this section presents: simulation setup (Subsection 5.5.1), results (Subsection 5.5.2), and notes on the λ parameter (Subsection 5.5.3).

Simulation results evaluate MooF and two other traditional and widely used buffer management schemes: DropTail and DropOldest. When using DropTail a node only requests data message replications when the buffer is not full. If the buffer gets full, the node will have to deliver a data message before it requests new data replications. When using DropOldest, a node discards the oldest message in the buffer and keeps requesting data message replications.

5.5.1 Setup

A realistic urban mobility simulator [Kim et al., 2009] and real mobility traces [Lee et al., 2012] were utilized in the simulations. The results using the synthetic mobility model are identified as UDEL. Such mobility model emulates 100 pedestrian nodes interacting directly with vehicular nodes. The mobility simulator mimics daily life pedestrian dynamics (e.g. arrival times at work, lunch time, breaks) and vehicle traffic dynamics (e.g. traffic lights). The results using the real mobility traces are identified as REAL. Such mobility traces were taken by 32 students who lived in the Korea Advanced Institute of Science and Technology (KAIST) campus.

The Nakagami-m [Kuntz et al., 2008] propagation simulates the physical layer. The IEEE 802.15.4 transmission range is $75m$. All nodes have synchronized clocks [Choi and Shen, 2010]. The data collection is over 40 simulation runs for each scenario. The simulation scenarios have different selfishness rates: less selfish nodes (scenario-1 = 25%), half-split nodes (scenario-2 = 50%) and, more selfish nodes (scenario-3 = 75%) on the UPN. Consequently, 120 simulation runs were executed with the UDEL mobility model, and 120 simulation runs were executed with the REAL mobility traces. Each run had a simulation time of 10000 seconds. In all three scenarios an isotropic delivery occurred. The other parameters used in the simulations are given in Table 5.1. The parameters were inspired by the simulation setups observed in the related work, in this case Subsection 2.2.3.

5.5.2 Results

The presentation of results appears in the following order: i) delivery rates and isotropic deliveries, ii) delays and credits, iii) network overhead, and iv) MooF + IWR.

Delivery Rates and Isotropic Deliveries

The total data message delivery average for the UDEL setup was 85%, considering all 120 simulation runs. The total data message delivery average considering independent scenarios was: 87% in scenario-1, 85% in scenario-2, and 83% in scenario-3. The total data message delivery average for the REAL setup was 76%, considering

Simulation Parameters	
General	
Simulation time	10000 sec
Selfish nodes	$c = 16$
Unselfish nodes	$c = 8$
Data message size	140 bytes
Buffer size	14800 bytes
Nakagami-m Propagation model	m = 1
IEEE 802.15.4 transmission range	$75m$
MooF λ parameter	$\lambda = 2.5 * 10^{-4}$
Scenario - 1	
Sefishness rate	25%
Scenario - 2	
Sefishness rate	50%
Scenario - 3	
Sefishness rate	75%
Urban Mobility Model Parameters (UDEL)	
N°of pedestrian	100
Playground size	$400000m^2$
City	RealisticCitiesV1.2 - Chicago
Pedestrian Speed (min/max)	0.7-3 m/s (considering cyclists)
Car Speed (min/max)	6-18 m/s
Fraction where pedestrian appear (Room)	0.5
Fraction where pedestrian appear (Parking lot)	0.5
Fraction of nonworkers	0.5
Traffic Lights	On
Real Mobility Traces (REAL)	
N°of pedestrian	32
Playground size	413346 m^2

Table 5.1: Simulation parameters.

all 120 simulation runs. The total data message delivery average considering independent scenarios was: 77% in scenario-1, 76% in scenario-2, and 75% in scenario-3. The system delivered more messages when the selfishness rate was lower. The 9% total difference between UDEL and REAL is due to the number of nodes and the playground size utilized within each mobility setup, as UDEL is denser than REAL.

Figure 5.5 presents selfish and unselfish data message delivery rates for the three buffer management solutions: MooF, DropTail and DropOldest. In all three scenarios, it is clear that MooF is the only solution preventing selfish behaviour. MooF is able to overcome the selfish epidemy, when the system becomes flooded by selfish data messages (scenario-3), and delivers more unselfish data messages. DropTail and DropOldest do not differentiate between unselfish and selfish data messages. Nevertheless, in general, DropOldest is more in favour of selfish data messages than DropTail. Figure 5.6 presents the percentage of selfish and unselfish isotropic deliveries. MooF guarantees more unselfish isotropic deliveries in all scenarios and in both mobility setups when compared to DropTail and DropOldest.

Figure 5.5: Delivery rates - Unselfish vs. Selfish data messages.

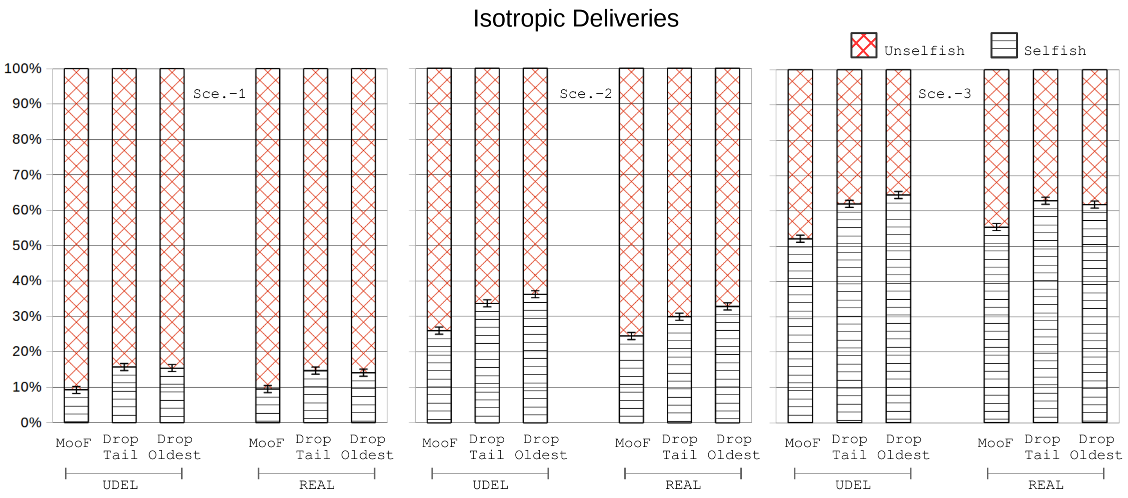

Figure 5.6: Isotropic Deliveries - Unselfish vs. Selfish data messages.

Delays and Credits

In UPN which uses BSW forwarding strategy, unselfish data messages will always have higher end-to-end delays than selfish data messages on average, because the first replicates fewer messages in the network. Table 5.2 presents the average end-to-end delay observed in each scenario. As expected, DropOldest always has lower delays. In all scenarios, MooF presents a larger variance between selfish and unselfish data messages when compared to the other two buffer management schemes. Another two important observations are: MooF presents lower end-to-end delay on average than DropTail in scenario-1, and DropOldest can deliver on average only 3 minutes and 12 seconds faster than MooF when considering the selfish and flooded scenario-3.

Average End-to-end Delay			
Scenario - 1	**Selfish**	**Unselfish**	**Average**
MooF - UDEL	445 *sec*	832 *sec*	638 *sec*
DropTail - UDEL	654 *sec*	697 *sec*	675 *sec*
DropOldest - UDEL	572 *sec*	625 *sec*	598 *sec*
MooF - REAL	527 *sec*	793 *sec*	660 *sec*
DropTail - REAL	670 *sec*	714 *sec*	692 *sec*
DropOldest - REAL	615 *sec*	642 *sec*	628 *sec*
Scenario - 2	**Selfish**	**Unselfish**	**Average**
MooF - UDEL	487 *sec*	844 *sec*	665 *sec*
DropTail - UDEL	612 *sec*	641 *sec*	626 *sec*
DropOldest - UDEL	535 *sec*	567 *sec*	551 *sec*
MooF - REAL	583 *sec*	821 *sec*	702 *sec*
DropTail - REAL	677 *sec*	724 *sec*	700 *sec*
DropOldest - REAL	550 *sec*	621 *sec*	585 *sec*
Scenario - 3	**Selfish**	**Unselfish**	**Average**
MooF - UDEL	521 *sec*	890 *sec*	705 *sec*
DropTail - UDEL	569 *sec*	604 *sec*	586 *sec*
DropOldest - UDEL	503 *sec*	524 *sec*	513 *sec*
MooF - REAL	591 *sec*	829 *sec*	710 *sec*
DropTail - REAL	647 *sec*	656 *sec*	652 *sec*
DropOldest - REAL	539 *sec*	569 *sec*	554 *sec*

Table 5.2: Average end-to-end delay with different selfishness rates.

Figure 5.7 presents the end-to-end delay as a cumulative distribution function. The charts in the top row show the selfish data messages end-to-end delay for the three proposed scenarios. In scenario-1, MooF only delivers the selfish data messages that had low end-to-end delay, avoiding the occurrence of selfish isotropic deliveries and enabling the occurrence of unselfish isotropic deliveries. However, when the number of selfish data messages increases (scenario-2 and scenario-3), MooF's selfish data messages end-to-end delay approximates to DropTail and DropOldest due to the flooding of selfish data messages. To guarantee the highly unselfish delivery rates and to avoid the flooding of selfish data message replications, MooF keeps unselfish data messages in the buffer longer. The charts in the bottom row of Figure 5.7 show the unselfish data messages end-to-end delay for the three proposed scenarios. Unselfish data messages will always have higher end-to-end delays than selfish data messages on average, because the first replicates fewer messages in the network.

When a user shares a buffer with other users, the data messages will eventually be delivered regardless of the used buffer management scheme, and users will consequently earn extra credit in all scenarios. But, MooF can achieve better results (delivering messages with a higher extra credit value when compared to the other two solutions) and this difference will consequently justify its implementation, compensating for MooF's demands for more energy resources (in the network layer) to process the optimization problem described in Subsection 5.4.2.

Table 5.3 presents average extra credits received for data messages delivery dur-

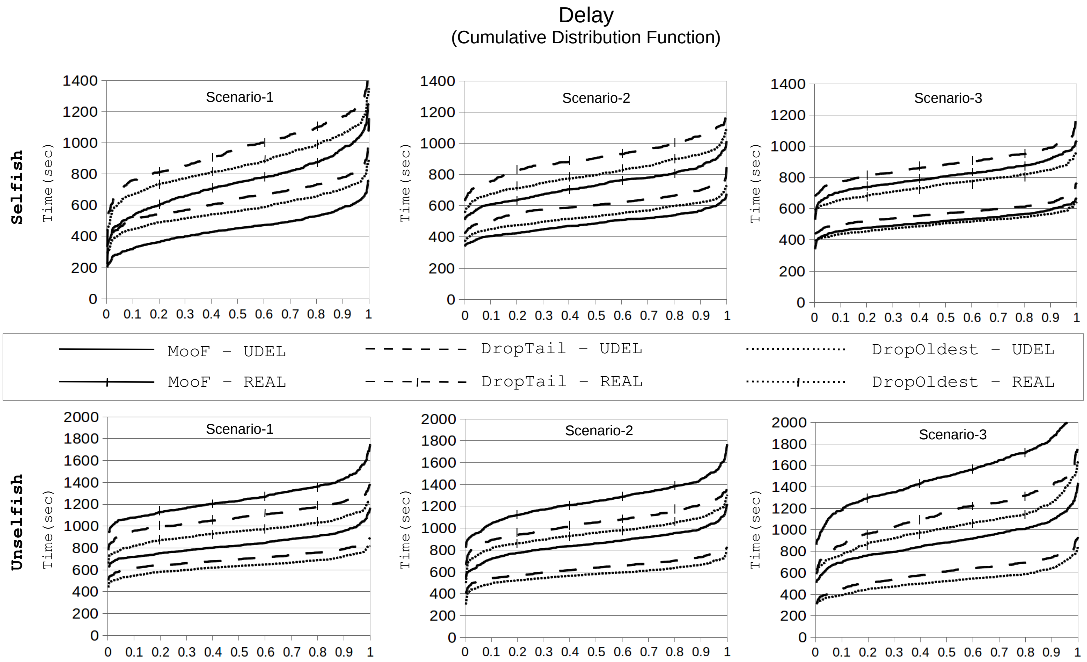

Figure 5.7: Delay as a cumulative distribution function.

ing 10000 seconds of simulation time for each evaluated scenario. MooF guarantees more extra credits on average in all scenarios. MooF is able to keep on the buffer the unselfish data messages for future delivery, while continuing to make extra credits from selfish data messages delivery. The ≈ 1.75 *dollars* or *euros* difference observed between scenarios within the UDEL mobility setup is due to total delivery rates (87% in scenario-1, 85% in scenario-2, and 83% in scenario-3). The ≈ 1.59 *dollars* or *euros* difference observed between scenarios within the REAL mobility setup is due to total delivery rates (77% in scenario-1, 76% in scenario-2, and 75% in scenario-3).

Network Overhead

The overhead can be measured by the amount of unnecessarily replicated and deleted messages. Such messages arrived late to the destination, or they were simply discarded from the buffer due to buffer overflow.

Table 5.4 shows the results on consumed battery in the physical and link layers, the number of data message replications and the number of data message deletions. The Omnet++ network simulator has a module for battery consumption measurement in the physical and link layers. In all scenarios, it is clear that MooF replicates

Average Extra Credits - (*dollars* or *euros*)	
Scenario - 1	**Credits**
MooF - UDEL	19.61
DropTail - UDEL	19.28
DropOldest - UDEL	19.38
MooF - REAL	18.94
DropTail - REAL	18.57
DropOldest - REAL	18.73
Scenario - 2	**Credits**
MooF - UDEL	17.67
DropTail - UDEL	17.25
DropOldest - UDEL	17.59
MooF - REAL	17.66
DropTail - REAL	16.82
DropOldest - REAL	17.62
Scenario - 3	**Credits**
MooF - UDEL	15.98
DropTail - UDEL	15.85
DropOldest - UDEL	15.94
MooF - REAL	15.61
DropTail - REAL	15.50
DropOldest - REAL	15.54

Table 5.3: Extra credits.

fewer messages, and consequently deletes fewer messages. Therefore MooF spends less individual and overall energy resources in the physical and link layers when compared to DropTail and DropOldest.

5.5.3 Notes on λ

The exponential decay constant λ is the only parameter in the proposed credit-based incentive mechanism for UPN. In the simulations presented in this work $\lambda = 2.5 * 10^{-4}$. According to equation (5.1), a given data message stored in a node's buffer that has an age of 600 seconds still has 86% from its original monetary value. That is why MooF can keep unselfish data messages for future delivery, while continuing to make extra credits delivering selfish data messages.

Future works suggests further studies on the λ parameter, although some insights are given here. When λ increases, MooF delivery rates approximate to DropTail and DropOldest, and the average received extra credit decreases equally in all solutions. When λ decreases, an accumulation of unselfish data messages in the buffer occurs, and results in highly unselfish delivery rates, and extremely low selfish delivery rates. From a certain point, MooF stops to deliver selfish data messages, consequently it receives less extra credits.

Results - Battery, Replication and Deletion			
Scenario - 1 (UDEL)	**MooF**	**DropTail**	**DropOldest**
Average consumed battery (mW)	206554	218917	218711
Average n^{o}of data messages replication	785	805	827
Average n^{o}of data messages deleted from buffer	360	394	401
Scenario - 1 (REAL)	**MooF**	**DropTail**	**DropOldest**
Average consumed battery (mW)	106999	110892	115983
Average n^{o}of data messages replication	722	744	791
Average n^{o}of data messages deleted from buffer	307	337	387
Scenario - 2 (UDEL)	**MooF**	**DropTail**	**DropOldest**
Average consumed battery (mW)	207727	225583	225387
Average n^{o}of data messages replication	947	953	983
Average n^{o}of data messages deleted from buffer	500	516	529
Scenario - 2 (REAL)	**MooF**	**DropTail**	**DropOldest**
Average consumed battery (mW)	108069	117434	109080
Average n^{o}of data messages replication	854	873	925
Average n^{o}of data messages deleted from buffer	403	455	478
Scenario - 3 (UDEL)	**MooF**	**DropTail**	**DropOldest**
Average consumed battery (mW)	211140	230356	229194
Average n^{o}of data messages replication	1101	1110	1140
Average n^{o}of data messages deleted from buffer	638	637	653
Scenario - 3 (REAL)	**MooF**	**DropTail**	**DropOldest**
Average consumed battery (mW)	110205	113183	114441
Average n^{o}of data messages replication	988	1024	1066
Average n^{o}of data messages deleted from buffer	511	571	586

Table 5.4: Results on consumed battery in the physical and link layers, number of data message replication and deletion.

5.5.4 MooF and IWR

In this subsection, the IWR protocol (presented in Chapter 3) is employed in conjunction with MooF. The goal is to assess the idea of using the Internet as a backbone and to evaluate how it contributes in overall system performance. Thus, ten home wireless routers (which employ IWR) were strategically positioned to maximize the delivery rate within scenario-2 (Selfishness rate = 50%). REAL was the mobility model chosen for this simulations. Only the unselfish messages were plotted. The combined approach (MooF + IWR) delivers on average 8% more messages than MooF alone.

Figure 5.8 shows the improvement on end-to-end delay when MooF is employed with IWR. Despite the fact that the combined approach delivers 8% more messages than MooF alone, the end-to-end delay was just slightly better. The low improvement observed in the end-to-end delay compared to the improvement observed when employing DTRB and IWR (Subsection 4.2.4) is explained by the fact that the playground area is much larger in the simulations performed in this chapter. Please, refer to Table 4.1 in Chapter 4 and Table 5.1 in Chapter 5. No network overhead improvement was observed when comparing MooF + IWR and MooF employed alone, because the routing strategy is the same. Please refer to Chapter 3, where different routing strategies are compared.

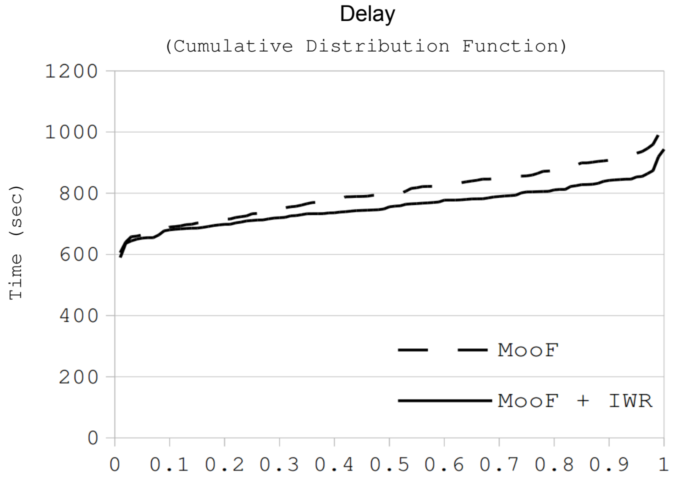

Figure 5.8: Delay (MooF vs. MooF + IWR)

5.6 Summary

This chapter proposes a credit-based incentive mechanism for UPN based on the optimization problem of maximizing the worth of a node's buffer during a meeting between two nodes. The proposed credit-based incentive mechanism considers a two-hop credit model and an off-line central trusted authority for virtual banking, only the intermediate node gets credit when delivering a data message. The mechanism guarantees that nodes are carrying (store) a buffer that has the largest monetary value. MooF [Rolla and Curado, 2014] is able to prevent selfish behaviour and guarantees high extra credits to the end-user.

This work introduces two new concepts to the computer networks field: i) the concept of isotropic deliveries presented in Section 5.3, isotropic deliveries have a tendency to have high end-to-end delays; ii) the incentive mechanism (the utility function and the optimization problem) described in Section 5.4.

Simulations were performed using a *tweet* sized data message on realistic urban mobility models which imitate daily life pedestrian and vehicular dynamic patterns and real mobility traces. In summary, results show that when the end-user agrees to share storage capacity to carry other users data messages, MooF avoids selfish behaviour using a buffer management scheme, and the end-to-end delay is on average around 11 minutes. The combined approach (MooF + IWR) delivers more messages than MooF employed alone.

Incentive mechanisms for UPN are important because they potentially solve the problem of selfish behaviour, encouraging the end-user to share his opportunistic connectivity, storage capabilities and energy resources. UPN lack continuous end-to-end connectivity, but enables data message exchange between mobile devices without the support of an ISP. It is a well-known fact that most ISP networks get congested. Incentive mechanisms for UPN is an alternative for short text message exchange.

Chapter 6

Conclusions and The Future

Challenges, Research Answers, and Contributions

In the new generation of UPN, the nodes will be able to route data without the support of the ISP. The power of information exchange combined with a proper incentive mechanism will stimulate the development of new applications which will facilitate user cooperation. These new applications introduce a different user behaviour, where he/she acts independently from the ISP, and can choose to exchange data peer-to-peer before using their contracted services.

The foundation for user provided networks already exists in densely populated urban areas throughout the world. The proliferation of the IEEE 802.11, Bluetooth, IEEE 802.15.4, and possibly IEEE 802.11p technologies, combined with the increased storage capacity available for the end-user, enables widespread ISP independent user communication communities. For instance, an end-user who agrees to share 1 gigabyte of memory on his smart phone in favour of the UPN community, could store more than one and a half million messages of 140 characters with its respective 4 bytes of destination addresses.

Incentivized user cooperation plans could result in lower Internet costs for UPN community members. It is a well-known fact that most 3G /4G networks become congested, and thus incentive mechanisms for 3G/4G offloading is an option to improve user satisfaction in 3G/4G networks. Different solutions help decrease data exchange over long-range, low-bandwidth wireless networks. Tethering-based UPN already stimulate competition between 3G/4G wireless ISP and fixed wired access ISP.

6.1 Contributions and Research Answers

In order to answer the research questions raised in Section 1.2, an in-depth analysis of the state of the art and the results presented in this thesis was conducted. This analysis revealed that DTRB improved the state-of-the art when the users of a UPN have a common interest, i.e., without the use of an incentive mechanism. Therefore, one can say that DTRB is a solution to the first research question raised in this thesis because of the performance results presented. Typically users do not belong to the same domain, which may lead to conflicting interests among users of a UPN, especially when they have limited resources, such as battery and storage capacity. Consequently, an incentive mechanism is essential when the users of a UPN must be incentivized to share their resources to enable the exchange of information. Taking into account the possibility of user cooperation and the results presented in Chapter 5, one can say that MooF is a solution to the second question raised in this thesis. In summary, the following contributions to the computer science academic community are present in this thesis:

Contibution 1, Internet as a backbone. The simple idea of using the Internet as a backbone to improve UPN communities. The results presented in Section 3.3, Subsection 4.2.4, and Subsection 5.5.4.

Contibution 2, Delay Tolerant Reinforcement-Based (DTRB). This delay tolerant routing solution for UPN utilizes artificial intelligence techniques to learn about routes in the network and forward the delay tolerant messages. The learning algorithm and the reward process presented in Subsection 4.1.3.

Contibution 3, Messages on oFfer (MooF). This credit-based incentive mechanism for UPN utilizes a utility function that represents the monetary value of a given data message during its journey in the network, and a buffer management optimization algorithm to prevent selfish behaviour among nodes. The concept of isotropic deliveries presented in Section 5.3. The utility function and the buffer management optimization problem presented in Subsection 5.4.1 and Subsection 5.4.2, respectively.

Contibution 4, Performance Evaluation and Results. The results extracted from the realistic urban mobility simulator for UPN. The results presented in Subsection 3.3.2, Subsection 4.2.2, and Subsection 5.5.2. Three different mobility models were considered: UDEL, RWP, REAL; and two propagation models:

TwoRayGroundModel and Nakagami-m.

6.2 Challenges

The greatest challenges which face UPN today are the lack of appropriate UPN enabling software, the fact that people are not accustomed to sharing, and the security issues behind incentive mechanisms.

Currently, open source and research communities develop software required for the new generation of UPN. Tethering software allows the end-user to act as a hotspots. However, no applications exist which enable peer-to-peer multi-hop IEEE 802.11 message exchange.

People are not accustomed to sharing. For decades people have been paying for their Internet services from a contracted ISP. The general public does not realize that it is possible to utilize some benefits of a network system without paying expensive monthly fees. Incentive mechanisms that promote sharing can provide an alternative option for some applications and can motivate users to become part of a UPN community.

The security assumptions, such as tamper-proof devices and virtual banking, deserve future investigation. Tamper-proof solutions are more expensive, but promise secure environments. Tamper-proof solutions and off-line central trusted authorities shall probably be implemented together to achieve secure UPN environments.

6.3 Future Works

The simulations presented in this thesis ran on a Linux 64 bit computer with a 2nd Generation Intel Core i7-2630QM Processor (6MB L3 Cache, 2.00GHz) with 8 GB Dual Channel DDR3 SDRAM at 1600MHz.

Future tasks for further development of the DTRB routing solution involve simulation in larger environment to study if the k parameter is able to scale, and the implementation of an IEEE 802.11 battery module to simulate the consumed energy in the network layer. An incentive mechanism compatible with DTRB is another research path.

Future research for further development of the MooF incentive mechanism include simulation in a larger environment (for instance 1000 nodes), the λ parameter observation and its scalability in this larger simulation environment, and an increase in the transmission range, for example, using IEEE 802.11 [Vassis et al., 2005] $250m$ transmission ranges. This work considers selfishness as the number c of data messages a user wants to replicate in the network to guarantee delivery. Thus, it is important to understand the impact of selfishness in the amount of buffer that a user is willing to share. The energy consumption implied by the MooF buffer management scheme deserves investigation. The theorem presented in Section 5.3 also deserves an investigation to verify if it is extensible to non-binary spray and wait forwarding strategies.

6.4 Final Conclusion

The technology in today's smart phones can enable widespread communication without depending upon traditional ISP. The independent network concept depends upon user cooperation and UPN. These new computer networks will have a different architecture, where the nodes accumulate the roles of router, server and client. New communication opportunities will co-exist and even compete against the traditional ISP formats, and in turn will reward those whom agree to share their individual resources.

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