



Mobile Ad Hoc Networks: Modelling, Simulation and Broadcast-based Applications

Luc Hogie

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European Ph.D thesis in Computer Science

Mobile Ad Hoc Networks: Modelling, Simulation and Broadcast-based Applications

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Defended the 18th April 2007.

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Summary

Over the last few years, personal communication devices have invaded most developed countries and today, the majority of the population owns a mobile phone and most people use personal digital assistants, mobile computers, etc. This tendency is reinforced and occurs at the same time with a new trend: most of these devices get equipped with one or several wireless networking interfaces. Practically, Wi-Fi or/and Bluetooth-enabled devices become of frequent use. More than allowing the connection to some access point (which can be found in airports, train stations, city-centers, restaurants, etc), these interfaces also permit to interconnect directly with one another in a decentralized way and hence to self-organize into “ad hoc networks”.

A mobile ad hoc network is a set of mobile nodes able to communicate with other nodes in their surroundings. These wireless communications happen in a peer-to-peer manner, without relying on any predefined infrastructure. Today, mobile ad hoc networks are mainly used for sensing, gaming and military purposes. But the steadily wider adoption of wireless technologies in daily life let one foresee the next generation of mobile ad hoc network applications: environmental and medical monitoring, groupware, customer-to-customer applications, risk management, entertainment, advertising, etc. In this document we will consider a subclass of mobile ad hoc network called “delay tolerant networks”. In such network, the mobility is hardly predictable and the disruption of connection is a common and normal phenomenon.

In order to enable the development and spreading of these applications, a number of issues have to be solved. First, in such networks, end-to-end connectivity cannot be guaranteed. Indeed mobile ad hoc networks may be partitioned and nodes may be sporadically present in the network. As such, mobile ad hoc networks can be considered as Delay Tolerant Networks (DTN). Second, the topology of the network changes over time because of the mobility of the stations. Then, the way the communication primitives were implemented in the context of wired networks is no longer applicable. It is hence necessary to propose new algorithms to take those primitives into account, like broadcasting that serves as a basic pattern for the design of many mobile ad hoc network applications.

The design and implementation of such communication schemes, and more generally of mobile ad hoc network applications, can be achieved using two different ways: either

by building a real network, or by resorting to modelling and simulation. Theoretical approaches failed at modeling the inherent complexity of mobile ad hoc networks in a comprehensive manner. Indeed, ad hoc networks are decentralised systems which are ruled by a variety of elements including radio signal, network traffic, mobility, collaborative behavior, etc. If theoretical approaches certainly are useful for represent one or the other elements, they do not suit the modelling of a system as a whole. In the context of this work, where city-scale environment were considered, simulation was hence unavoidable.

The development of such simulators took place at the crossroad of some projects in relation to complex system modelling, optimization and middleware design for mobile ad hoc networks, and conducted in several European countries.

This diversity led to the design of a custom simulator called MADHOC. Indeed the mobile ad hoc simulators which are already available on the market most often are designed in such a way they allow the simulation of specific applications. They also generally suffer from a complex architecture (often poorly documented) that make them hardly adaptable to other applications. Consequently, none of them apparently turn out to be flexible enough so as it would have met our diverse needs. MADHOC captures the major characteristics of DTNs, by providing an extendable set of mobility models as well as a framework for the definition of new applications.

By looking at the State of Art protocols for mobile ad hoc networks and delay tolerant networks, it appeared that the broadcast issue had not yet been solved in a satisfactory manner. Indeed none of the protocols proposed so far proceed nicely in specific conditions of delay tolerant networking. MADHOC was then primarily used for the investigation of the broadcasting issue. In this specific context, networks composed of thousands devices using a variety of wireless technologies were considered. These networks are partitioned and exhibit heterogeneous densities. This led to the design of a bandwidth-efficient broadcasting protocol called DFCN.

Résumé

Au cours des dernières années, l'utilisation de téléphones mobiles, d'ordinateurs portables et, dans une moindre mesure, d'assistants personnels a explosé. Le phénomène est tel que dans les pays industrialisés, la quasi-totalité de la population utilise un téléphone mobile. Dans le même temps, la majorité de ces équipements se voit associée à une interface pour réseau mobile, en particulier Wi-Fi et/ou Bluetooth. En plus de permettre la connection à Internet par le biais de points d'accès, ces technologies permettent aux machines mobiles de se connecter de façon décentralisée et par là même de s'auto-organiser en "réseaux mobiles ad hoc".

Un réseau mobile ad hoc est un ensemble de nœuds mobiles capables de communiquer avec les nœuds présents à proximité géographique. Ces communications sans-fil opèrent en mode pair-à-pair : elles se passent d'infrastructure de télécommunication. A l'heure à laquelle ces lignes sont écrites, les réseaux mobiles ad hoc sont principalement utilisés dans le cadre de réseaux de capteurs, pour les applications de jeux et les applications militaires. Cependant, l'adoption croissante des technologies de réseau sans-fil par le grand public permet d'entrevoir les applications futures : surveillance environnementale et médicale, travail en équipe, applications entre particuliers, gestion du risque industriel, publicité, etc.

Pourtant, afin que ces applications soient réalisables, un certain nombre de problèmes doivent toujours être solutionnés. En premier lieu, dans les réseaux mobile ad hoc, il n'est pas possible de garantir qu'il existe un chemin entre deux nœuds donnés. En effet le réseau peut être partitionné et la présence des nœuds est sporadique. En second lieu, à cause de la mobilité des nœuds, la topologie du réseau change au cours du temps. De ce fait, les implémentations courantes des primitives réseau ne sont plus utilisables. Il est nécessaire de proposer de nouveaux algorithmes permettant l'utilisation de ces primitives dans le cadre contraint des réseaux mobiles ad hoc. Ces primitives incluent la diffusion, qui est une pierre de base de nombreuses applications pour réseaux ad hoc.

L'expérimentation de services (ou plus généralement d'applications) pour réseaux mobiles ad hoc peut être effectuée soit sur des réseaux dédiés (appelés *testbeds*), soit sur des simulateurs logiciels. Dans le cadre des travaux présentés dans cette thèse, pour lesquels un environnement de type urbain est considéré, la simulation s'est avérée inévitable.

Le développement d'un tel simulateur s'est opéré dans le cadre de plusieurs projets liés aux systèmes complexes, à l'optimisation et à la conception d'intergiciel. Ces projets impliquent des universités de différents pays d'Europe.

Cette diversité des besoins a conduit à la conception d'un simulateur dédié, appelé MADHOC. MADHOC considère un certain nombre de caractéristiques des réseaux mobiles ad hoc en proposant un ensemble de modèles de mobilité ainsi qu'une interface de programmation pour la définition de nouvelles applications.

MADHOC a été initialement utilisé pour l'expérimentation de protocoles de diffusion dans le cadre de réseaux hétérogènes de grande taille (réseaux impliquant plusieurs milliers de nœuds, et plusieurs technologies réseaux). Ces réseaux sont généralement partitionnés et ont des densités non-homogènes. Ceci nous a amené au développement de DFCN: un protocole de diffusion efficace en terme de bande passante utilisée.

Kuerzfaassung

Déi lescht Joeren ass de Gebrauch vun de Mobiltelefonnen, de Laptops an an engem manner groussen Ëmfang, de perséinlechen Hëllefsmittelen, explodéiert. De Phänomen ass esou grouss, datt an den Industrielänner praktesch jiddereen en Handy benotzt. Eng Majoritéit vun dësen Equipementer gi mat enger Interface vu mobilen Netzer verbonden, besonnesch dem Wi-Fi an/oder Bluetooth. Dës Technologien erméiglechen de mobile Maschinnen net nëmmen eng Verbindung mat Internet duerch Zougankspunkten, mä och sech dezentraliséiert unzeschléissen an doduerch selbststännesch a Mobil Netzer ad hoc ze organiséieren.

En zweckméisseg Mobilnetz ass en Ensembl vu mobile Kniet, déi fäeg si mat anere mobile Punkten, déi sech an engem noe geografesche Beräich befannen, ze kommunizéieren. Dës kabellos Kommunikatiounen verfuere no der binomer Method : si brauche keng telekommunikativ Infrastruktur. Momentan ginn dës Netzer haaptsächlech am Beräich vun Ëmfangnetzer fir d'Applikatiounen vu Spiller an och fir déi vum Militär benotzt. Dës wuessende Gebrauch vun de kabellosen Netztechnologien duerch d'Öffentlechkeet erlaabt ons déi zoukënfteg Applikatiounen virauszegesinn : Iwwerwachung vun der Ëmwelt an am medezinesche Beräich, Applikatiounen tëscht privat Leit, Verwaltung vum Industrierisiko, Publicitéit asw. Fir dës Applikatiounen ausschaffen ze kënnen, mussen awer nach gewësse Problemer geléist ginn. Éischtens kann an de mobilen Netzer ad hoc net garantéiert ginn, datt et e Wee tëscht zwee bestëmmte Kniet gëtt. An der Tat kann d'Netz gedeelt an d'Virkomme vun de Punkte sporadesch sinn. Zweetens ännert sech duerch d'Mobilitéit vun de Kniet d'Topologie vum Netz mat der Zäit. Doduerch gëtt et onméiglech déi gängesch praktesch Ëmsetzung vum de Primitiven vum Netz ze benotzen. Et ass also néideg nei Algorithmen virzeschloen, déi de Gebrauch vun dësen Primitiven am ageschränkte Kader vun de mobilen Netzer ad hoc erméiglechen. Dës Primitive begräfen d'Verbreedung, déi eng vun de Grondformen vu villen Applikatiounen fir d'ad hoc Netzer duerstelt.

D'Experimentatiounen vu Servicer (oder méi allgemeng vun Applikatiounen) fir mobil Netzer ad hoc kënnen souwuel op adequaten Netzer (sougenannten testbeds), wéi och mat Simulationslogiciellen erfollegen. Am Kader vun de virgestallten Aarbechten an dëser Thes fir déi en urbanen Typ a Betracht gezu ginn ass, huet missen op d'Simulatioun zeréckgegraff ginn.

D'Entwécklung vu sou engem Simulator ass am Kader vun etleche Projekter, déi mat komplexe Systemer verbonne sinn, an d'Optimisatioun an d'Konzeptioun vun Intergiciel erméiglecht hunn. Un dëse Projekter sinn Universitété vu verschiddenen europäesche Länner bedeelegt.

D'Diversitéit vun de Bedierfnësser huet zu der Konzeptioun vun engem adequate Simulator gefouert, dem MADHOC. MADHOC betruecht eng gewëssen Unzuel vun Eegeschafte vun de mobilen Netzer ad hoc an deems en en Ensembl vu Mobilmodeller, wéi och eng Programmatiounsinterface fir d'Definitioun vun neien Applikatioune virschléit.

MADHOC ass am Ufank fir d'Experimentatiounen vun de Verdeelerprotokollen am Kader vu groussen heterogenen Netzer (Netzer, déi e puer dausend Kniert ëmfaassen a verschidden technologesch Netzer) benotzt ginn. Dës Netzer sinn am allgemenge gedeelt an hu keng homogen Dichten. Dat huet zu der Entwécklung vum DFCN gefouert: e wierksamen Diffusionsprotokoll duerch déi gebrauchten Reseauskapazitéit.

Special thanks to Jeanne Meskens, who translated the abstract into Luxembourgish.

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Introduction

Recent studies performed by popular technology magazines like Point Topic ¹and DSL Forum² stated the number of citizens equipped with a broadband access to the Internet has followed an amazing increase: a growth of 40% per year since 2000. Moreover, most current commercial offers include a DSL-Wifi router, making people more and more comfortable with this technology. At the same time, small communicating objects – PDA, mobile phones, multimedia players, gaming console, etc – are becoming more and more common in our daily life. For instance, the spreading ratio of mobile phones is close to 100% in most western European and Northern American regions. In addition, it is noticeable that next generations of most of them come with Wi-Fi interfaces: more and more mobile phones are now able to communicate using the traditional GSM/UMTS media but also using wireless interfaces, and cumulate the features of classical mobile phones, PDAs, multimedia players and even gaming consoles. This general tendency leads us to envision a future in which most people will be equipped with devices able to communicate using wireless interfaces.

Oppositely to classical wired network, in a Wi-Fi network the nodes communicate by sending and receiving electro-magnetic (radio) waves. Wi-Fi networks can operate in two modes: “infrastructure” and “ad hoc”. In infrastructure mode, the nodes communicate with each other via an access point. This access point rules the communications in the local wireless network (WirelessLAN). Most often, the access point also enables the nodes within the WirelessLAN to communicate with nodes outside of the network (access to the internet in particular). This mode, which is the default one for most Wi-Fi devices, is commonly used in public places where access to the internet is provided (train stations, airports, etc), at home, and in the company. In ad hoc mode, nodes communicate directly without resorting to any infrastructure. Although this mode is not commonly used, it presents some advantages. In particular ad hoc communications require neither the construction of expensive infrastructure nor network administration. Unfortunately ad hoc networks face a number of difficulties which have to be solved in order to permit their deployment. In ad hoc mode, a set of devices can build in an autonomous and spontaneous way a communication network and have the capacity to self-organize in order to maintain it. This kind

¹<http://point-topic.com/>

²<http://www.dslforum.org/>

of network is gaining interest, although it is so far limited to gaming or to the building of temporary networks for answering peculiar situations for which a communication network is required for assisting a group of people in its action when no infrastructure is available. All along this document, the focus will be put on mobile ad hoc networks, as they are defined in the following.

Mobile ad hoc networks are wireless networks built on-the-fly by mobile computers (also called “nodes”, “terminals” or “stations”) getting in and out of range with each others. In the literature, mobile ad hoc networks are also commonly referred to as MANETs. Two important keywords for mobile ad hoc networking are “radio communication” and “mobility”. On the one hand, because the nodes have a limited radio range, nodes can communicate using the radio communication medium if they are close to each other (in that case one say that the nodes are *in range*). This is not enough however. Wireless communication exhibits a variety of issues which lead to some situations where the communication between two nodes in range fails, or two nodes in range do not detect each other. On the other hand, node mobility heavily impacts the connectivity of the network. The way the nodes move (note that not necessarily all of them move, though) results in a variety of topologies and dynamic properties of the network. For example, in a network in which the nodes move in a random way, no connection can be assumed durable; but in a network in which the nodes move in groups, then the creation of long-lived clusters may occur. These characteristics lead to a situation in which the current implementation of the common network operations (broadcast, unicast, routing, etc) is not applicable. Indeed enabling these operations in mobile ad hoc networks is achievable only by providing new implementations that handle parameters like dynamic network discovery, delays, etc.

All along this document, we will consider a subclass of mobile ad hoc networks, called delay tolerant networks. One of the most prominent properties of delay tolerant networks are a high and unpredictable mobility and disruption of the network connections.

A variety of technologies already enable mobile ad hoc networking. The most commonly referred one is the ad hoc mode of the IEEE802.11 class of protocols. On the consumer market, IEEE802.11 is known as “Wi-Fi”. Bluetooth, whose design apparently suits better mobile ad hoc networking, is becoming popular in the context of Personal Area Networking (PAN). Protocols such as Hiperlan, ZigBee, etc, provide alternative—some say better—solutions to mobile ad hoc networking but, up to now, they sort of failed at attracting the attention of the research groups. Practically, as of writing, a vast amount of the papers published on the topic of mobile ad hoc networking present experiments based on IEEE802.11.

Today, mobile ad hoc networking is a popular area of research which gathers researchers working on the topics of networking, distributed systems, complex systems, security, telecommunications, etc. In the future, when mobile ad hoc networks will be deployed

at a real scale, they will allow the deployment of applications such as e-commerce, conferencing, gaming, mobile grid computing applications, etc.

Today, mobile ad hoc networks are not developed in a real-scale. As a consequence, mobile ad hoc networks have recourse to experimentation networks (which are named “testbeds”) or to software simulators ; simulators being apparently the most commonly used solution. In fact, testbeds exhibit many inherent drawbacks (like their high cost, the difficulty to built one, the difficulty of monitoring them, etc) which refrain research laboratories to build and use them. The studies of large-scale applications—which is our concern— most of the time requires modelling and simulation. Two directions can then be followed: either using existing (and often general purpose) simulators like *ns-2* [ns2], or conceiving a simulator tailored to specific purposes.

My work occurs in the context of several multi-national academic projects, having separate requirements. In particular the SoNi project (Luxembourg) [Uni07]—which was the initial source of funds— targets to providing a middleware solution to application-level ad hoc communications. This consists in identifying the network properties that play a role in application-level communication, in proposing an adequate communication paradigm as well as a set of network primitives, and in an implementing these.

In the context of the GraphStream project (France) [AD07], the MIV team (which is of subset of the LITIS laboratory (France)) studies dynamic graphs as models for complex systems. Complex systems are made of many locally interacting entities, which global behavior is obtained out of local interactions. Particularly, MIV researchers try to put into light the mechanisms which permit the creation of organizations in such networks. This work takes place in the context of complex system research. Indeed mobile ad hoc networks can be considered as complex systems, especially when they exhibit mobility models which, however based on basic individual behavior, exhibit complex organizational structures like clusters, chains, etc.

The SARA project (France) focuses on the design of an experimentation platform allowing the study of Delay Tolerant Networks (DTNs). In this context, a key issue is to couple a test-bed and a simulator so as the test-bed would be virtually expanded by a simulated network.

The ABASMUS project [Uni] addresses the issue of topology control for ad hoc networks. More precisely it aims at providing new topology control protocols by considering “injection points”—connections from ad hoc nodes to some infrastructure.

Last, researchers at Málaga University needed a simulation tool permitting the genetic multi-optimization of broadcast protocols. Using some results one single simulation process as the value of the fitness function for their optimization algorithms, an issue was to use a simulator that would be able to operate the simulation of one broadcasting process in a very short time.

Laboratory	Resort to simulation for...
Universidad de Málaga (SP)	Multi-objective optimization of broadcast protocols
Université du Luxembourg (LU)	Broadcast and topology control protocols
Université de Bretagne-Sud (FR)	Network emulation
Université du Havre (FR)	Generation of dynamic graphs
Université de Bordeaux (FR)	Military applications
Université de St. Etienne (FR)	Topology control protocols
SES/Astra	Content delivery in VANETs
Université de Toulouse (FR)	Mobility of agents on ad hoc nets

Table 1: The diversity of applications of MADHOC.

This diversity of requirements of our academic partners imposed the development of a custom simulator. Table 1 illustrates these needs. In addition to the requirements formulated hereinbefore, from a software engineering point of view, a simulation tool must provide a comprehensive programming user interface and it must be designed so as incorporating new components (mobility models, user applications, metrics, GUI elements, etc) is easy.

Most studies on mobile ad hoc networking use the random waypoint as a reference for node mobility [BRS03]. But recent studies have shown that the random waypoint mobility model fails at reproducing human mobility in an realistic fashion. Moreover, the simulation settings generally used in experimentation favor the execution of protocols. When using more realistic mobility as it is presented hereinbefore, many applications, like broadcasting, no longer operate.

Broadcasting constitutes one of the fundamental low-level network operations which serves as the basis of higher level applications such as routing. As such, it is one of the earliest research interests on mobile ad hoc networking. Broadcasting is commonly considered as an operation which consists in sending a message from one given node (the source station) to all the nodes in the network. In a decentralized network, the message that is subject to broadcasting is relayed by intermediate nodes so that all the network graph is eventually spanned. Unfortunately, this definition cannot be applied in the context of mobile ad hoc networks. Indeed the limited radio range of the nodes, as well as node mobility, make that it is very likely that some nodes are unreachable at a given moment. Consequently, we define as a multi-objective problem targeting at maximizing the number of nodes reached, at minimizing the time required to reach them, and at minimizing the network overhead [?]. Minimizing the network overhead is particularly important because too many emissions is likely to lead a broadcast storm, and the congestion of the network.

Generally when the mobility is an important properties of networks, spanning trees-

based methods are applied. These aim at determining the minimal set of relay nodes that must participate to the broadcast process. Contrarily, when mobility is considered, different strategy, mostly based neighborhood information, are employed. These include Probabilistic schemes, Scalable Broadcasting Algorithm (SBA), Multipoint Relaying, Ad hoc Broadcasting Protocol (AHBP), etc. These strategies work well when the network is connected, but they fail as soon as partitioning occurs. There exist solutions like the extension of AHBP (called AHBP-EX) which overcomes this problem by triggering re-emission on the discovery of a new neighbor. This strategy unfortunately leads to waste much bandwidth. Additionally, SBA and AHBP, which are the most effective protocols in their class, require the knowledge of 2-hop neighborhood information (nodes must know their neighbors, as well as the neighbors of their neighbors). In reality, when the mobility is high, we assume that 2-hop information is not achievable.

This document presents, in last chapter, the Delay Flooding with Cumulative Neighborhood (DFCN) protocol [?, HBG⁺06]. DFCN is a broadcast protocol which achieves performances comparable to SBA and AHBP, but that content with 1-hop neighborhood information.

Contributions

The contribution of my work is mostly twofold. Briefly, it consists of (1) a mobile ad hoc network simulator and (2) a versatile broadcasting protocol. Details are given in the following.

First, my investigation of mobile ad hoc networking started with the study of broadcasting protocols for large-scale metropolitan ad hoc networks. This requires a simulation tools that enables to instantiate large amount of nodes. It also requires the ability to simulate heterogenous networks as well as to make the nodes move similarly to the way people move in reality. At the best of my knowledge, when this research started (mid-2003) none of the simulators available were proposing all of these features in a single package. Thus, the development of the MADHOC simulator was motivated by both the need to have a tool specifically tailored to my purposes and by the will to explore the profound details of the wireless communication paradigm. Briefly, MADHOC provides a lightweight simulation engine for the simulation of large numbers of nodes as well as a mobility model which reproduces some properties of the citizen mobility. Additionally, MADHOC provides its user with a graphical user interface which allows the precise monitoring of the simulation processes at the moment is it running.

Second, after a survey of the broadcasting protocols suited to mobile ad hoc networking, we found out that no truly efficient protocols operated both with 1-hop neighborhood information and when the network is sparse. Delayed Flooding with Cumulative Neighborhood (DFCN) was build with these two constraints in mind. Through experimentations, DFCN exhibited the expected results, not to say better ones. On the one hand the strategy it employs makes that DFCN keeps working even when the node density is extremely low (very sparse network). On the other hand, when the density is high enough the state-of-the-art protocols have shown that they work well, DFCN exhibits lower bandwidth utilization. A counterpart of these good results, is that DFCN does not ensure that all the nodes in the network will be reached. But anyway, in a mobile ad hoc network, even protocols which theoretically ensure that all nodes will be reached will actually reach all the nodes belonging to the partition in which the broadcasting process has begun—and these protocols do not ensure that this partition includes all the nodes in the network.

Part I

Ad hoc networking: generalities

According to recent studies by Point Topic ³and DSL Forum⁴, the ration of the population having an Internet access at home has increased at the astonishing rate of 40% per year since 2000. In addition to this, more and more commercial toolkits for Internet access propose a wireless networking adapter. At the same time, personal communicating devices—like PDAs, mobile phones, multimedia players, gaming consoles, etc— are becoming part of our daily life. For instance, the spreading ratio of mobile phones is close to 100% in most western European and Northern American regions. Moreover, next generations of such devices will likely come with Wi-Fi interfaces. Many mobile phones are already able to communicate using Wi-Fi or Bluetooth, and provide features generally found in PDAs, multimedia players or gaming consoles. This general tendency leads us to envision a future in which most people will be equipped with devices able to communicate using wireless interfaces.

In a wireless network the nodes communicate by sending and receiving electro-magnetic (radio) waves. Wi-Fi networks—which are wireless networks that use the Wi-Fi technology for data encoding— can operate in two modes, named “infrastructure” and “ad hoc”. On the one hand, in infrastructure mode, the communication relies on some access point. This access point rules the behavior of the local wireless network (WirelessLAN). Most often, the access point also allows the nodes in the WirelessLAN to access nodes outside of it. In particular this provides access to the Internet. The infrastructure mode is most commonly used, and is used to enable access to the Internet in public places such as train stations, airports, companies, and at home. On the second hand, in ad hoc mode, nodes communication occurs in a peer-to-peer manner. In this case no infrastructure is required. This mode presents the great advantage that communications do not require any infrastructure. Hence ad hoc networks are cheap and robust. Unfortunately they face a number of issues that still prevent their deployment. In particular, the technology still needs to gain more maturity, and ad hoc applications are still a topic of research: so far, gaming, sensing and military applications constitute the main applications of ad hoc networks. All along this document, the focus will be put on mobile ad hoc networks, as defined in the following.

Mobile ad hoc networks are wireless networks built on-the-fly by mobile computers (also called “nodes”, “terminals” or “stations”) getting in and out of range with each others. In mobile ad hoc networking, “radio communication” and “mobility” are key aspects. On the one hand, nodes have limited radio range, which implies that they can communicate only if they are close to each other—if they are *in range*. This requirement is not enough however. Wireless communication have a number of issues which lead to situations in which two nodes in range cannot communicate because the communication fails or because they do

³<http://point-topic.com/>

⁴<http://www.dslforum.org/>

not detect each other. On the other hand, node mobility heavily impacts the connectivity of the network. Mobility leads to network specific topologies and dynamic properties. For example, if the nodes move in a random manner, the connection cannot be assumed durable. Another example, if the nodes move in groups, then it is likely that cluster will appear. In such situations, the current implementations of common network operations like broadcast, unicast, routing, are not operable. Researchers steadily propose solutions for enabling these basic operations in mobile ad hoc networks.

All along this document, we will consider a subclass of mobile ad hoc networks, called delay tolerant networks. One of the most prominent properties of delay tolerant networks are a high and unpredictable mobility and disruption of the network connections.

There exist a number of technologies which enable mobile ad hoc networking. The most popular one is IEEE802.11, used in ad hoc mode. IEEE802.11 is commonly referred to as “Wi-Fi”. Less frequently encountered, Bluetooth is becoming popular in the context of Personal Area Networking (PAN). However its design apparently suits better mobile ad hoc networking. Protocols such as Hiperlan, ZigBee, etc, provide alternatives solutions to mobile ad hoc networking but, up to now, they sort of failed at attracting the attention of the research groups. As of writing, most articles published on the topic of mobile ad hoc networking present experiments based on IEEE802.11. Mobile ad hoc networking is today is a vast area of research which gathers researchers working on the topics of networking, distributed systems, complex systems, security, telecommunications, etc. In the future, when mobile ad hoc networks will be deployed at a real scale, they will allow the deployment of applications such as e-commerce, conferencing, gaming, mobile grid computing applications, etc.

This chapter provides some definitions of what is a mobile ad hoc network, in Section 1. Then, in Section 2 it gives some technical details on the wireless networking technologies that are available today, and that suit the deployment of a mobile ad hoc networks. Finally, in Section 3 it presents some applications which are likely to be deployed over the future mobile ad hoc networks.

Chapter 1

Definition for “ad hoc network”

Ad hoc networks are gaining more and more interest. Not only their importance in military applications [BZG04] is growing, but also their future impact on business is becoming clear. Indeed the wide spread of lightweight and low-cost mobile devices—mobile phones, PDAs, Pocket PCs, etc—which now embed Bluetooth and IEEE802.11 (Wi-Fi) network adapters enable the spontaneous creation of city-wide mobile ad hoc networks. These networks could then constitute the infrastructure of numerous applications such as emergency and health-care systems [KGSMG02], groupware [BLH01], gaming [RTVS03, GFH05, RWW03], advertisements, customer-to-customer applications (like the UbiBay project [FLS02]), etc.

A prime issue when dealing with ad hoc networks certainly is to define what it is. Indeed, there is no consistency in the literature about the definition of an ad hoc network. The large variety of wireless networks—ranging from city mesh networks to sensor networks [ASSC02]—makes it difficult to get a clear picture of the topic. What brings some more difficulty is the gap between what is it possible to do today and what will be possible in the future. For instance, as of 2006, building an ad hoc network is not an easy task. Even if the technology exists, there still are a number of issues which makes the deployment of a multi-hop ad hoc network a very challenging task.

In the coming sections are given and detailed a variety of the definitions found in the literature. The reason for choosing these definitions is that they prove complementary. Altogether, they provide a fairly good picture of what ad hoc networking is.

1.1 Definitions from the literature

From the etymological point of view, the term “ad hoc” is a Latin adjective which has two possible substances, as given by Wordnet [Fel98]:

1. *concerned with one specific purpose ;*
2. *improvised.*

The term “ad hoc” were borrowed some time ago by computer scientists who extended its meaning to characterize a network—or a connection—involving wireless devices. The etymology for “ad hoc” suggests that an ad hoc network would be a network made of a set of nodes collaborating to achieve a common goal. Further, the reason for being of an ad hoc network IS this common goal. But in reality ad hoc networking is not primarily about collaboration. Unfortunately, this has led to the use of confusing definitions.

Surprisingly, even if the concept of “ad hoc network” is clear to researchers, none of the definitions proposed by researchers got universally accepted. Instead, a wealth of them are in use in the literature.

1.1.1 IEEE802.11 specification

According to the IEEE802.11 specification [ANS99]:

Definition — “An ad hoc network is a network composed solely of stations within mutual communication range of each other via the wireless medium.”

This definition implies that an ad hoc network is a complete one, in the sense that all stations are in the neighborhood of each others. Among the consequences, an ad hoc network is necessarily single-hop; it cannot be partitioned; and the mobility of the stations has no impact on the network topology. Our understanding goes far beyond this mere definition, as detailed in Section 1.2.

1.1.2 Stojmenovic and Wu

According to [SW04],

Definition — “*wireless networks consist of static or mobile hosts (or nodes) that can communicate with each other over the wireless links without any static network interaction. Each mobile host has the capability to communicate directly with other mobile hosts in its vicinity. They can also forward packets destined for other nodes. Examples of such networks are ad hoc, local area, packet radio, and sensor networks, which are used in disaster rescues, wireless conferences in the hall, battlefields, monitoring objects in a possibly remote or dangerous environment, wireless Internet etc.*”.

This definition precisely defines what is a pure ad hoc network. In such a network, no wireless access point is used and the nodes rely on themselves (and on their peers) to established the communication links within the network. Note that this allows the presence of static nodes. This implies that if the ratio of static nodes in the network is high, they could act altogether as a set of access points. This would be contrary to the definition.

1.1.3 Bhaskar

[BR03] does not leave out the eventuality that a mobile ad hoc network includes some wired connections.

Definition — “*Essentially a mobile ad hoc network is a collection of mobile nodes communicating over wireless channels with little (if any at all) fixed, wired infrastructure.*”

More generally, close to Bhaskar’s definition, many researchers consider that it is always possible to set up some—even minimal—infrastructure prior to the deployment of an ad hoc network. Because mobility and wires are two components that do not mate well, this infrastructure can be made of a set of wireless access points, or even one single long-range one, located in the middle of the network. One might think that the use of some infrastructure solves most of the issues inherent to ad hoc networking. But since this does not mean that *all* the nodes are connected to the infrastructure, solutions (like the use of central services) are not practicable.

1.1.4 Gerla

According to [GLR05]:

Definition — “*A mobile ad hoc network (mobile ad hoc network) is a collection of mobile nodes that dynamically self organize in a wireless network without using any pre-existing infrastructure. In a MANET, the applications are typically “peer-to-peer” rather than “client-server”. Moreover, a MANET is often built to support a specific application, thus the networking is application-driven.*”

This definition highlights two relevant things.

First, self-organization is an important concept of ad hoc networking. It is a generic term that appears at several levels. Mostly it refers to routing: flat (in opposite to hierarchical) ad hoc architectures are not scalable. In order to overcome this major drawback, hierarchical routing is introduced. The main challenge in hierarchical routing is to group nodes into clusters, each cluster being represented by one cluster head. Self-organization is also mentioned when dealing with topology control issues. In this context, the nodes of the network move and alter the strength of the radio signal they emit so that they collaboratively work at improving the connectivity of the network (that is reducing the number of partitions as well as the shortest path length).

Second, the concept of application is to be discussed. Due to the particular characteristics of ad hoc networks, not all distributed applications can be adapted to execute on

them. For example, because they are intrinsically highly dynamic, only loosely distributed applications are possible. More details on applications for ad hoc networks are described in Section 3.

1.1.5 MobileMANs

Metropolitan ad hoc networks are spontaneous wireless network resulting of the radio interactions of the citizen's mobile devices. Up to now, few groups have studied metropolitan ad hoc networks. At the best of our knowledge, the most advanced research is conducted in the frame of the MobileMAN project [CGMT03]. The following definition is adapted from the MobileMAN project description:

Definition — A MobileMAN is a wireless mobile ad hoc network built up solely from citizen devices. As such, it is autonomous and self-organized. The kind of devices that populate MobileMANs are mobile phones, Personal Digital Assistants (PDAs) equipped with wireless interfaces and, to a lesser extent, mobile computers. Except from mobile computers, such devices are (relatively) low cost, and operate without per-use service fees. The only external resource needed for operation is the bandwidth in the (unlicensed) industrial, scientific and medical (ISM) band. The devices forming a MobileMAN must cooperatively provide some services such as naming, security, service discovery, etc. These services are needed to support user-level applications.

Applications supported by a MobileMAN might range from text messaging systems, up to more demanding multimedia (voice and video) services. Eventually, they might even range from simple interactive games to ones that truly merge real, and virtual worlds.

MobileMANs are very likely to be the sort of ad hoc networks that will be most frequently encountered in the future.

Because of the variety of configurations which compose a city, the topology of MobileMANs is heterogeneous; that is MobileMANs exhibit areas whose the concentration of nodes ranges from highly dense to very sparse. Analogously, the mobility of the nodes within a MobileMAN is complex: some nodes move in groups, some others do it in an independent manner; some move fast, some other move slowly, etc. This characteristics constitute obstacle to the execution of (distributed) applications for MobileMANs.

1.1.6 Delay Tolerant Networks

Delay tolerant networks (DTNs) [Fal03, JFP04, JLW05] constitute an emerging subclass of mobile ad hoc networks that feature frequent and long-duration partitions. Indeed, under some particular conditions like fast mobility or poor connectivity, the topology of

the network is steadily affected, leading to low densities. In a delay tolerant network, the disruption of connections is not considered to be a situation of error, instead it constitute a normal behavior of the system. Consequently there must be a software layer which take into account this prominent property of delay tolerant networking.

DTNs have a variety of applications like Vehicular Ad hoc Networks (VANETs) [TMJH04], sensor networks [ASSC02], military networks, etc.

All along this document, the term “mobile ad hoc network” will be mostly referring to delay tolerant networks.

1.2 Synthetic definition

On the basis of the previous definitions and the literature on the topic, in the rest of this document, the following synthetic definition will be assumed:

Definition — A mobile ad hoc network (also referred to as mobile ad hoc network) is a collection of communication nodes which are generally mobile. The nodes may be of different natures (mobile phones, laptops, PDAs, wearable devices, workstations, etc).

The network connections the nodes use to communicate cannot be assumed reliable (because of node motion, connections might break down at any time). They may be of various types (Wi-Fi, Bluetooth, Ethernet, etc).

The network resulting of the interaction of the nodes exhibits a topology that is generally not predictable. It operates in a complete peer-2-peer manner, that is node-to-node communication do not rely on any network infrastructure. Instead nodes establish direct communications with their peer nodes, hence peer-to-peer.

In this document we will use the term “pure ad hoc network” for referring to ad hoc networks whose the connections are all peer-to-peer. In other words, an ad hoc network in which at least one connection connects a node to a fixed infrastructure will not be referred to as “pure”.

Often in this document we will refer to the neighborhood of a node.

Definition — A node a is a neighbor of a node b if there exists a network link that directly interconnects a and b . The neighborhood of a given node is then the set of nodes which are neighbors of this node.

This definition implicitly considers the nodes which are “direct” neighbors of a given node. But the concept of neighborhood can be broaden, as given by the following definition:

Definition — A node a is said to be at n hops of a node b if there exists a path from a to b which is established by $n - 1$ intermediate different nodes. The n -hop neighborhood of a given node then is the set of nodes which are at n -hops of this node.

Chapter 2

Ad hoc networking technologies

Theoretical mobile ad hoc networking research [CCL03] started some decades ago. But commercial digital radio technologies appeared in the mid-nineties. Since then, few proposal for enabling ad hoc communications were made. The first technology (IEEE802.11, also referred to as Wi-Fi [ANS99]) is still strongly leading the market, although there is great room for improvement. This section provides an overview and a technical description of the technologies that have been proposed hitherto.

A common feature of most wireless networking technologies is that they operate in the unlicensed Industrial Scientific and Medical (ISM) 2.4GHz band. Because of this choice of frequency band, the network can suffer interferences from microwave ovens, cordless telephones, and other appliances using this same band plus, of course, other networks. In particular, Farrell and Abukharis studied the impact on Bluetooth on IEEE802.11g [ST04]

2.1 Packet radio

Packet radio [GFS78] was used for the earliest versions of mobile ad hoc networks. It was sponsored by DARPA in the 1970s. It allows the transmission of digital data over amateur radio channels. Using special radio equipment, packet radio networks allowing transmissions at 19.2 kbit/s, 56 kbit/s, and even 1.2 Mbit/s have been developed.

Since the modems employed vary in the modulation techniques they use, there is no standard for the physical layer of packet radio networks. Packet radio networks use the AX.25 data link layer protocol, derived from the X.25 protocol suite and designed for amateur radio use. AX.25 has most frequently been used to establish direct, point-to-point links between packet radio stations, without any additional network layers.

However, in order to provide routing services, several network layer protocols have been developed for use with AX.25. Most prominent among these are NET/ROM, ROSE, and TexNet. In principle, any network layer protocol may be used, including the Internet protocol (IP), which was implemented in the framework of the AMPRNet project.

2.1.1 AMPRNet

The AMPRNet [amp] (AMateur Packet Radio Network) is an effort by Amateur radio operators to build a computer network connected over amateur radio. The AMPRNet is connected by links over amateur packet radio. Because of the bandwidth limitations of the radio spectrum, links are usually restricted to a maximum of 9600 baud and are commonly 1200 baud and on occasion as low as 300 baud. The AMPRNet fully supports TCP/IP allowing for support of FTP, Telnet, Ping, Finger and Http.

2.2 IEEE802.11

Wi-Fi is a wireless networking technology based on the IEEE802.11 specifications. The first—and still most used—Wi-Fi standard is referred to as IEEE802.11b in the scientific literature. It was then declined into IEEE802.11a, IEEE802.11g and IEEE802.11n. IEEE802.11i and IEEE802.11h, which respectively focus on Quality of Service (QoS) and security, are out of the scope of this document. All Wi-Fi technologies operate on the 2.4GHz band, except from IEEE802.11a which operates within the 5GHz band. These technologies use significantly different PHY layers which, from the user point of view, make them differ in term of the bandwidth (i.e. the data rate) that they provide.

Typically, Wi-Fi enabled devices have coverage distances ranging from 50 to more than 100 meters. In practise, this coverage distance depends greatly on the nature of the antenna and on the environment in which the devices evolve.

The IEEE802.11 protocol family relies on the same MAC layer, which is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Briefly, CSMA is a probabilistic network control protocol in which a node verifies the absence of traffic (it senses the carrier) before transmitting on the shared physical medium, particularly the electromagnetic spectrum. Collision detection is aimed at improving CSMA performance by interrupting a transmission as soon as a collision is observed.

2.2.1 IEEE802.11a

IEEE802.11a uses Orthogonal Frequency Division Multiplexing (OFDM). It is the only wireless radio technology that works in the 5GHz band.

The main idea behind OFDM is that since low-rate modulations (i.e modulations with relatively long symbols compared to the channel time characteristics) are less sensitive to multipath, it should be better to send a number of low rate streams in parallel than sending one high rate waveform. OFDM then works by dividing one high-speed signal carrier into several lower-speed subcarriers, which are transmitted in parallel. High-speed carriers, which are 20MHz wide, are divided into 52 subchannels, each approximately

300KHz wide. OFDM uses 48 of these subchannels for transporting data, while the four others are used for error correction.

OFDM delivers higher data rates and a high degree of multipath reflection reconstruction, thanks to its encoding scheme and error correction. The IEEE802.11a standard permits the data rate to be set at 24 Mbit/s. But it also allows vendors to extend it beyond that. However, the more bits per cycle (Hz) that are encoded, the more fragile the signal will be to interference and fading, and unless power output is increased, the shorter the range.

In practise, vendors typically sell IEEE802.11a devices that boast data rates up to 54 Mbit/s.

2.2.2 IEEE802.11b

IEEE 802.11b uses Direct Sequence Spread Spectrum (DSSS) as the physical layer technique for the standard.

DSSS uses a complex technique which consists in multiplying the data being transmitted by a *noise* signal. This noise signal is a pseudo-random sequence of 1 and -1 values, at a frequency much higher than the original signal.

The resulting signal wave looks much like white noise. This white noise can be filtered at the receiving end in order to recover the original data. This filtering happens by again multiplying the same pseudo-random sequence by the received signal (because $1 \times 1 = 1$, and $-1 \times -1 = 1$). This process, known as “de-spreading”, mathematically constitutes a correlation of the transmitted pseudo-random sequence with the receiver’s assumed sequence. For allowing de-spreading to work correctly, the transmit and received sequences must *synchronized*.

So far, IEEE 802.11b is the implementation of the IEEE 802.11 standard that has been most heavily studied in the framework of mobile ad hoc networks.

2.2.3 IEEE802.11g

IEEE802.11g, just like IEEE802.11a, uses Orthogonal frequency-division multiplexing (OFDM), it then boasts similar bandwidths. OFDM is described in Section 2.2.1. But unlike IEEE802.11a, IEEE802.11g works in the 2.4 GHz band.

Since the draft 802.11g standard combines fundamental features from both 802.11a and 802.11b, it leads to the development of devices that can inter-operate with technologies based on both of the previous versions of the specification.

2.2.4 IEEE802.11n

IEEE802.11n [dMSG LA06] is built on previous 802.11 standards by adding MIMO (multiple-input multiple-output). MIMO uses multiple transmitter and receiver antennas to allow increased data throughput and range.

2.3 Bluetooth

Bluetooth is essentially the same kind of microwave radio technology that has given us wireless door chimes and automatic garage door openers. It was initially restricted to an operating distance of just 10 meters and a speed of approximately 1 Mbit/s.

When Bluetooth devices come within range of each other, they establish contact and form a temporary network called a Personal Area Network (PAN). In the Bluetooth terminology, this is also known as a Piconet. A multi-hop ad hoc network formed by the interaction of Bluetooth devices is called a Scatternet. When using Bluetooth, the devices must establish a network session before being able to transmit any data.

Bluetooth uses the Frequency-Hopping Spread Spectrum (FHSS) technique. Unlike IEEE802.11 which establishes a communication link on a certain frequency (a channel), FHSS breaks the data down into small packets and transfers it on a wide range of frequencies across the available frequency band. Bluetooth transceivers jump among 79 hop frequencies in the 2.4 GHz band at the rate of 1,600 frequency hops per second. 10 different types of hopping sequences are defined, 5 of the 79 MHz range/79 hop system and 5 for the 23 MHz range/23 hop system. This technique trades off bandwidth, in order to be robust and secure. More precisely, Spread Spectrum communication techniques have been used for many years by the military because of their security capabilities.

Thanks to this, Bluetooth allows the transmission of data as well as voice (VoIP applications).

2.4 Hiperlan

The HiperLAN2 standard is very close to 802.11a/g in terms of the physical layers it uses—both use OFDM technology—but is very different at the MAC level and in the way the data packets are formed and devices are addressed. On a technical level, whereas 802.11a/g can be viewed as true wireless Ethernet, HiperLAN2 is more similar to wireless Asynchronous Transfer Mode (ATM). It operates by sharing the 20MHz channels in the 5GHz spectrum in time, using Time Division Multiple Access (TDMA) to provide QoS through ATM-like mechanisms.

It supports two basic modes of operation: centralized mode and direct mode. The centralized mode is used in the cellular networking topology where each radio cell is controlled

by an access point covering a certain geographical area. The direct mode is used in the ad hoc networking topology - mainly in the context of Personal Area Networking - where a radio cell covers the whole serving area. In this mode, mobile terminals in a single-cell home “network” can directly exchange data.

HiperLAN2 support came mainly from European telecommunications equipment vendors.

2.5 BLAST

Announced in 1998, BLAST [GDG98], which stands for Bell Labs Layered Space-Time, is a wireless communication technique which uses multi-element antennas at both transmitter and receiver. BLAST boasts bandwidth eight times bigger than conventional approaches. The BLAST project does no longer show clear signs of activity, since the last related publications date from 2002. IEEE802.11n (see section 2.2.4) uses the same principle.

2.6 ZigBee

ZigBee-enabled devices conform to the IEEE 802.15.4-2003 standard. This standard specifies its lower protocol layers, the physical layer (PHY), and the medium access control (MAC). It targets Low-Rate Wireless Personal Area Network (WPAN). ZigBee-style networks research began in 1998. Zigbee was intended to operate in contexts in which both Wi-Fi and Bluetooth are not suitable.

Zigbee operates in the unlicensed 2.4 GHz, 915 MHz and 868 MHz ISM bands. It uses direct-sequence spread spectrum (DSSS) coding. This makes the data rate to reach 250 kbit/s per channel in the 2.4 GHz band, 40 kbit/s per channel in the 915 MHz band, and 20 kbit/s in the 868 MHz band. The maximum output power of ZigBee antennas being generally 1 mW, the transmission range of ZigBee nodes is between 10 and 75 meters. Observations have shown that the transmission range is heavily dependent on the environment.

The MAC layer specified by IEEE 802.15.4-2003 is CSMA/CA (carrier sense, multiple access/collision avoidance).

2.7 Broadband wireless networking

WiMAX (IEEE 802.16) stands for Worldwide Interoperability for Microwave Access. IEEE 802.16 boasts data rates up to 70 Mbit/s over a distance of 50 km. However practical limits from real world tests seem to be between 500 kbit/s and 2 Mbit/s at a distance of around 5-8kms.

WiBro is a wireless broadband internet technology being developed by the Korean telecoms industry. It has been announced that WiBro base stations will offer an aggregate data throughput of 30 to 50 Mbit/s and cover a radius of up to 5 km. The technology will also offer Quality of Service.

HIPERMAN [HPF03, HPF04], which stands for High Performance Radio Metropolitan Area Network, is a European alternative to WiMAX. The standard was created by the European Telecommunications Standards Institute (ETSI). It provides a wireless network communication in the 2-11 GHz bands.

The adequation of these technologies to ad hoc networking is discussable, since they would permit to establish ad hoc networking at a level at which technologies for infrastructure networks (like GSM or UMTS) are available.

2.8 Adequation to ad hoc networking and issues

Not all of the protocols described hereinbefore were initially designed for enabling ad hoc networking. More precisely most of the effort on Wi-Fi (IEEE802.11) aimed at enabling wireless local area networking (WLAN). In this context, IEEE802.11 works nicely. When used in ad hoc mode, it proves to be barely utilizable. Bluetooth was primarily designed and implemented for enabling Wireless Personal Area Networking (WPAN). A WPAN is a network used for communication among computer devices (including telephones and personal digital assistants) close to one person. In this context Bluetooth competes standards such as the wireless WUSB (Wireless Universal Serial Bus, technically referred to as IEEE802.15.3) and IrDA (Infrared Data Association), and the wired USB and Firewire (IEEE 1394).

2.8.1 Synchronization issue

Used in ad hoc mode, IEEE802.11b (section 2.2.2), and more generally the Direct Sequence Spread Spectrum (DSSS) physical-layer technique, suffers from several problems that make it hardly usable. In particular, the time synchronization techniques used by DSSS for de-spreading the frame received constitute a strong constraint at the level node discovery. For example, let us consider the simple case of four nodes a, b, c, d , a being in sync with b , and c in sync with d . c moves in the direction of b . When c arrives in the vicinity of b , none of them may emit beacons —nor listen to incoming ones— because they may be synchronized on d and a , respectively. In such a situation b and c would be perfectly unable to detect their new geographical neighbor. Figure 2.1 illustrates this.

This is an issue since it hardly impedes the creation of multi-hop ad hoc networks.

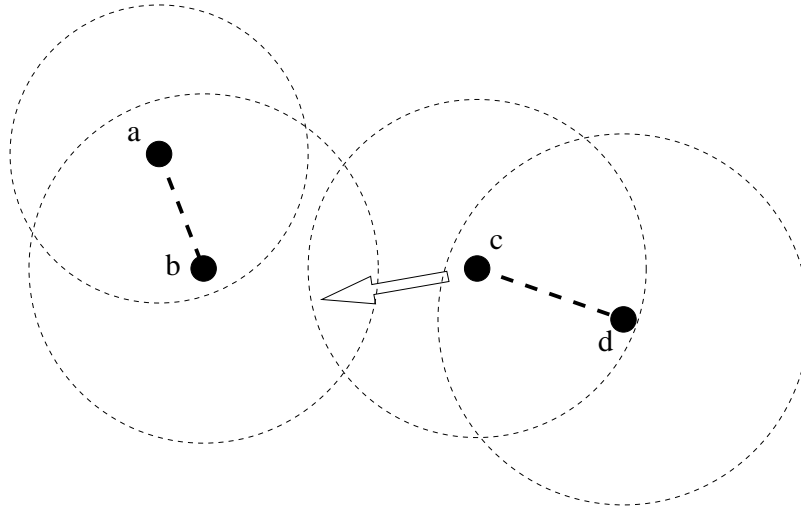


Figure 2.1: *b* and *c* are unable to detect one another because they do not emit nor receive beacons.

2.8.2 Latency of the discovery

When two given nodes get in range, if there is no synchronization issue, they should be capable to detect the presence of each other. The duration of this discovery process is sometimes an issue.

Using IEEE802.11b-enabled devices, the discovery is reasonably fast if at least one of the two nodes is emitting a beacon frame. The node that is not emitting any beacon frame (or whose the clock is set backward) will synchronize to the other nodes' clock. Since ten beacon frames are sent during one second, the discovery of a new node lasts at most one tenth of a second plus the time needed to perform the synchronization and to establish the link. This generally lasts less than a second. As explained in Section 2.2.2, if both nodes previously received beacons frame from other nodes, they have turned to passive, thus they are not emitting any beacon. Consequently they are not visible and have no chance to discover each other.

Using Bluetooth, two mechanisms are at issue. On the one hand, the time required by Bluetooth module to scan the carrier for new neighbor takes a few seconds. In the case of mobile nodes, this is an issue: since the diameter of coverage area of Bluetooth nodes do not generally exceed twenty meters, a module moving faster than 6 m/s (roughly the speed of a bicycle) crosses the coverage area of another module in at best 3 seconds. Which is too short to allow detection. Bluetooth as it works now it then now suitable for highly dynamic ad hoc networks. On the other hand, because Bluetooth modules use only 3-bit MAC addresses, Bluetooth piconets (that is how Bluetooth ad hoc networks are called) cannot gather more than 8 devices (1 master and 7 slaves). Moreover, Bluetooth scatternets are not well-developed today. Most researchers have focused on theoretical

concepts. Some algorithms for scatternet formation were proposed [CMA04], on the basis of simulations. The BTnode project [BKM⁺04], conducted at ETH Zurich, is one of the first actual implementations of Bluetooth scatternets.

Chapter 3

Target applications

Mobile ad hoc networks are mostly used today for physical sensing (temperature, pressure, etc) and for military applications. Their probable deployment in the near future will make them a new execution platform for many distributed applications. But because of their intrinsically highly dynamic nature, mobile ad hoc network will likely serve as the execution support of loosely distributed applications. In the coming subsections are describe some applications that should be executable on a mobile ad hoc network. Indeed distributed application whose the components are tightly coupled do not support connection disruption. For example, in the case of a J2EE three-tiers distributed application, when the database gets disconnected from the application server, the whole application gets out of order.

3.1 Vehicular ad hoc networks

Vehicular Ad hoc Networks (VANETs) [TMJH04] represent one of the most promising civil application scenarios for ad hoc networking since it already constitutes a business involving several big companies like XEROX, BMW and many others.

VANETs rely on two approaches:

- Inter-Vehicle Communication (IVC). In this approach, all vehicles behave equally. They are connected to each others (in accordance to their distance) so that they constitute a pure ad hoc network.
- Roadside-to-Vehicle Communication (RVC). In that approach, access points are installed on the roadside. Located regularly, they constitute a backbone to the vehicular wireless network. However, although it is made of mobile entities communicating via the wireless link such a network could not be be qualified as ad hoc.

VANETs will help to avoid crash situations but also significantly improve the comfort and efficiency of driving with respect to time and energy. Further, they can also be used for reducing traffic congestion and for enabling automatic driving.

VANETs exhibit an issue which seems to have apparently not been tackled up to now: there exists a threshold in how relatively fast (emitting and receiving) nodes move above which the receiver are no longer capable to demodulate the incoming signal. For instance, Hiperlan is announced to feature a tolerance to mobility which is about 10m/s, meaning that two nodes moving at a relative speed greater than about 35km/h would not be able to communicate. This upper-bound limit might pose problems in the context of VANETs.

3.2 Sensing

A wireless sensor network [ASSC02] is a computer network consisting of many, spatially distributed devices which embed sensors to monitor conditions at different locations, such as temperature, sound, vibration, pressure, motion, etc. Sometimes these devices are small and inexpensive, so that they can be produced and deployed in large numbers. The size and price requirements implies that their resources in terms of energy, memory, computational speed and bandwidth are severely constrained. Each device is equipped with a radio transceiver, a small micro-controller, and an energy source, usually a battery. Each device relays information from other devices to transport data to a monitoring computer.

[DM05] states that sensor networks actually are ad hoc networks, but mobility is absolutely not central to ad hoc networks. As a matter of fact, most sensor networks are made of immobile sensor, strategically located so as the collaborative measurement system is appropriate. But in some case sensors are deployed in mobile terrain. For example there exist sensors which are meant to study the behavior of tornados. Then hundred of them are carried by the wind and report location, speed and pressure measures. In such a case of a sensor network, mobility is key. Applications of sensor networks include environmental and medical monitoring, seismic Detection, habitat monitoring, acoustic detection, military surveillance, etc.

3.3 Personal area networking

A personal area network (PAN) is a network used for communication of computer devices close to one person. Those devices include mobile phones, personal digital assistants, home computer, audio systems, etc. The coverage range required is generally of a few meters. PANs can be used for ad hoc communication among the devices themselves or for connecting to a backbone network like the Internet.

Up to now, personal area networks have been wired, relying on technologies such as USB and FireWire. In the past years, IrDA and Bluetooth became of common use. Efforts to turn Wi-Fi to a PAN technology have already started and Wi-Fi enabled devices (typically printers, video cameras) can be found on the public market.

3.4 Military systems

Military applications are one of the most often described applications of mobile ad hoc networks. Unfortunately, since military projects are discrete—if not secret—few information is available. One of the main objectives of the militaries is to be able to deploy digital networks on difficult terrains— terrains on which it is not possible to install any infrastructure prior to the arrival of the soldiers. For example, such a digital network would allow soldiers to continuously be aware of the location of their peers. Today soldiers communicate with their peers using analog communication techniques such as radio-frequency. Using digital communication would allow them to exchange structured data such as maps or pictures of the terrain.

Within a military ad hoc network, the soldier is the network node. In this context, one of the main issues are to find strategies which ensure that the ad hoc network will remain connected as soldiers move. This problem is known as topology control. Military ad hoc networks also have a deep concern with security and reliability.

3.5 Peer-to-peer computing

The term grid computing [TL03, AvLM04], whose the ideas were brought together by Ian Foster and Carl Kesselman, originated in the early 1990s. It is a metaphor for making computer power as easy to access as an electric power grid.

More precisely, grid computing (or “metacomputing”) provides a model for solving massive computational problems: it makes use of the CPU and storage resources of large numbers of computers (generally desktop computers) seen by the application as a large virtual one. Grid Computing focuses on supporting computations across clusters of computers located in distinct administrative domains. It then aims at federating the resources generally used for cluster computing (or distributed computing) [ANG01, ASG97] which operates on one single set of nodes located at one spot. Grid computing is then mostly concerned by inter-operability and security issues, while cluster computing is more concerned by job-scheduling, load balancing, etc. Grids can be declined according to what they aim at:

- Computational grids [FK00] which focuses primarily on computationally-intensive operations, job-scheduling, (dynamic) load balancing, etc.
- Data grids [Old01, CFK⁺99] which focus on strategies maximizing the storage space available and reliability, minimizing the latency of retrieval.

The most prominent project in grid computing is Globus [All]. Other projects include Unicore, Legion [GWT97, ANG01, GWF⁺94].

The idea behind ad hoc grid computing is to use the massive computational power provided by the huge amount of mobile devices for solving computationally hard problems. A number of issues must be solved before in order to enable this.

- the high dynamic nature of mobile ad hoc network imposes that the distributed components of the grid-application must be loosely coupled;
- because of the high likeliness of node mobility or link failure, some robust scheduling strategies must be defined;
- an inter-operability mechanism has to be designed, in order to overcome the diversity of the devices ;
- because the nodes do not belong to a single administrative entity, security is a prime issue: the nodes have little knowledge of one another ; trusts mechanisms must then be employed. In this context, the concept of “reputation” is promising.

3.6 Risk management

Emergency applications are of prime importance, for example, in the populated areas in which lots of hazardous companies are present. This is particularly the case in certain region where the chemical industrial areas are a few kilometers away (sometimes even less) from densely populated areas. In such a context, it seems essential to be able to provide the population with some information on the danger and instructions on what to do, as fast as possible. Currently, such warning systems are achieved by the use of sirens (sometimes hardly audible) evenly located in the populated areas. Another solution would be the use of a citizen ad hoc network.

There would then be an emergency application (some sort of broadcasting protocol) deployed on all the mobile devices (mobile phones, PDAs, etc) of the civilians. A company facing an highly dangerous issue could trigger the dissemination of a “catastrophe message”. Rapidly, relayed by the mobile devices of the citizen, such a message would be received by almost everyone. The broadcasting of such a message would operate without any consideration of the bandwidth utilized, since its importance would be much higher than *any* other application.

3.7 Advertising

The implication of mobile ad hoc networks in e-business applications is not well described in the literature. So far, only few applications considered it. This is the case of the UbiBay project [FLS02], a decentralized auction system for mobile ad hoc networks.

The diffusion of small advertisements constitutes another interesting e-business application. Given a metropolitan ad hoc network deployed at the level of a city (or a large sub-set of it), it would be commercially relevant to be provided with the possibility to broadcast advertisement messages across the network. Common broadcasting scheme could not be applied in this context: commercial applications should leave most of the bandwidth available to more important applications, such as emergency ones 3.6.

The principle of small-advertising over mobile ad hoc networks is as follows: a person (the seller) willing to sell a good write a short description of it, and attaches to it his contact information. The description—the small ad itself—is broadcasted over the network. In order to restrict the propagation of the message, a maximum number of allowed hops is specified in the message. Upon reception of the message, the recipient node decreases this maximum number of hops. Then the message is candidate to forwarding only if the number of hops is greater than zero. A person whose the mobile device has received a small-ad is alerted by a sound or something similar. If this person (the buyer) wants to acquire the advertised good, he might simply use the contact information embedded in the message for reaching the seller.

Part II

Simulation

In the situation today, real mobile ad hoc networks are not yet developed at a city-scale, conducting research on mobile ad hoc networks is achievable either by using experimentation networks (called “testbeds”) or by resorting to software simulation. In the literature, it appears that most of the work today is done by using simulators. Indeed testbeds have a number of drawbacks like their high cost, the difficulty to build one, the difficulty of monitoring them, etc. These drawbacks still refrain research labs from building large test-beds. The study of large-scale applications—which is our very concern herein—most often opt for modelling and software simulation. Researchers can then follow two directions, depending on their needs: either using one of the simulators made available to the community or developing a custom simulator tailored to their purpose.

The world of simulators is largely dominated by ns-2. ns was originally targeted at the simulation of wired networks. Its subsequent versions, ns-2, came with an extension for mobile ad hoc networks. ns-2 is open-source and provides an implementation for most of the protocols for mobile ad hoc networking. Less popular, simulators like GloMoSim or Qualnet have advantages like the possibility to distribute the simulation over a cluster of workstation, or to provide commercial support.

Although there already is a good wealth of simulators available on the market, as mobile ad hoc networking research evolves it appears that more and more research groups favor the development of custom simulators. Among the limitations of the most popular wireless network simulators are the inability to simulate heterogeneous networks (that is networks consisting of several radio communication technologies like IEEE802.11b or Bluetooth), the difficulty to simulate large networks (on sequential simulators like ns-2, a few hundred nodes seems to be an upper limit) and the lack of realistic mobility models. Currently, most of the work in the field of mobile ad hoc networking rely on randomized mobility models, such as the so-called “Random waypoint mobility model” is the one which is most commonly used. These drawbacks constitute as many challenges that will be considered in the rest of this document.

My work takes place in the framework of several multi-national academic projects. Each of them came with different requirements. In particular the SoNi project [Uni07] (Luxembourg) which was the initial source of funds aims at providing a framework allowing the prototyping of fresh network primitives as well as ad hoc applications, all considering realistic network conditions.

In the context of the GraphStream project [AD07] (France), researchers were looking for a tool permitting the study of mobile ad hoc networks seen as complex systems (systems made of highly numerous autonomous entities working independently at the emergence of a global behavior).

One of the issues tackled by The SARA project (France) is the design of an experimentation platform for the study of Delay Tolerant Networks (DTNs). A key issues was then how

to couple a test-bed and a mobile ad hoc network simulation so that the test-bed would be virtually expanded by the simulated network. More precisely, the researches had before build a IEEE802.11b-based network of laptops. On top of this they have implemented a groupware application for the dissemination of documents. One of the perspective was then to extend the network (in terms of the number of nodes) in order to observe the behavior of the application. MADHOC was then used at managing a number of “virtual” nodes. A software bridge then enables real nodes to transparently interact with virtual ones.

The ABBASMUS [Uni] project addresses the issue of topology control for ad hoc networks. More precisely it aims at providing new topology control schemes based on the use of “injection points”—connections from the ad hoc nodes to some infrastructured network. This project hence required a simulator allowing the representation of links.

Last, in the framework of studies on multi-objective optimization (MOO), researchers at Málaga University needed a simulation tool permitting the optimization of broadcast protocols. Using some results of one single simulation process as the value of the fitness function for their MOO algorithms, the key issue was to use a simulator that would be able to operate the simulation of one broadcasting process in less than a second, in average.

The diversity of the requirements formulated by our academic partners imposed the development of a custom simulator, named MADHOC. Indeed no other simulator would have permitted us to meet the needs.

MADHOC is characterizable in a number of ways. Maybe its more relevant aspects lie in its hybrid simulation engine and its mobility models, as explained in the following.

The philosophy design of MADHOC is twofold. From a general perspective, MADHOC is object-oriented. In particular, the application programming interface it exhibits is made of classes and objects, as it is usual in software design. However, as often as possible, MADHOC models things in a probabilistic way. In particular, the model for the physical network layer makes use of statistics. Doing this lightens the simulation engine. This provides MADHOC with the ability to efficiently simulate large population of nodes (up to twenty thousands nodes on regular desktop computers). The use of statistics avoids MADHOC to implement loads of complex low-level mechanisms that would have required a huge computational power and long time to execute. Instead an statistic-based implementation rely on a small set of equations that are executable in a short time.

MADHOC provides a set of mobility models which includes the ubiquitous random waypoint and random walk mobility models. In addition to this, it provides a more sophisticated mobility model aiming at reproducing some properties of the mobility of humans. This mobility model is called the “human mobility model” (HMM). Briefly, HMM considers that the environment in which the nodes evolve has a number of particular areas (called “spots”) in which nodes tend to go and stay for some time. These areas may

represent shop, or traffic lights, for example. For the moment, a randomized decision function rules the motion of the nodes which move from spot to spot, taking care at not visiting twice the same spot.

This part of the present document focusing on ad hoc networking experimentation tool. It is divided in two sections. It first presents in Chapter 4 a State of the Art of the experimentation platforms for mobile ad hoc networking, which include testbeds and simulators. Then Chapter 5 describes MADHOC, a simulation-based experimentation environment targeting the simulation of city-scale ad hoc networks.

Chapter 4

State of the Art

The State of the Art presented in this chapter first briefly introduces in Section 4.1 mobile ad hoc networking testbeds, by providing a list of remarkable ones, and by explaining the pros and cons for the use of such networks. Then it provides in Section 4.2 a description of the wireless network simulators available, indicating the criteria that should guide the researchers in search of the simulator that will best meet his needs. In section 6.1 is given an analysis of the mobility models that are commonly employed in the context of the investigation of human mobility. Finally, Section 4.3 presents a list of the issues that are encountered when dealing with mobile ad hoc network simulation, and section 4.4 consists of the author's point of view on how mobile ad hoc network simulation will/should change in the future.

4.1 Testbeds

Definition — Testbeds are in-lab networks built and used by researchers. They are dedicated to the experimentation of protocols and applications over mobile ad hoc networks.

A survey of the existing testbeds is proposed by De and al. [DScC].

Typically, testbeds consists of devices communicating through the TCP/IP network stack. Most research projects use testbeds to find out of how TCP/IP operate in the context of ad hoc networking. Ultimately, they permit the development of extensions that make TCP/IP work better. Aside to this research focusing on the possible applications of the internet protocols to ad hoc networking, some projects are based on the assumption that such protocols do not suit mobile ad hoc networking. These projects hence aim at defining brand-new techniques for enabling single-hop (defining physical and data-links layers, respectively referred to as PHY and MAC layers) and multi-hop communication (which is vastly concerned by routing techniques, seated at the network layer). Such projects include DoDWaN [GR04], described in Section 4.1.1.

4.1.1 Some testbeds

Among all existing testbeds, the following ones are remarkable because of the number of devices they gather, or because of the nature of communication link they use.

- The APE project [LLN⁺02] experimented routing on 37 IEEE802.11 nodes. Numerous participants were involved—particularly for moving the devices—which impacted the high costs and difficulty of the experiments. APE was built by the department of Computer Systems at Uppsala University (Sweden) and was partly funded by Ericsson.
- The RoofNet project (MIT) [CACM03], conducted over the city of Cambridge (UK), uses 40 IEEE802.11 nodes. It primarily aims at studying mesh networks but it is also employed at investigating multi-hop routing on MANETs. Citizens can connect to the Internet through the research network. The RoofNet project uses static nodes. It hence does not deal with mobility issues.
- Focusing on multi-hop routing, Douglas and Raichle [KR01] used a MANET testbed made of 8 IEEE802.11 nodes.
- Ritter and al. [RTVS03] built a Bluetooth network for experimenting gaming and home automation. In order to have a global view of the network—which makes monitoring it a lot easier—they used 300m-range EWM adapters. This testbed is one of the rare projects that make use of the Bluetooth technology.
- The Ad Hoc City project [JHP⁺03] uses an mixed approach: both wired and wireless stations are used. By covering in time and space the whole city of Seattle (Washington, USA), real information of nodes' movements could be gathered. This testifies the current trend towards realistic mobility models.
- the DoDWaN testbed is dynamically created by mobile devices joining a single-hop network. The devices communicate with one another by using the IEEE802.11 MAC. DoDWaN takes into accounts the properties of the delay tolerant networks. For example, in a document dissemination application, stations that are not present when the document dissemination was initiated will receive it when they will get in contact with stations that were present at that time.

4.1.2 Issues

On the one hand, testbeds allow the researchers to run experiments using the real devices. While, as described in Section 4.3.1, accuracy of the experimentations is at issue when dealing with simulators, testbeds always provide accurate response.

On the other hand, testbeds suffer from numerous drawbacks, as listed in the following:

- the number of devices they involve is limited: the cost of the hardware (one node is several hundred euros) limits testbeds to few dozen nodes;
- the experimentations conducted on testbeds are not reproducible—reproducibility being a prime feature of scientific experimentation;
- they are not scalable;
- the inherently distributed nature of ad hoc networks constitutes a great lack of flexibility. More precisely, because the network cannot be handled as a whole, monitoring is difficult. Because the network is made of several devices, deploying an application implies a deployment on all devices.
- unless the devices are embedded on some sort of vehicle, they become mobile only if someone is here to move them.

There have been a few attempts to overcome this issues, as presented in the next section.

4.1.3 Proposed solutions

In order to overcome these limitations of real-scale testbeds, assorted solutions were proposed. Among them:

- the EWANT project [SBBD03] reduces the dimensions of the network to make it fit on a table-top. The downscaling of the radio links is achieved by the use of two-way attenuators.
- Zhang and Li [ZL02] emulate the IEEE802.11b communication links by ethernet cables. The impact of mobility is replicated by altering the routing tables.

These techniques aim at overcoming one issue of testbeds but they in no way make them usable in the framework of an experimentation campaign, for example.

So far, no techniques was proposed in order to increase the number of nodes implied in a testbed. In the analyzed literature no testbed of more than 50 nodes were proposed. On the contrary many studies drastically require the use of large networks, as explained by Riley and Ammar [RA02].

4.2 Existing simulators

Researchers who investigate ad hoc networking through simulations either use full-featured simulators or rely on some custom simulators (which sometimes are quite simple models) built for that purpose. In this section, only a small subset of the custom simulators is

taken into consideration, since it is impossible to have a global picture of what they allow and who is using them. Nevertheless, it is interesting to know that, discussing with the researchers among the ad hoc network community, many researchers prefer to rely on such custom tools instead of fighting the complexity of popular simulators.

The literature mentions about twenty MANETs full-featured simulators currently in use. Wired network simulators [ACGW95] and sensor network simulators [SPS00, PBM⁺04] are not taken into consideration here.

Since the wireless extension for ns-2—which constitutes the first MANETs simulator—numerous tools have been made available to the community. Some of them have even broken through and are now massively used. Because of the variable needs of research projects, many researchers do not wish to use these simulators. Indeed not all research projects focus on the lowest layers of the network stack. More and more people are actually looking at the highest layers, i.e. at developing new concepts and applications for MANETs (service discovery, customer-to-customer applications, gaming, etc). For example, Hellbrück and Fischer developed ANSim [HF02], an interactive MANETs simulator, in order to analyze the structural properties of the MANETs. Görgen and al. [GFH05] work on ad hoc gaming, using the Jane simulator [FGLS03, LGFS04]. Working on advanced broadcasting protocols and messaging applications, Hogie and al. wrote MADHOC [Hog05] because none of the simulators available both featured an interactive mode making debugging of broadcasting protocols easy and permitted the simulation of large networks. More custom simulators are described in the following.

The simulators described in this section are either commercial solutions or lab-tools that gather some users thanks to their specificities.

4.2.1 Major simulators

This section provides descriptions of the simulators dominating the market. They are ordered by decreasing popularity.

4.2.1.1 ns-2

ns-2 [ns2] is the *de facto* standard for network simulation. Its behavior is highly trusted within the networking community. It is developed at ISI, California, and is supported by the DARPA and NSF. *ns-2* is a discrete-event simulator organized according to the OSI model and primarily designed to simulate wired networks.

The support for wireless networking had been brought by several extensions. The Monarch CMU projects [Mon98] made available an implementation of the IEEE802.11 layers (Wi-Fi). The BlueHoc [Lab] and BlueWare [Bar02] projects provided the Bluetooth layers.

ns-2 provides a set a randomized mobility models, including random waypoint. Advanced node mobility had been make available by the Graph Mobility project [THB⁺02], the GEMM project [RS04], and the Obstacle Mobility [JBRAS03, JBRA⁺05] model. These constitute a progress towards realistic simulation.

The core of *ns-2* is a monolithic piece of C++ code. It is extendable by adding C++ modules. The configuration relies on OTCL (a dialect of TCL, developed by the MIT) scripts. *ns-2* then appears to the user as an OTCL interpreter. More precisely, it reads scenarios files written in OTCL and produces a trace file in its own format. This trace needs to be processed by user scripts or converted and rendered using the NAM tool.

Thanks to its open source licence and its popularity, new extensions are sporadically proposed. For example, Dricot and De Doncker [DD04] proposed a highly accurate physical model based on ray tracing and Markov chains. This extension, which can be very useful for MANETs simulation, makes the simulator to be about 100 times slower.

ns-2 is a sound solution to MANET simulation. Unfortunately it suffers from its lack of modularity as well as from its inherent complexity (*ns-2* was candidate to be the basis for the Qualnet [Net04] simulator but got finally rejected). Indeed, adding components/protocols or modifying existing ones is not as straightforward as it should be. For a long time, *ns-2* has been said to have few good documentation. The situation recently changed, as several users have put online their experience in the form of tutorials or example-driven documentations.

Another well-known weakness of *ns-2* is its high consumption of computational resources. A harmful consequence is that *ns-2* lacks scalability, which impedes the simulation of large networks (*ns-2* is typically used for simulations consisting of no more than a few hundreds nodes). Several projects have aimed at improving *ns-2*'s runtime. For example, staged simulation [WS04] (see section 4.3.2.2) and parallelism (see section 4.3.2.1 and next item) have turned out to be efficient solutions. [ESB⁺04] used was ns-2 version 2.26 and reported their experience, as follows: the wireless ad hoc version of ns-2 can handle a few hundred nodes, but the simulation time grows at least quadratically so more than just a few hundred is simply not feasible, in fact most current work [BMJ⁺98, SRDY98] is done simulating about 50 wireless nodes or less.

The Parallel/Distributed Network Simulator, *pdns* [RFA99], is developed at Gorgia Tech institute, California. It aims at overcoming the limitation of *ns-2* regarding its scalability. *pdns* boosts *ns-2* processes by distributed the simulation over a network of closely coupled workstations (a common TCP/IP-based local area network is usable). More precisely, it achieves an efficient parallelization of the simulation process by making distinct instances of *ns-2* simulating distinct sub-networks. *pdns* is said to be able to simulate networks consisting of up to hundreds of thousands nodes.

Although its code (particularly its library of protocols) have not been validated entirely,

it is a heavily trusted simulated among the community.

The development of the next major revision of the ns-2 simulator has started in July 2006. The ns-3 project [Inf06] is presently a work in progress. For the moment it does not include any code for the simulation of mobile wireless networks.

4.2.1.2 GloMoSim

GloMoSim [ZBG98] is developed at UCLA (California, USA). It is the second most popular wireless network simulator. GloMoSim is written in Parsec [BMT⁺98] and hence benefits from the latter's ability to run on shared-memory symmetric processor (SMP) computers. New protocols and modules for GloMoSim must be written in Parsec too. GloMoSim respects the OSI standard.

The parallelization technique used by GloMoSim is the same than *pdns*'s one; that is the network is split in different subnetworks, each of them being simulated by distinct processors. The network is partitioned in such a way that the number of nodes simulated by each partition is homogeneous.

GloMoSim uses a message-based approach to discrete-event simulation. More precisely, network layers are represented as objects called “entities”. Events are represented as time-stamped messages handled by entities. GloMoSim's network model does not define every network nodes as entities because this would lead to too numerous objects. Instead, GloMoSim uses entities to model network layers. Messages—which represent network events—then cross the layer stack by being interchanged by the entities. GloMoSim can simulate networks made of tens of thousands devices.

Just like *ns-2*, more realistic simulation have been made possible by extensions such as the Obstacle mobility model [JBRAS03][JBRA⁺05] and the GEMM project [RS04]. A java-based visualization tool is provided.

The qualities of GloMoSim permitted it to be chosen as the core of the commercial QualNet simulator (detailed in Section 4.2.1.5). GloMoSim is said to suffers from a lack of a good and in-depth documentation.

4.2.1.3 OPNet

OPNet [DBD93] (Optimized Network Engineering Tools) is a discrete-event network simulator first proposed by MIT in 1986. It is a well-established and professional commercial suite for network simulation. It is actually the most widely used commercial simulation environment. OPNet Modeler features an interactive development environment allowing the design and study of networks, devices, protocols, and applications. For this, an extensive list of protocols are supported. Particularly, MAC protocols include IEEE802.11a/b/g and Bluetooth ones. One of the most interesting features of OPNet is its ability to exe-

cute and monitor several scenarios in a concurrent manner. In spite of its wide adoption, some doubts remain regarding the dependability of its MANETs simulation engine. More precisely, Cavin and al. [CSS02b] simulated a broadcasting process on the OPNet, *ns-2* and GloMoSim simulators (each of them is detailed in this section). It came out that the results obtained using OPNet were barely comparable to those harvested out of *ns-2* and GloMoSim, which exhibited similar behaviors. The divergences were quantitative but also qualitative (not the same general behavior). OPNet is written in C++.

4.2.1.4 OMNET++

OMNet++ [SI01] is a well-designed simulation package written in C++. OMNet++ is actually a general-purpose simulator capable of simulating any system composed of devices interacting with each others. It can then perfectly be used for MANETs simulation. The mobility extension for OMNeT++ [DSH⁺03] is intended to support wireless and mobile simulations. This support is said to be fairly incomplete. OMNet++ is used in the context of academic research and education.

4.2.1.5 QualNet

QualNet [Net04] is a commercial ad hoc network simulator based on the GloMoSim core. It extends the GloMoSim offer by bringing support, a decent documentation, and a complete set of user-friendly tools for building scenarios and analyzing simulation output. QualNet also extends the set of mobility models and protocols supported by the initial GloMoSim distribution. As it is built on top of GloMoSim, QualNet is written in Parsec [BMT⁺98].

4.2.1.6 GTNets

GTNetS [Ril03] is developed at GeorgiaTech institute (Atlanta, USA). According to its authors, the design philosophy of GTNetS is to create a simulation environment that is structured much like actual networks are structured. More precisely, in GTNetS, there is clear and distinct separation of protocol stack layers and the network programming interface used by applications use function calls similar to the ubiquitous POSIX standard. The parallelization ability of GTNetS makes it possible to distribute a single simulation over either a network of loosely coupled workstations, a shared-memory symmetric multiprocessing system (SMP), or a combination of both. This provides GTNetS with good scalability. It consequently allows the simulation of large networks. Concerning the support of protocols, IEEE802.11b as well as Bluetooth [ZR04] are implemented. Another benefit of GTNetS is that the simulator gathers statistics regarding its own performance. The graphical user interface provided with GTNetS supports the graphical representation of the simulation topology, with selective enabling and disabling of display for specified

nodes and links. It is open source.

4.2.2 Some custom simulators

This section provides descriptions for some of the simulators made available recently. The simulators which are mentioned here stand out for the characteristics they have or because they started a break through.

4.2.2.1 NAB

NAB [ISI04] (Network in A Box) is a discrete event simulator developed at EPFL (Lausanne, Switzerland). NAB is dedicated to MANETs simulation. By focusing on scalability and visualization and by featuring a very realistic mobility model (a constrained waypoint based on city maps), it meets the needs of cutting-edge applications. According to its author, NAB was born out of the inability to simulate large ad hoc networks with existing tools, and some impatience in dealing with their internal complexity, which tended to make implementing new functionality a lengthy and bug-ridden task. NAB's design is node-oriented (as well as object-oriented); that is each node is represented by an object. It is written in OCaml and is actually the only simulator written in a language whose syntax is not derived from C. It is open source.

4.2.2.2 SWANS

SWANS [Bar04], developed at Cornell university, is a Java-based wireless network simulator built atop the JiST discrete event platform. SWANS boasts a highly efficient sequential simulation engine. It has been compared to GloMoSim, in terms of quality.

JiST relies on the concept of virtual-machine simulation. The way SWANS implements simulated time is singular: the simulated time is not managed by some shared clock. Instead, each entity (referred to as a *TimeFull* entity) is in charge of determining the time needed to its execution. By invoking each TimeFull entities in a sequence, SWANS gets able to determine the current simulated time. SWANS appears to the user as a framework. It must be programmed in plain Java, using an application programming interface. SWANS is developed in Java. It is open source.

4.2.2.3 J-Sim

J-Sim [CL] (formerly known as JavaSim) is developed at Ohio and Illinois Universities (USA). It is a component-based, compositional simulation environment. Initially designed for wired network simulation, its Wireless Extension proposes an implementation of the IEEE802.11 MAC—which is the only MAC supported so far. This extension turns J-Sim to a viable MANETs simulator. J-Sim also features a set of components which facilitates basic

studies of wireless/mobile networks, including three distinct radio propagation models and two stochastic mobility models. J-Sim is written in Java. It is open source.

4.2.2.4 Jane

Jane [FGLS03, LGFS04] is developed at Trier University (Germany). It consists of both a simulation environment and an execution platform. Its main interestingness is that it allows the simulation code to be migrated to the real devices without any modification. Jane also features an emulation mode that allows real devices to participate to simulations. In addition to that, Jane features high-level concepts (such as the notions of *service*, *message*, etc) that are suitable to the simulation of applications-level services. It also makes use of GPS information, what turns it to an appealing tool for the simulation location-based services. Jane is written in Java. It is open source.

4.2.2.5 Dianemu

DIANEmu [Kle03] is a discrete-event simulator developed at Karlsruhe University (Germany). It aims to enable the simulation of ad hoc applications in realistic contexts. So far, most simulators have been designed to permit simulations at a protocol-level. DIANEmu's approach is different: it assumes that the lowest network layers (up to the fourth one) are available. DIANEmu then focuses on the application model. DIANEmu belongs to a new class of simulators which allow the large-scale simulation of high-level applications such as gaming and e-business.

DIANEmu provides a complete environment for application design. Its simulation engine is closely coupled to its graphical interface. Attesting of its modern design, its measurement system is event-driven. More precisely it defines that to each event class is associated to a given handler (referred to as a *gauge*). This handler is then dynamically invoked when the events of the specified class occur. This technique is detailed in Section 4.3.3. DIANEmu is written in Java. It is free.

4.2.3 Simulation languages and frameworks

Several simulators like GloMoSim [ZBG98] and SWANS [Bar04] have been developed using languages, libraries and frameworks dedicated to discrete-event simulation. These middleware technologies typically focus on performance, concurrency and distribution. As detailed by Barr and al. [BHvR04], one approach has been to create new simulation languages that are closely related to popular existing languages, with extensions for message dispatch, synchronization and time management. Csim [Sch96], Yaddes [Pre89], Maisie [BL94], and Parsec [BMT⁺98], for example, are derivatives of C and C++. Others, such as Apostle [BB97] and TeD [PFO98] have taken a more domain-specific language approach.

Finally, projects like Moose [WB94], Sim++ [Ba90], JIST [Bar04], J-Sim [CL] and Pool [AvdL90] investigated various object-oriented (OO) possibilities for check-pointing, inheritance, concurrency and synchronization in the context of simulation. Currently, the most popular development language/platform for MANETs simulation is Java McNab and Howell [MH] discusses the pros and cons of Java for discrete-event simulation.

4.2.4 Which simulator for what need?

When starting research of mobile ad hoc networking, many researchers directly look at *ns-2*, neglecting the wealth of simulators available. This is because *ns-2*'s behavior is highly trusted and that it features (unlike most other simulators) an extensive library of pre-implemented protocols. This latter feature often simplifies greatly the experimentations since it saves a lot of time to the researchers who hence do not have to re-invent the wheel.

But MANETs simulators exhibit various features and models. The choice of a simulator should be driven by the requirements.

Only one of the key criterion for deciding on which simulator to use is the level of details required by the experimentations. If high-precision PHY layers are needed, then *ns-2* (coupled with the highly-accurate PHY [DD04]) is clearly the wisest choice. On the contrary, if the wireless technology is thought to have little impact on the targeted protocol (as the stage of the experimentation, this has to be an assumption), simulators like NAB or Jane which propose high-level abstractions and polished object-oriented designs will be more adequate.

The number of nodes targeted should determine the choice of the simulation tool as well. Sequential simulators should not be expected to run more than 1,000 nodes. If larger scales are needed, then parallel simulation may be necessary. Highly optimized simulators like *ns-2* coupled with stage simulation might also be at consideration.

In the context of academic research, using a simulator which has very few users may be a wise choice since its author is easily reachable and might be convincing for developing custom extensions.

Finally, most non-commercial simulators suffer from a lack of good documentation and support. Using a commercial one might help in case of troubles. Moreover, commercial simulators usually feature extensive lists of supported protocols while open source solutions give full empowerment.

4.3 Issues

Mobile ad hoc network simulation presents many advantages. However a number of issues still impedes correct experimentation. Some of the major issues are presented in the following.

4.3.1 The accuracy of mobile ad hoc networks simulators

A general severe drawback of simulation is accuracy. Indeed, simulators use discrete or incomplete models of the reality leading to results that can be qualified from “insignificantly imprecise” to “qualitatively erroneous”, with few possibilities to measure the degree of error.

In particular, there have been some studies [RA02, HBE⁺01, CSS02b] focusing on the accuracy of simulations. Some of them have pointed out that there exists some significant variations in the way simulators operate. One cannot state that these variations can be expressed in terms of accuracy. Formally speaking, no network simulator is accurate. At best a simulator can be said to be *dependable* and *realistic*. Researchers who drastically need accuracy will want to conduct their experiments on the real devices, using testbeds. When this is not possible they will have to resort to simulation and hence to content with a certain level of uncertainty stemming from various causes listed in the sequel.

4.3.1.1 The impact of granularity

Building a computerized model that includes all details of the targeted system is merely impossible and generally not wanted. As such, models of real-world systems are designed with a certain granularity. In the specific case of MANETs, if software layers are relatively easy to re-implement within simulators, modelling the hardware inevitably leads to severe compromises.

Unfortunately, as studied by Heidemann and al. [HBE⁺01], neglecting details has in some cases a serious impact on the results obtained. Ideally the granularity of the model used should be defined according to the needs of the simulated application.

Table 4.1 gives some elements of the dependability for each simulator. Concerning table 4.1, as no metric is available for characterizing the level of granularity, we define `finest < finer < fine < medium < application-level`.

4.3.1.2 Mobility models

Up to now, most studies have relied on randomized mobility models [Bet01, WC02, JLH⁺99, PGHC99], especially on the Random Waypoint Mobility Model [YLN03]. Thanks to several studies focusing on the wallop of random waypoint mobility model [YLN03, BRS03, SLRV03], researchers are now aware of the harmful impact of stochastic mobility patterns. On the other hand, an effort towards more realistic mobility models can be observed through papers and projects like the Group Mobility Model [HGPC99], the Graph-based Mobility Model [THB⁺02], the Obstacle Mobility Model [JBRAS03, JBRA⁺05], the UDEL model [BS04a, BS04b], and the GEMM project [RS04]. Surveys of mobility models can be found in [CBD02, RS04]. Studying the impact of realistic mobility model on distributed applications, Tugcu and Ersoy [TE04] have shown that the choice of the

Name	Granularity	Metropolitan mobility
<i>ns-2</i>	Finest	Support
DIANEmu	Application-level	No
Glomosim	Fine	Support
GTNets	Fine	No
J-Sim	Fine	Support
Jane	Application-level	Native
NAB	Medium	Native
OMNet++	Medium	No
OPNet	Fine	Support
QualNet	Finer	Support
SWANS	Medium	-

Table 4.1: Elements of dependability: ganularity and mobility.

mobility model has a significant impact on the performance of the mobile systems. Furthermore, the effect on the relative performance becomes more important especially when the algorithms try to predict the mobility of the nodes.

4.3.1.3 Radio propagation models

Radio waves propagation constitutes another important aspect of dependability. Up to now, most studies have considered the free path loss propagation model, often coupled with randomized mobility patterns. It is advisable to remind that path loss is the power reduction of an electromagnetic signal upon the distance. The free path loss is the theoretical path loss of a signal whose the propagation does not suffer from the presence of any obstacle. Radio wave propagation is generally associated to mobility because both are constrained by the same environmental elements. Particularly, radio waves are subject to diffraction, refraction, and scattering. Up to now, no simulator implement these three properties of radio propagation. Current implementations rely either on statistical models [CP99] or on partial models of refraction. For instance, the UDEL project [BS04a, BS04b] as well as Dricot and De Doncker [DD04] model radio waves by using ray-tracing and Markov-chains. Unfortunately these time-consuming techniques dramatically impact the performance of the simulation processes (which are slowed down of up to 100 times, as stated in [DD04]).

4.3.1.4 Number of simulated nodes

Riley and Ammar [RA02] explained that there exists a threshold of the number of stations in the network for which the results obtained no longer vary as the number of stations increases. This threshold depends on the simulated application. Because of the lack of scalability of most simulators, this important aspect of protocol validation is generally neglected. Scalable simulators [ISI04, ZBG98] and runtime improvements techniques [RFA99, WS04, NG03] should overcome this problem.

Further, the quantity of nodes simulated does not only affect the results in a quantitative way. Sometimes, a simulation which involves not enough nodes leads to results that would be qualitatively different if more nodes were involved. A trivial example is the broadcast storm: experimenting the broadcasting issue (using the simple flooding protocol) over a network in which the average neighbor density (see section 6.1.3.4) is low will lead to the conclusion that the simple flooding protocol is perfectly fine for broadcasting in ad hoc networks. On the contrary, there exists a threshold of node neighborhood (actually a threshold of the number of nodes) for which simple flooding leads to a broadcast storm: not all nodes will then receive the broadcasted message. Note that this threshold depends of the bandwidth of the network connections and on the individual neighbor density of every nodes.

4.3.2 Simulation acceleration techniques

Most simulators for mobile ad hoc networks rely on discrete-event simulation. Briefly, discrete-event simulation is a modelling method that is worth applicable to systems that can be decomposed into a set of logically separate autonomous processes. The usage of discrete-events engines permit them to profit from the extensive research on scheduling and distributed systems. Table 4.2 details, for each simulator, which techniques have been employed in order to fasten the execution, or to improve the scalability.

4.3.2.1 Parallelism and distribution

Many simulators provide parallel engines. This is the case of *pdns*. Parallelism allows the user to execute them on computers equipped with several processors sharing memory. These simulators already benefit from the recent availability of low-cost multi-core processors. Farther, some simulators have the ability to be executed on distributed platforms (no resource is sharing in that case). This is the case for GloMoSim, GTNets, OMNet++, etc. These simulators are currently executable on cluster of workstations. In the close future, the rise of grid computing should permit these simulators to be efficiently executed over clusters belonging to different administrative domains.

Let us point out the COMPASS [com] project at GeorgiaTech, which makes an ex-

tensive use of distribution by building heterogeneous distributed simulations consisting of instances of *ns-2* and GloMoSim operating together.

Name	Parallelism	Interface
<i>ns-2</i>	No	C++/OTCL
DIANEmu	No	Java
Glomosim	SMP/beowulf	Parsec (C-based)
GTNets	SMP/beowulf	C++
J-Sim	RMI-based	Java
Jane	No	Java
NAB	No	OCaml
OMNet++	MPI/PVM	C++
OPNet	Yes	C
<i>pdns</i>	beowulf	C++/OTCL
QualNet	SMP/beowulf	Parsec (C-based)
SWANS	No	Java

Table 4.2: How simulators are parallelized and how they can be programmed.

4.3.2.2 Staged simulation

Staged simulation is described by Walsh and Sirer [WS04]. It is a general technique which improves the performance of discrete-event simulators by identifying and eliminating redundant computations. It consists of three parts: function caching, event-restructuring, and time-shifting.

Function caching avoids redundant computations by placing into a memory cache the arguments and results of function calls.

Event-restructuring improves on function caching by exposing low-level events that otherwise would have not been treated by function caching.

Time-shifting reorders the events into a sequence that is better suited to the computer architecture that executes the simulator. It also enables a sequence of small, consecutive events to be computed altogether by a single, more efficient algorithm.

The SNS project [WS04] applies staged simulation to *ns-2* and boasts a runtime 30 times faster than the original one.

4.3.2.3 Bining

Bining makes good use of the spatial localization of network nodes in the MANETs—it is actually practicable and widely employed in all systems made of spatially located objects. It consists in the division of the simulation area into a list-based (applicable on 1-dimensional simulation space), grid-based (also referred to as “flat binning”, applicable on 2D spaces) or tree-based (also referred to as “hierarchical binning”, applicable on 3D spaces) structures. Bining dramatically improves the determination of the communication links in the network. For example, applying flat binning reduces the complexity of this process from $O(n^2)$ to $O(n)$ (n being the number of stations in the network). This technique is described by Naoumov and Gross [NG03], who applied it to *ns-2*.

Recently, [BBDD05] proposed within the ARTIS simulator a method for adaptable binning. The principle is to divide the space according to the space distribution (see section 6.1.3.1) of the nodes. Then, the areas of the simulation in which the node density is high will exhibit more cells.

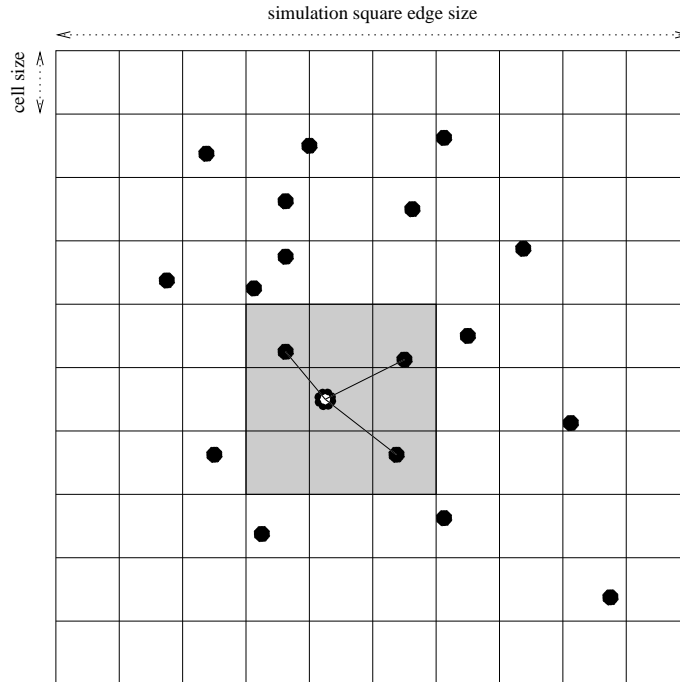


Figure 4.1: The emphasized station uses binning to reduce the search space (in which new neighbors must be found) to its immediate surrounding cells

4.3.2.4 Statistical simulations

Statistical simulation consists in replacing cumbersome object models or time-consuming analytical models by statistical models which, although they may provide a less precise

result, are much more lightweight in terms of the computational resource they require. This technique is getting more popular in the context of mobile ad hoc network simulation. In particular, it is extensively used in MADHOC (see section 5.2.2).

4.3.3 Visualization and debugging facilities

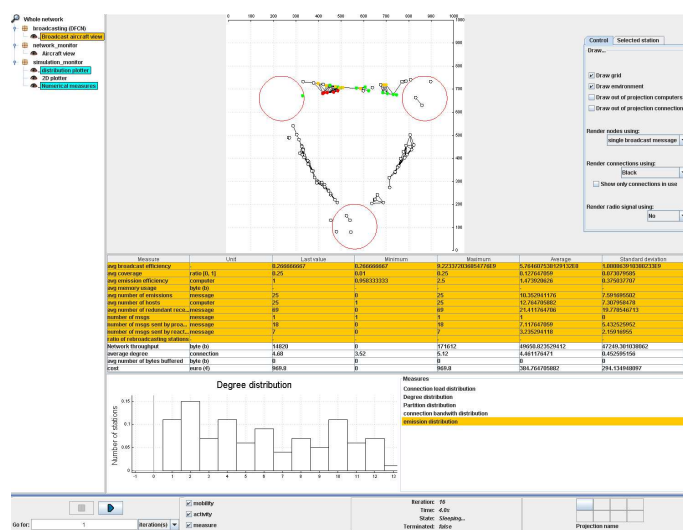
It has been recognized that distributed programming is inherently difficult. In addition to being distributed, “ad hoc applications” are typically decentralized. Worse, the highly dynamic nature of mobile ad hoc networks makes the development of protocols and applications extremely error-prone. It is then of a chief importance that the user is provided with efficient debugging and visualization mechanisms.

There exists two techniques which provide feedback on what happens within the simulation. Discrete-event simulation encourages the generation of a trace file containing a description of each event that occurred. This general technique reports all events to the user. Unfortunately because of the huge size of the generated trace, this technique consumes a lot of CPU resource (because of input/output operations) and thus significantly slows down the simulation process. Finally, the user needs to write text filters in order to retain only what he is interested in and to generate drawings. The alternative consists in dynamically interacting with the simulation engine by resorting to the *observer design pattern*. The measurement system is then event-driven. More precisely, the user initially announces the classes of events he is interested in. He will then be dynamically notified of such events as the simulation process progresses. DIANEmu [Kle03] and GloMoSim [ZBG98] use such a technique. Because the filtering process described before happens in the simulation engine, the CPU time required for outputting useless traces is saved. Besides, it permits the construction of interactive graphical interfaces, which proves to be of a prime importance for debugging and monitoring purposes.

MADHOC features a graphical user interface (showed on Figure 4.2) which allows the user to visualize an aircraft (2D) representation of the network it simulates. Through a set of numerical measures, the user has a view of the internal behavior of the simulated application as well as of the simulator itself.

4.4 New trends in mobile ad hoc networks simulation

Since the debut of the simulation of mobile ad hoc networks, many simulators were proposed, less than twenty are still active projects. Some are dedicated to MANETs simulation [ISI04, FGLS03, Bar04] and some others consist in extensions of wired network simulators [ns2, ZBG98] and general-purpose discrete-event simulation engines [BMT⁺98, BL94]. As the needs of researchers continue to evolve, it is likely that existing simulators will integrate new functionalities and concepts as well as fresh simulators will be developed.



By looking at the current status of MANETs simulation and networking technologies, we envision that the following trends will drive the future developments.

Second, too few simulators facilitate the migration of the simulation code to real devices [FGLS03, LGFS04]. The code then needs to be written twice. Either common APIs for “ad hoc programming” should be strictly followed or simulators should also provide execution environments allowing the simulation code to be directly executable on devices.

4.4.1 Application-level simulation

For a long time, mobile ad hoc network research has focused on the lowest layers of the network stack. Now that many techniques solve the physical layer issue, and that many researchers work at enabling multi-hop applications (by proposing new routing protocols), more and more researchers start to look at the applications that will make mobile ad hoc networks appealing for the user.

Currently, the most advertised applications include vehicular ad hoc networks (VANETs) [TMJH04], sensor networks [ASSC02] and, along with recent implementations and products from Sony and Nintendo, gaming. The first generation of mobile ad hoc network simulators (which include tools such as *ns-2* [Inf03], GloMoSiM [ZBG98], OPNet[DBD93] and so forth) provide heavy models for the lowest network layers, and consume serious computational power for this, leaving a few of it to the simulation of the applications. In this context, in order to leave as much computational power as possible to the execution of the simulated application, a new generation of simulators generally use fairly basic models of the underlying network layers, by sometimes resorting to statistics (as explained in Section 4.3.2.4).

Chapter 5

The Madhoc simulator

MADHOC is a simulator targeted at the simulation of pure ad hoc networks. Its development started in March 2003 and continues today (as of January 2006).

In this section, we will present, sequentially, the models for the network, for the ad hoc applications and for the simulation engine.

MADHOC is written in Java. Extensions are written in Java too and must conform a specific application programming interface. Dissimilarly, *ns-2* and many other simulators use a natively compiled language such as C or C++ in their core and require the user to write extensions in some interpreted language like TCL.

5.1 Objectives

The design and development of a new simulator were primarily driven by the will of investigating broadcasting over mobile ad hoc networks. A key challenge was then to define a broadcasting protocol that would operate well in realistic conditions. The literature on broadcasting over mobile ad hoc network is vast, but lots of the studies rely on hardly realistic network parameters. For example, in many cases, the radio range considered for IEEE802.11b devices is 250m, while the hardware specification most often boast a range of up to 100m.

The objective of building a new simulator is manifold. It is supposed to:

1. is able to simulate large populations (consisting of several thousands nodes);
2. provides models for heterogeneous PHY layers (support for both IEEE802.11b/g and Bluetooth is seen as essential);
3. provides a programming model for ad hoc applications;
4. provides mobility models allowing the representing of the citizens;

5. proposes a graphical user interface which provides geometric views of the simulated networks and applications, and both numerical and graphical representations of the effectively helps the development of ad hoc applications, by allowing the user to have precise views of what happens within the simulated applications.

Although there exists publicly available tools that permit some of the requirement aforementioned, none allows all of them in the same single package.

5.2 Network model

In this section the model for the network is presented. First, in Section 5.2.1, the description of the hardware components that constitute the network nodes is given. Second, in Section 5.2.2, the physical and logical concepts that serve as the basis for node communication is described.

5.2.1 Models for the hardware

What MADHOC models constitutes the first divergence with other simulators. MADHOC is targeted to the simulation of MobileMANs (see section 1.1.5). As such it models the kind of devices that will be likely to populate MobileMANs, that is the mobile devices that are already on the market: mobile phones, personal assistants, laptops, etc.

5.2.1.1 Different devices

On today's electronics market, mobile communicating devices can be found embedded on laptops, PDAs and mobile phones. These machines are very different in their technical characteristics and in the way they are used. More precisely, Laptops are much more capable (in terms of computations) than a PDA, and the latter is in turn much more capable than a mobile phone. A mobile phone is mobile, as well as PDAs and laptops. However, when switched on, PDAs and laptops usually do not move (except in the case of people working in a vehicle). This constitutes the major difference between these devices.

This variety of behaviors is modelled in MADHOC via the concept of "volatility model". The volatility model of one given node specifies if the node is on at a given time. Obviously, a node that is stated "off" cannot communicate with other nodes, neither it can compute anything. For example, one could define a volatility model, say, the "citizen mobile phone" volatility model which specifies that a node should be switched on at day and switched off at night. One could also define a volatility model, say, the "laptop" volatility model. which specifies that a node should be switched off at soon as it moves.

5.2.1.2 Different networking technologies

The nodes which will be involved in mobile ad hoc networks (mobile phones, PDAs, laptops, etc) do not feature the same communicating technologies. A description of the technologies available can be found in Section 2. The very limited energy storage of a mobile phone refrains from using powerful radio signals. Hence mobile phones (as well as PDAs) are generally operating in a 8-12 meters range, thanks to their built-in Bluetooth adapter (although some mobile phone/PDAs equipped with Wi-Fi interface are appearing on the market). On the other hand, all today's laptops feature Wi-Fi network interfaces, and all new devices come with a high-speed Wi-Fi interface which provides a bandwidth up to 54Mbps. Some of them also integrate a Bluetooth adapter. These divergences in the way devices are equipped have a serious impact on the topology of the network. Imagine a Bluetooth mobile phone moving in an area populated with dozens of Wi-Fi laptops. Since Wi-Fi and Bluetooth are incompatible, the mobile phone will not be able to establish any connection with its geographical neighbors.

MADHOC provides a generic model for the definition of communication technologies. More precisely, a communication technology is represented in terms of:

bandwidth which is shared by all communicating devices operating on a common media.

range of coverage defines the maximum distance to/from which the devices can send/receive data;

packet size emitted data is organized into packets. A packet is the smallest chunk of data that can be emitted over the network, for a given protocol.

data transfer cost defines the price for emitting one byte over the network. MADHOC defines several basic cost models, including situations when:

1. the cost is fixed, it does not depend on anything. Since ad hoc (peer-to-peer) communication do not involve any infrastructure, they are generally free. This cost model is then adequate in most cases ;
2. The cost of the communication is proportional to the amount of data transferred ;
3. The cost becomes higher when a certain limit (in terms of amount of data transferred has been reached) ;

By default MADHOC provides such descriptions for Wi-Fi (IEEE802.11b), Bluetooth and Wireless USB.

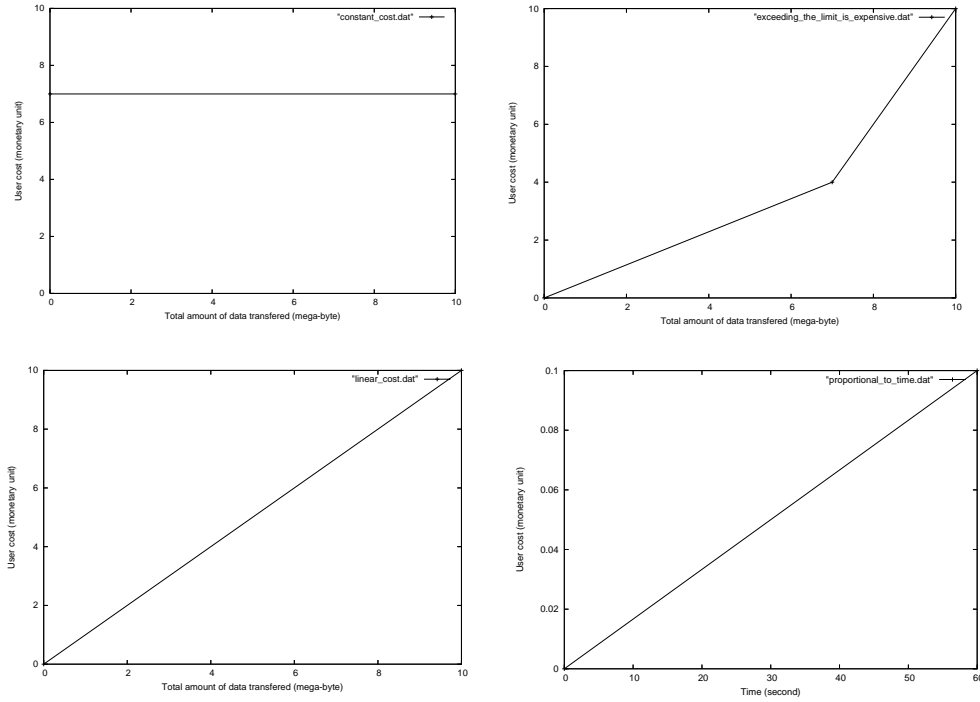


Figure 5.1: The cost models MADHOC uses for the communications.

5.2.1.3 Different computational/storage capacities

In the long run, MADHOC targets the simulation of ad hoc grids. For this, it integrates a basic model for ad hoc grid nodes. More precisely, it endows the nodes with computational power and storage abilities. MADHOC assumes that the abilities depend on the type of device considered. A laptop will generally embed a fast processor coupled with a quite large central memory and a several gigabytes hard-disk. PDAs and mobile phones take the energy from embedded batteries, thus their computation capacities are severely limited.

5.2.2 Models for the communication links

MADHOC does not provide models for all the layers of the OSI stack. Instead it focuses on the three lowest level ones, as detailed in the following.

Figures 5.3 and 5.2 shows via the UML syntax how MADHOC models the networking components of mobile nodes.

5.2.2.1 PHY and MAC layer

MADHOC does not make any clear difference between PHY and MAC layers. It simply considers some of the most important phenomenon which happen in these layers, that are packet collisions and radio interferences.

In the situation in which two nodes a and b are both in range of a node c but are not

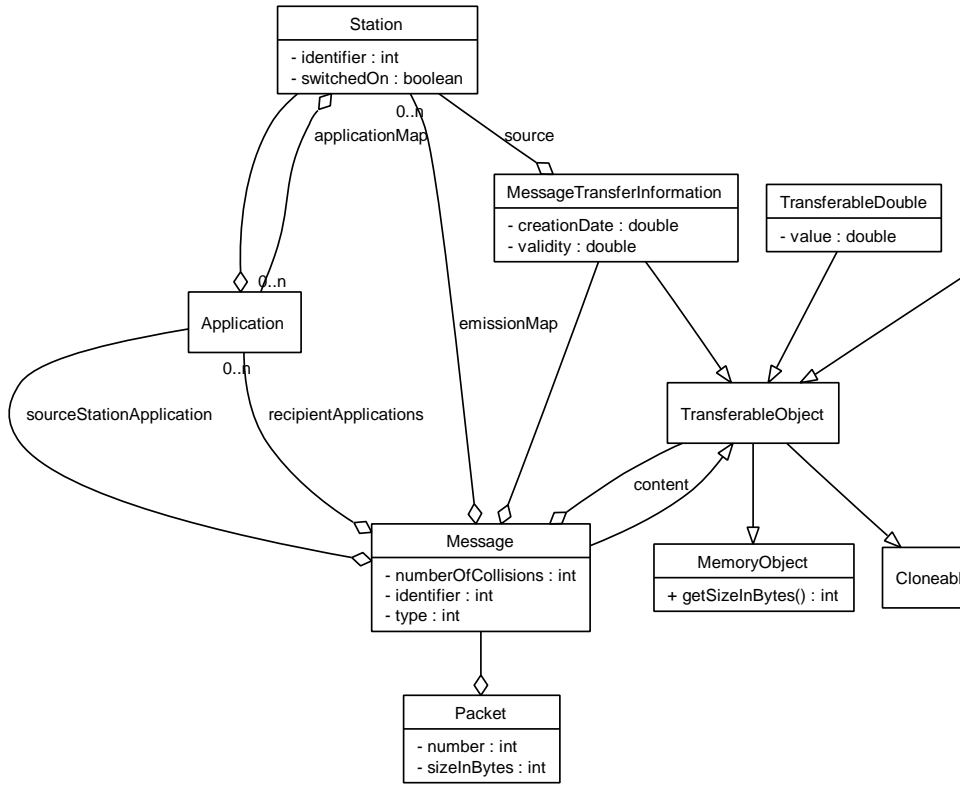


Figure 5.2: The UML representation of the networking equipment of MADHOC's nodes.

in range of each other, a risk of packet collision appears. More precisely if node a checks if the medium is free before emitting, it cannot see if b is already using it or not (CSMA does not work in such a situation), because a and b are out of range. Then a might try to send a packet to c while b is using the medium. In that case the packet sent by a will enter in collision with a packet probably sent by b at the same time. This problem is known as the hidden node problem. It is illustrated on Figure 5.4.

MADHOC considers this issue in a specific way: instead of modelling the medium and the bit transmission at a detailed level, it defines that the likeliness of collision for a packet emission is proportional to the traffic originated from the hidden nodes. When hidden nodes do not emit anything, the probability of collision is considered null; when hidden nodes occupy all the bandwidth available, the probability of collision is considered to be one. The probability $P(a, p)$ that a packet p consisting of $s(p)$ bytes sent by node a on the link l collides with some packet sent by an hidden node c is given by:

$$P(p, a) = \min \left(1, \frac{sd(c) + s(p)}{ms(l)} \right)$$

Assuming that $sd(c)$ is the size of the data sent by node c and $ms(l)$ is the capacity of the link l .

Several works have started the investigation of the impact of interferences in mobile

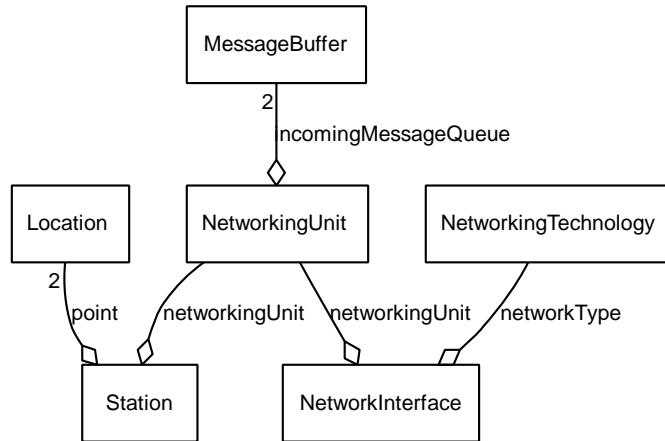


Figure 5.3: The UML representation of what is a station within the MADHOC simulator.

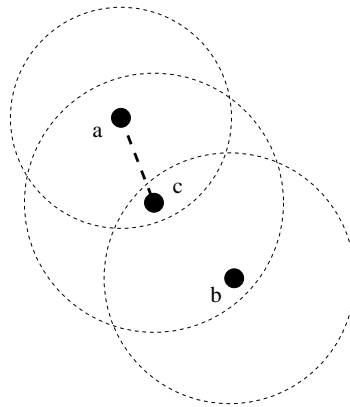


Figure 5.4: A network topology which may let appear the hidden node problem.

ad hoc networks [vRSWZ05, ST04, BCGLV01]. Briefly, interferences happen when two wireless networking technologies which use similar frequencies operate in the same geographical area. It has been shown for example that IEEE802.11b and Bluetooth, which both operate in the 2.4GHz band, have a significant impact on one another. In practise, interferences alter the digital stream. This alteration is detected by the error correction codes used in the protocols which permits the nodes to detect corrupted frames and drop them. MADHOC provides a model for the handling of interferences. In order to evaluate the probability $P(p)$ that a packet p will get corrupted because of interference, we make a few assumptions. First, a link l is assumed not to interfere anymore if its distance $d(l)$ from the link on which p will be sent is greater than the maximum coverage distance $c(l)$ of l . Second it assumes that the probability that a link l interferes is related to the ratio of capacity of the $m(l)$ that is used by the data of size $sd(l)$ that will be sent on l . The

probability $P(p, l)$ that p will be corrupted because link l interferes is then given by:

$$P(p, l) = \min \left(1, \frac{c(l)}{d(l)} \times \frac{sd(l)}{m(l)} \right)$$

Let L be the set of the network links that may interfere with the link which carries the packet p . The probability $P(p)$ that the packet p will suffer from interference is then given by:

$$P(p) = \min \left(1, \sum_{l \in L} P(p, l) \right)$$

The idea of using such statistical models makes the simulator lightweight and consequently enables the simulation of larger networks.

5.2.2.2 Network layer

Within MADHOC, nodes are allowed to communicate asynchronously by sending packets to each others. In order to send a packet to one of its neighbors, the source node needs to deposit the packet in an output buffer. The packet will be sent to its recipient node as soon as possible. What may delay the effective emission of a packet is the limited bandwidth of the network link between the source and the destination, the potentially long queue of the outgoing message buffer, or the current inability of the destination node to be reached or to receive the packet. Every packet is stamped with an expiration date. Until this date has expired, the packet is candidate to emission.

A packet is delivered to the destination node by being appended to a buffer of the incoming packets. This is commonly known as the “message box” paradigm.

A packet contains a chunk of data with a fixed size. It can be sent in three different ways:

unicast , which means that the packet has one single destination node;

multicast , meaning that the packet has a list of destination nodes. In that case, if all of the destination nodes are reachable as well as able to receive the packet, sending a packet to several nodes does not utilize more bandwidth then sending to one single node. Otherwise message will be left in the outgoing message buffer and will be sent later. This will generate two distinct message emission and will hence use more bandwidth. Indeed the nature of the radio medium makes that all the nodes in range receive all the packets sent by other nodes. On reception of a packet, a node simply has to check if he is a receiver of this packet or not.

broadcast , which means that a packet is sent to all 1-hop neighbors of the source node.

In this mode the packet is sent only once.

5.2.2.3 Application layer

At the application layer, nodes directly communicate with their neighbors by sending and receiving messages. Messages are not sent in one shot. Instead they are split in a sequence of packets. The way packets are handled is detailed in Section 5.2.2.2.

5.2.2.4 Heterogeneous networks

Most studies resorting to mobile ad hoc networks simulation draw conclusions on the basis of homogeneous networks. More precisely, it is often conjectured that network nodes use one single networking technology—generally IEEE 802.11b—and that radio signals all have the same strength. However one of the most relevant characteristics of metropolitan mobile ad hoc networks is their intrinsic heterogeneity. Indeed, communication in the mobile ad hoc networks is already possible through various protocols implemented in a wide variety of dissimilar network adapters. Currently available protocols are Bluetooth and IEEE802.11 but it is very likely that new technologies such as Wireless USB (WUSB) and WiMax will come along in the future. Bluetooth and IEEE802.11 are complementary co-existing technologies. Their specifications regarding the bandwidth and power consumption make IEEE802.11 suitable to the LAN (Local Area Networking) and Bluetooth ideal for the PAN (Personal Area Networking) as well as for sensor networking [ASSC02]. Although for sensing, generally dedicated technologies are used. Consequently, most laptops are equipped with IEEE802.11 adapters, many mobile phones feature a Bluetooth interface, and PDAs often embed both.

This paragraph highlights the impact of heterogeneity on the connectivity of the network (see Figure 5.5). In order to evaluate the connectivity, we chose to look at one of the most common metrics used for this purpose: the degree distribution. The degree distribution gives the number (resp. the ratio) of occurrences of all values for the degree (resp. the number of connections for one node) in a given graph (resp. network). By plotting the degree distribution of typical instances (using the same parameters as for Figure 5.5) of an homogeneous network as well as an heterogeneous one not only we could observe quantitative but also qualitative differences, as illustrated on Figure 5.6. More precisely, quantitative variations are explainable by the fact that distinct radio communication technologies (RCTs) feature different coverage radius. Qualitative variations are observed on the value of the distribution for small values of the degree (e.g less than two). Briefly, networks which use a combination of Bluetooth and Wi-Fi exhibit more partitions than those which use only Wi-Fi. This is because of the lower coverage radius of Bluetooth.

In order to make obvious the importance of the consideration of heterogeneity, we decided to execute the same application both on homogeneous and heterogeneous networks. The considered application retained is message broadcasting using the DFCN protocol

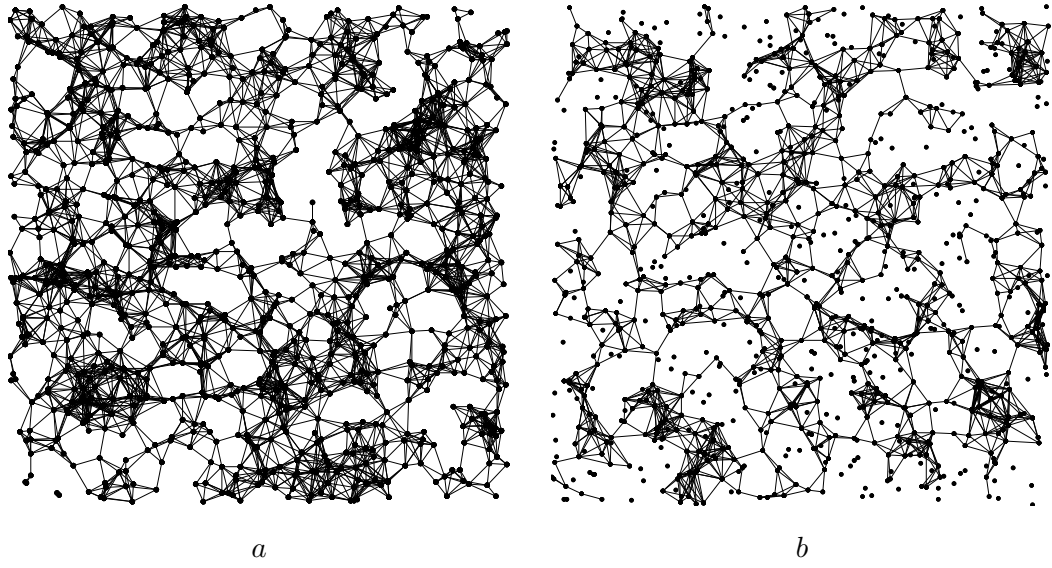


Figure 5.5: The graph resulting of the simulation of 1,000 stations roaming in a $1km^2$ area, according to the random waypoint mobility model. The graph (a) is obtained when all stations embeds a IEEE 802.11b network adapter. The graph (b) is obtained when half of the stations have a IEEE 802.11b network interface, the remaining ones having a Bluetooth one.

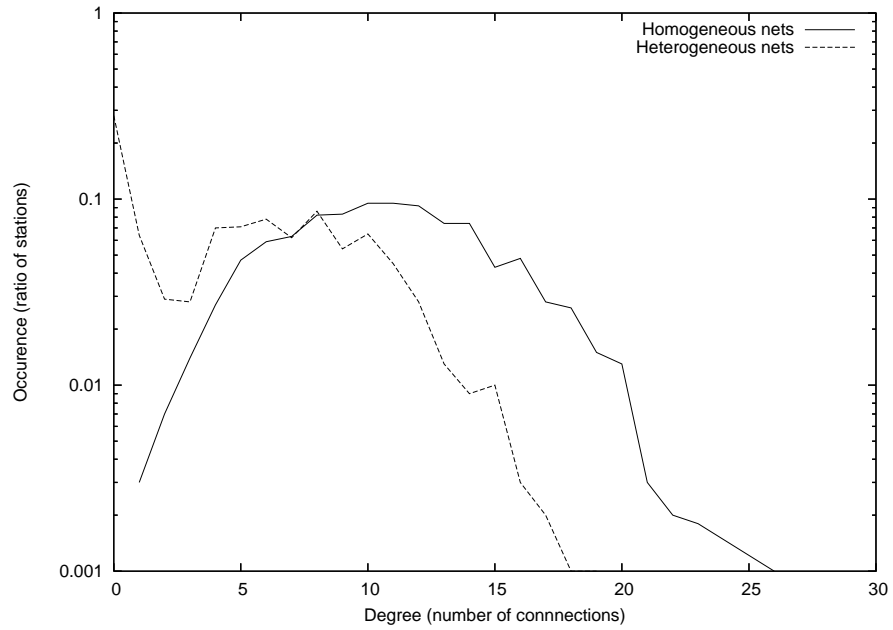


Figure 5.6: The comparative degree distributions of homogeneous and heterogeneous networks

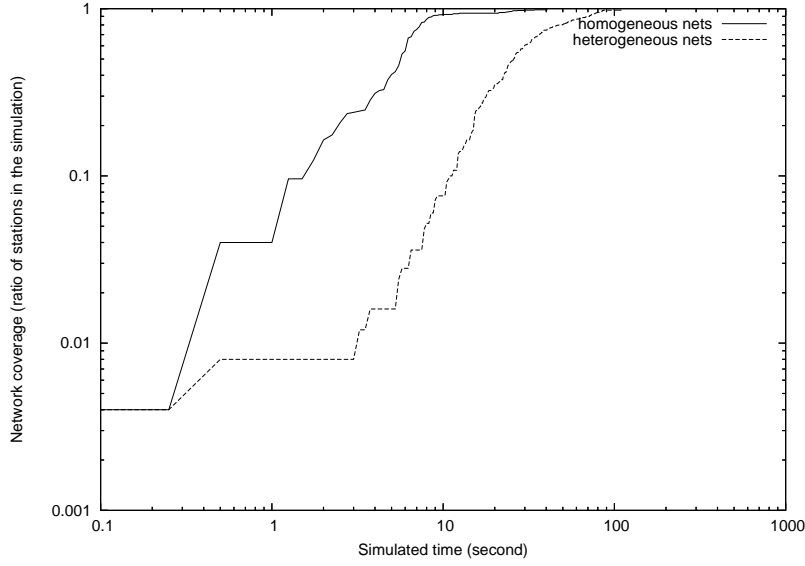


Figure 5.7: The evolution along the time of the network coverage generated by a DFCN broadcasting process.

[HBG⁺06] that will be presented in details in Chapter 8. In order to study the difference of the two processes, we look at the variation of the network coverage along the time; that is the variation on time of the ratio of the number of nodes that have received the message being broadcasted over the total number of nodes. As shown on Figure 5.7, heterogeneity dramatically slows down (by a factor of about 10) the broadcasting process. The reason for this is that the broadcasting process must utilize the station mobility. In addition, the broadcasting process finally reaches all the nodes because the protocol we chose is robust to disconnections.

5.3 Models for ad hoc applications

There is not yet any universally accepted definition of what is an ad hoc application. In our context:

Definition — An ad hoc application is an application whose the distributed components are executed on a set of mobile nodes in the network. These components have weak interactions ^a. Loose interactions permit the application to execute properly in the dynamic environment provided by the underlying ad hoc network.

^aA strong interaction would be for example “node *a* has sent a request to node *b* and waits for its response”, but in our case *b* may have been turned off and might be never turned on

It is assumed that an ad hoc application has a one-hop visibility of the network.

Examples of ad hoc applications have been given in Section 3.

Within MADHOC, an application can be executed on a subset of the nodes in the network. Moreover, several applications can be executed on one single node.

5.3.1 Connections/disconnections

In order to enable the nodes to be aware of new neighbors, simulators sometimes use event-driven notification. More precisely, when the simulator finds a new link, it dynamically invokes a handler method on the two nodes involved. This method, defined abstract, must be implemented by the application that defines what to do in case of a connection/disconnection event. This application of the *observer* design pattern, based on polymorphism, has proved elegant and flexible. However, MADHOC assumes that event-based programming can hardly be used in the context of the simulation of ad hoc applications. Instead MADHOC provides all nodes with an utility method that returns a set of the nodes that were not yet in range last time it was invoked. Applications are then free to invoke this method or not.

Note: Another drawback of the event-based notification is that the code of handler methods is executed by the kernel of the simulator in a routine dedicated to the construction of the interconnection network: a routine that should not execute any application-level code.

5.3.2 Application identification

As nodes can execute several applications, there is the need to have a way of identifying the different applications running on one given node. MADHOC defines that applications running on a given node are identified by their class (similarly, IP identifies processes by their port numbers). MADHOC does not allow two applications with the same leaf class to execute on one single node. Similarly, TCP/IP or UDP/IP do not allow two servers processes to share the same port.

5.4 Simulation model

In this section is detailed the way the simulation engine is modelled. It focuses on the components that participate to the particularities of MADHOC.

5.4.1 Time management

Time management is a critical issue to any simulation engine. This section details the way MADHOC makes use of time and how it schedules the execution of the applications over time.

5.4.1.1 Discrete-time simulation

Unlike many other simulators, MADHOC is not a discrete-event simulator. Instead of jumping from event to event, the kernel of MADHOC iterates from time steps to time steps. It hence discretizes time. The time-interval between two iterations is called the *resolution*.

The resolution of a simulation process is defined by the user. The greatest is the resolution, the faster—and the less accurate—is the simulation process. The resolution of the simulation ideally depends on the application the user want to simulate. In the specific case of RAD¹-based broadcasting, the resolution should be at least twice smaller than the maximum RAD otherwise the benefit of using a RAD is simply lost. In the specific case of the simulation of mobility, the resolution should ensure that mobile nodes move with reasonably low speed, otherwise some connections that would have occurred in the real world would not be simulated.

5.4.1.2 Simulator internal scheduler

The application scheduler implemented in the core of the simulator works in a sequential manner. The reason for this is performance: because MADHOC is not likely to run on massively parallel computers, dedicating one thread by node would have been way too cumbersome and the number of simulated nodes would have been a lot lessened.

Practically, the scheduler manages a list of the simulated applications. It iterates on this list by giving to each application the opportunity to execute.

Initially the list of nodes on which the scheduler iterated always featured the same order. On runtime, we could notice that some nodes processed faster than others, that some nodes transmitted over the network without any problems while other nodes constantly could not. We then noticed that on the low-bandwidth communication links, only a few nodes were able to transmit before the link was saturated, the others—if any— were blocked. Moreover these privileged few nodes were always the same, the scheduling was hence unfair.

In order to give all applications the same chance to execute and to emit data on the network during an iteration of the simulator, the application scheduler performs in a stochastic fashion. More precisely, along one single iteration, all applications are asked to execute multiples times, each time for a very short period. The order of the applications are invoked is randomized. At each turn all applications are invoked, but in a non-predefined order.

¹Random Assessment Delay

5.4.2 Simulation area and network projections

MADHOC defines that the mobile nodes evolve in a square area. The surface of this area can be defined by the user. The number of nodes in the simulation area does not vary over time: the simulation area is assumed to be closed.

Instead of measuring the effects of its application on all nodes in the network, the user might want to consider only a subset of it. For example, he may want to observe what is going on only on a specific zone of the simulation area, he may want to observe what happens only on Bluetooth nodes, etc. In order to make this possible, MADHOC defines the concept of *network projection*. Just like the mathematical definition of projection,

Definition — A projection of the simulated network is a subset of the nodes that match a given criterion. The network links retained in the projection are the links whose the two nodes involved have been retained in the projection.

The metrics available in the simulation will be used on each projection, generating several measure repositories. Several projections have been predefined.

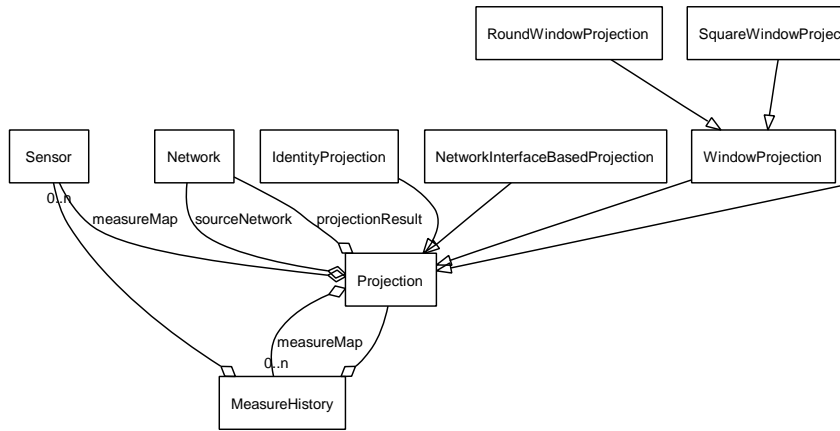


Figure 5.8: An UML representation of the concept of network projection.

As convenient as projections are, processing the projections is a cumbersome task for the simulator: at each iteration it needs to find out which nodes belong to a projection, and then apply the measurement available on this newly created set of nodes. It is then important that the user defines only the projections that are relevant to him.

MADHOC has a set of predefined projections, among which:

identity projection gathers all the stations in the initial network. This is the most basic projection as it projects everything.

window projection considers a sub-area of the simulation area whose center is the center of the latter. The window can be either a square or a circle. The size of the window is parametrizable.

network technology-based projection considers the subset of the nodes in the network that embeds a network adapter of a given type.

only-connected-nodes projection gathers all the nodes that have at least one neighbor.

random projection is a projection made of a set of nodes that are randomly selected. This projection is useful if the user wants to operate on a subset of the simulated nodes—for performance reasons, for example—while keeping a certain degree of statistical confidence.

5.4.3 Monitoring the ad hoc applications

A “monitor” aims at deploying, initializing and monitoring the ad hoc applications it is in charge of. It is an abstraction defined at the level of the simulation. It does not have any instance in the real world. It serves as the software interface between the user and a set of applications running on the network nodes.

In particular, monitors provide the user with software sensors which allow him to observe what is going on in the simulation process. Just like a physical sensor (thermometer, barometer, etc), a MADHOC sensor will take measures on a given system. Measures are taken at each iteration. Each new measure is appended to an history.

Unfortunately, sensing takes time. The more sensors, the longer the simulation. Then, for the development process, it is advisable to use as many sensors as possible in order to detect the slightest flaw of the code, but for the research experimentation campaign, it is better enabling only the metrics which will be used for result interpretation.

5.4.4 Termination of the simulation process

A simulation is said to be terminated if all the applications it executes are terminated. Sometimes the mere concept of termination does not make sense to some application. For example, the “beaconing” application (which consists in periodically emitting “hello” packets in the neighborhood so that the node can build a 1-hop neighborhood information) has no reason to terminate. In such a case, the application is not considered in the termination condition of the simulation.

Since the termination condition of an application depends on it, it must be defined by its developer.

5.4.5 Random number generation

Random number generation is an important feature of simulators. MADHOC uses one single random number generator. This generator uses a gaussian law. This random number generator can be seeded by:

- a fixed number, making all the runs be the same;
- the system clock, which has as a result that experiments started at different time will execute in different manners. When seeding with the system clock, several experiments executed at the same time on different nodes of a clusters in which nodes are time-synchronized (NTP—Network Time Protocol) will be the same;
- the IP address of the computer running the simulation. This makes the simultaneous execution be different. By coupling a fixed number to the system clock, the experiments become reproducible, which is a necessary condition for scientific experimentation. ;
- a combination of the system clock and the local IP address, which makes all runs differ, whatever host is used and whenever the simulation is executed.

Chapter 6

Modelling Mobility

The representation of mobility is a key issue in mobile networks simulation. The literature mentions loads of mobility models which cover various aspect of human mobility. If it were possible to combine them, the community would be provided with a fairly complete representation of how people move. However in practise, only one of them is of common use: the random waypoint mobility model. Researchers propose more and more sophisticated mobility models, using for example real traces or realistic radio waves propagation models.

This chapter presents the contributions of this thesis in the topic of mobility for mobile ad hoc network simulation. Primarily, Chapter 6.1 provides an overview of the mobility models used in ad hoc network simulation, and presents a set of mobility models aiming at simulating the motion of citizens. Chapter 6.2 it introduces a classification of mobility models. Finally Section 6.4 is presented a new mobility model called the Human Mobility Model.

6.1 State of the Art

Mobility models are considered as a major issue in the field of simulation of mobile ad hoc networks. This section introduces the concept of mobility models, then it describes two classifications of such models, prior to finally exposing the ones which are subject to global agreement and usage.

6.1.1 Preliminary discussion

As explained in [TG05],

Definition — a mobility model is a set of rules used to generate trajectories for mobile entities. Mobility models are used in network simulations to generate network topology changes due to node movement.

This vision of a mobility model is very often broadened by some research groups which associate the notion of movement to other notions like environmental properties or radio propagation. For example, the UDEL mobility model [BS04b] defines that radio waves bounce onto walls, using ray-tracing.

Mobility models aim at reproducing the reality of stations mobility. In the context of city-based environments, researchers try to design environmental models of the cities and to reuse human mobility patterns that define how people move in such environments, some also develop radio propagation models that take into consideration the impact of environmental components on the way radio waves get spread. Thus, mobility models should be defined in such a way that they allow the simulation of real-world situations. For instance, let us consider a limited number of lanes on roads, coupled with an important flow of vehicles. This situation may lead to the apparition of traffic jam lines. If cars used inter-vehicle communication systems, then the topology of the local network would globally look like a chain. Simulators should be able to reproduce this kind of scenario since the topology is of great importance in the achievement of most of mobile ad hoc networks applications.

6.1.2 Mobility models in use

There exists a variety of mobility models which are currently used within the mobile ad hoc networking community. The most popular one is the random waypoint mobility model. It is described in Section 6.1.2.2. The most important mobility models are presented in the following.

6.1.2.1 Random walk mobility

Random walk is extensively described in [PN04, Bet01]. It defines that a mobile node moves from its current location to a new location by randomly choosing a direction and speed in which to travel. The new speed and direction are both chosen from pre-defined ranges, $[speedmin; speedmax]$ and $[0; 2\pi]$ respectively. Each move in the Random Walk Mobility Model occurs in either a constant time interval t or a constant distance travelled d . At the end of a move, a new direction and speed are calculated. If a node which moves according to this model reaches a simulation boundary, it “bounces” off the simulation border with an angle determined by the incoming direction.

There exists many variations of the random walk mobility model. For instance the Random Direction Mobility Model forces nodes to travel to a boundary of the simulation area before changing direction and speed.

6.1.2.2 Random waypoint mobility

Random waypoint is the most popular mobility model. In the random waypoint mobility model, as described in [BRS03], each node randomly chooses a destination location (in terms of its x, y coordinates) in the simulation area and moves towards this destination with a randomly chosen velocity. When the destination is reached, the station remains at the same place for a while. Once this time expires, the node chooses a random destination in the simulation area and a speed that is uniformly distributed in $[minspeed, maxspeed]$. The node then travels toward the newly chosen destination at the selected speed. This process is repeated by each station until the end of the simulation.

Often in the model, the nodes are initially distributed randomly around the simulation area. As long as the simulation runs, the space distribution of the nodes tends to some “stable value”, referred to as its “stationary distribution”. However this stationary distribution does not exhibit a fair distribution of the nodes over the simulation area, and might lead to some troubles when simulating. This problem is detailed by [NC04].

The random trip [BV05] mobility model is a generic mobility model that generalizes random waypoint and random walk to realistic scenarios. It is implemented in ns-2. The implementation performs perfect initialization meaning that the mobility model has no transient phase.

6.1.2.3 Obstacle mobility model

The obstacle mobility model [JBRA⁺05, JBRAS03] is a realistic mobility model which incorporates obstacles in the simulation area. These obstacles are utilized to both restrict nodes movements as well as wireless transmissions. In addition to the inclusion of obstacles, it constructs movement paths using the Voronoi diagram [Aur91] of obstacle vertices. More precisely, the obstacle mobility models defines that the obstacles are polygons. Polygons point are considered to be Voronoi points. This permits the calculation of the Voronoi partition of the simulation space. Every Voronoi partition is defined by a set of segments. Any segment which does not have any point within an obstacle is considered to be a possible movement path. Nodes can then be randomly distributed across the paths, and can use shortest path route computations to destinations at randomly chosen obstacles. Simulation results shows that the use of obstacles and pathways has a significant impact on the performance of ad hoc network protocols. The obstacle mobility model is implemented in several simulators, including ns-2 and GloMoSim.

6.1.2.4 City-section mobility

The mobility of the vehicles in town gathers a lot of interest among the researchers as well as among the businesses implicated in vehicular ad hoc networks. A variety of city

mobility models were defined. The two models described below belong to those.

6.1.2.4.1 City Section Mobility Model In the City Section Mobility Model, the simulation area is a street network that represents a section of a city where the ad hoc network exists. The streets and speed limits on the streets are based on the type of city being simulated. For example, the streets may form a grid in the downtown area of the city with a high-speed highway near the border of the simulation area to represent a loop around the city. Each mobile node begins the simulation at a defined point on some street. A mobile node then randomly chooses a destination, also represented by a point on some street. The movement algorithm from the current destination to the new destination locates a path corresponding to the shortest travel time between the two points. Upon reaching the destination, the mobile node pauses for a specified time and then randomly chooses another destination (i.e., a point on some street) and repeats the process.

6.1.2.4.2 Manhattan mobility model The Manhattan mobility model is proposed to model movement in an urban area. In the Manhattan model, the mobile node is allowed to move along the horizontal or vertical streets on the urban map. At an intersection of a horizontal and a vertical street, the mobile node can turn left, right or go straight. The probability of moving on the same street is 0.5, the probability of turning left is 0.25 and the probability of turning right is 0.25. Manhattan mobility model focuses on nodes moving along horizontal or vertical streets, which is not enough to model nodes moving along non-horizontal and non-vertical paths. Moreover, Manhattan model is not suitable to model the movement happening in the intersections of highway systems, which is much more complex than the intersection of local streets.

6.1.2.5 Group mobility models

In entity mobilities, the motion of the nodes does not depend on the motion of other nodes. However, there are many situations where it is necessary to model the behavior of mobile nodes as they move together. In order to model such situations, group mobility models [HGPC99] are needed to simulate this cooperative characteristic. For example, a complex specific mobility model was defined for the simulation of troop mobility [BZG04]. More generally, A variety of generic group mobility models were defined, as detailed in the following.

6.1.2.5.1 Reference point group mobility The Reference Point Group Mobility (RPGM) model represents the random motion of a group of mobile nodes as well as the random motion of each individual mobile node within the group. Group movements are based upon the path travelled by a logical center for the group. Individual mobile nodes

randomly move about their own pre-defined reference points, whose movements depend on the group movement.

6.1.2.5.2 Columobile node mobility model The Columobile node Mobility Model proves useful for scanning or searching purposes. This model represents a set of mobile nodes that move around a given line (or columobile node), which is moving in a forward direction. A slight modification of the Columobile node Mobility Model allows the individual mobile nodes to follow one another. Each mobile node is placed in relation to its reference point in the reference grid; the mobile node is then allowed to move randomly around its reference point via an entity mobility model.

6.1.2.5.3 Nomadic community mobility model Nomadic Community Mobility Model: a set of nodes move together from one location to another. Within each community or group of mobile nodes, individuals maintain their own personal spaces where they move in random ways. In the Nomadic Community Mobility Model, each mobile node uses an entity mobility model (e.g., the Random Walk Mobility Model) to roam around a given reference point. When the reference point changes, all mobile nodes in the group travel to the new area defined by the reference point and then begin roaming around the new reference point. The parameters for the entity mobility model define how far a mobile node may roam from the reference point. Compared to the Columobile node Mobility Model, the mobile nodes in the Nomadic Community Mobility Model share a common reference point versus an individual reference point in a columobile node.

6.1.2.5.4 Pursue Mobility Model Pursue Mobility Model: a set of nodes follow a given target. As the name implies, the Pursue Mobility Model attempts to represent mobile nodes tracking a particular target. The random vector value is obtained via an entity mobility model. The amount of randomness for each mobile node is limited in order to maintain effective tracking of the mobile node being pursued. The current position of a mobile node, a random vector, and an acceleration function are combined to calculate the next position of the mobile node.

6.1.2.6 Boundless Simulation Area

The mobility models described hereinbefore are considered to operate in a simulation area that is geographically limited. The presence of bounds leads to topological specificities such as a non-uniform distribution of the nodes in the simulation area. This also participates to the appearance of dynamical phenomena like nodes which get in contact too often because they are in the same edge of the simulation area.

The Boundless Simulation Area Mobility Model is an attempt to limit these harmful effect. It consists in converting a 2D rectangular simulation area into a torus-shaped one. A node reaching an edge of the simulation areas, instead of bouncing onto the edge, will show up at the opposite edge of the area.

However this technique has to be used with care because it also has harmful effects. For instance, consider a broadcasting process which starts at one corner of the simulation area. The broadcasted message is supposed to cross—by jumping from node to node—the simulation area. But because of nodes instantly travelling to the opposite corner, the message is able to cross the simulation area much faster than it would be able to do it in reality.

6.1.3 Characterizing mobility models

From the user point of view, mobility models differ in the resulting network topology they generate and the way this topology varies upon time. When it comes to mathematically characterizing these mobility models, most researchers have recourse to the spatial distribution of the nodes across the simulation area to the degree distribution of the network graph.

6.1.3.1 Space/speed distribution

As detailed in [NC04], the distribution of the initial locations and speeds of the nodes differs from the distribution at later points in the simulation. Furthermore, the probability distributions of both location and speed generally vary continuously over time and converge to a “steady-state” distribution, known in the probability literature as the stationary distribution.

6.1.3.2 Link duration

The link duration of a given network connection is the time elapsed between its establishment and its break down. The average link duration is the average duration for all links that appear along the simulation. This metric is important because bandwidth-demanding protocols may not be able to operate at all with (too) short link durations.

Sometimes simulators consider that a link is available as soon as two nodes get in range, that is the distance to each other is lower than a given threshold. In practise this is not true. More precisely when the network adapter of a given node detects the presence of an electro-magnetic signal, it first need to synchronize on it, in order to be able to communicate with the other nodes sharing this same medium. This process can take a while and its duration can never be neglected. For example, in the case of nodes

implementing the Bluetooth specification, it is commonly observed that two nodes in range need a few seconds to be able to get synchronized, that is to communicate.

Considering that nodes may move fast, it is very probable that two nodes moving in opposite direction cannot communicate with each other (even if they get very close to each other at some moment) because the time for establishing the data connection is greater than the time required for them to become out of range of each other.

6.1.3.3 Degree distribution

The number of nodes that are neighbors of a node n is called the degree of n . The degree distribution $D(k)$ gives the probability that a selected node has exactly k links. The degree distribution provides useful information in the framework of the study of mobile ad hoc networks. Particularly it clearly indicates whether the network is partitioned or not: in a partitioned network, the probability of finding a node which has a zero degree is greater than zero.

6.1.3.4 Neighbor density

The neighbor density of a given node is the number of nodes which are within radio range. In networks in which the space distribution is homogeneous, the average neighbor density is a relevant measure.

6.2 A new classification for mobility models

The aim of this section is to provide a comprehensive classification methodology that considers every important behavioral and structural feature of mobility models. The classification presented hereinafter is based on seven criteria which are: whether or not the mobility model considered makes use of randomness, whether or not it uses predefined movement data, whether or not its motion is ruled by the motion of other nodes, whether or not the way it moved in the past impact the way it will move in the future, whether or not the environment in which it moves features some geographical constraints. The two last criteria are whether all the nodes in the simulation obey the same mobility rules or not, and if their motion is directed by the simulation application. All these characteristics are summarized on Table 6.1 and detailed below.

6.2.1 Randomness

A mobility model is said to be *randomized* if it makes use of randomness. Generally constant, the degree of randomness is sometimes adjustable, like in the groups mobility models in which nodes follow a given direction with a certain degree of imprecision in the

name	random	trace	group	memory	spat. const.	plural	app. driven	
Random walk	yes	no	no	weak	no	no	no	no
Random Waypoint	yes	no	no	weak	no	no	no	no
Obstacle	yes	no	no	weak	yes	no	no	yes
Nomadic	yes	no	yes	weak	no	no	no	no
Pursue	yes	no	yes	weak	no	no	no	no
HMM	yes	no	no	strong	yes	yes	no	yes
City	yes	no	no	strong	yes	yes	no	yes

Table 6.1: A classification of the mobility models.

movement. Resorting to stochastic mobility is generally a good idea since it is the sole way to achieve a high number of mobility configurations (or particular ones) with little coding.

6.2.2 Traces

A mobility model is said to be *using traces* if it makes use of real data on the motion of people. Trace information is now available thanks to some geographical studies which aimed at defining the activity of the citizen during the day.

6.2.3 Group/entity

A mobility model is said to rely on “group” if the decision of how a given station moves is based upon the motion of other stations. In opposition, “entity” mobility models define nodes that move independently. Group mobility models can be sub-classified in terms of locality/centrality according to the amount of station location information they require. More precisely, a station uses a *localized* collaborative mobility model if its motion is decided based on some mobility information (speed, angle, etc) of the stations around. On the contrary, a mobility model that requires a global (or quasi-global) knowledge of the motion of the stations in the network is said to be *centralized*.

6.2.4 Memoryful/less

A mobility model is said to be *memoryful* if the decision of how a given station moves is based upon how the station moved in the past. There exists huge variation regarding the amount of information memorized by mobile nodes during their travel. Generally only the previous location (the location at the previous step of the simulation) is stored and reused. Storing more information would be useful to generate more realistic motion on the long run.

6.2.5 Spatial constraints

A mobility model is said to be *spatially constrained* if there exists a point in the simulation area to which a station cannot be located.

A station moving according to the random waypoint mobility model could be located at any point in the simulation area; thus the random waypoint mobility model is spatially unconstrained. On the contrary, a station moving according to the obstacle mobility model cannot be located within the bounds of an obstacle, consequently the obstacle mobility model is spatially constrained.

6.2.6 Plurality

A mobility model is said to be *plural* if there exists at least two stations whose motion is not directed by the same rules.

For instance, the mobility model defined in [BZG04] relies of distinct mobility rules to ensure a certain heterogeneity on how devices move.

6.2.7 Application-driven

A mobility model is said to be *application-driven* if there exists a node which deliberately moves in a way so that it helps an application to operate. Once again, in the specific case of ad hoc network simulation, an application-driven mobility model can be classified either as localized or centralized, depending upon the amount of information it requires to tune its rules.

As an example of application-driven mobility, consider the mobility of the police in the case it has to warn the population of some danger: the policemen cross the city in such a way that they maximize the number of people who can hear the signal.

6.3 New metrics for mobility models

As described in Section 6.1.3 the network topology resulting from the application of mobility models is commonly analyzed in terms of node speed, spatial distribution and degree distribution. For some specific studies researchers resort to metrics such as the clustering coefficient, shortest path length, etc. In the context of the study of broadcasting and topology control, better metrics for the structural analysis of ad hoc networks were needed.

6.3.1 Size of the greatest connected component

When considering realistic communication technologies and mobility models, it appears that networks may be largely partitioned. This is because of the limited radio range of the

nodes, their uneven spatial distribution and PHY-level synchronization issues. The size of the partitions observed may vary greatly.

This metric is particularly useful in the context of research on topology control protocols. More precisely, a topology control protocol primarily aims at improving the connectivity of the network. Briefly this can be achieved by dynamically adjusting the power of the antennas, on the basis of a variety of rules. Another solution is making clever use of directional antennas. Sometimes different solutions are used: disconnected partitions can become connected by the use of a backbone network such as GSM or UMTS. The challenge is then to find the network nodes which will take the initiative of connecting to the backbone in such a way that both the number of partitions and the cost are minimized.

6.3.2 Probability of meeting again

When dealing with security issues, it is important to know how frequent is it to meet some node that we have met in the past. This is especially important when working on trust and reputations. In this context, the average time for two nodes in range to get in contact again is clearly relevant.

6.4 Human mobility

Human mobility is the default mobility model in MADHOC. It is a generic mobility model that roughly represents the intention-driven mobility of people in metropolitan areas.

Simulating metropolitan mobility is difficult because urban zones feature an extensive list of dissimilar configurations (avenues, pedestrian areas, places, shopping malls, etc). Building a generic model that takes into consideration all the components of a city is a daunting task. So far, attempts at modelling metropolitan mobility focus on specific configurations. The UDEL mobility model [BS04b] is one of the most advanced initiatives.

Humans do not move randomly. When moving, they have a determined target spot and move towards it. The target may be a few meters away (next shop, next crossroads, other sidewalk, etc) as well as far away (next district, next city, etc). Upon time, their target changes. Most of the time, people have a dynamically changing list of targets. This list of target spots is dynamically changing because of various parameters that will appear upon time (locations of the target places, closure times, high frequentation times, etc).

6.4.1 Algorithm

The human mobility model defines that the simulation area is a bounded area. This area contains a set S of destinations for nodes. These destinations are called “spots”. A spot is located by its x, y coordinates. It is a round area defined by the length of its radius. Spots

do not overlap. Nodes can be located either in or out of spots. The mobility model used by the node which move out of a spot is a variant of the random walk mobility model.

On the first hand, when a node n is located out of any spot, it must choose a destination spot $d(n)$. To do this, it maintains a set $VS(n)$ of the spots it visited in the past. A node cannot visit twice a same spot. $d(n)$ is chosen so as it is the closest spot which has not yet been visited (which does not belong to $VS(n)$). The node then move towards its destination spot, with a certain degree of random variation in its direction. The direction is periodically adjusted; this ensures that the node will eventually reach its destination spot at one moment. The mobility of nodes out of any spot is a specialization of the random walk mobility.

On the other hand, when the node n is within a spot $d(n)$, it moves according to the random direction mobility models. When the node reaches the edge of the spot, $d(n)$ is added to $VS(n)$ and a new destination spot $d(n)$ must be defined. If all spots have been visited ($V = VS(n)$) then $VS(n)$ is emptied and the search for a new destination is triggered again.

6.4.2 Radio waves

The human mobility model (HMM), just like the obstacle and UDEL mobility models, defines that the elements which constraint the motion of the node also rule the propagation of the radio waves. It assumes that spots are surrounded by a circular wall, and that walls have an absorbtion ratio ranging from 0 to 1. 0 means that the wall does not impact the radio signal. 1 means that the signal is totally blocked. An intermediate value means that the signal is proportionally attenuated. HMM does not model how the signal bounces.

6.4.3 Scenarios

6.4.3.1 Mall

The mall scenario represents people wandering within a shopping mall. The spots stand for shops. They are located randomly with a constraint for non-overlapping. The mall scenario can generate highly dense wide areas. It allows to study the behavior of protocols in dense network conditions.

6.4.3.2 City-center

The city-center environment represents people walking and driving in the streets of a city center. The spots stand for crossroads. They are located according to a grid-like structure. Their location is then slightly randomly modified using an amplitude specified by the researcher. Nodes move faster outside of the spots than inside. The city-center

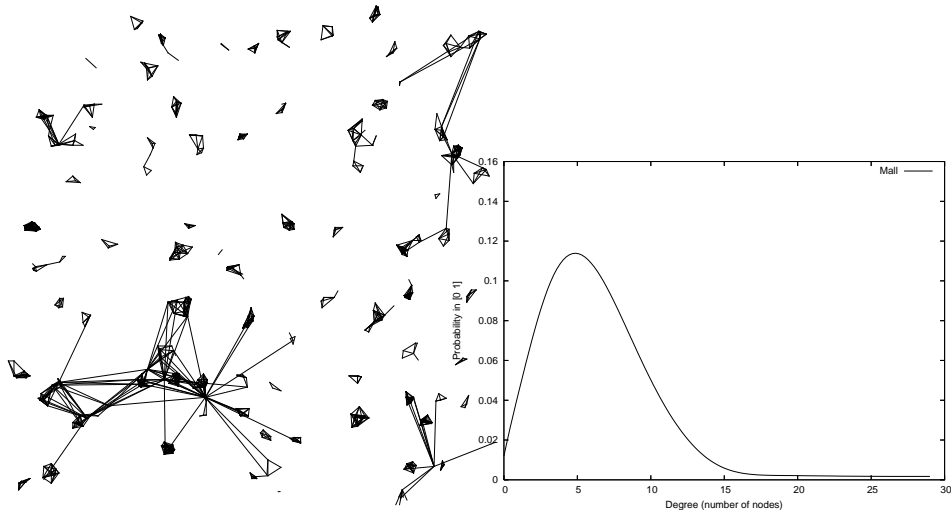


Figure 6.1: On the left, an example of a network formed by people shopping in a mall. On the right, the average degree distribution for such networks.

scenario generates both dense and sparse regions. It then allows to check if the protocol can adapt to a constantly varying connectivity or not.

Figures 6.2 and 6.3 illustrate the effects of the street environment.

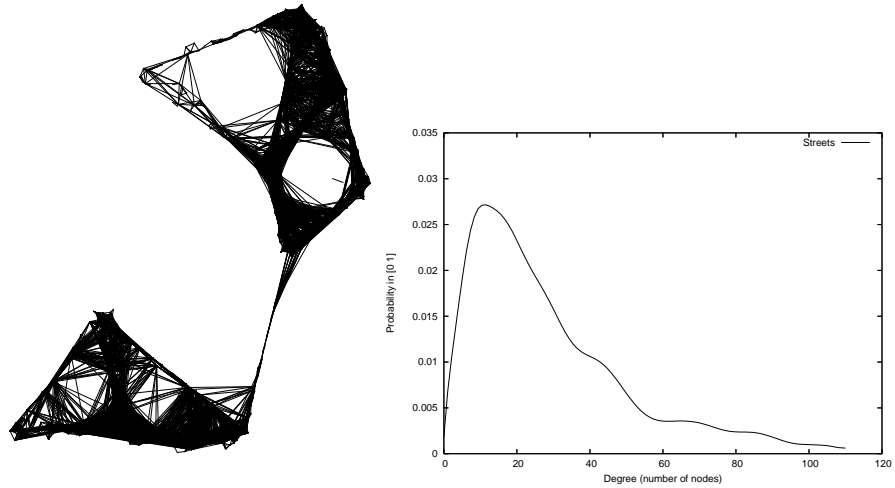


Figure 6.2: On the left, an example of a network formed by cars driving in a city section. On the right, the average degree distribution for such networks.

6.4.3.3 Highway

The highway mobility environment is characterized by nodes moving at a very high speed. The density of spots is defined so as there are preferably only 3 spots in the simulation area. Numerous spots would result in too many intersections of nodes which would lead

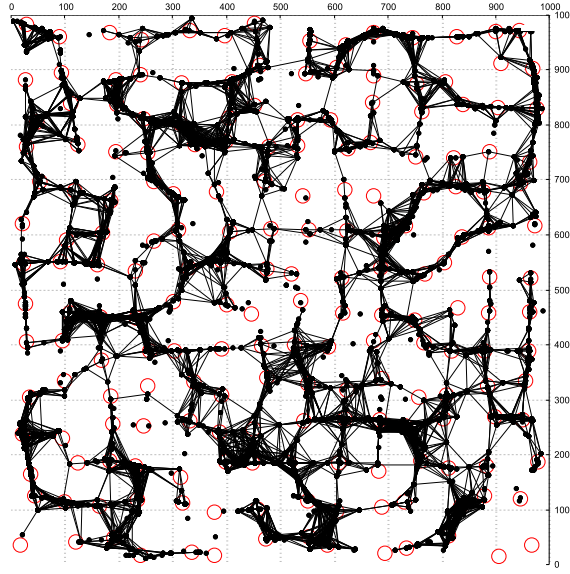


Figure 6.3: The graph resulting of the simulation of 2,000 nodes roaming in a 1km^2 area. Nodes have a either IEEE802.11b or a Bluetooth interface, with the same probability.

to unrealistic behavior. The highway environment is very different from the other ones in the sense that the connectivity it produces is specific: most links are organized into chains of nodes moving in opposite senses.

As the nodes move very fast, the duration of connections is very short. The highway scenario then allows to check if an application is opportunistic enough.

Figures 6.4 and 6.5 illustrate the effect of the highway environment.

6.4.4 Open issues

6.4.4.1 Initialization of the mobility

As long as the simulation runs, the space distribution of the nodes converges to a stable state known as the stationary distribution. Except in some specific cases (for example if the mobility model is analytic) the stationary distribution is not known at the moment the simulation starts. An issue is hence where to locate the nodes at the beginning of the simulation. Until the stationary distribution is reached, the results of the simulation cannot be considered valid. A solution would then be to wait for this stationary distribution to be reached. Unfortunately in the case of the human mobility model, if the evolution of the space distribution is clearly visible on 2D graphs, we did not figure out which metric should be used to automatically detect it. Even if we experimentally found out some rules of thumbs making it possible to detect the stationary distribution in many cases, the strategy did not prove versatile enough to be applied on the variety of configurations of the human mobility model.

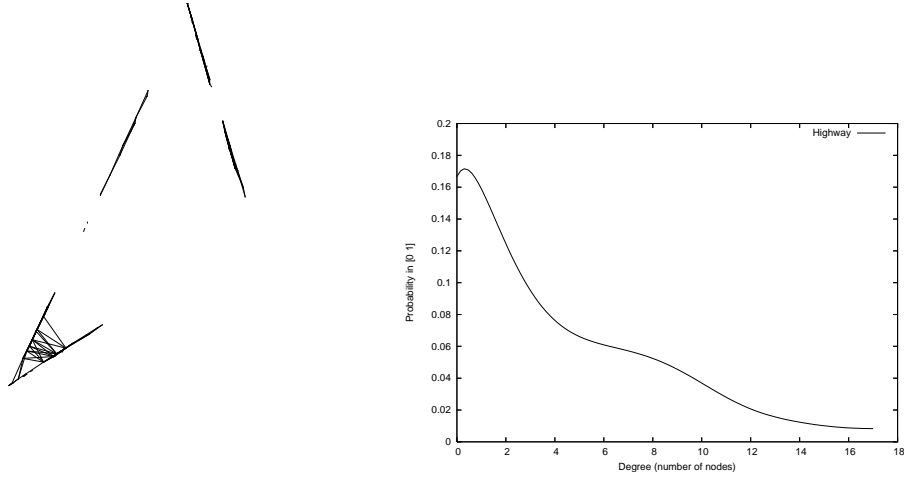


Figure 6.4: On the left, an example of a network formed by cars driving on a highway section. On the right, the average degree distribution for such networks.

6.4.4.2 Defining the resolution of the simulation

The concept of resolution is described in Section 5.4.1.1. The resolution of the simulation is definable by the user. The lower the resolution step, the more precise the simulation. If the user needs to simulate bigger networks or longer periods of network activity, increasing the resolution may be necessary, otherwise the simulation would be too slow. But the higher the resolution step, the less precise the simulation. There is no theoretical upper limit for the resolution step. The question is: what is the threshold of the resolution step above which the simulation process does not output precise-enough results? MADHOC has initially been developed considering a fixed resolution of four iterations per second, with was a reasonably precise time step in the context of the simulation of broadcasting protocols for mobile ad hoc networks. In the later versions of MADHOC, the resolution of the simulation has become a user-definable parameter. On the one hand, applications such as clock synchronization [CW04] require much more precise simulations. On the other hand, applications like the dissemination of trust information [SKJ⁺00] does not have to deal with short communication delay and hence can be simulated using greater resolution steps.

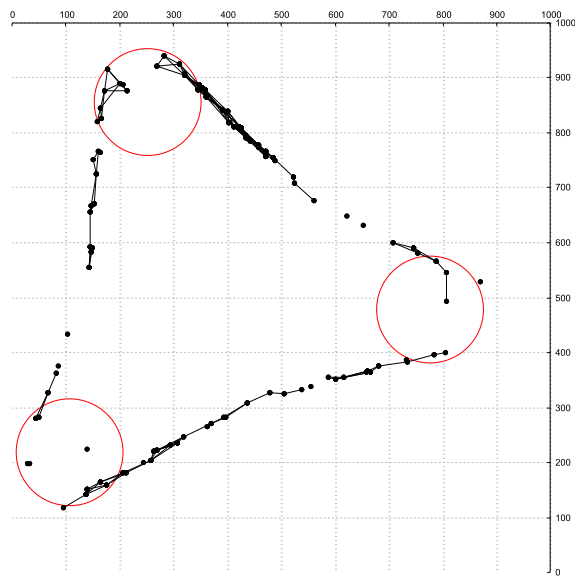


Figure 6.5: The interconnection graph resulting of the simulation of 100 nodes driving on a 3 kilometers-long highway section. Most of the nodes have a Bluetooth adapter as well as a IEEE802.11 one.

Part III

Broadcasting across mobile ad hoc networks

Broadcasting—also called flooding—is one of the earliest research interests about mobile ad hoc networking. This is because broadcasting constitutes one of the fundamental low-level network operations which serves as the basis of higher level applications such as routing. Traditionally, broadcasting means sending a message from one given node (the source station) to all the nodes in the network. In a (multi-hop) decentralized network, the broadcasted data has to be relayed by intermediate nodes in such a way that all the network graph is spanned. However in mobile ad hoc networks, broadcasting cannot be defined in these terms. Indeed the limited radio range of the nodes and their mobility make that all the nodes might not be reachable all the time. As a consequence, the mere definition of broadcasting had to be adapted: the broadcasting problem across mobile ad hoc networks can be seen as a multi-objective problem targeting at maximizing the number of nodes reached, at minimizing the time required to reach them, and at minimizing the network overhead. This latter objective is particularly important because too much emissions (causing great network overhead) may lead to the congestion of the network; this problem is known as the broadcast storm problem.

In networks with no or slow mobility, spanning trees-based methods prove effective. Briefly they aim at determining the minimal set of relay nodes that must participate in the broadcast process. In networks whose nodes have high velocity, different strategies are employed. These strategies are all based on local neighborhood information. They include Probabilistic schemes, Scalable Broadcasting Algorithm (SBA), Multipoint Relaying, Ad hoc Broadcasting Protocol (AHBP), etc. While these strategies operate well when the network density is such that the network is connected, they fail as soon as some partitions appear. An extension of AHBP (called AHBP-EX) overcomes this problem by triggering re-emission on the discovery of a new neighbor. This strategy unfortunately generates too high network overhead. Additionally, SBA and AHBP, which are the most effective protocols in their class, assume 2-hop neighborhood information. In reality, when the mobility is high, it is still not sure that 2-hop information is achievable.

The broadcasting protocols which have been targeted at mobile ad hoc networks are presented in Section 7. Then Section 8 introduces Delayed Flooding with Cumulative Neighborhood (DFCN), a protocol which exhibits better results in terms of the network overhead it generates as well as in terms of broader range of mobility models and node density it tolerates.

Chapter 7

State of the Art

Network broadcasting commonly consists in sending a packet from one node to every node in a network. When considering fixed network, the main issue of broadcasting is to find the spanning tree [PR02] of the network; that is the subset of the network nodes that span all the nodes. The Spanning Tree Protocol, which is also referred to as STP, is defined in the IEEE Standard 802.1d, and later, in 1998, the Rapid Spanning Tree Protocol (RSTP) (defined by the 802.1w specification) operates very well in the context of fixed networks. When dealing with mobile networking, and particularly with mobile ad hoc networking, the protocols described hereinbefore are not applicable.

The main challenge when broadcasting across mobile ad hoc networks comes from its inherent mobility. Because in such network the network links are volatile, the Spanning Tree Protocol cannot be applied as is. There exists strategies, based on dynamic spanning trees, which consist in maintaining an accurate spanning tree as long as the nodes move [SW04]. The nodes are likely to move fast, consequently the technique for updating the spanning tree must be extremely reactive. In this context, [Cas06] have developed a method which ensures that the maintenance of the spanning tree after a node move is achieved in one single operation. Their algorithm, which is a localized one (it runs on every devices, relying on 1 or 2 hops neighborhood information, see section 7.3.3), is well suited to large mobile ad hoc networks, in which localized protocols are preferred. However, these techniques make the implicit assumptions that the mobility (if some) is low and that the network is non-partitioned (meaning that all nodes are reachable through multi-hop connections). Some other protocols [RP04], proposed more recently, feature more dynamic approaches (such as self-pruning [WC02]), in which the mobility is central issue. The protocol presented inhere belongs to the latter category. More precisely, its aim is to enable efficient broadcasting in networks in which the topology is very heterogeneous and dynamic. This is the case of the metropolitan ad hoc networks (MobileMANs). MobileMANs are described in Section 1.1.5. In such network, the broadcasting process cannot propagate data to all nodes: only a subset of the nodes can be reached at a given time.

7.1 Technical challenges

This section lightens some of the main issues that must be faced during the design of broadcasting protocols.

7.1.1 Hidden and exposed node problems

The hidden node problem (defined in Section 5.2.2.1) constitutes a major obstacle to broadcasting. More precisely, this issue makes it impossible to ensure that, within a given network partition of the network, all nodes will be reached. This problem could be overcome by the use of acknowledgement packets (ACKs) but doing this would be contrary to the very principle of broadcasting which is to minimize the number of packet emission. Consequently, the actual target of broadcasting within mobile ad hoc network is to reach as many nodes as possible, ideally all of them.

Without the use of acknowledgement packets, even a broadcasting protocol which theoretically ensures that all nodes will be reached would turn out to fail at reaching a subset of them.

7.1.2 Mobility and Partitioning

The mobility of the nodes constitutes another major challenge broadcast protocols have to deal with.

On the one hand, mobility constitutes an obstacle to the operation of the broadcast protocols based on spanning trees. Thanks to algorithms like [Cas06], it is now possible to deal with dynamic spanning trees in efficient and distributed ways. However these techniques operate regardless of the application they serve. In the specific case of broadcasting, the spanning tree should be constructed on the basis of the (continuously growing) set of nodes that have received the message. Since localized protocols have no kind of global information on the network, doing so is challenging.

On the other hand, mobility (when applied in realistic networking parameters) inevitably leads to partitioned networks. Network partitioning constitutes one of the greatest issues when it comes to broadcasting. In particular, broadcasting protocol must find a technique which allows the broadcast message to “jump” from partition to partition, in order to reach as many nodes as possible. This idea is central to epidemic diffusion models.

7.2 Protocols

This section described the broadcasting protocols that are seen as referenced in the literature and commonly used for experiments.

Most often broadcasting protocols make use of a random assessment delay (RAD). When a given node a receives a broadcast message from another node b , if it decides to forward it, this does not happen immediately. Instead it will wait a certain duration picked randomly in $[0, max_delay]$ ms. This delay is called the random assessment delay (RAD) before re-emitting. When b sent the message, its others neighbors, if any, also received the message at the very same time as a . So if all neighbors which decide to forward the message do it immediately, collisions are highly likely to happen. Randomly delaying every emission dramatically reduces the risk of collisions.

7.2.1 Simple Flooding

As explained in [WC02], in the Simple Flooding [OVT01] each node forwards received messages exactly once. Simple Flooding does not make any attempt to reduce the number of re-broadcasting nodes and does not require any knowledge. This strategy is not suitable for environments with high density regions because it would then generate too much network traffic and sometimes could even lead to network congestion. This problem is referred to as the broadcast storm problem [NTCS99].

7.2.2 Probabilistic scheme

Upon the reception of a broadcast message, a node executing a probabilistic broadcasting protocol will forward the message with a probability p and will take no action at all regarding this message with a probability $1 - p$. Then the value of p depends on the user of the protocol. If $p = 1$ then the probabilistic scheme behaves just like simple flooding. The value of p should be adapted according to the topological properties of the network the protocol will be executed on.

7.2.3 Distance-based methods

In distance-based methods, the decision of forwarding broadcast messages depends on the estimation of the distance between nodes. The distance between nodes can be estimated according to the electrical strength of the received radio signal. A node a receiving a broadcast message from another node b will compute the distance d between a and b . If d is lower than a given threshold t , then the message is dropped because a assumes that the (short) extra distance that would be covered by a new emission would not justify the expense (in terms of bandwidth and battery consumption) of one emission.

7.2.4 Area-based methods

Area-based methods are very similar to distance-based methods, which are presented in Section 7.2.3. In area-based schemes, nodes do not evaluate the benefit of a new emission

in terms of the extra distance that would be then covered. Instead they base their decision on the basis of the extra surface that would be covered. If the devices are equipped with omnidirectional antennas, surfaces are calculated using the strong assumption that the coverage area of nodes is circular, which is wrong most of the time.

7.2.5 Flooding with Self-Pruning

Flooding With Self-Pruning (FWSP) [WC02] which implements a neighborhood-aware strategy based on 1-hop knowledge. Each broadcast message includes the list of identifiers of the neighbors of the sender node. FWSP-enabled nodes upon reception of a broadcasted message retrieve the set of identifiers embedded in the message and subtracts it to the set of identifiers of its own neighbors. If the resulting set is empty, the message is dropped, otherwise it is forwarded.

7.2.6 Scalable Broadcast Algorithm

SBA [PL00] implements a neighborhood-aware strategy based on 2-hops knowledge. SBA differs from Flooding with Self-Pruning only in the neighbor-knowledge it requires. Each SBA broadcast message includes a list of identifiers of the 2-hop neighbors of the sender node. The strategy carried out by SBA-enabled nodes is as following: upon reception of a broadcasted message, the node retrieves the set of identifiers embedded in the message and subtracts it to the set of identifiers of its own neighbors. If the resulting set is empty, the message is dropped, otherwise it is forwarded. SBA also defines a technique which consists in re-adjusting the RAD (see section 7.2) according to the degree of the node concerned and the maximum degree of its neighbors.

7.2.7 Multipoint relaying

Just like SBA, Multipoint Relaying [LQV01] relies on the knowledge of 2-hops neighborhood. Multipoint Relaying's messages contain the set of nodes that must act as relays. Multipoint Relaying then works this way: upon message reception, the node finds out if its identifier is contained in the message-embedded set of relays. If yes, it constructs the smallest set of 1-hop relays that cover all the 2-hop neighbors. In turn, it embeds this set in the broadcast message itself before sending it around. The construction of the set of the forwarding nodes is done according to the greedy algorithm described in [Lov75].

7.2.8 Ad Hoc Broadcast Protocol (AHBP)

The Ad Hoc Broadcast Protocol (AHBP) [PL01] AHBP is based on the Multipoint Relaying protocol. In AHBP, only nodes who are designated as a Broadcast Relay Gateway (BRG) within a broadcast packet header are allowed to rebroadcast the packet. BRGs are

proactively chosen from each upstream sender which is a BRG itself. The algorithm for a BRG to choose its BRG set is identical to the one used in Multipoint Relaying.

The main difference between AHBP and Multipoint Relaying is that a node using AHBP informs 1-hop neighbors of the BRG designation within the header of each broadcast packet. This allows a node to calculate the most effective BRG set at the time a broadcast packet is transmitted. In contrast, Multipoint Relaying informs 1-hop neighbors of the MPR designation via “hello” packets.

7.2.9 AHBP-EX

AHBP-EX [PL01] is an extension of the AHBP 7.2.8 protocol. It aims at supporting high mobility networks. Its strategy is as follows: upon detection of a new neighbor, the node re-trigger the AHBP strategy consisting of designing 1-hops neighbors as relays and emits the message. Upon experiments, this technique proved to generate a huge network overhead. In some cases in which the node density is high and nodes move fast, it even generates more network overhead than simple flooding does.

7.2.10 INOP

INOP [CSP06] is designed to use two-hop neighborhood information. It utilizes a novel technique for determining the transmission power level at each node during the broadcast. Each transmitting node first sorts its neighbors based on the required power to reach them. Then, starting from the closest neighbor, the node compares the required power levels to reach the next neighbor either directly or indirectly via some other neighbor. Based on this comparison, the transmitting node decides on the transmission power level to use in its broadcast.

Simulation based comparisons the existing set of variable power approaches (BIP [WNE00], PABLO, (AHBP) have shown that compared to other variable power approaches, INOP achieves better results in terms of energy efficiency, and competes and exceeds other approaches in terms of a number of other performance metrics including traffic overhead, coverage, and convergence time.

7.3 Classifications

There exists three classifications for the mobility models, as detailed in the following.

7.3.1 Camp’s classification

Williams and Camp [WC02] classify broadcasting protocols according to the network knowledge that the nodes need to have in order to execute them. They define four cat-

egories: simple flooding, probability-based methods, area-based methods and neighbor-knowledge-based methods. This categorization is based on the way protocols select re-broadcasting nodes.

In Simple Flooding [NTCS99], nodes forward received broadcast messages exactly once, which could lead to network congestion.

In probability-based methods [NTCS99], nodes forward received broadcast messages with a certain probability. This probability is locally re-evaluated every time a message is received. Probabilistic scheme, just like simple flooding, require not information on the network.

When information about nodes location is available, the decision of re-broadcasting a given packet can be taken according to the additional geographical area covered by a potential emission. Area-based and location-based [NTCS99] methods define that if the surface or distance of this area is lower than a given threshold, the message is not re-emitted. Network information can be obtained by GPS or evaluated by triangulation or by measuring the power of the radio signals.

Finally, neighbor-knowledge-based methods (SBA, Flooding With Self-Pruning (FSWP), AHBP, Multi-point Relaying, etc) require the knowledge of some neighborhood information (FWSP uses 1-hop neighbors, SBA, Multipoint Relaying and AHBP uses 2-hops neighbors). They constitute the last class of broadcasting strategies. This class can be divided in two subclasses: *neighbor-designating* and *self-pruning* methods. On the one hand, the nodes running protocols belonging to the *neighbor-designating* subclass (AHBP, Multipoint Relaying) operate by designing their neighbors that will be in charge of relaying the message. On the other hand, the nodes running protocols belonging to the *self-pruning* subclass (SBA, FWSP) decide by themselves whether to rebroadcast or not.

7.3.2 Stojmenovic's classification

Stojmenovic and Wu [SW04] recently proposed some classifications for broadcasting protocols. In their proposal protocols can be classified according to their algorithmic nature (determinism, reliability) or the information required by their execution (network information, "hello" messages content, broadcast messages content).

A broadcasting algorithm is said to be deterministic if it behaves predictably. If it runs on a particular input, it will always produce the same output. Most broadcasting protocols are deterministic.

An algorithm is assumed to be reliable if it ensures that all nodes in the network will be covered. Probabilistic schemes and area-based methods (see section 7.2) are usually unreliable as they rely on randomness and heuristics, respectively. Note that the concept of *reliability* does not make sense if the network is partitioned. In such case reaching all the nodes is not possible to achieve.

<i>Protocol</i>	<i>Scope</i>	<i>Deter.</i>	<i>Reliable</i>	<i>Mobility</i>
DFCN	1-hop	yes	no	yes
Simple flooding	-	yes	yes	no
Location-based	1-hop	yes	no	no
Probabilistic	-	no	no	no
FWSP	1-hop	yes	yes	no
SBA	2-hop	yes	yes	no
Multi-point relaying	2-hop	yes	yes	no
AHBP-EX	2-hop	yes	yes	yes

Figure 7.1: The table summarizes the properties of the broadcasting protocols mentioned in the paper. It provides, correspondingly, the name of the protocol, the amount of topology information it requires, whether it uses a deterministic approach or not, whether its is reliable or not, and if it takes into consideration the mobility of nodes.

7.3.3 Wu’s classification

Another classification was proposed by Wu and Lou [WL03]. It is based upon the amount of state information required for performing broadcasting. More precisely, they categorized protocols on whether they rely on a *global*, *quasi-global*, *local* or *quasi-local* knowledge of the network. *Global* and *quasi-global* broadcasting algorithms are also called *centralized* protocols. Centralized protocols are listed in [Pel02]. Their main drawback is that they are not scalable. They are hence unusable in the MANETs. Localized protocols are those which need a *local* (or *quasi-local*) view of the network. Example of the protocols belonging to this class are 1 and 2-hops neighborhood-knowledge protocols.

The network state information (node’s identifier, location, degree), and network topology information are interchanged between nodes. Such information is carried by either “hello” messages (which are specifically meant to represent topology information) or broadcast messages. The amount of data embedded in those messages has a serious impact on the network throughput. Protocols can then be classified according to the amount of data is carried either in the “hello” or broadcast messages [SW04].

Chapter 8

DFCN

In this section we present the Delayed Flooding With Cumulative Neighborhood (DFCN) protocol. DFCN related papers are [HGB04, HBG⁺06, LND⁺06].

First the objectives for the DFCN protocol are given in Section 8.1. Then its strategy is detailed in Section 8.3. Further, the iterative (and chronological) construction of DFCN is given in Section 8.3.2. Then the effectiveness of DFCN is illustrated in detail through experiments, in Section 8.4. Finally, Section 9 describes the application of some multi-objective optimizations of DFCN, aiming at tuning it at best.

Using Stojmenovic and Wu’s classification (see sections 7.3.2 and 7.3.3), DFCN is a deterministic algorithm. It does not consist in a new approach for calculating dominating sets. Instead it defines heuristics based on local network information. Only 1-hop information is required, which permits DFCN to achieve very good level of scalability. The “hello” messages exchanged by the nodes do not carry any additional information. Only broadcast messages must embed the list of node neighbors.

Using Williams and Camp’s classification (see section 7.3.1), DFCN belongs to the self-pruning neighbor-knowledge-based class.

8.1 Objectives

The objectives of the Delayed Flooding with Cumulative Neighborhood (DFCN) are manifold:

1. to provide a protocol which has lower network overhead. Scalable Broadcast Algorithms (SBA), the Ad Hoc Broadcast Protocol (AHBP), and Multipoint Relaying are some of the most efficient in terms of network overhead.
2. to provide a protocol which operates well regardless of the network density. More precisely, as illustrated on Figures 8.1 and 8.2, broadcasting in a low density network (top-left figure, $50nodes/km^2$) is difficult because the protocol needs to make a very

good use of the mobility to achieve a good coverage. When the density increase (top-left figure, $1,000 \text{ nodes}/\text{km}^2$), the connectivity gets better, but the network may be partitioned. When the network is highly connected (bottom left and right figures, respectively $5,000$ and $10,000 \text{ node}/\text{km}^2$), the broadcasting protocol must be bandwidth-efficient in order to minimize the risk of packet collisions.

3. to provide a localized protocol which operates with 1-hop neighborhood information. Both SBA and AHBP require 2-hops neighborhood information. One challenge is then to achieve better performance by using less network information.

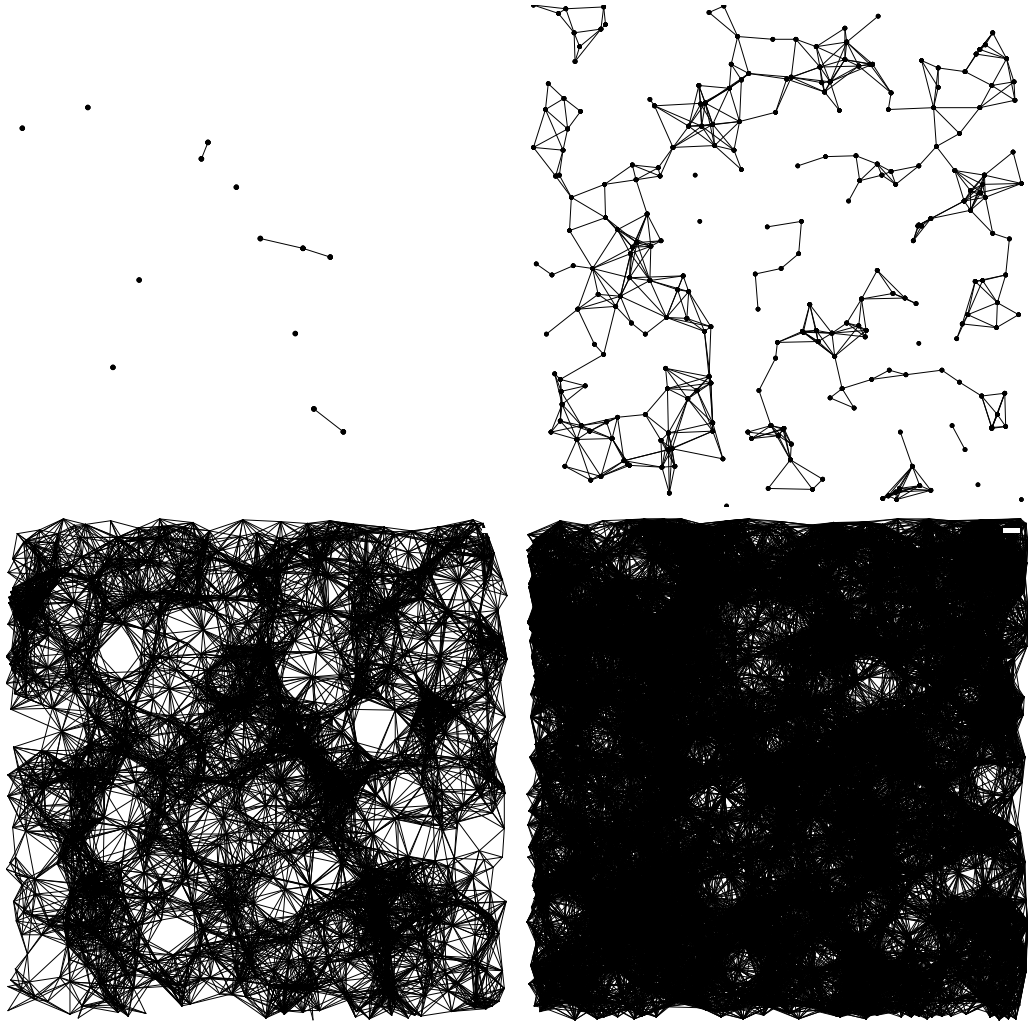


Figure 8.1: The node density in a network impacts greatly its topology. Broadcasting protocols should be able to operate regardless of the density condition. Up to now, few protocols support such great variation of the node density.

Not knowing the network size in advance makes the goal of reaching all nodes impossible to measure in practice. Furthermore, minimizing the duration of the broadcasting process

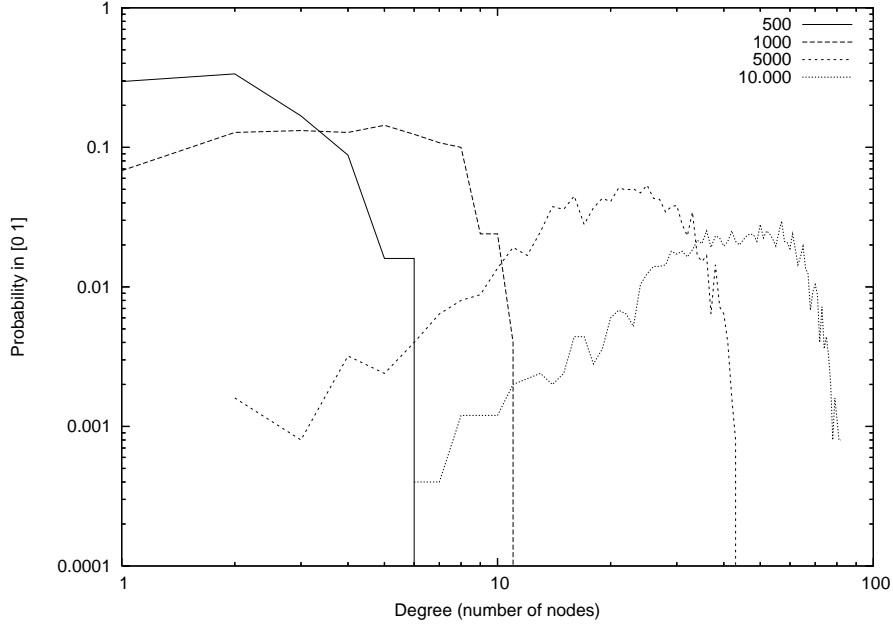


Figure 8.2: The evolution of the average degree distribution when the density grows

is not always the primary target.

8.2 Requirements

For being able to run the DFCN protocol, the 4 following assumptions must be met:

1. Like many other localized neighbor-knowledge-based broadcasting protocols (FWSP, SBA, etc) and as mentioned in the previous section, DFCN requires the knowledge of 1-hop neighborhood. One way of obtaining this information is by using “hello” packets. We denote the set of neighbors of the node s by $N(s)$.
2. Each message m embeds in its header the set of IDs of the 1-hop neighbors of its most recent sender. We refer to this set as $T(m)$.
3. Each node maintains local information about all messages received. Each instance of such information consists of three items:
 - the ID of the message received;
 - the set of IDs of the nodes that are known to have received the message, referred to as $K(m)$;
 - the decision of whether the message should be forwarded or not, referred to as $a(m)$.

4. DFCN requires the use of a RAD before possibly re-emitting a broadcast message m . The random delay for a given message m is referred to as $r(m)$.

8.3 DFCN's strategy

In this section, the DFCN protocol is presented. The strategy for decision making relies on a set of reactive and proactive rules, implemented in components that are described and explained in the next sections. Before entering the details, let us perform a careful analysis of the problem. Broadcasting in mobile ad hoc networks in the context of DTNs corresponds to the search of a trade-off that can be expressed as meeting two criteria: reaching as many stations as possible (first criterion), and limiting the number of re-emissions (second criterion). In order to reach as many stations as possible, the protocol executed on each node should decide of a reemission as soon as new stations are encountered. If such a strategy is applied when the network is sparse, this would lead to good results for both criteria since every reemission prove to be useful because of the reduced number of meeting points between station. And thanks to the low density of the network, the number of reemission should be limited. However the same strategy applied in a dense environment would lead to catastrophic results in terms of useless (re)-emissions. Indeed, in a dense network, the number of events corresponding to the meeting of two stations that don't know each other is a huge number. Unfortunately, in the context of metropolitan environments, both situations may occur. Some areas may be underpopulated while other may be, at the same time, densely populated. As a consequence, the decision part of the protocol should rely on the perceived density of the station, which density corresponds directly to its neighborhood. We achieve this adaptivity with the help of two thresholds: *minBenefit* and *densityThreshold*. The first, *minBenefit*, measures the opportunity to (re)-emit a message according to the composition of the neighborhood. This threshold is built as the ratio between the number of new stations in the neighborhood, over the total number of stations in the same neighborhood. When a suitable ratio of new stations appear in the neighborhood, the node (re)-emit the message. But, when the density is too low, this only mechanism leads to poor performances. To prevent this problem, the other threshold, *densityThreshold* was defined in order to allow the release of the limitation of the previous mechanism. The next section describes in details how these thresholds are embedded in the different components that compose DFCN.

8.3.1 Description of the algorithm

When a node receives a message, the forward decision may depend on different elements: RAD, neighborhood, density, etc. In order to allow the protocol to self-adapt to the customer application but also to the density, we have introduced a new parameter called

”benefit” that will be further described.

As previously mentioned in the ”DFCN requirements” (section 8.2, first item), a node s maintains for a message m a list $K(m)$ which contains the identifiers of the nodes that are known to have already received m . The list $K(m)$ is managed as follows: when s sends a message m to its neighbors, it knows that all of them will receive m (unless some collisions occur). If ever the same situation happened (if s had the same neighborhood), then m would not be forwarded again, as all the nodes around are already known to have received it. When a node n receives a message m from one of its neighbors b , it also adds all the neighbors of b in $K(m)$, as all of them should have received m as well.

However, this simple mechanism is too reactive. Indeed, as soon as a new station becomes present in the neighborhood, the message is re-emitted. And in some situations, especially when the density is very high, this may entail a continuous re-emission of the messages. In order to prevent such scenario, we use the *minBenefit* threshold which is formally defined as the ratio between the number of neighbors of s which do not belong to $K(m)$, and the number of neighbors of s : $\frac{|N(s)-K(m)|}{|N(s)|}$. The smaller is the required benefit, the less DFCN will be restricted in emitting messages, hence the lower throughput it will generate.

The behavior of DFCN is driven by three events. These events are:

- the reception of a message referred to as *reactive* behavior
- the expiration of the RAD of some messages
- the detection of a new neighbor referred to as *proactive* behavior.

When one of these three events occurs, DFCN reacts by behaving in a specific manner, as described in the following sections.

8.3.1.1 Message reception event

If a message m is received for the first time, $K(m)$ is equal to $T(m)$ and a RAD is then assigned to m . Otherwise the set $T(m)$ and the ID of the sender node are added to $K(m)$. This behavior corresponds to algorithm 1.

Figure 8.3 gives an example of this behavior. Here the threshold *densityThreshold* is set to 0.2. The node s holds a message that is candidate to broadcast. The black node is a new neighbor of s . Since s knows that only 2 neighbors out of 12, (ratio of $2/12 = 0.16$) do not hold the message, s does not emit the message. On the right figure, 6 of them do not have the message yet, the ratio is then $6/12 = 0.5$ which is greater than *densityThreshold*. The message is then emitted.

Algorithm 1: The section of the algorithm executed upon message reception.

Data: m : the incoming broadcast message

Data: s : the node which has sent m

```

1 if  $m$  is received for the first time then
2    $K(m) \leftarrow T(m)$ 
3    $rad(m) \leftarrow random \in [0, maxRAD]$ 
4 else
5    $K(m) \leftarrow K(m) \cup T(m) \cup \{s\}$ 
6 end

```

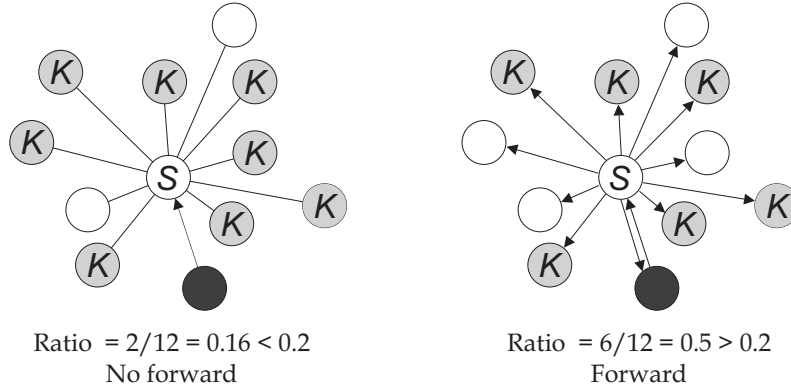


Figure 8.3: An example of the DFCN reaction to the reception of a new message.

8.3.1.2 RAD expiration event

When the RAD of a message expires, its hosting node computes the ratio of neighbors that did not yet receive it. If the ratio is greater than the threshold $minBenefit$, the message is forwarded, otherwise it is dropped. If the message is emitted, then $N(s)$ is added to $K(m)$. Algorithm 2 expresses this behavior.

8.3.1.3 New neighbor event

Each time a node s gets a new neighbor, the RAD for all messages is set to zero. Messages are hence immediately candidate to emission. If $N(s)$ is less than the threshold $densityThreshold$, this behavior is disabled. Algorithm 3 expresses this behavior.

Figure 8.4 gives an example of this behavior. Here the threshold $densityThreshold$ is set to 0.45. The node in the center holds a message that is candidate to broadcast. The black node is a new neighbor of the center node. Since the center node has more than $10 \times densityThreshold$ neighbors it does not emit the message.

Algorithm 2: the decision function defines if a given message is worthwhile to be forwarded or not.

Data: the broadcast message m , candidate to immediate emission.

Data: s : the node that receives m

```

1  $benefit \leftarrow \frac{|N(s)-K(m)|}{|N(s)|}$ 
2  $a(m) \leftarrow benefit \geq minBenefit$ 

3 if  $a(m)$  then
4    $K(m) \leftarrow K(m) \cup N(s)$ 
5 end
```

Algorithm 3: The algorithm executed upon message reception. $M(s)$ is the set of messages received—and not yet expired—by the node s .

Data: s : the node which has a new neighbor.

```

1 if  $|N(s)| < densityThreshold$  then
2   foreach  $m \in M(s)$  do
3      $rad(m) \leftarrow 0$ 
4   end
5 end
```

8.3.2 Reactivity and Proactivity in DFCN

This section presents the reactive and proactive aspects of the DFCN protocol and the way they impact its performances. It also discusses the way both approaches were coupled in order to improve the results with respect to the aforementioned criteria: minimizing the network traffic while maximizing the number of reached stations. In order to illustrate this analysis, some intermediate results are presented. These results were obtained by varying the density in $[0, 10.000]$ nodes by square kilometer. Since the simulation area was $250,000m^2$ ($500 \times 500m$), the number of nodes varied from 0 to 2,500. Finally, in order to achieve some decent statistical confidence, the various measures were obtained by averaging the measures out of 30 distinct simulations.

8.3.2.1 Reactive behavior

The reactive part of the DFCN protocol can faithfully be compared to all reactive-only protocols (like Simple Flooding, SBA, AHBP, etc). Experiments (Figure 8.6) show that all the reactive-only protocols tested here exhibit a linear increase of the number of emissions with respect to the number of nodes, and thus they are linearly dependent of the density value.

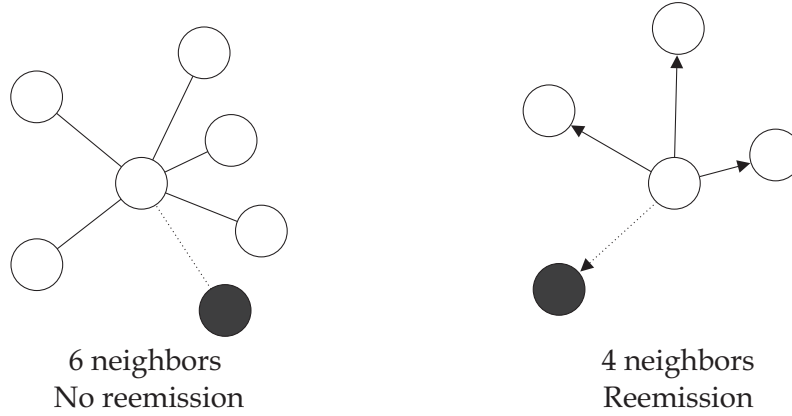


Figure 8.4: An example of the DFCN reaction to a new neighbor event.

Intuitively, if the number of rebroadcasting nodes was lessened proportionally to the density increase, the average number of emissions should be bounded. DFCN relies on this intuition. Practically, the threshold *minBenefit* which depends on the size of the neighborhood is intended to play a major part for that. Experiments confirm that this threshold has a serious impact on the performance of DFCN. By testing several values in its definition interval $]0, 1[$ (see Figure 8.5), we found out that the number of emissions performed by DFCN increases as the threshold grows, the best value being 0.5. When using values greater than 0.55, DFCN does not work at all. Because the performance drop-off is sharp, one can consider that using 0.5 is risky. Then for the experiments presented hereinafter, we used 0.4, which is considered safer. 0.4 is a safer because because 0.5 is the upper limit for the "controllable" behavior of DFCN. When using 0.6, DFCN did not work properly. Using 0.5 solved the problem. Since we could not find out with precision the "limit" value, we consider 0.5 to be the actual limit. A value below the limit had to be chosen. The value 0.4 is then arbitrary.

The results presented on Figure 8.6 show that using DFCN, the number of emissions in the network remains low as the density in the network grows. Moreover, it appears that AHBP/SBA carry out at least 2.5 more emissions than DFCN.

8.3.2.2 Proactive behavior

Reactive strategies do not operate if the density of the network is lower than a given threshold *densityThreshold*. The reason is that below this threshold, the network is split in several partitions, preventing the broadcasting message to propagate. A common solution to this issue is to re-execute the broadcasting strategy each time a new neighbor connects. This technique is used—and proved effective—by the AHBP-EX protocol. DFCN uses it too. This behavior is here referred to as *proactive*. As illustrated by Fig-

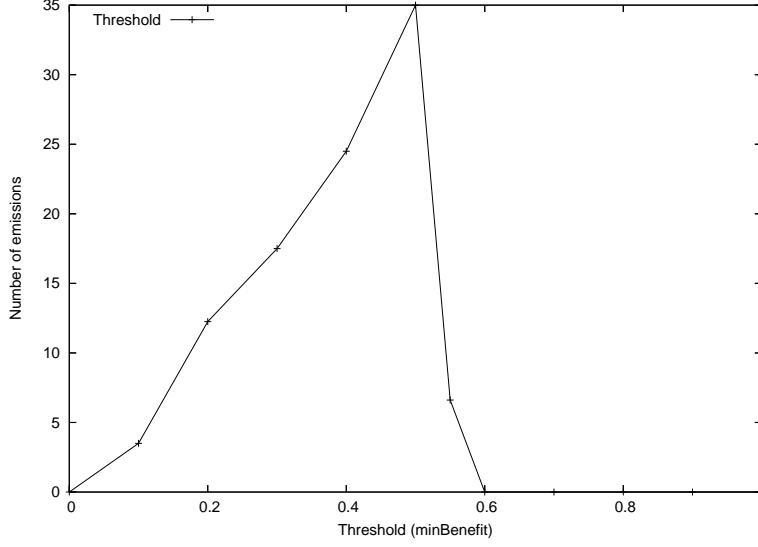


Figure 8.5: The number of emissions obtained when applying various values for the *minBenefit* thresholds when the density is 2,000.

ure 8.7, this technique permits to DFCN (as well as AHBP-EX) to operate with success when the density is as low as 100 devices per square kilometer.

Moreover, because the proactive strategy of DFCN uses the same decision function as the one used by the proactive strategy, DFCN behave smoother: unlike AHBP, DFCN does not systematically emit broadcast messages. The impact of this feature is clearly visible on Figure 8.7, DFCN emits about twice less than AHBP-EX.

8.3.2.3 Reactive and proactive coupled

Even though the proactive strategy is efficient, it leads to poor performances when the density is higher than 1,000. By probing the behavior of the reactive and proactive parts of both AHBP-EX and DFCN, we found that the pro-action spoils the qualities of the reactive behavior (see Figure 8.8). More precisely, when the density increases, the number of proactive message emissions is way too high. The reason is simple: as the density increases, there are more connections/disconnections, hence more message emissions. But most of these proactive emissions are actually totally useless.

DFCN solves this problem by using the threshold *densityThreshold* defined in Section 8.3.2.1. More precisely, DFCN disables its proactive strategy when the number of neighbors is greater than *densityThreshold* (see Figure 8.9). This turnaround makes both the reactive and proactive strategies to operate only when they are needed (see Figure 8.10). *densityThreshold* = 4 has experimentally shown to be a good value. Figure 8.11 shows that using the threshold improves the performance of DFCN, by dramatically reducing the number of messages emitted by the proactive strategy. As a matter of fact,

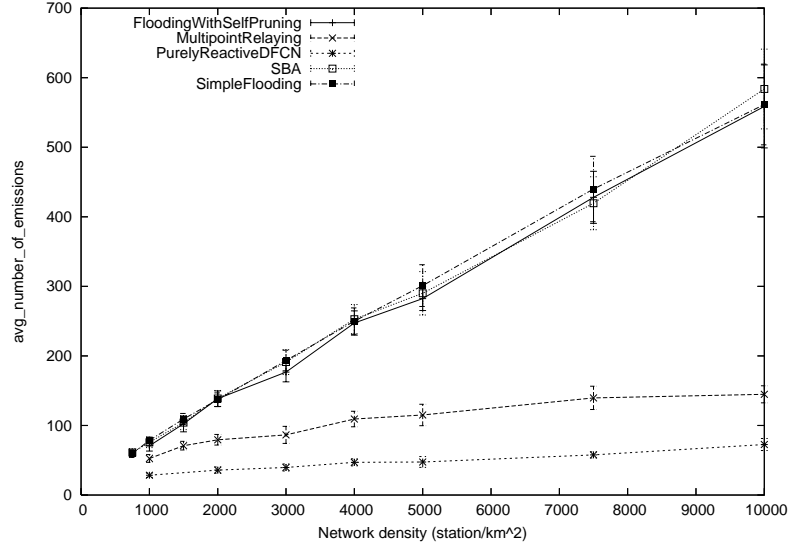


Figure 8.6: The reactive behavior of the DFCN protocol keeps the number of emissions low, whatever the network density is.

when the density is high—more than $2,500 \text{ node}/\text{km}^2$ —the proactive strategy does not operate anymore.

8.3.2.4 Application domain

As explained in Section 8.1, the network density has a serious impact on the behavior of broadcast protocols. Experiments show that, given any broadcast protocol, there exists a density threshold below which that protocol does not work. the protocols that do not feature any proactive management of the mobility (Simple flooding, SBA, Multipoint Relaying, etc) are unusable in the environment where the density is lower than 1,000 nodes by square kilometer.

Based on reaction to neighborhood changes AHBP-EX and DFCN perform well down to $100 \text{ nodes}/\text{km}^2$. Broadcasting in partitioned ad hoc networks relies on the mobility of the nodes. Because there are several partitions in the network, the only way for the broadcast message to jump from one partition to another is to find temporary paths heading to other partitions or to be carried by nodes moving to other partitions. This process may last a while, since the temporary paths appear erratically and the speed of the nodes is limited.

8.4 Experiments

This section described the experiments which were conducted in order to show the properties of the DFCN protocol. The conditions of the experimentation are described, then

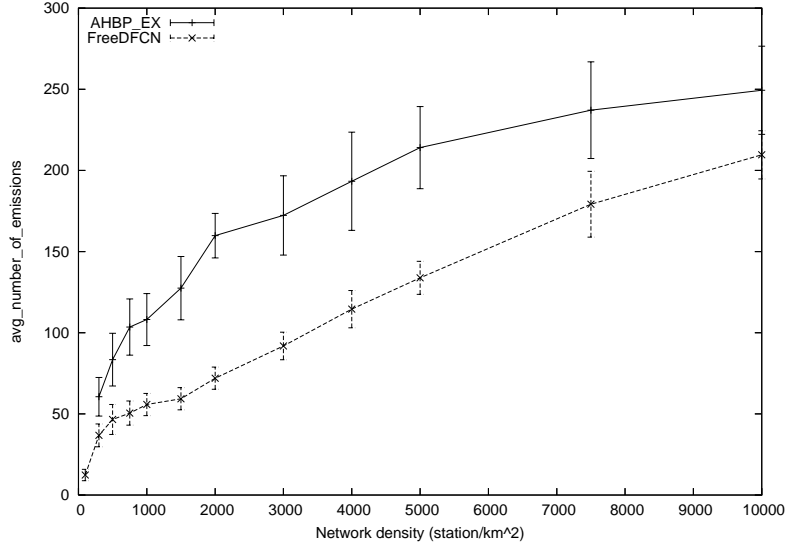


Figure 8.7: Improvement of DFCN over AHBP-EX. DFCN is here referred to as FreeDFCN.

the numerical results are illustrated and explained in details.

8.4.1 Description of the experiments

The results presented in Section 8.4.2 were obtained by using an implementation of the DFCN protocol for the MADHOC simulator (see section 5). This section details the conditions in which the experimentations were conducted, that is the mobility model for the simulated nodes, and PHY/MAC layer characteristics the simulator considers for communicating, the radio propagation model which that were used, the parameters which concern the protocol by itself (as described in Section 8.3), and metrics which were taken into consideration for the evaluation of the performance of DFCN.

8.4.1.1 Node mobility

The nodes move according to the random waypoint [CBD02, BRS03] mobility model. As described in [BRS03], the random waypoint mobility model defines that each node randomly chooses a destination in the simulation area. The node moves towards this destination with a randomly chosen velocity. When the node reaches its destination, it remains static for a predefined duration and then starts moving again according to the same rule.

In order to reduce the harmful behavior inherent to the random waypoint mobility model, as detailed in [YLN03], the first iterations of the simulation process are not taken into account in the presented results: these first iterations serve for the initialization of the mobility of the nodes which then reach some stationary space distribution [NC04].

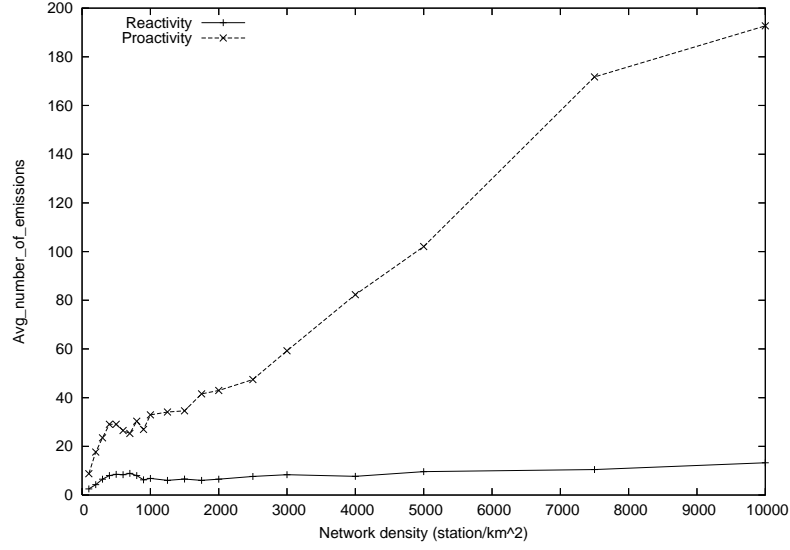


Figure 8.8: When the density is high, the proactive strategy of DFCN emits lots of messages. But with such density, the reactive behavior only would be sufficient for broadcasting. The bandwidth utilization of the proactive behavior is then useless.

The simulated area is a square whose edge is 500m. The velocity of nodes is randomly chosen between 3 and 6km/h. The pause lasts 5 seconds.

8.4.1.2 PHY/MAC

The coverage radius (maximum distance from the source from which the signal can be sensed and demodulated) used for the simulations, can vary between 30 and 60 meters. The *maximum bandwidth* (theoretically obtained when the signal is not attenuated and when the link is free of interferences) is 11Mbps. These characteristics correspond to the IEEE 802.11b specifications.

Communications are established according to the rules defined by the CSMA (Carrier Sense Multiple Access) MAC layer. No collision management mechanism like CA (Collision Avoidance) or CD (Collision Detection) is used here. CSMA was chosen because it is the smallest common set of the specific MAC layers used by existing wireless networking technologies (IEEE 802.11a/b/g).

8.4.1.3 Radio wave propagation

Radio wave propagation depends on the natural environment of the nodes. In open space the propagation is omni-directional and the covered area is a circle. Some works aiming at modelling the propagation of radio waves use techniques like advanced statistical models or ray-tracing [BS04a]. For simplicity most of the works in the area of broadcasting considers

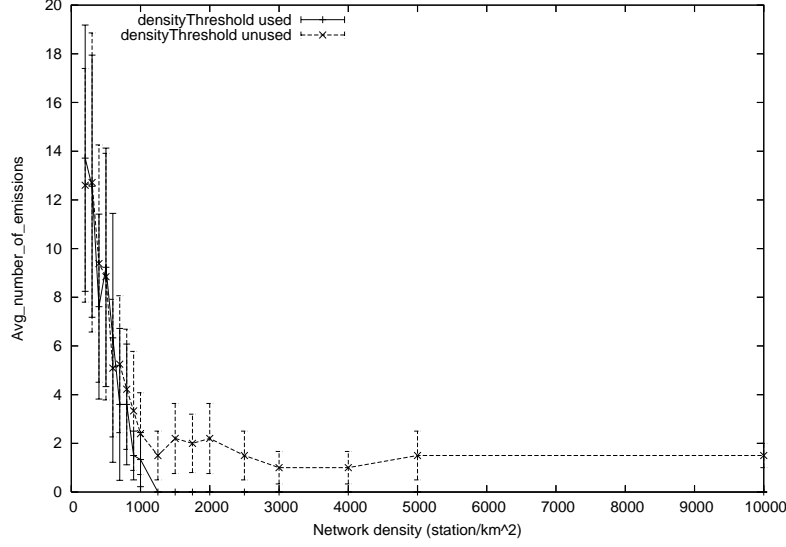


Figure 8.9: The use of *densityThreshold* allows DFCN’s proactive strategy to become discrete as the density increases.

the open space path loss as the radio wave propagation model. According to open space path loss model radio signal gets attenuated as the distance grows.

8.4.1.4 Parameters of the protocol

As explained in Section 8.3.1, DFCN relies on the *minBenefit* and *densityThreshold* thresholds. It has experimentally been found out that 0.4 and 4, respectively, are good values for these threshold. The following benchmarks rely on these values.

8.4.1.5 Benchmarking process

The simulation of a broadcasting process starts with the selection of some random nodes. These nodes are the starting places of the broadcast message. In order to prevent the broadcasting process from starting from an isolated node (from which reactive-only protocols would have no chance to operate), the source node is chosen so that its number of neighbors is greater than the average number of neighbors in the whole network.

The broadcasting process is said to be:

completed if it could satisfy the coverage constraint. Coverage satisfaction ensures the validity of the broadcasting process. More precisely, if the coverage cannot reach the constrained value, then the broadcasting process is considered to have failed.

failed if the broadcast message expires before the broadcasting process could satisfy the coverage constraint. The lifetime of broadcasting messages depends upon the application. Packet routing layers need quite short lifetimes while high-level applications,

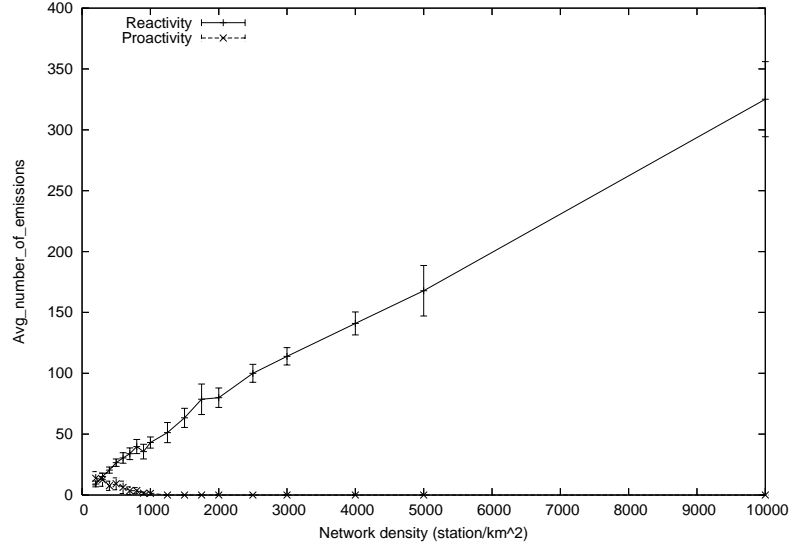


Figure 8.10: The use of a threshold makes both the reactive and proactive strategies to operate only when they are needed.

like advertising application, may want the message to be alive several hours. In our simulations we set the message lifetime to 1 minute. Upon expiration of its lifetime the message can no longer be transmitted. Thus the broadcasting process is terminated.

In order to evaluate the performance of the DFCN protocol, it is compared to other competing protocols. As mentioned in Section 7.2, numerous broadcasting protocols have been proposed. But not all of them have the same objectives as DFCN. More precisely, centralized (global and quasi-global) broadcasting protocols cannot be applied in the context of mobile ad hoc networks. Protocols relying on location information like [SS00, NTCS99] cannot be used as references because we assumed that such information is not available. Similarly, some broadcasting protocols use mechanisms that enable the nodes to adjust power of the transmitter and receiver of its communication interface [CSS02a]. As the availability of such mechanisms is not assumed, DFCN is not compared to such protocols. As a consequence, the retained protocols for the evaluation are Simple Flooding (section 7.2.1), Flooding with Self-Pruning (section 7.2.5), the Scalable Broadcast Algorithm (section 7.2.6), Multipoint Relaying (section 7.2.7), and AHBP-EX (section 7.2.9).

8.4.2 Results

Based on the simulation parameters described in Section 8.4.1, we illustrate and explain the performance of DFCN.

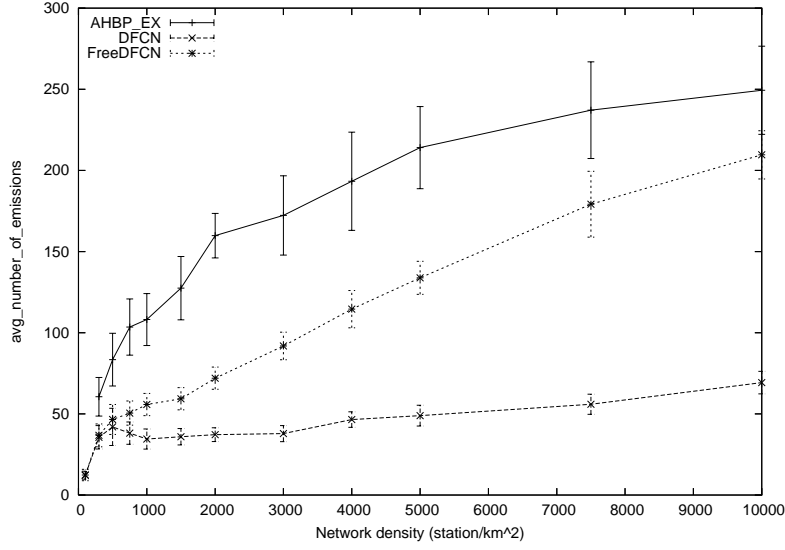


Figure 8.11: *Improvement of DFCN over FreeDFCN and AHBP-EX. FreeDFCN stands for “DFCN without densityThreshold”.*

8.4.2.1 Number of emissions

The number of emissions is one of the most relevant measure because it has a direct impact on the network bandwidth used (network overhead). This value has to be minimized. Figure 8.12 shows the average number of emissions in case when only one node initiates the broadcasting process. A situation when 10% of the nodes initiate broadcast simultaneously is shown on Figure 8.13. In both cases it can be seen that DFCN emits far less messages than Multipoint Relaying, one of the most bandwidth efficient protocol.

8.4.2.2 Number of redundant receptions

The number of redundant receptions directly depicts the waste of resources (bandwidth, energy, etc). It has to be minimized. Figure 8.14 shows that DFCN uses about 3 times less resources than its competing protocols.

8.4.2.3 Duration of the broadcasting process

We look here at the time required to complete the broadcasting process.

Figure 8.15 shows that DFCN is not the fastest broadcasting protocol. This result comes from its selective strategy. Because DFCN carries out less emissions, the broadcasting process needs more time to complete. It is a tradeoff (enlightened in several studies on broadcasting protocols for ad hoc networks): the more greedy a broadcasting protocol is, the faster it is.

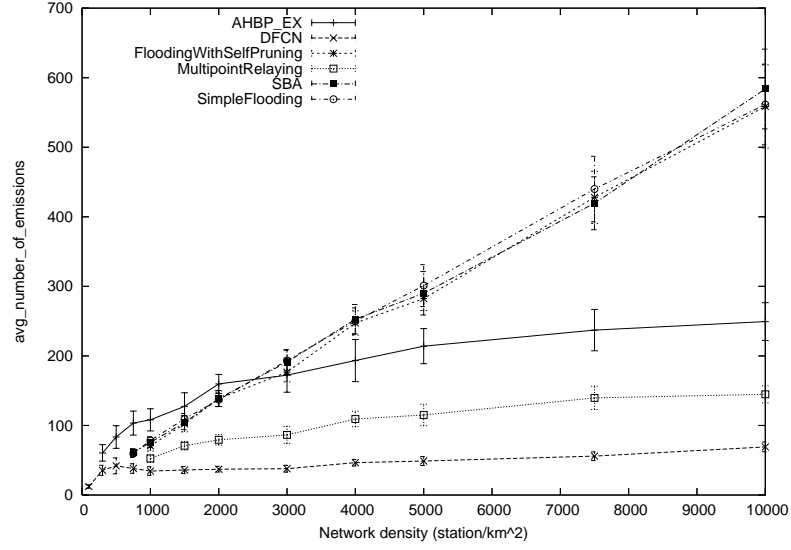


Figure 8.12: The number of emissions carried out by each broadcasting protocol. Only one single node initiates a broadcasting process

8.4.2.4 Emission efficiency

Defining the quality of a protocol is application-dependent. The objective function may rely on various parameters: speed, bandwidth consumption, bandwidth waste, etc. In our work, we consider as a relevant measure of efficiency, $\frac{\text{number of emissions}}{\text{number of nodes reached}}$. The good results shown by Figure 8.16 testifies that DFCN carries out message emissions when it is really worthwhile.

8.4.2.5 Application to different topologies

DFCN was tested on a variety of network topologies. In particular its application in the context of the random waypoint mobility model is described in the previous sections. DFCN was also analyzed in the context of metropolitan mobility model, and in particular on network generated by the use of the human mobility model (see section 6.4) and its mall scenario (see section 6.4.3.1), which exhibits a greatly varying neighbor density. In order to harden the conditions for broadcasting, different networking technologies were simulated, that is a number of nodes had only a IEEE802.11b adapter, others had only a Bluetooth adapter and some others had both.

The results observed were qualitatively very similar to those exposed hereinbefore. It can hence be concluded than DFCN is robust, and it does not suffer from changing conditions.

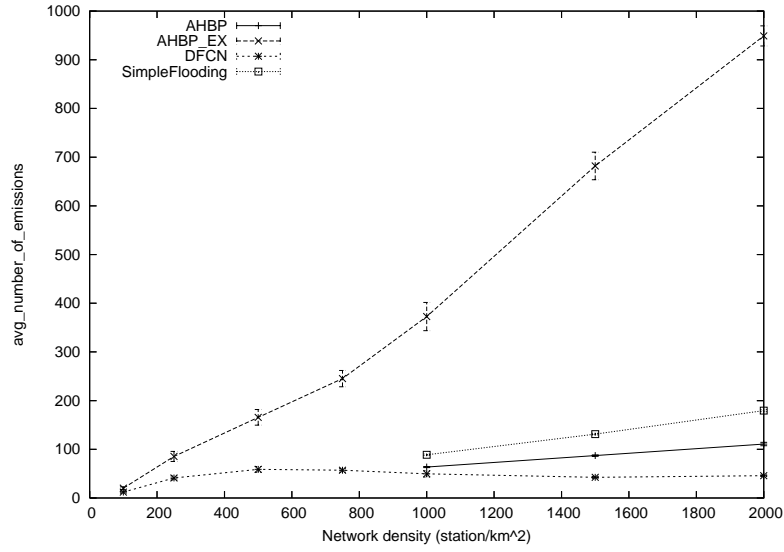


Figure 8.13: The number of emissions carried out when 10% of the nodes initiate a broadcasting process. Because of the computational limitations of the worknodes used for the simulation, we could not use densities greater than $2,000 \text{ nodes}/\text{km}^2$.

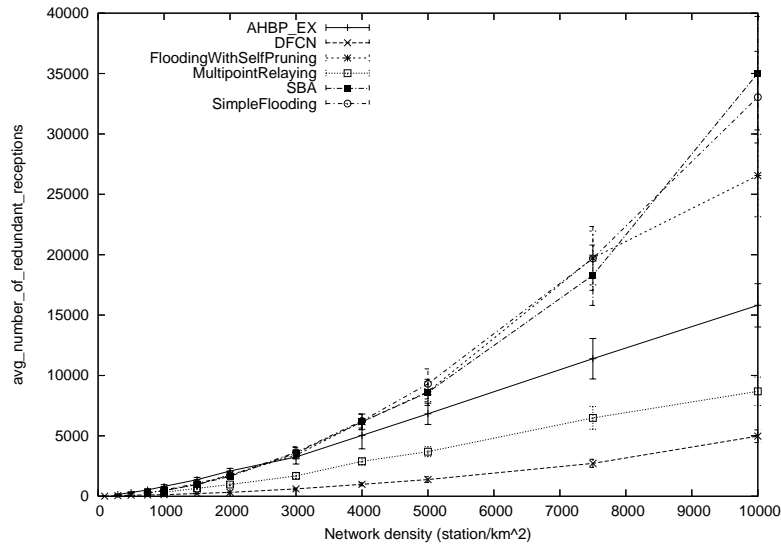


Figure 8.14: The number of redundant receptions generated by each broadcasting protocol.

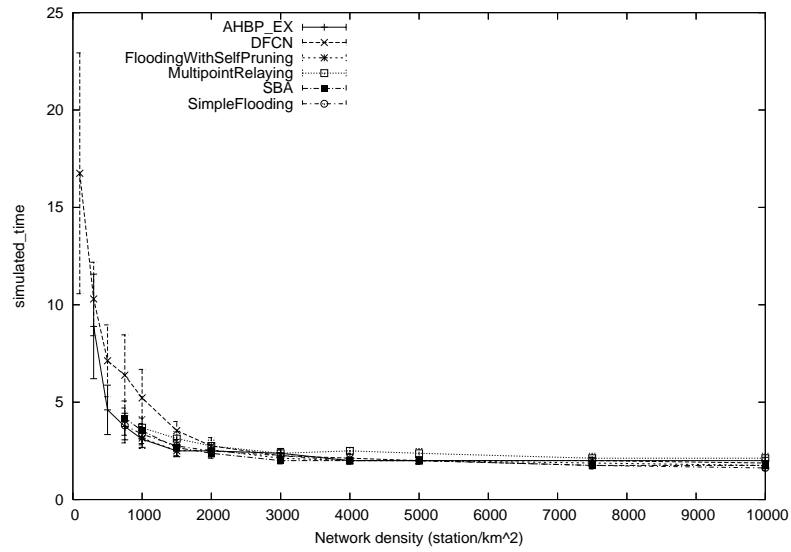


Figure 8.15: The execution time of each tested broadcasting protocol. The lower the better.

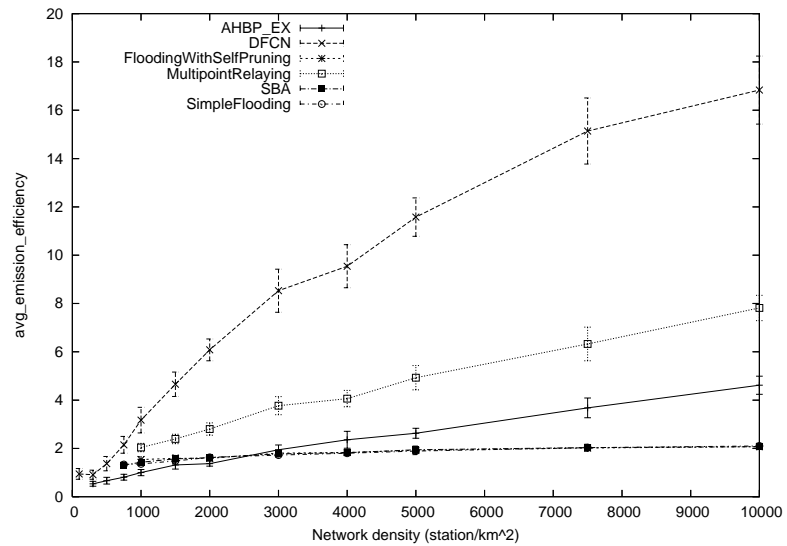


Figure 8.16: The results testify that DFCN carries out message emissions when it is really worthwhile.

Chapter 9

Optimization of the broadcasting process

The MADHOC implementation of DFCN was used as the basis for a study of the multi-objective optimization of broadcasting protocols, as described in the following.

This section first gives a basic overview of genetic optimization, then of multi-objective optimization. Then it describes the DFCNT and the cDFCN problems. For both of them it presents the adopted solution and the obtained results.

This research was conducted in tight collaboration with the team of Prof. Enrique Alba (Málaga University).

9.1 Genetic optimization

As explained in [Nas], genetic optimization works on a population of individuals representing possible solutions to a specific problem. Each individual is evaluated using a fitness value which is a measure of how well this individual is adapted to its environment. Individuals (which are represented by a genotype—a suitable sequence of bits) reproduction rate is proportional to their fitness. The bit-coded representation of individuals creates a quantization of the solution space. A genetic algorithm starts with an initial population of candidate solutions or individuals, and modifies it until the population converges to a solution. A problem-dependent fitness function must be chosen to measure the appropriateness of an individual. The modification of the population is achieved by using the application of three genetic operators which are: selection, crossover, and mutation.

9.2 Multi-objective optimization

Contrary to single objective optimization (which can be achieved by using genetic algorithms, as explained in Section 9.1), multi-objective optimization is not restricted to find

a unique solution of a given multi-objective problem, but a set of solutions known as the *Pareto optimal set*. For instance, taking as an example the problem we are dealing with, one solution can represent the best result concern the number of reached stations, while another solution could be the best one concerning the makespan. These solutions are said *non-dominated*, that is there do not exist any other solution that consists in a Pareto-improvement of these. A pareto improvement is a solution that can make at least one individual better, without making any other individual worse. The result provided by a multi-objective optimization algorithm is then a set of non-dominated solutions (the *Pareto optima*) which are collectively known as the *Pareto front* when plotted in the objective space. The mission of the decision maker is to choose the most adequate solution from the Pareto front.

A general multi-objective optimization problem can be formally defined as follows:

Definition — Find a vector $\vec{x}^* = [x_1^*, x_2^*, \dots, x_n^*]$ which satisfies the m inequality constraints $g_i(\vec{x}) \geq 0, i = 1, 2, \dots, m$, the p equality constraints $h_i(\vec{x}) = 0, i = 1, 2, \dots, p$, and minimizes the vector function $\vec{f}(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \dots, f_k(\vec{x})]^T$, where $\vec{x} = [x_1, x_2, \dots, x_n]^T$ is the vector of decision variables. ■

The set of all values satisfying the constraints defines the *feasible region* Ω and any point $\vec{x} \in \Omega$ is a *feasible solution*. As mentioned before, we seek for the *Pareto optimum*. Its formal definition is given by:

Definition — A point $\vec{x}^* \in \Omega$ is Pareto Optimal if for every $\vec{x} \in \Omega$ and $I = \{1, 2, \dots, k\}$ either, $\forall_{i \in I} (f_i(\vec{x}) = f_i(\vec{x}^*))$ or, there is at least one $i \in I$ such that $f_i(\vec{x}) > f_i(\vec{x}^*)$. ■

This definition states that \vec{x}^* is Pareto optimal if there exists no feasible vector \vec{x} which would decrease some criterion without causing a simultaneous increase in at least one other criterion. Taking as an example the problem we are dealing with, one solution can represent the best result concerning the number of reached stations, while another solution could be the best concerning the makespan.

The mission of the decision maker is to choose the most adequate solution of the given multi-objective optimization problem from the resulting Pareto front.

9.3 The DFCNT problem

From the description of the previous section, the following DFCN parameters are to be tuned:

minBenefit is the minimum benefit for rebroadcasting. This is the most important parameter for tuning DFCN, since minimizing the bandwidth should be highly dependent on the network density. It ranges from 0.0 to 1.0.

lowerBoundRAD, *upperBoundRAD* defines the RAD value (random delay for rebroadcasting in milliseconds). Both parameters take values in the interval $[0.0, 10.0]$ milliseconds.

proD is the maximal density ($proD \in [0, 100]$) for which it is still needed to use the proactive behavior (i.e., reacting on new neighbors) for complementing the reactive behavior.

safeDensity defines a maximum safe density of the threshold which ranges from 0 to 100 devices.

These parameters, i.e., a DFCN configuration, characterize the search space. Here, the objectives to be optimized are: minimizing the makespan (in seconds), maximizing the network coverage (percentage of devices having received the broadcasting message), and minimizing the bandwidth used (in number of transmissions). Thus, we have defined a triple objective multi-objective problem, which has been called DFCNT (standing for DFCN Tuning). For obtaining the values of these objective functions we have used MADHOC because it implements the DFCN broadcasting protocol. Our goal is to obtain the Pareto front of DFCNT (and the corresponding DFCN configurations) in terms of these three objectives.

9.3.1 Using a cellular genetic algorithm

Cellular genetic algorithms are a subclass of GAs in which the population is structured in a specified topology, so that individuals may only interact with their neighbors. These overlapped small neighborhoods help in exploring the search space because the induced slow diffusion of solutions through the population provides a kind of exploration, while exploitation takes place inside each neighborhood by genetic operations. In cMOGA, the cGA that is considered herein, the population is structured in a 2D toroidal grid, and the neighborhood defined on it always contains 5 individuals: the considered one (position(x,y)) plus the North, East, West, and South individuals.

9.3.1.1 Targeted network

Three very different realistic scenarios, implemented in MADHOC, are used in this study. These scenarios correspond to real world environments, and they aim at modelling a shopping mall (see Section 6.4.3.1), a metropolitan area (see Section 6.4.3.2), and a highway (see Section 6.4.3.3). They are detailed in the following:

DFCNT.Mall is a shopping center of 200×200 square meters of surface with densities of 800 stores and 2 000 devices per square kilometer. Stores are circles of radius between 1 and 10 meters, and the obstruction of the walls is computed with a penalty of 70% in the signal strength. Finally, devices travel with a speed ranging between 0.3 and 1 m/s in the corridors and between 0.3 and 0.8 m/s when they are inside the stores. The resulting network is illustrated on Figure 9.1.

DFCNT.Metropolitan . This environment has a surface of 400×400 square meters, with a density of 50 spots (standing for crossroads) per square kilometer having a circle surface of radius between 3 and 15 meters. The wall obstruction is in this case higher than for the mall environment (up to 90%), and the density of devices is 500 elements per square kilometer. When setting the speed of devices, the cases when people move on foot or by car must be taken into account, so its value ranges between 0.3 and 10 m/s when they are in a crossroad, and between 1 and 25 m/s in other case (streets). The resulting network is illustrated on Figure 9.1.

Figure 9.1: The three studied scenarios for mobile ad hoc networks.

DFCNT.Highway MADHOC for modelling the network with the particularity of setting the wall obstruction to 0%. The simulated surface was set to 1000×1000 square meters with a density of only 50 devices per square kilometer. These devices travel at random speeds between 30 and 50 m/s. We define the roads as straight lines connecting two spots, and we establish a density of only 3 spots (highway entrances and/or exits) for modelling the scenario. The speed of devices within the spots must be reduced to between 20 and 30 m/s. The size of each spot (length of the entrance/exit) is set to a random value between 50 and 200 meters (spots radius $\in [25, 100]$ meters). The resulting network is illustrated on Figure 9.1.

In order to make our studies more realistic, an *observation window* has been included in the simulations, such that only the devices located in this window are taken into account

Table 9.1: Main features of the proposed environments

	Mall	Metropolitan	Highway
Surface	40 000 m ²	160 000 m ²	1 000 000 m ²
Density of spots	800 (shops/km ²)	50 (crossroads/km ²)	3 (joints/km ²)
Speed out of spots	0.3–1 m/s	1–25 m/s	30–50 m/s
Devices Speed in spots	0.3–0.8 m/s	0.3–10 m/s	20–30 m/s
Density	2 000 dev./km ²	500 dev./km ²	50 dev./km ²
Wall obstruction	70%	90%	0%

for measurements. This makes it possible to simulate nodes exiting and joining the network by entering or leaving the observation window, respectively. Therefore, the existence of a changing number of devices in the network is allowed, as it is the case in real mobile ad hoc networks. In all our tests in this work, this observation window covers 70% of the whole area. As an example, Figure 9.2 shows that a mobile ad hoc network simulating a mall environment (left), and the observation window that is studied (right); (70% of the whole network). The circles represent the shops, while the points stand for devices (those outside the observation window are grey colored, meaning that they are not considered for measurements).

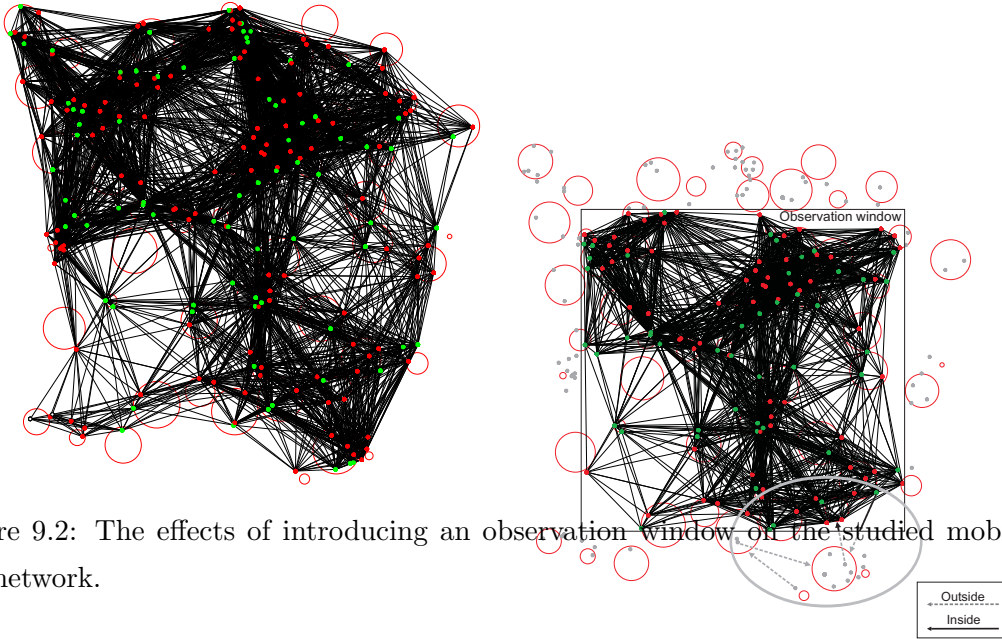


Figure 9.2: The effects of introducing an observation window on the studied mobile ad hoc network.

9.3.1.2 Experiments

cMOGA has been implemented in Java and tested on a PC with a 2.8 GHz Pentium IV processor with 512 MB of RAM memory, and running SuSE Linux 8.1 (kernel 2.4.19-4GB). The Java version used is 1.5.0_05. All the values presented are the average over 30 independent runs of cMOGA.

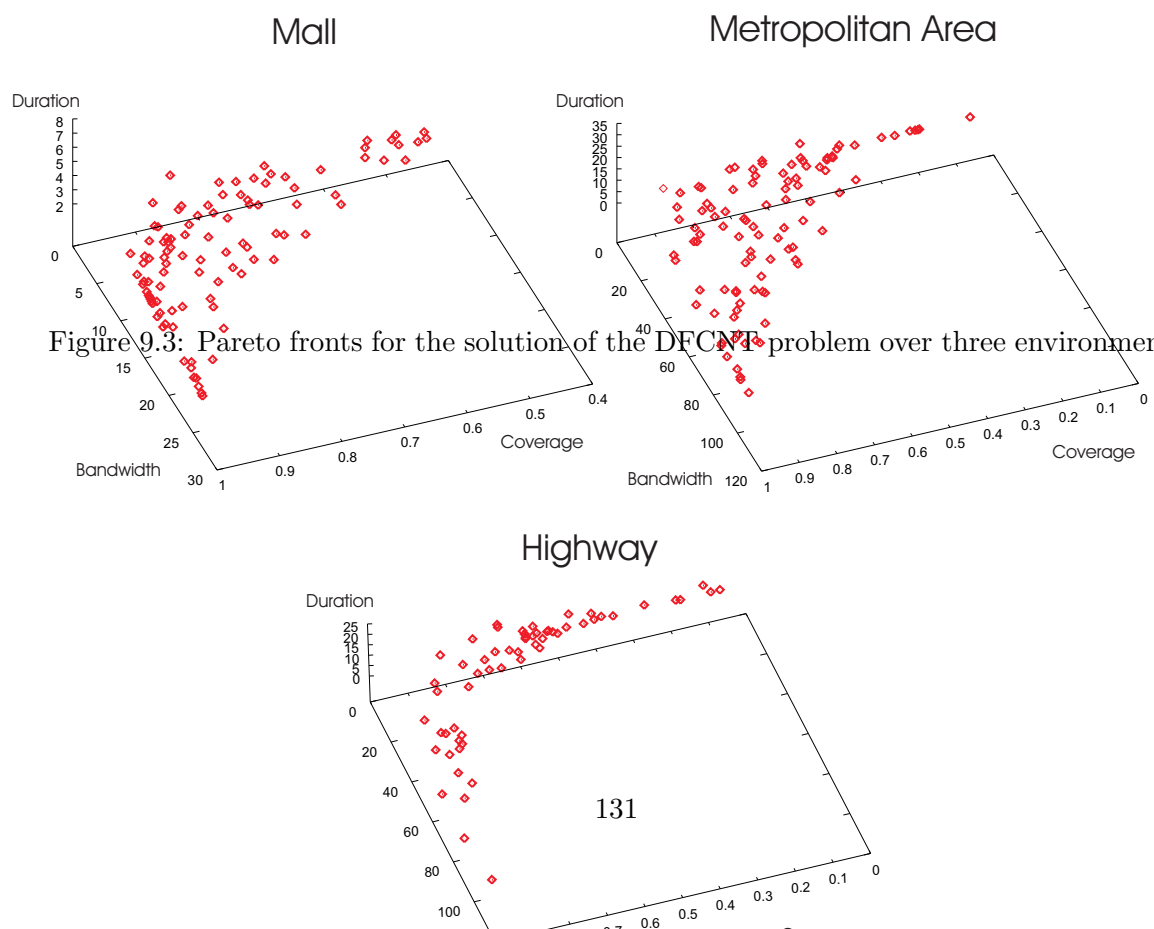


Figure 9.3: Pareto fronts for the solution of the DFCNT problem over three environments

The Pareto fronts on Fig. 9.3 expose the design objectives of the DFCN protocol: most of the plots (in the center of the clouds) provide sets of parameters that make DFCN achieving a coverage rate close to 100%, keeping the network throughput very low. What makes the DFCNT problem particularly interesting from an applicative point of view is that it permits the decision maker to discard this default behavior by setting a *degree of coverage* for the broadcasting application. Indeed not all applications require the maximization of the coverage rate. For example, *local advertising*—which consists in spreading advertisement messages to devices a few hops away from the source—needs the broadcasting process to cease after a while. Sometimes high coverage is even to be avoided. For example trying to achieve a high coverage on metropolitan mobile ad hoc networks (which may realistically be made of thousands of devices) is harmful, since it is likely to lead to severe network congestions.

9.3.2 Using scatter search

This section first briefly describes multi-objective scatter search algorithms, then it details which parameters the experiments were conducted. Finally it presents the metrics that were used in order to evaluate the significance of the results obtained, explains the result themselves.

9.3.2.1 Multi-objective Scatter Search

This section presents the description of scatter search algorithms, then it gives an overview of the Archive-based Scatter Search (AbSS) which is used here.

9.3.2.1.1 Scatter Search Scatter search [Glo97, GLM00, GLM03] has been successfully applied to a wide variety of optimization problems [GLM00], but it has not been extended to deal with multi-objective optimization problems until recently [NLD⁺05, Bea05, dSCF04, NLA05]. This meta-heuristic consists of five methods: diversification generation, improvement, reference set update, subset generation, and solution combination.

The scatter search technique starts by creating an initial set of diverse individuals in the initialization phase. This phase consists in iteratively generating new solutions by invoking the diversification generation method; each solution is passed to the improvement method, which usually applies a local search procedure in an iterative manner, and the resulting individual is included into the initial set P . After the initial phase, the scatter search main loop starts.

The main loop begins building the reference set from the initial set by invoking the reference set update method. The reference set is a collection of both high quality solutions and diverse solutions that are used for generating new individuals. Solutions in this set are systematically grouped into subsets of two or more individuals by means of the subset

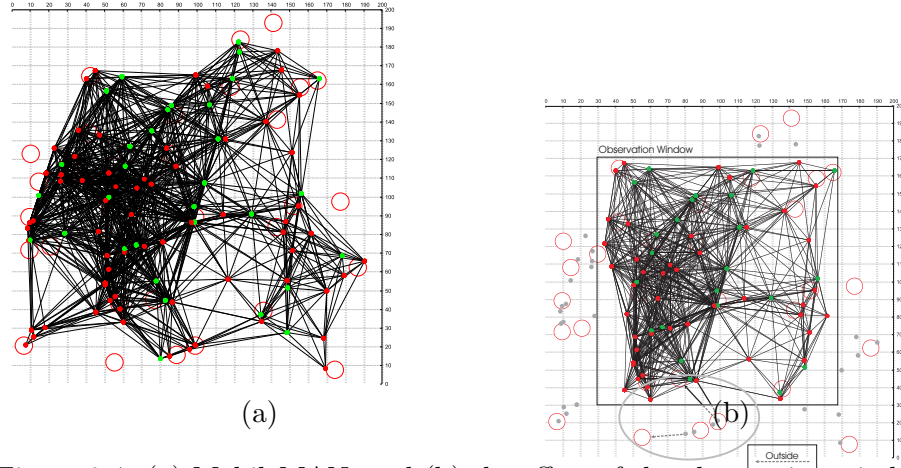


Figure 9.4: (a) MobileMAN, and (b) the effect of the observation window

generation method. In the next step, solutions in each subset are combined to create a new individual, according to the solution combination method. Then, the improvement method is applied to every new individual. The final step consists of deciding whether the resulting solution is inserted into the reference set or not. This loop is executed until a termination condition is met (for example, a given number of iterations has been performed, or the subset generation method does not produce new subsets).

9.3.2.1.2 AbSS AbSS (Archive-based Scatter Search) [NLD⁺05] is based on the aforementioned scatter search template (see section 9.3.2.1.1) and its application to solve bounded continuous single objective optimization problems [GLM03]. It uses an external archive for storing non-dominated solutions and combines ideas of three state-of-the-art evolutionary algorithms for solving MOPs. In concrete, the archive management follows the scheme of PAES [KC99], but using the crowding distance of NSGA-II [DPAM02] as a niching measure instead of the PAES adaptive grid; additionally, the density estimation found in SPEA2 [ZLT01] is adopted for selecting the solutions from the initial set that will build the reference set.

9.3.2.2 Targeted network

In order to make the simulations more realistic, MADHOC has been extended with an observation window such that only the devices located inside this window are taken into account for measurements. This allows the number of devices in the network to change, just like it happens in real mobile ad hoc networks. This feature of MADHOC is illustrated on Figure 9.4, where both an example of a MobileMAN (a) and the effects of introducing an observation window on it (b) are shown. In all the tests, this observation window is 70% of the total simulation area. The main parameters of MADHOC used for defining the network characteristics are the following:

size: defines the network simulation area in terms of square meters.

density: is the average density of nodes per square kilometer (i.e., the number of devices per square kilometer).

environment: determines the mobility model (see section 6.1) of the stations as well as the radio wave propagation model (see section 6.4.2). That is, this feature defines how the stations are moving as well as the area within which they are moving (open areas, buildings, streets, etc.), thus determining how radio waves propagate.

9.3.2.3 Results

This section is devoted to present the experiments performed for this work. First we describe the metrics used for measuring the performance of the resulting Pareto fronts. Next, the parameterization of AbSS and MADHOC is detailed. Finally, the results of DFCNT are shown and compared against cMOGA [ADL⁺05] (see section 9.3.1).

9.3.2.3.1 Metrics Three metrics for assessing the performance of both AbSS and cMOGA were used: the number of Pareto optima that the optimizers are able to find, the Set Coverage [Zit99] which allows two algorithms to be compared in terms of Pareto dominance, and the Hypervolume [ZT98] which measures both convergence and diversity at the same time in the resulting Pareto fronts. They are defined as:

Number of Pareto optima , which can be considered as a measure of the ability of the algorithm for exploring difficult search spaces defined by hard MOPs like DFCNT.

Set Coverage , which is the set coverage metric $\mathcal{C}(A, B)$ calculates the proportion of solutions in B which are dominated by solutions of A . A metric value $\mathcal{C}(A, B) = 1$ means that all members of B are dominated by A , whereas $\mathcal{C}(A, B) = 0$ means that no member of B is dominated by A . This way, the larger the $\mathcal{C}(A, B)$, the better the Pareto front A with respect to B .

Hypervolume which calculates the volume (in the objective space) covered by the non-dominated solutions. Algorithms with larger hypervolumes are desirable.

9.3.2.3.2 Parametrization The behavior of MADHOC has been defined based on three parameters: the size of the simulation area, the density of mobile stations, and the type of environment. For our experiments, we have used a simulation area of 40,000 square meters, a density of 2,000 stations per square kilometer, and, from the available environments of MADHOC, the mall environment has been used. This environment is intended to model a commercial shopping center. People go from one store to another by

Metric	AbSS		cMOGA		<i>t</i> -test
	average	std	average	std	
Number of Pareto Optima	98.7586	2.8119	98.1053	2.9000	–
Set Coverage	0.9865	0.0103	0.9793	0.0076	+
Hypervolume	0.8989	0.0695	0.8199	0.0854	+

Table 9.2: Performance metrics for AbSS and cMOGA when solving DFCNT

these corridors, occasionally stopping for looking at some shopwindows. Both the mobility of devices and their signal propagation are restricted due to the walls of the building. A metropolitan mobile ad hoc network with such a configuration has been shown in Figure 9.4. The result shown were averaged out out five non-deterministic runs.

The configuration used for cMOGA is the same as that used in [ADL⁺05]. Regarding AbSS, we have utilized the parameterization proposed in [NLD⁺05]. Both cMOGA and AbSS stop when 25,000 function evaluations have been computed. It is important to note that 25,000 evals \times 5 simulations/eval means that DFCN has been optimized over 125,000 different network instances.

9.3.2.3.3 Results The results presented are averaged out of 30 independent runs of each multi-objective optimizer.

Considering that the two algorithms are configured for obtaining 100 non-dominated solutions at most (maximum archive size), values shown in Table 9.2 point out that most executions of the optimizers fill up the whole archive. Though AbSS returns a slightly higher number of Pareto optima on average than cMOGA does, the difference is negligible. This shows that both optimizers have a similar ability for exploring the search space of DFCNT.

The *t*-test assesses whether the means of two samples are statistically different from each other. If we consider that the two algorithms are configured for obtaining 100 non-dominated solutions at most (maximum archive size), values shown in Table 1 point out that most executions of the optimizers fill up the whole archive. Though AbSS returns a slightly higher number of Pareto optima on average than cMOGA does, the difference is negligible and no statistical confidence exists (“–” symbol in *t*-test column), thus showing that both optimizers have a similar ability for exploring the search space of DFCNT. As regards to the Set Coverage metric, we want to clarify that results shown in column “AbSS” correspond to $C(AbSS; cMOGA)$ whereas those presented in column cMOGA” are $C(cMOGA; AbSS)$. As it can be seen in Table 1, AbSS gets larger values for this metric than cMOGA and there exists statistical confidence for this claim (see “+” symbol in the last column). This fact points out that AbSS can find solutions that dominate more solutions of cMOGA than vice versa. However, Set Coverage values are similar in both the

cases, what indicates that each algorithm computes high quality solutions that dominate most solutions of the other, but those high quality solutions are in turn non-dominated.

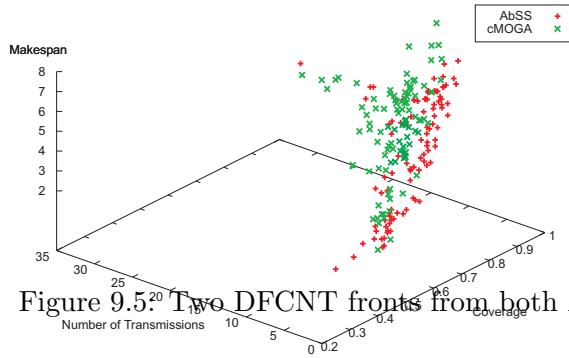


Figure 9.5: Two DFCNT fronts from both AbSS and cMOGA

Last row in Table 9.2 presents the results of the Hypervolume metric. They clearly show that AbSS overcomes cMOGA when considering at the same time both convergence and diversity in the resulting Pareto fronts. Since the Set Coverage metric showed that both optimizers were similar in terms of convergence, we can conclude that AbSS is reaching this Hypervolume value because of the diversity in the found Pareto front, as illustrated on Figure 9.5. Consequently using AbSS provides the network designer (decision maker) with a wider set of DFCN parameter settings which ranges from configurations that get a high coverage in a short makespan but using a high bandwidth to those cheap solutions in terms of time and bandwidth being suitable if coverage is not a hard constraint in the network.

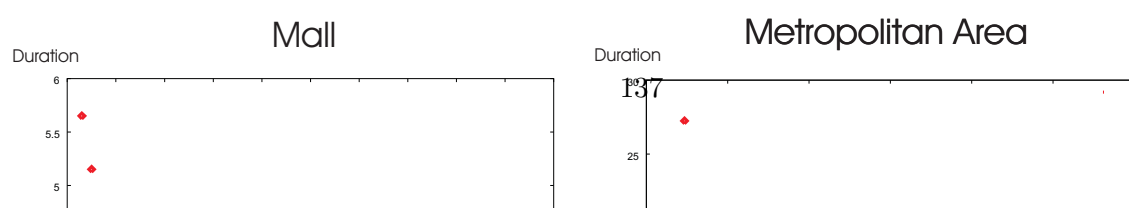
9.4 The cDFCNT problem

The cDFCNT problem is derived from the DFCNT problem described in Section 9.3. cDFCNT is not a three objective problem which consists in minimizing the makespan (in seconds), maximizing the network coverage (percentage of devices having received the broadcast message), and minimizing the bandwidth used (in number of transmissions). Instead, cDFCNT considers the network coverage as a constraint instead of a goal for practical purposes. cDFCNT, is then a bi-objective problem with one constraint.

cDFCNT is applied on the same networks as used for DFCNT. The network configuration is detailed in Section 9.3.2.2.

The genetic algorithm used to solve it is the same cellular genetic algorithm as we used for DFCNT. It is described in Section 9.3.1.

Figure 9.6: The Pareto fronts for cDFCNT problem over three environments



9.4.1 Results

As suggested before, all broadcasting protocols follow the next rule: the more opportunistic they are the faster they proceed (by not considering the impact of packet collisions), but the higher bandwidth they use. DFCN has been designed with this in mind: its behavior—when used with appropriate parameters—makes it break this rule. Herein, since we seek for Pareto-optimal set of parameters, our objective is different. Consequently the common behavior exhibited by all broadcasting protocol shows up on the Pareto fronts illustrated on Figure 9.6. Achieving very short duration times entails high bandwidth and very low bandwidth is only achievable by using slow forwarding policies. Aside to this asymptotic behaviors, the Pareto fronts also show that DFCN can be tuned in such a way that it permits to obtain a reasonably short duration of the broadcasting process while keeping the network throughput (eg, the number of packet emission) low. Since good coverage is guaranteed, these settings are appropriate for most broadcasting applications.

Conclusion

My work takes place in the context of several collaborative projects involving researchers from universities in Luxembourg, France and Spain. The range of topics tackled include network broadcasting, network emulation, study of mobile ad hoc networks from the point of view of complex system research, topology control from hybrid networks and multi-objective optimization of network protocols. These applications had various requirements and imposes the design and implementation of different features. In all cases the consideration of networks consisting of thousands nodes evolving in a metropolitan environment and the representation of several wireless networking technologies is required. In addition to this, fast simulation engine, a polished model and a friendly graphical user interface was strongly expected.

MADHOC is a mobile ad hoc network simulator which is tailored for these specific needs. It proved actually usable in all the situations described hereinbefore. In particular, in the framework of the investigation of broadcast protocols, it made it possible to simulate of twenty thousands nodes. In the context of multi-objective optimization, the time needed to perform one simulation (which is a crucial aspect in this case) could be lowered up to a few milliseconds in the best cases and up to thirty seconds in the worst conditions. In the context of network emulation, MADHOC's users have successfully interfaced the simulator with DoDWaN, an existing IEEE802.11b-based ad hoc network. Then, in the context of topology control for ad hoc network, MADHOC could successfully be extended in order to model connections from mobile nodes to a simulated infrastructure, making MADHOC stepping a bit outside the world of pure ad hoc networking.

MADHOC is characterizable in a number of ways. Maybe its more relevant aspects ly in its hybrid simulation engine, in the way it considers mobility and in its modularity.

The philosophy design of MADHOC is twofold. From a general perspective, MADHOC is object-oriented. In particular, the application programming interface it exhibits is made of classes and objects, as it is usual in software design. However, as often as possible, MADHOC model things in a probabilistic way. In particular, the model for the physical network layer makes use of statistics. Doing this lightens the simulation engine. This provides MADHOC with the ability to efficiently simulate large populations of nodes (up to twenty thousands nodes on regular desktop computers).

MADHOC provides a set of mobility models which includes classical ones, in particular, random-based ones. However, in the context of a metropolitan environment, most of these mobility models are irrelevant. Indeed, small communicating objects are linked to human beings and as such their mobility is constrained by the one of their owners. It becomes obvious that human mobility should be considered instead of a pure mathematical model of mobility. This is the way we have chosen and we propose several different mobility models in that context that should be considered as first attempts towards more integrative ones. The main model we have presented is called the "Human mobility model" (HMM). Briefly, HMM considers that the environment in which the nodes evolve have a number of particular areas (called "spots") in which nodes tend to go and stay for some time. These areas may represent shops, schools, residential buildings but also traffic lights, etc. The next generation of mobility models we intend to develop will focus on an aspect rarely taken into consideration, the collective behavior of people. Coupled with a planning based mobility, such a model should reproduce some interesting features of more realistic topologies.

In addition to the design and the implementation of the simulator, this work also addressed the broadcasting problem. Indeed, one of the target objective was to provide the user with a framework for the design of mobile ad hoc network applications, and broadcasting appears to be one of the basic blocks of such applications. This work was motivated by the fact that most broadcasting protocols have difficulties for managing simultaneously different levels of density, when in fact it is one of the main characteristics of city-like environments. This lead us to propose the Delayed Flooding with Cumulative Neighborhood (DFCN) protocol with the aim of meeting the trade-off between minimizing the number of message emission and maximizing the number of reached stations.

This protocol operates both when a broadcast message is received and when a new neighbor is detected. Its threshold-based design makes it customizable to the requirements of the user. When tuning it in a proper way, experimentations exhibited very satisfactory results. On the one hand the strategy DFCN employs makes it keep working even when the nodes density is extremely low (very few connections). On the other hand, when the density is high enough so that the state-of-the-art protocols can operate, DFCN exhibits lower network overhead. Furthermore, when the density is huge, DFCN does not lead to a situation in which the number of emission would congest the network. The number of emissions (which impacts the bandwidth utilization) carried out by DFCN remains in general lower than the ones shown by SBA and AHBP. On the other hand, DFCN proves slightly slower than these. Here appears a general rule when it comes to broadcasting: the faster the broadcasting process operates, the greater bandwidth it consumes. Conversely, the slower it is, the lesser network overhead it generates. As a consequence, DFCN is not suited when the duration of the broadcast process is at issue because, through ex-

periments, it proves to be significantly slower than State of the Art protocols like SBA and Multipoint Relaying. In such a case, SBA turns out to be more adapted or; if 2-hop neighbor information is not available, protocols like Flooding With Self-Pruning should be preferred. However their limitations in term of connectivity may be an unavoidable obstacle for application design. On the contrary, the adaptivity to the context of DFCN makes this protocol an interesting candidate for the design of broadcasting-based applications in DTNs.

Some of the projects which carried the MADHOC simulator are still running and new others have started. This allows us to keep on working on the simulator and its applications. In particular, one of the on-going and future works include the extension of the DFCN protocol in order to make it operate differently, function of the “urgency” of the broadcast message. Another perspective is the definition of a long-run mobility model based on realistic information of people activity along the working day. More technically, short-term perspectives include the parallelization of MADHOC.

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