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MANET ROUTING ASSISTED BY SATELLITES

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Introduction

Mobile ad hoc networks (MANETs) are an open research field in the last years. Despite this intense activity, few commercial products have emerged. The reason lies in two aspects: (a) commercial operators do not like unstructured networks which by definition are not easily controllable and (b) MANETs pose serious technical challenges.

The ad hoc paradigm consists of networks without infrastructure, where hosts have new capabilities to provide the functionality of traditional network routers. The mobility adds extra complexity to the hosts due to the dynamics of the topology, however it extends the range of applications of this kind of networks. Their infrastructure independence favors their use where terrestrial communication infrastructures stations are knocked out. That is the case of a terrorist attack or natural disasters as earthquakes or hurricanes. The infrastructure could even never exist, e.g., in case of rescue teams or military units during operations in hostile environments. They can be also useful during events because of their spontaneity.

However, a mobile network without infrastructure yields new challenges. MANETs opened new research lines to adapt traditional solutions to an environment without a central administration. Security, self-organization, medium access control, routing or quality of service are some of the open issues in MANETs.

Security is affected by the lack of infrastructure. The division between user devices and operator equipments disappears and confidential data must go through several hosts to reach the destination. Malicious users find a direct way to intercept this data or even to affect the correct operation of the network.

The self-organization is a desired property of mobile ad hoc networks. Its main objective is to allow hosts to join or leave the network without the requirement of a prior configuration. For example the address autoconfiguration of traditional networks lies on centralized servers (e.g., DHCP protocol). New protocols have been developed to provide these capabilities in a distributed manner.

Traditional medium access control protocols are designed to work in an infrastructure mode. The IEEE 802.11 standard allows two terminal hosts to directly communicate without a router entity in ad hoc mode. However this is only a basic approach, so medium access control protocols more adapted to multi-hop wireless networks have been proposed in the last years.

Routing is also impacted by the lack of infrastructure and the mobile condition of the hosts. In traditional networks the infrastructure is responsible of the routing tasks. These traditional networks cope with mobility through handover procedures. On the other hand the hosts must perform the routing tasks in mobile ad hoc networks facing continuous topology changes. Also, traditional solutions should be adapted to provide quality of service to assure the management of the resources in a network without a central administrator.

Summarizing, mobile ad hoc networks are complex systems that lead to several research fields. This PhD work is focused on the routing field. It proposes to alleviate routing problems in MANETs by distributing routing signaling through satellite transmissions. It offers a new perspective of the satellite role in mobile ad hoc networks. Traditionally, satellite communications have been proposed in mobile ad hoc networks to forward data traffic: as bridges, connecting the MANET to external networks (e.g. the Internet) or interconnecting isolated hosts or group of hosts inside a partitioned MANET. The motivation of this work is completely different: the satellite segment may help in the distribution of routing signaling to improve the data traffic routing of the MANET.

Therefore, the satellite network is used as a complementary out-of-band channel to help in the distribution of MANET routing signaling. We expect to improve the MANET routing signaling distribution and therefore achieve better routing decisions. However, satellite transmissions present important delay contributions and bandwidth costs. Also, not all the nodes of a MANET would have access to the satellite channel. Therefore we should adapt MANET routing to the terrestrial-satellite overlay networks and analyze if the routing signaling can be improved in this new context.

First, a survey of MANET routing protocols must be performed. There exists a great amount of publications on MANET routing and the proposed solutions must be classified and analyzed. The distribution of signaling by satellite will be suitable for some protocols but useless for others.

The proposed solution will then be evaluated by means of simulation so to have access to measures with a granularity down to the packet level. But MANET modeling for simulation is not a trivial task. For example, there are a wide range of scenarios where a MANET can be deployed. Most of the researchers use scenarios with the random waypoint (RWP) model as mobility model. This model creates random dynamic topologies to test routing protocol performance. However, it can not be associated to any real situation. To evaluate the performance of the routing protocols, it make sense to use generic scenarios, but also a specific scenario of a real situation is recommended.

A forest fire fighting situation is proposed. Nowadays, in the first hours of a forest fire fighting mission, when there is no deployed infrastructure, the communication is mainly voice transmissions over digital professional mobile radios. As we have seen in the beginning of this introduction, this is a favorable scenario to deploy a mobile ad hoc network. A MANET will offer IP data transmissions to the firefighters with new services such as distribution of mapping information, transport of sensor data, tracking of fire fighting units, voice over IP, etc. In this scenario, it is feasible that some of the firemen vehicles carry satellite dishes.

Working with two contrasting scenarios makes it possible to analyze the impact of the network context on the routing performance. Also, all the simulation steps from the model election to the result analysis have to be described. The complexity of MANET simulation will be reflected during this process.

Objectives

Since no similar studies has been proposed, this work intends to present the first conclusions about the possibilities of satellite communications in the distribution of MANET routing signaling. The improvements on MANET routing protocols will be evaluated to figure out if it is interesting or not to introduce this new role for satellites.

For that purpose we shall delimit the applicative context. Mobile ad hoc networks are suitable for a wide range of applications. However, the presence of satellite terminals are not always guaranteed. One of the objectives of this work is to identify the applicative contexts where the hybrid terrestrial-satellite signaling distribution is suitable.

Another point is the routing protocol itself. A lot of MANET routing protocols are available from the literature. Therefore we need to analyze the different routing solutions so to identify the most adaptable to a hybrid terrestrial-satellite signaling distribution.

Finally, we intend to describe the steps and the crucial points of MANET routing protocol evaluation. Several tasks are involved: network modeling, scenario and performance metrics, output analysis techniques, etc. Therefore we highlight the complexity of MANET routing evaluation and present guidelines to achieve valid and representative results.

Plan

The document is divided into three parts.

The first part, the state of the art, presents a background on routing and simulation in MANETs. Chapter 1 covers the role of satellites in terrestrial networks and more specifically in MANETs. Then, it analyzes how a satellite system can contribute to effective signaling distribution of MANET routing protocols. For that purpose, a classification of MANET routing protocols is performed and the possibility of complementing with a satellite system is studied. Chapter 2 surveys the simulators and the mobility models used in MANET research. It also presents the problematics associated to MANET simulation.

The second part addresses the scenarios used in simulation. Two different scenarios are used, a generic and a specific scenario. The use of more than one scenario is interesting: it allows us to compare routing protocols in different situations, and how the network context impacts the performance. For that purpose, a set of metrics is introduced in Chapter 3 to characterize the network topology. Chapter 4 describes the generic scenario in details. Finally the specific scenario, a forest fire fighting mission, is presented in Chapter 5.

The third part presents the proposed routing solution. The OLSR protocol is chosen because of its link state nature, its popularity and because it is standardized. The basics of this protocol are presented in Chapter 6 with the required modifications to take advantage of satellites for signaling distribution. Then the routing protocol performance is tested in the context of the aforementioned scenarios. Finally, Chapter 7 discusses all the issues of the simulation e.g., confidence intervals, performance metrics, duration of the simulation, etc. Then it presents an analysis of the results.

The document closes with a conclusion and outlook.

Part I

State of the Art

Chapter 1

Mobile Ad Hoc Networks and Satellites

The objective of this PhD work is to investigate how satellites can help in the distribution of routing signaling in MANETs. However, before designing a routing protocol which takes advantage of satellite signaling distribution, a background on the relations between satellite and terrestrial networks must be acquired. A survey on current MANET routing solutions must be also performed.

Section 1.1 presents existing and future satellite-terrestrial hybrid architectures. Then, the current role of satellite systems on MANETs are identified with a survey on MANET literature. MANET projects including satellite terminals are described.

Section 1.3 describes the main MANET routing protocols. The description is focused on the signaling distribution. Finally, the combination of satellite and terrestrial signaling distribution is considered for each protocol. The protocols whose signaling is more suitable for a satellite distribution system are identified.

1.1 Satellite-Terrestrial Hybrid Networks

The concept of connection everywhere and anytime sinks in the new offers of telecommunication providers. One of the objectives of satellite industry is to adapt the satellite systems to these new services. Satellite-terrestrial hybrid architectures gain significance within this new context. Satellites may complement terrestrial networks thanks to their wide coverage and broadcast nature.

The Satellite Communications Network of Excellence (SatNEx), in the focus topic *Hybrid broadband network architectures*[1] identifies and analyzes the following categories of satellite/terrestrial hybrid architectures:

Satellite multicast/broadcast network [1] A terrestrial network is used as a return channel to allow user interactivity in traditional one-way satellite broadcast and multicast networks. This is a common practice in TV systems where the broadcasting and coverage of the satellite is used for the transmission of the TV channels while traditional terrestrial networks like a xDSL or a narrowband connection provide the return channel allowing near video or audio on demand and interactive services.

Satellite radio access network [1] Satellite Radio Access Network (S-RAN) can act as a collaborative extension of the classical terrestrial cellular networks. It is used to extend the radio coverage or to perform load balancing or traffic differentiation with overlapping coverage areas.

Satellite as a backup solution for critical infrastructures [1] Satellite communications are used as an alternative redundant system to the terrestrial communications for critical infrastructures as oil refineries, banks or in applications as telemedicine.

Satellite trunking [1] Satellite trunking consists of connecting two sections of the public switched telephone network (PSTN) with a satellite link. As an example, this solution was applied by France Telecom in the communication with the DOM-TOM (overseas departments and territories). Communication among users of different sections are carried over the satellite and high delay characteristics must be confronted.

Satellite backhauling [1] Satellite backhauling connects a local access network to a fixed terrestrial core network. This solution offers connectivity to specific group of users where conventional telecommunications services are not available. The area of applications is wide, for instance military purpose, rescue teams, ships, aircrafts, etc.

Satellites are also used to interconnect private, Local Area Networks (LANs). Therefore it is possible to create Virtual Private Networks (VPNs) of users over satellite. A possible application is the creation of secure networks to link remote sites of a corporation.

SatNEx has also proposed that satellites provide Mobile Ad hoc Network interconnection and the connection of MANETs to external networks. Figure 1.1 illustrates this example.

We have surveyed several architectures where satellite and terrestrial networks were combined. However this combination is only possible in some particular cases due to the specific satellite properties in terms of delay and throughput.

1.2 Mobile Ad Hoc Networks and Satellites in the Literature

Papers can be found in the literature covering diverse aspects of MANETs like routing, security, medium access or self organization. MANET routing projects

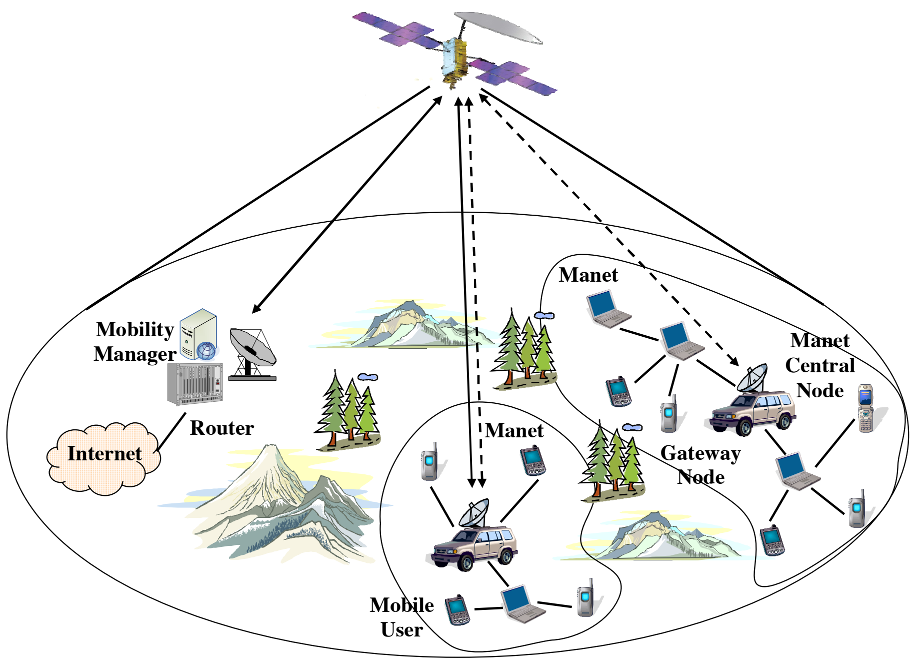

Figure 1.1: Hybrid satellite-MANET architecture [1].

including satellite systems were surveyed.

P2PNET [2] proposes a MANET based emergency communication for disaster management. It presents a serverless peer-to peer based MANET network to support temporary group communications. It also proposes optional nodes with satellite gateway capabilities so that all other nodes can access Internet through them if they are available. In P2PNET the satellite communications do not participate in the construction of the routes among the MANET nodes.

An ad hoc Walkie-Talkie-like communication was implemented in the first phase of the project development. More complex experimentations entailing multi hop communications are planned. The satellite gateways are planned for addition to the system architecture, thus they are far from being considered in the next phases of the development since it is not the main objective of the project.

Savion is a project that integrates a satellite segment [3] for emergency situations. It proposes the use of the Savion MANET commercial solution to bridge teams involved in emergency activities and a satellite gateway to interconnect teams with the high level managers not present in the emergency area.

In this project, satellite communications do not contribute in the routing of packets among the members of a team. However data packets among different teams are routed through satellite links when the MANET is partitioned.

It presents a test bed connecting the Savion MANET to a generic private mobile radio (PMR), an IP phone and a PC through Globalstar terminals. Both non-TCP/IP and TCP/IP connections have been successfully set up and used for chatting and file exchanges.

DUMBONET [4] is an emergency network platform where satellite links are set up to connect diverse disaster sites and the command headquarters. A virtual private network (VPN) is used to hide the network heterogeneity.

Like the Savion project, DUMBONET uses satellite communications to face the MANET partitioning. In the related testbed, two simulated disaster areas and a simulated remote site are interconnected through the IPStar geostationary satellite. Thanks to the VPN, all devices belong to the same private subnet and the Optimized link state protocol (OLSR) is used to route the traffic among them. Thus there are no differences between the terrestrial and the satellite links for the OLSR protocol. They achieved successful transmissions between the remote site and the field. One of their research aims is to introduce link-characteristic awareness into OLSR.

MONET (Mechanisms for Optimization of hybrid ad hoc networks and satellite NETworks)[5] is a European collaborative project started on January 2010. Its objective is to investigate the re-organization of a MANET to connect to satellite access points, the selection of which satellite access points to use, the adjustment of routing in accordance with the current network situation and the exchange of cross layer information to improve resource management.

MANET routing and satellite communications are closely related in this project, however the MONET project is in its early stage and only the objectives, the methodology and the developments were proposed.

Conclusions

The main role of satellites in the previous MANET projects involve forwarding inbound and outbound data traffic to connect the MANET to external networks. Solely the MONET project proposes an in-depth study of the satellite possible contributions in MANETs. Nevertheless this project is in its early stage and no significant conclusions have been reached.

The main interest of these projects in our work is the proposed scenarios. We identify emergency situations as typical scenarios where a MANET could be deployed and some of the devices may have satellite capabilities to interconnect a MANET to external networks such as remote headquarters or the Internet. Our work proposes a new perspective in the role of the satellite terminals. Since several devices of the same MANET may have satellite capabilities for gateway operations, we propose to use these capabilities to share routing signaling information among them.

So we identify a suitable scenario in the emergency situations where a MANET is deployed and there exists a satellite infrastructure to connect to external networks. Therefore we can use the existing satellite infrastructure for our purposes designing a solution for this context.

1.3 Mobile Ad Hoc Network Routing Protocols

In a MANET, when a node has to send a packet to another node outside its radio range, it is necessary to use intermediate nodes in a multi-hop way. Therefore all nodes have to support routing capabilities, i.e., to know which is the next node in the path to reach a given destination. However, this is not a trivial task. The mobility of the nodes yields a dynamic network where the links between nodes are temporary. Traditional routing protocols do not perform well in this context.

Several solutions have been proposed from the adaptation of traditional protocols to new concepts as geographical routing. However, the signaling of these routing protocols share the transmission medium of the data traffic and therefore is impacted by the same wireless constraints of bandwidth, bit errors and collisions. Our objective is to improve the routing signaling distribution with the use of satellites. If the signaling distribution is improved, better routing decisions should be achieved.

Surveys of MANET routing protocols can be found in [6, 7, 8, 9, 10, 11]. Some of these protocols are presented next, focusing on signaling distribution and how satellite communications may contribute.

1.3.1 Proactive Routing

Also called pre-computed routing or table-driven routing, it consists in maintaining paths to all destinations. To do so, each node manages tables with topology information and sends periodic updates in order to respond to topology changes. Traditional proactive algorithms are not suitable for MANET routing since the dynamics of these networks entails constant updates and the overhead is significantly increased. Several solutions to this problem are presented next.

Destination-Sequenced Distance Vector (DSDV)

DSDV [12] is a modification of the traditional Routing Information Protocol (RIP) where a sequence number field is added to the routing table to differentiate between stale and fresh routes. Regarding the signaling, it differentiates two kinds of updates: `full-dump` and `incremental` messages. The former includes all the available routing information while the latter carries out only the information changed since the last full dump. In spite of these modifications, DSDV is not suitable for networks which have high mobility and a large number of nodes because the amount of signaling is in the order of $O(n^2)$, n being the number of nodes.

Regarding the routing computation algorithm, DSDV belongs to the distance vector family, based on the Bellman-Ford algorithm. The nodes maintain tables with the next-hop and distance to each destination. This information is periodically sent to neighbors. When a node receives the distance table from a neighbor, it calculates the shortest routes to all other nodes and updates its own table consequently. In the beginning of the algorithm, a node will only know the distance to its neighbors. Then the information is spread node by each node until the algorithm converges and the routing tables are completed.

Potential satellite contribution Since the main problem of DSDV is the overhead due to the signaling information, we could think of satellite distribution as a solution. However, the route computation and the topology information distribution are not dissociated. Therefore, the inclusion of satellite transmissions in the topology information distribution affects the route computation since a node receiving an update via satellite will assume a distance of one hop to the source of the message. While this is true if the satellite is used for data traffic, our objective is to route data traffic only via terrestrial links.

We can conclude that distance vector algorithms are not adaptable to satellite signaling distribution.

Optimized Link State Routing (OLSR)

OLSR [13] belongs to the link state family of routing protocols. In these protocols, each node maintains topology information by means of periodic broadcasting of the link states. Then, a shortest-path algorithm is applied to the received topology information to determine the routes towards all possible destinations. OLSR tackles the overhead problem of proactive protocols by employing the multipoint relaying (MPR) strategy. This strategy decreases the size of signaling messages and the number of retransmissions during the broadcast process. Each node selects a set of neighbors as its multipoint relays. These MPRs must cover all its two-hop neighbors, so when receiving a broadcast message from the node, only the multipoint relays are allowed to retransmit the message.

Regarding the signaling, there are two main processes: the link sense and link state distribution. The link sense process allows nodes to obtain information about the links up to a two-hop distance via a local exchange of `hello` messages. Then, `topology control` messages are broadcast in the whole network taking advantage of the MPR topology.

Potential satellite contribution Unlike DSDV, OLSR differentiates the signaling for topology distribution and the route computation task. Routes are computed applying Dijkstra's shortest-path algorithm to the broadcast link state information. Therefore, the method that distributes the topology information does not impact the computation of the routes. Due to the broadcasting nature of satellites, a satellite-terrestrial hybrid broadcasting technique can be considered to optimize the topology information distribution. Indeed, the wireless medium of MANETs displays several shortcomings such as bit errors, collisions and a limited bandwidth. Moreover, OLSR signaling shares the wireless channel with the data traffic without any prioritization mechanism. A satellite can offer a dedicated channel for the OLSR signaling so to avoid these problems.

1.3.2 Reactive Routing

Also called on-demand, reactive routing decreases the overhead inherent to proactive protocols by maintaining information for active routes only. That is, routes are computed for nodes that have to send data to a particular destination. This is achieved mainly with two procedures: route discovery and route maintenance. When a node has to send data to a particular destination, it broadcasts a route request to discover and set up the route. Then, route maintenance is performed in order to keep the active routes updated and react to link outage produced by the node mobility.

The main advantage of this routing strategy is to save bandwidth, avoiding the computation of unused routes. However, the route request procedure introduces a route acquisition latency before the transmission of the first packet to the destination. Conversely, in proactive protocols the nodes are not affected by this latency as they maintain the routes for all the possible destinations.

Reactive routing protocols differ from each other in the way they perform the route request and maintenance. Some examples are presented next.

Ad Hoc On-Demand Distance Vector (AODV)

The AODV [14] routing protocol is the result of the MANET group of the Internet Engineering Task Force (IETF) effort and is standardized in the RFC 3561. Its primary objectives are:

- To broadcast discovery messages only when necessary.
- To distinguish between local connectivity management (neighborhood detection) and general topology maintenance.
- To disseminate information about changes in local connectivity to those neighboring mobile nodes that are likely to need the information.

Three processes carry out these objectives: route discovery, route maintenance and local connectivity management.

The route discovery process is initiated by the source node issuing data. It broadcasts a `route request` (`RREQ`) message to its neighbors in order to build up the route to the destination. A node receiving a `RREQ` replies with a `route reply` (`RREP`) message if it knows a route to the destination. Duplicate messages are detected and filtered out by the inclusion of a `BROADCAST_ID` in the message. While the `RREQ` is disseminated over the network, a reverse path to the source is set up so the `RREP` message can be unicast to the source node. During the unicast, the route to the destination is stored in the intermediate nodes with the forward path setup. AODV is a hop-by-hop routing, that is, the route is stored in the intermediate nodes in the form of destination-next hop pairs.

An active route could be broken because of the mobility. The route maintenance process finds out an alternative route when that happens. A link outage can be detected with the local connectivity management or by using link-layer acknowledgements (`LLACKS`). When a node detects a link outage, it sends an unsolicited `RREP` to all active upstream neighbors. If the source node or any other node along the route decides to rebuild the route to the destination, it sends out a `RREQ` to setup a new route.

The objective of the local connectivity management process is to maintain a list of neighbors in each node. For that purpose, each node must send a `hello` message to its neighbors in the event that it did not send any message within a `HELLO_INTERVAL`. Local connectivity changes are detected when receiving a `hello` message from a new neighbor of failing to receive a number of consecutive `hello` messages (two by default). Failing notifications from inactive neighbors do not trigger any protocol action. The local connectivity management process can also be used to ensure bidirectional connectivity among neighbors.

Potential satellite contribution AODV signaling is analyzed in order to identify possible improvements when using satellite communications. The local connectivity management is discarded since it is by definition limited to direct neighbors.

The route discovery process has a broadcast component (sending `RREQs`) that fits with the satellite capabilities. However, while performing the broadcast of `RREQs`, the routes towards the destination are discovered. These routes are then used to forward data packets. If the satellite participates in the broadcast then the satellite links may be part of the discovered routes. Since we want the satellite to only transmit signaling information and not to forward the data packets, broadcast must be performed through the wireless LAN MANET interfaces.

Satellite transmissions could be used to inform the nodes inside an active route about a link outage. However the active route is stored in the intermediate nodes in a distributed way, so the node detecting the link outage does not know which nodes to inform, unless it follows the reverse path to the source. Therefore, the satellite is also discarded for the route maintenance process.

Finally, new processes could be introduced to optimize route discovery. Satellite transmissions could then be used to share advanced topology information such as network congestion to guide route discovery.

Dynamic Source Routing (DSR)

The Dynamic Source Routing [15] protocol is related to AODV. The main difference is that DSR is a source routing protocol while AODV is a hop-by-hop routing protocol. It means that the route is stored in the data packet and not distributed in the intermediary nodes as for AODV. This entails some changes in the route discovery and the route maintenance process.

When broadcasting a `route request` during the route discovery process, the *id* of the nodes that processed the message are stored in the message header. When it reaches destination, it should be sent back to the source. This is achieved by piggybacking the hop sequence in a new `route request` bounced back to the source. Therefore unidirectional links are compatible for data transmission in DSR. Also, a *request_id* field is used to detect duplicate requests. When the `route reply` arrives to the source node, the hop sequence is extracted and then included into the header of the data packets to the destination. The explicit route information in `route replies` and data packets are cached by the intermediate nodes. Moreover, promiscuous techniques can be used to allow other nodes in the transmission range to also cache the routing information.

When a node detects a link outage, it must inform the source. The node has several options to do so: search in its route cache for an entry to the original sender, reverse the route of the packet header or piggyback the route error as in the case of a `route reply` message.

The main disadvantage of DSR is the overhead due to the route information stored in data packet headers. Because of that, the protocol is not efficient in large networks as the size of the packet header increases with the diameter of the network. Therefore, in large and highly dynamic networks the overhead may consume significant bandwidth.

Potential satellite contribution As in the AODV protocol, the route computation is linked to the route discovery process and therefore satellite transmissions are not applicable. Once the `route request` is in the destination node, the satellite could transmit it to the source node however the return path would not be discovered.

On the other hand, satellite transmissions can take profit of the source routing nature of DSR. The nodes have complete information about the routes in their caches and it can be shared using the satellite. Also, the satellite can play a role in the route maintenance process since all the nodes of a broken route are known and the outage can be reported to them via satellite.

1.3.3 Location-Aware Routing

MANET routing protocols may benefit from information about the location of the nodes. Several localization methods have been designed for ad hoc networks [16, 17, 18, 19], specially for sensor networks. Also the Global Position System (GPS) is now a popular feature in mobile devices. There are two main ways to use location information in MANETs: to forward data packets or to perform selective flooding. The former is used by geographic routing protocols while the latter is used to optimize the route discovery process of reactive protocols.

Geographic Routing Protocols

The geographic routing protocols are based on isolated forwarding algorithms, that is, the next-hop computation is based solely on information about the current node, its neighbors and the destination. These algorithms can be classified depending on the method they use: position, distance and direction based.

Most of position-based algorithms use the concept of progress. That is, the projection of the neighbors of a node onto the line connecting the node and the final destination. Progress is positive if the neighbor projection point is closer to the destination than the current node. Examples of these methods are the Random Progress Method [20] which chooses a neighbor with positive progress randomly, Most Forward within Radius [21] which selects the neighbor with the highest progress, and Nearest Forward Progress [22] which selects the closest neighbor with positive progress.

Another family of protocols is based on the distance to the destination. The Greedy scheme [23] selects the neighbor closest to the destination. There are variants of this method like the Nearest Closer [24] or the 2-Hop Greedy Method [25] which selects the best candidate from its 1-hop and 2-hop neighbors.

A protocol can also route a packet considering the direction to the next hop. In compass routing [26], a node forwarding a packet uses location information to calculate the direction to the destination. Then the packet is forwarded to the neighbor whose direction is the closest to the direction of the destination.

It is assumed that a localization method (e.g., GPS) is present in each node. Also, the neighbor position can be easily known through a local message exchange. However, to know the location of the destination is non-trivial, and geographic routing protocols should operate in parallel with a location service. A location service provides under request the location of a network node. Traditional location services are not adapted to MANETs. Distributed solutions have been proposed in the literature like the Acquaintance Based Soft Location Management (ABSLM)[27], the Scalable Update Based Routing Protocol (SLURP)[28], the Scalable Ad hoc Location Management (SLALoM)[29], the Hierarchical Grid Location Management (HGRID)[30] or the Grid Location Service (GLS)[31].

Potential satellite contribution Geographic routing protocols are based on isolated algorithms so the only signaling involved is (a) the local exchange of location among neighbor nodes and (b) the signaling of the location services. Satellite transmissions do not make sense in a local exchange of information. On the other hand location services are potential candidates to take profit of the broadcasting nature of satellite communications.

Location-Aided Routing (LAR)

Location-Aided Routing [32] uses location information to reduce the search space in the route discovery process. LAR assumes that the location of the destination and its average speed v are known at a past time t_0. Based on this information, it computes the region that potentially contains the destination node at time t_1 as a circular area centered in the destination position at t_0 and radius $v(t_1 - t_0)$. This circle is called the expected region. Another important concept in LAR is the request zone. Only nodes which belong to the request zone forward the `route request` message. Depending on the way the request zone is defined, there are two schemes in LAR.

In the first scheme, the source node defines the request zone as the rectangle that contains the expected zone and itself. Then, it sends the position of the four corners in the `route request` message. Nodes receiving the `route request` only retransmit the message if they belong to the request zone.

In the second scheme, the request zone is implicitly defined. The source node sends the destination location at time t_0 and its distance to this location. Then, the receiving nodes compare their distance to the destination with the one of the message. If they are not farther than a predefined threshold, they retransmit the message replacing the distance on it with its own distance to the destination.

Both methods are graphically explained in Figure 1.2.

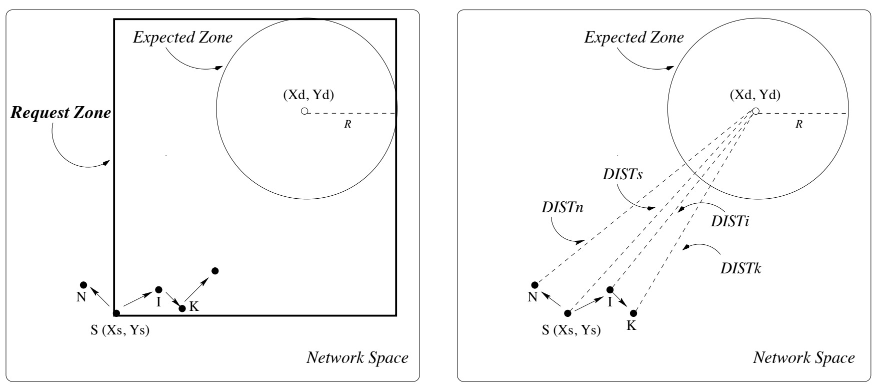

Figure 1.2: Comparison of two LAR schemes [32].

Potential satellite contribution The LAR protocol is a reactive protocol based on an optimization of the route discovery process. Therefore, the same reasoning as for AODV and DSR is valid for LAR: the route computation is linked to the route discovery process and satellite transmissions are not suitable.

However, like geographic routing protocols, a location service is needed for the LAR operation and satellite communications can help in the implementation of such a location service.

Summary

This chapter starts with a survey of satellite communications in terrestrial networks. The literature presents two main roles of satellite systems in mobile ad hoc networks: to bridge isolated MANET nodes and to act as gateways to connect them to other networks as the Internet. Therefore, the main use of satellite in MANETs is to forward data traffic. The use of satellite communications in the distribution of MANET routing signaling has not been considered as far as we are documented. During the literature survey, we also identified emergency situations as the more likely MANET scenario to involve satellite terminals: some of the nodes may already have satellite interfaces to interconnect the MANET with external networks for data transmissions. We could take advantage of this satellite infrastructure for improving terrestrial signaling distribution.

Then, the most popular MANET routing protocols have been described. They are divided into reactive, proactive and geographical routing protocols. The possible contribution of satellite communications in their signaling distribution has been studied for each family. It has been shown that proactive link state protocols, reactive source routing protocols and location services are the best candidates to be modified to use satellites in the distribution of signaling information.

Chapter 2

Mobile Ad Hoc Network Simulation

The most common method to evaluate MANETs is through simulations. Other evaluation methods as testbeds and emulation are not popular in MANET research because of the potential high number of nodes and the complexity stemming from the mobility.

However, MANET simulations are not exempt of problems. Section 2.1 provides an overview of the problematics of MANET simulations. It identifies the common problems on the network simulators, focusing on the pitfalls of MANET simulations. Then, a brief description of the OMNET++ simulator is provided and the main reasons of its election for the evaluation of this work are exposed.

Another problem in MANET simulations is how to model the mobility of the nodes. The subject is presented in Section 2.3. It covers the entity and group models and describes the Random Waypoint Mobility (RWP) and the Reference Point Group Mobility (RPGM) models as typical examples.

2.1 Problematics of Mobile Ad Hoc Network Simulation

This section presents the main problems when evaluating MANET routing protocols via simulation. The wireless transmission and the mobility of these networks pose problems of inaccuracy during simulation.

The main source of errors in MANET simulations is the simulators themselves, their models and the improper simulation practices.

2.1.1 Network Model Inconsistencies

There are several sources of error inside a network simulator. Simulators have diverse design solutions to deal with the complexity of MANET systems. These differences can lead to different simulation results. As an example, [33] implements a simple flooding protocol in OPNET, ns-2 and GloMoSim. The results show not only quantitative but also qualitative differences between the simulators. Also [34] identifies design variations on the physical layer modeling, and shows how that affects the result accuracy.

Another key property of a model is its granularity. The first impression is to think that network models with a higher level of detail are better because they are closer to the reality. However, a great number of details also means more probability of bugs and an increased difficulty to find them. The processing time to perform the simulations also increases. Thus, in a wireless, mobile network with a large number of nodes this could become quickly prohibitive. [35] evaluates the effects of the details in five case studies of wireless simulations for protocol design. It concludes that the researcher must judge the level of detail required for its work.

Interaction between models can also be a source of errors. Complex systems are usually divided into several components to be independently modeled. The layered TCP/IP model is an example. However, the evaluation of one of its layers is not independent of the rest. For example, the traffic generators affect the simulation outcome of a routing protocol as they determine the traffic load conditions. In MANET simulations, [36], [37] and [38] show how the mobility model affects the connectivity graph of the nodes and therefore the routing protocol behavior.

2.1.2 Improper Simulation Practices

A study of 114 MANET publications between 2000 and 2005 is performed in [39]. It is concluded that MANET simulation is not rigorous or credible, since most of these papers did not cite the number of simulation runs, the confidence intervals or even the simulation package used. Without this information, independent researchers are not able to repeat the simulation studies to ensure their credibility.

[40] identifies network partitioning and the average hop count as key parameters in MANET routing protocol evaluation. Poor routing protocols appear successful in scenarios with a low average hop count while good protocols will appear unsuccessful in scenarios with a high level of partitioning. These improper practices were detected in many MANET publications.

2.2 Simulator Choice

The network simulator used in this thesis to test the performance of MANET routing protocol is OMNET++ [41]. This general purpose discrete event simulator has been developed by András Varga since 1992 and its popularity is based on its modularity, component-based and open-source approach. Implemented in C++, its latest stable release (4.1) dates from June 2010. It does not have specific networking solutions by itself but there are several networking frameworks based on OMNET++.

The main reason motivating the use of OMNET++ is its open-source approach. Open-source simulators are free to use and their behavior can be inspected and modified. They are easier to extend than their proprietary equivalent. They also have a user community to help in the debugging of errors.

NS-2 is another simulator widely used for MANET simulation. NS-2 is a very complete network simulator, however it is also quite complex. That is the reason because OMNET++ was chosen instead of NS-2.

The INETMANET [42] is the OMNET++ framework chosen for our project. It implements several MANET routing protocols (OLSR, AODV, DSDV, DYMO and DSR). Based on December 2009 version of the framework, we modified the source code to combine MANET routing signaling with satellite communications.

Comparisons of the major network simulators can be found in [43, 44, 45].

2.3 Mobility Models

Mobility models specify the nodes positions and motion throughout the time. They are a key concept in MANET simulations because they determine the links that exist among the nodes (i.e., the network topology or connectivity graph). A survey of mobility models is performed in [46]. It differentiates between trace-driven and synthetic models. The former use traces, mobility patterns observed in real life. They provide accurate information, however it is not always possible to obtain traces of real systems, because it is not practical to track all nodes in the network or even the network has not been deployed yet. In those cases, synthetic models are used. They include a set of rules defining how the nodes must move. If the movement of a node is independent of any other node of the network, it is an entity model. Examples of entity models are the random waypoint [47], the random walk [48], the boundless simulation area [49] or the Gauss-Markov [50] mobility models.

If the movement of a node depends on the other nodes, it is a group mobility model. Some examples are the exponential correlated random mobility model[51], the column mobility model [52], the nomadic community [52], the pursue [52] and the reference point group [38] mobility models.

Next, a detailed description of the random waypoint mobility model and the reference point group mobility model is performed. The first is chosen since it is the most popular entity model in MANET simulations. The reference point group mobility model is explained because many mobility applications can be represented using this model with suitable parameters (e.g., column mobility, pursue mobility, random waypoint, etc.).

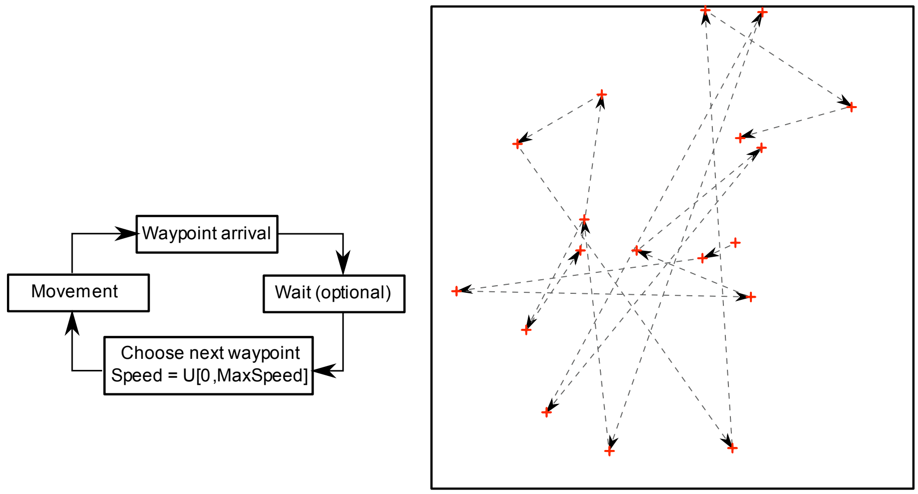

Figure 2.1: The random waypoint movement cycle and example of movements.

2.3.1 Random Waypoint (RWP)

A study of which mobility models are used in MANET simulations is performed in [40]. Johnson's random waypoint mobility model is the most popular, with 64% of the simulations that were part of the study. It is an entity model, therefore each node moves independently.

The movement rules are the following: nodes move from waypoints to waypoints. When a node reaches a waypoint, it randomly selects a point inside the playground as its next waypoint and it moves straight towards it with a speed uniformly distributed between 0 and a maximum speed value. An optional waiting time can be set for the nodes to stay in the waypoints. See figure 2.1 for an example.

One of the problems of this model is to reach a steady state. Random waypoint initially places nodes uniformly in the playground. As the simulation advances, it can be observed that the nodes tend to move close to the center of the simulation compromising the expected random behavior. A possible solution is to discard the results in the beginning of the simulation until the steady state is reached. This duration depends on the speed and pause time of the nodes and the size of the playground. Another solution is presented in [53], based on stationary distributions for the initial position of the nodes.

A problem related to the node speed is described in [54]. It concludes that random waypoint fails to reach a steady state in terms of instantaneous average node speed, but rather the speed continuously decreases as simulation progresses. Slow nodes maintain low speed for relatively long periods until they reach the destination. Solutions presented in [54] propose to choose a positive value of the minimum speed or to set the speed correlated with the travel distance.

2.3.2 Reference Point Group Mobility (RPGM)

The reference point group mobility model is rather a mobility framework than a mobility model. Several mobility models can be developed inside this framework, as the column, the nomadic community, the pursue or the fire mobility model proposed in this thesis (Chapter 5).

RPGM organizes the mobile hosts by groups according to their logical relationship. Each group moves independently. The three main variables to define the motion of the nodes inside a RPGM group are:

Group motion vector ($\vec{GM}$). Each group has a group logical center. The trajectory of the center defines the entire group motion behavior and is given by the group motion vector. The group motion vector follows a sequence of check points along a motion path. The motion path can be the result of an entity mobility model such as random waypoint, map routes, real world traces or can be manually assigned.

Reference point (rp). Each node has a reference point inside the group. This reference point moves following the group motion vector. Therefore, the reference point of each node varies like: $rp(\tau+1) = rp(\tau) + \vec{GM}$. The position of the virtual reference points of the nodes with regard to the group logical center is a design choice. For example choosing a column formation will lead to the representation of the column mobility model.

Random motion vector ($\vec{RM}$). It represents the motion of the node around the reference point. The position of the node (p) is generated by adding the random motion vector to the reference point: $p(\tau+1) = rp(\tau+1) + \vec{RM}$. Vector $\vec{RM}$ has its length uniformly distributed within a certain radius and its direction uniformly distributed between 0 and 360 degree.

Figure 2.2 gives a graphical example of the previous explanation. It represents the movement of one RPGM group with three nodes. Circles represent nodes and squares represent node reference points.

Summary

The main problems associated to MANET simulation were introduced in this chapter. It appears that without an universal framework for MANET simulation, the best we can do is to document all the simulation process to allow other researchers to replicate it. For that reason we include Chapter 4 and Chapter 5 that describes the configuration of the proposed MANET scenarios of this work. Then, the election of the network simulator was explained. OMNET++ and the INETMANET framework were chosen because of their open-source nature, facility to be extended and fast learning.

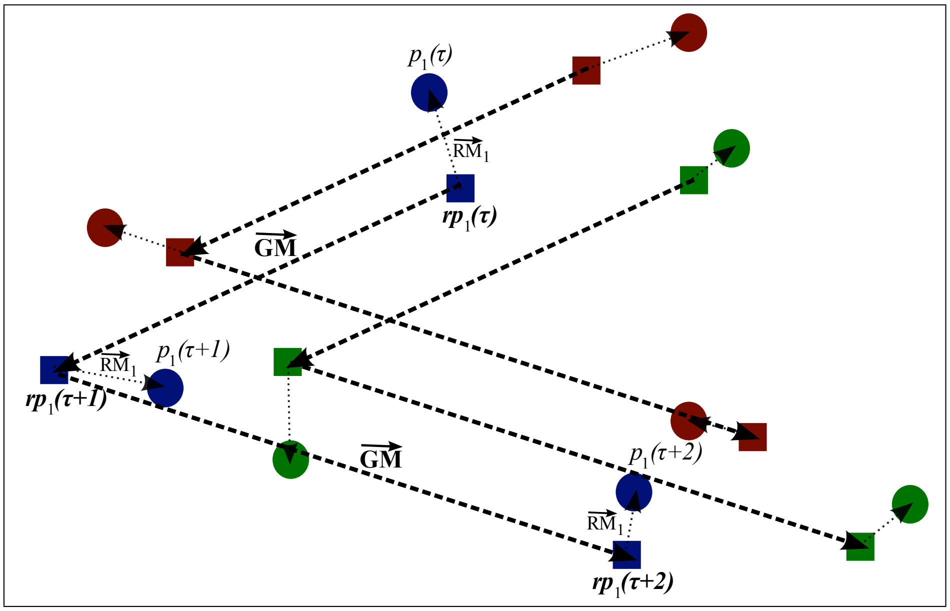

Figure 2.2: Example of movement of a three host group using RPGM.

Finally, the importance of the mobility in MANET simulation and how to model it was described. The random waypoint mobility model was chosen as the representative entity model. The reference point group mobility is described as an example of group model.

Part II

Scenarios

Chapter 3

Topology metrics

Mobile ad hoc networks are suitable for a wide range of scenarios. A routing protocol can perform well in some of these scenarios but be impractical in others. The scenario properties that could cause these changes are diverse: the number and density of the nodes, their RF capabilities, the way they move, the kind of traffic, the source and destination of the traffic, etc. Therefore a set of metrics to classify MANET scenarios is necessary.

Section 3.2 presents the current studies on MANET scenarios and describes the most common metrics to identify scenarios of reference for MANET simulation. Section 3.3 presents some weaknesses in the previous metrics and complements them with specific metrics related to the source and the destination nodes of the data traffic. Les algorithmes des routages ne sont pas utiliss pour ces simulations, les mtriques de topologie utilises sont indpendantes de lalgorithme de routage, ils mesurent les caractristiques des liens entre les noeuds au niveau de la couche physique.

These topology metrics are independent of the routing protocol: they represent the topology of the network at the link layer level. They will be used to characterize the proposed scenarios in this thesis. Following the recommendations of [46], [55] and [38], more than one mobility model is used and several scenarios are proposed. Because of its popularity, the random waypoint mobility model is used for the generic scenarios described in Chapter 4. A specific scenario using a custom mobility model is also described in Chapter 5.

3.1 Nomenclature and Metric Considerations

The metrics presented in this chapter are used to characterize a network topology. The network topology is defined by the node locations and related links. A link between two nodes exists depending on the node positions and their transmission range. Because of the node motion the topology evolves with time. For that reason, the considered metrics will be expressed as a function of time.

An important consideration is the presentation of representative values for the metrics. We must distinguish standard deviations from confidence intervals. Table 3.1 provides a description of which representative values are chosen depending on the context. In the remaining part of the document, the use of either standard deviation or confidence interval will be indicated in the graph legends.

Type of measure	**Representative metrics**	**Example**
Properties of a network at a time instant	Space-dependent metric: average and standard deviation over the set of nodes	Network density at a given time
Properties of a node for a period of time	Time-dependent metric: average and standard deviation of a node metric over time	Number of neighbors of a given node over a simulation run
Properties of a network for a period of time	Space/time-dependent metric: average and standard deviation over time of the related space-dependent metric	Network density over a simulation run
Estimation of the properties of a network	Estimator of the metric average and confidence interval of this estimator	Network density for the simulation campaign

Table 3.1: Using representative metrics depending on what to measure.

In the following sections the words *path* and *route* are used with two different meanings. Both words are used interchangeably in most of the routing papers. However, in this document *route* will be used when referring to a set of links connecting a given source/destination nodes and *path* will be used for general definitions, not for a particular pair of nodes.

The nomenclature is presented before defining the metrics. The notation common to set theory is used in the metric definitions:

- $|...|$: $|X|$ stands for the size or cardinality of set X.
- N: set of network nodes. Each node is represented by a letter of the alphabet $(a...z)$.
- $l_{a,b}(t)$: link from node a to node b.
- $L(t)$: set of all available links at instant t.
- $r_{a,b}(t)$: shortest-route from node a to node b at instant t according to the number of hops. $r_{a,b}(t) = \{l_{a,x}(t), l_{x,..}()t, ..., l_{..,z}(t), l_{z,b}(t)\}$.
- $R(t)$: set of all available shortest-path sets at instant t according to the number of hops.

3.2 General metrics

To evaluate the performance of routing protocols in MANETs is a complex task. The first challenge that must be tackled is the election of the scenario where the routing protocol will be evaluated. The mobility of the nodes creates unlimited possibilities when choosing the simulation scenario since a wide range of mobility models exists hence input parameters to be instantiated. As a consequence, MANET routing protocol evaluations are often not comparable.

The IETF MANET group highlights the necessity of considering the network context in which a protocol performance is measured [56]. It proposes a list of essential parameters like the network size, the network connectivity or the topological rate of change.

Additional proposals are expressed in [57] and [58]. The former proposes a mobility metric intended to capture and quantify the kind of node motion relevant for an ad hoc routing protocol. The latter studies the need of a MANET scenario classification and proposes a flexible and consistent mobility measure.

A tentative methodology for the performance evaluation of MANET routing protocols is found in [40]. Two scenario metrics are proposed : the average network partitioning and the average shortest-path hop count. It also determines that for rigorous MANET routing protocol performance evaluation, the average shortest-path hop count should be large (i.e., 4 hops or more) while the network partitioning should be kept low (at most 5%). A third metric is added in [59]: the average neighbor count.

Following the previous recommendations, we will characterize our proposed scenarios for MANET simulation with the following metrics:

Number of Nodes The number of nodes is linked to the size of the network.

$$n = |N| \tag{3.1}$$

Number of Neighbors It is also called the network density. A large number of neighbors is recommended in [59] to build scenarios with several routes from source to destination. The neighbors of a node x are the set of nodes with a bidirectional link with node x.

$$\mathrm{NB}_x(t) = \{y \in N : (\ l_{x,y}, l_{y,x}) \in L^2(t)\}$$

The neighbors of a node may vary from one node to another so the metric is represented by average and standard deviation.

$$\bar{\mathrm{NB}}(t) = \frac{\sum_{x \in N} |\mathrm{NB}_x(t)|}{|N|} \tag{3.2}$$

$$\sigma(\mathrm{NB})(t) = \sqrt{\frac{1}{|N|} \sum_{\forall x \in N} (\mathrm{NB}_x(t) - \bar{\mathrm{NB}}(t))^2} \tag{3.3}$$

Network Partitioning A network is affected by partitioning when there are isolated nodes (i.e., without a path to any other node) or islands of nodes (i.e., without a path to all other nodes). In MANETs, link outages are quite common because of the mobility and their wireless nature. Therefore, partitioning is also a common problem.

Network partitioning can cause low performance on any routing protocol because some of the paths among nodes may not exist. [40] recommends a low network partitioning for general routing protocol evaluation, since in partitioned scenarios, the routes that routing protocols should compute do not exist.

Network partitioning P at time t is defined as the unit minus the size of the path set at time t ($|R(t)|$) divided by the number of all possible paths among the network nodes (2-permutations of N):

$$P(t) = 1 - \frac{|R(t)|}{|N| \cdot (|N| - 1)} \tag{3.4}$$

with $|R(t)|$ the number of non empty sets in $|R(t)|$.

Shortest-Path Hop Count This metric takes into account the number of hops of the shortest-paths of the network. It is related to the diameter of the network topology. [40] proposes scenarios with a large shortest-path hop count. A scenario with an average shortest-path hop count of 1 or 2 is a scenario in which many packets are only sent between neighbors. In this environment most protocols perform well.

The shortest-path hop count is represented by the average and the standard deviation of the hop count of all the shortest routes at time t:

$$\mathrm{P\bar{H}C}(t) = \frac{\sum_{\forall x,y} |r_{x,y}(t)|}{|R(t)|} \tag{3.5}$$

$$\sigma(\mathrm{PHC})(t) = \sqrt{\frac{1}{|R(t)|} \sum_{\forall x,y} (|r_{x,y}(t)| - \mathrm{P\bar{H}C}(t))^2} \tag{3.6}$$

Link lifetime MANETs links are continuously created and broken because of the node motion and the wireless nature of the network. This metric is used to measure how dynamic the network is. It is represented by the average and the standard deviation of the duration a link is available in the network.

3.3 Specific Metrics

We have presented the main metrics found in the literature to characterize MANET scenarios and to test whether they are suitable for routing protocol performance evaluation.

These metrics measure general network topology properties of MANET scenarios, e.g., the length of the network paths. However, it is of interest to distinguish between metrics characterizing a network and metrics characterizing the routes that are used. In scenarios where not all nodes can act as source or destination or there are not symmetry in their network topology, this difference actually exists. This is the case of the firemobility model described and used later.

For that reason, a set of new metrics is proposed in this section. They are used to measure the properties of the network topology between two given nodes. These metrics are also useful to demonstrate the impact of the chosen node pairs on the routing protocol performance.

It must be noticed that the specific metrics are routing-protocol independent.

Shortest-Route Hop Count The performance of a routing protocol to deliver data packets from a source to a destination node depends on the length of the route. Routing protocols will behave similarly if the distance is one or two hops. The challenge of routing protocols is to build routes that are several hops long.

We devised the shortest-route hop count metric to measure the length of the routes between source and destination. The shortest-route hop count between node x and node y is the size of the smallest set of links which connect both nodes.

$$\mathrm{RHC}_{x,y}(t) = |r_{x,y}(t)| \tag{3.7}$$

In the case no route exists the hop count is infinite. When calculating the average and the standard deviation over time for this metric, infinite values are discarded. Therefore, the metric is only representative in scenarios where a route between x and y exists most of the time, i.e., scenarios with low partitioning.

Shortest-Route Lifetime The second property that impacts the performance of a routing protocol is the lifetime of the routes. The challenge of routing protocols are the dynamic topologies where routes are continuously changing.

The shortest-route lifetime measures the amount of time a shortest-route is available in the network. It is the difference between the time all hops are possible and the time at least one hop is not possible (i.e., the corresponding link is broken). It is represented by the average and standard deviation of the duration of all the shortest-routes created during the simulation.

Summary

Several MANET scenarios will be proposed to evaluate our routing solution. This chapter has presented topology metrics to classify MANET scenarios and identifies the recommended values to perform rigorous MANET routing performance evaluations. A set of general metrics was first identified in the literature to characterize the properties of the MANET scenarios. This set comprises: the number of nodes, the number of neighbors, the network partitioning, the shortest-path hop count and the link lifetime.

Then, the need to measure the properties of specific routes in the networks is discussed. Two specific metrics are introduced for that purpose: the shortest-route hop count and the shortest-route lifetime.

Chapter 4

Generic Scenario

MANET routing protocols are suitable for a wide range of scenarios. This is a problem when evaluating new MANET protocols because the results may vary depending on the chosen scenario. Protocols are often evaluated in generic scenarios which present sometimes a lack of realism but are easy to implement and configure.

The models and parameters used for the generic scenario are described in this chapter. The models are implemented in the December 2009 version of the INETMANET framework for OMNET++ 4.1. Section 4.1 gives a rationale for choosing the number of nodes and playground size of the scenario. The mobility model is defined in the Section 4.2. Finally Section 4.3 and 4.4 describes the wireless and satellite transmission models.

4.1 Playground Size and Number of Nodes

The number of nodes and playground size impact the network partitioning and the average shortest-path hop count of the scenario. These two metrics are introduced in [40]. The paper proposes MANET scenarios with low network partitioning because it is impossible for a routing protocol to build a route if it does not physically exist. The scenarios should also have a large average shortest-path hop count, since different routing protocols may perform equally for short routes; the demanding situation for a MANET routing protocol is when long routes must be set up. The proposed values are less than 5% for network partitioning and more than four hops for the average shortest-path hop count. According to [40], the minimum number of nodes needed to achieve these constraints is 95.

However, MANET simulations are computationally demanding. To simulate one second of 95 nodes with the OLSR protocol, around 25 seconds are needed on a 2GHz Intel Core 2 Duo with 2GB of RAM. Section 7.1 justifies the minimum simulation duration to achieve representative values for MANET routing protocol evaluation, with typical values of several thousand of seconds.

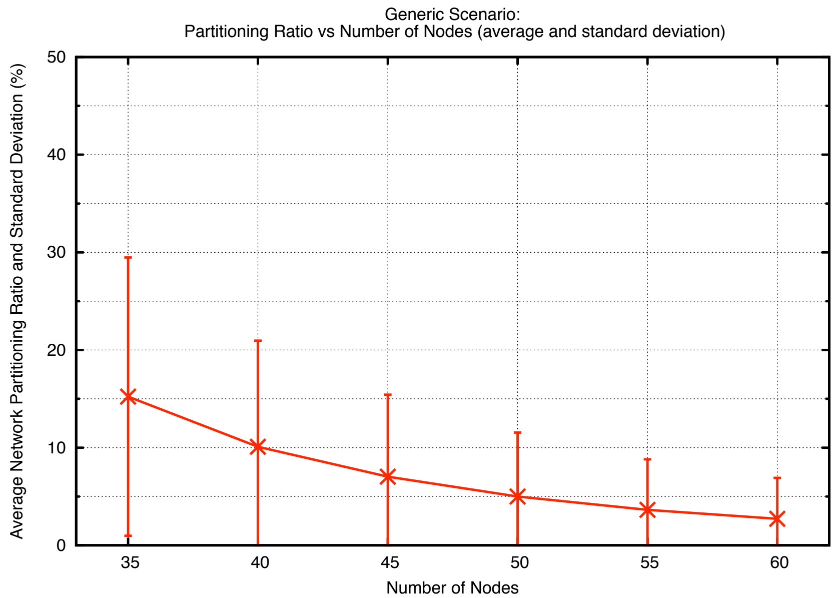

Figure 4.1: Average and standard deviation of network partitioning over a varying number of nodes in a generic scenario of $5R \times 5R$ (with R, the radio range). The partitioning is averaged over the simulation duration (3000 s).

Therefore, a single simulation of a 95 node scenario takes more than one day. Since several simulations must be done to find the confidence interval of the results, this scenario is not affordable.

The number of nodes is decreased to reduce the simulation complexity. The size of the scenario must be decreased accordingly, to keep partitioning minimal. A square scenario with a side of 5 times the radio range (R) is chosen. The mobility model of the nodes is a random waypoint with a uniform speed between $0.02R$ m/s and $0.05R$ m/s and no waiting time. All the distances and speeds of the generic scenarios are defined with respect to the radio range. The reason for this is that the effect of distance is not determined by its absolute size, but by its size relative to the transmission range. We follow the advice of [40] allowing a maximum network partitioning of 5%. Figure 4.1 shows the average and the standard deviation of network partitioning ratio for scenarios from 35 to 65 nodes. The partitioning constraint is fulfilled for scenarios with 50 nodes or more. Figure 4.2 represents the elapsed seconds per second of simulation for the previous scenarios. The value for 50 nodes is 3 seconds, a more tractable value than 25 seconds for 95 nodes.

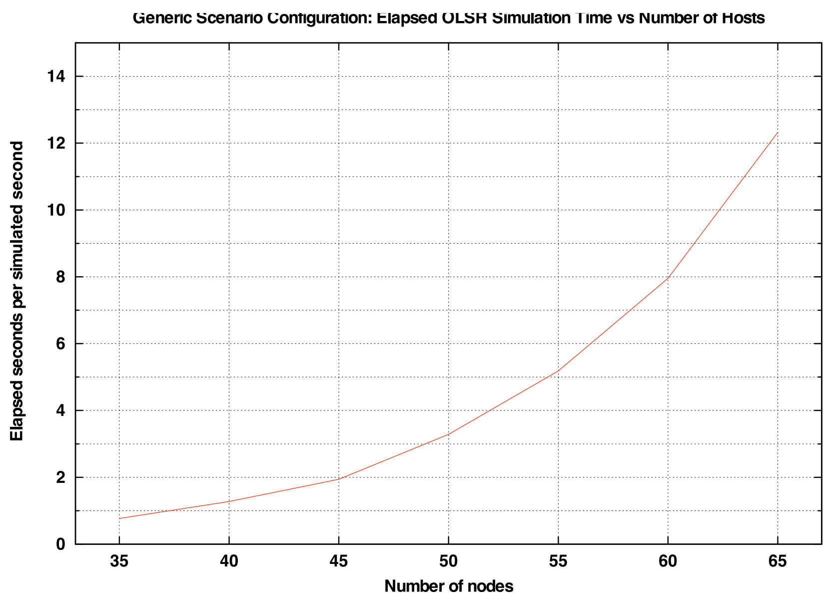

Figure 4.2: Time needed to simulate one second in scenarios of $5R \times 5R$ with different number of nodes.

4.1.1 Path and Route Hop Count

Decreasing the scenario size and the number of nodes leads to lower shortest-path hop count. With the scenario of size $5R \times 5R$ and 50 nodes, the average shortest-path hop count decreases to 3.5 hops with a standard deviation of 1.7 hops (these values are obtained averaging through 30000 seconds of 20 simulations). This value is not enough to evaluate the routing protocol behavior in the presence of long routes. The problem is addressed in the following paragraphs by fixing the position of the source and destination nodes.

A common method to evaluate a routing protocol is to analyze how data packets are handled from an end-to-end perspective. One or more pair of nodes are configured to exchange data and the delay or the delivery ratio of the data packets are presented as metrics for the routing performance. Therefore the measured performance depends on the routes between the node pairs. The specific metrics measure the properties of these routes. While the shortest-path hop count measures the length of all the paths in the network, the shortest-route hop count measures the length of the route between a given node pair.

In the $5R \times 5R$ scenario with 50 nodes, the average number of hops between source and destination are the same as the average shortest-path hop count since all nodes move following the random waypoint model. To increase the shortest route hop count without increasing the number of nodes and the playground size, we decided to fix the position of the source and the destination nodes. Doing so, we ensure that because the source and destination are distant, a sufficient

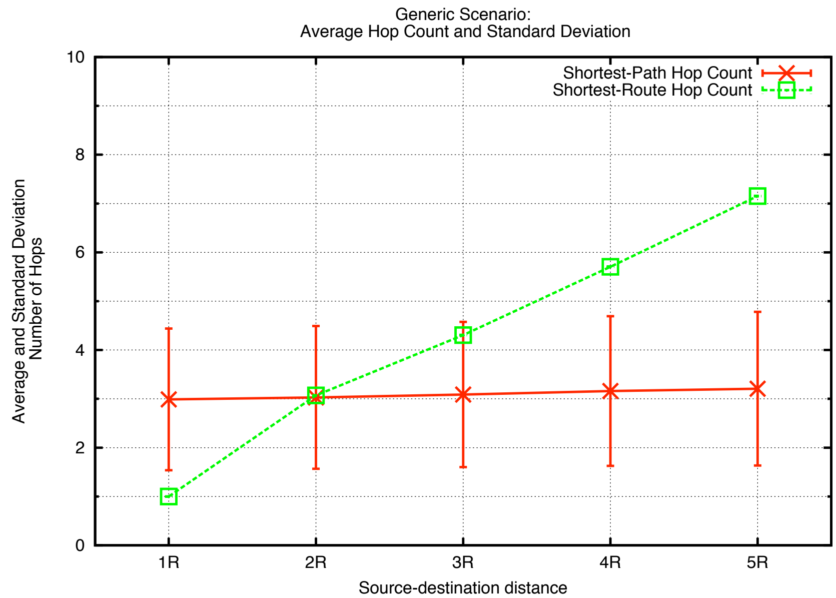

Figure 4.3: Average and standard deviation of shortest-path and shortest-route hop count metrics according to the source-destination distance.

number of hops will be required to join them. The distance between the source and the destination can be configured so to test the routing protocol performance according to different route lengths. Figure 4.3 represents the shortest-path hop count and the shortest-route hop count for scenarios with a distance between the source and the destination from 1 to 5 times the radio range (R). The standard deviation over the nodes is also represented for the shortest-path hop count (for the shortest-route hop count, there is a single value therefore no standard deviation). All the scenarios have similar values of shortest-path hop count but they differ in the shortest-route hop count. It demonstrates the importance of the specific metrics to measure properties of the routes between the source and the destination nodes that classical metrics as shortest-path hop count do not reflect.

The same occurs in Figure 4.4 between the link lifetime and the route lifetime. The link lifetime value is similar for all scenarios. On the other hand, the source-destination route lifetime decreases with longer routes. Here is an example of the importance of specific metrics to distinguish scenario conditions which are not reflected by the general metrics.

Finally, the average number of neighbors and the standard deviation over the network nodes are presented in Figure 4.5. We notice similar values for all scenarios, with a slight decrease in the scenarios with long distances between the source and destination. The reason is that the source and destination nodes are farther from the playground center when their distance increases, so the

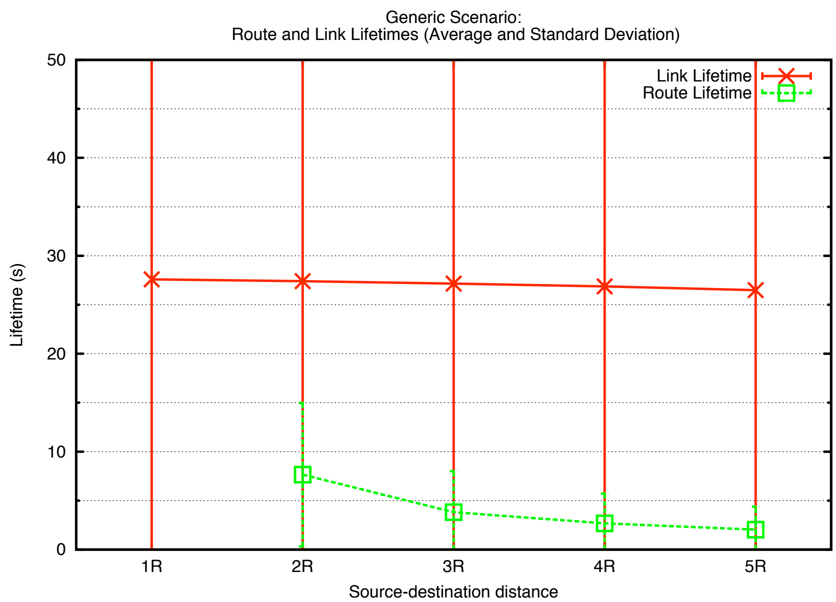

Figure 4.4: Link and route lifetime average and standard deviation as a function of the source-destination distance. The route lifetime for 1R is infinite.

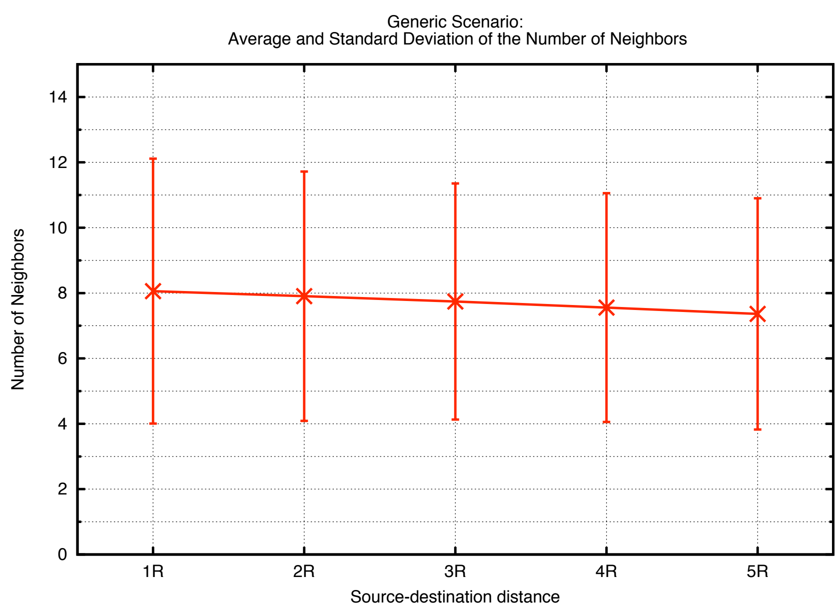

Figure 4.5: Average number of neighbors and standard deviation over the nodes in the generic scenario.

Module	Parameter	Value
channelControl	pMax	1mW
channelControl	sat	-110 dBm
channelControl	alpha	2
channelControl	carrierFrequency	2.4 GHz
radio	transmitterPower	1.0 mW
radio	pathLossAlpha	2
radio	snirThreshold	4 dB
radio	bitrate	54 Mbps
radio	thermalNoise	-110 dBm
radio	sensitivity	-90 dBm
radio	phyOpMode	2 = 802.11g-only
radio	channelModel	1 = Rayleigh
radio	berTableFile	"per_table_80211g_Trivellato.dat"

Table 4.1: Simulation parameters of the wireless model.

concentration of nodes around this area is slightly lower.

4.2 Mobility Model

The mobility model chosen for the generic scenario is the random waypoint mobility model (RWP) because of its popularity in MANET simulations. This random mobility model accepts three parameters: the node maximum and minimum speed, and the node waiting time. These parameters impact the topology evolution. Increasing the speed leads to more dynamic topologies while increasing the waiting time produces more static topologies. The speed is chosen regarding the radio range R. It is uniformly chosen between $0.02R$ m/s and $0.05R$ m/s with no waiting time. These values are high enough to evaluate MANET routing protocols in a dynamic topology but low enough to allow the protocols to track the topology changes.

4.3 Wireless Model

The wireless terrestrial communications are simulated using the *ChannelControlExtended* and the *802.11g* modules of the INETMANET framework. The input parameters are presented in Table 4.1. The radio propagation model is the free-space path loss reception model. With the parameters of Table 4.1 the wireless transmission range is:

$$R = \sqrt[\alpha]{\frac{p_{tx}\lambda^2}{p_{rx}16\pi^2}} = \sqrt[2]{\frac{0.001 \cdot 0.125^2}{10{-}12 \cdot 16\pi^2}} = 314.46 \text{ m}$$

The channel is modeled using a packet error rate table for 802.11g obtained using a dedicated OFDM physical layer simulator by Matteo Trivellato integrated into the INETMANET framework.

4.4 Satellite Model

The INETMANET framework for OMNET++ does not provide any satellite model, hence a new model had to be created. The channel delays data and delivers it to the connected satellite interfaces.

Two modules constitute the satellite model: a satellite channel and a satellite interface. Each node with a satellite interface module is registered into the satellite channel module. When a satellite interface sends a packet, it checks the registered satellite interfaces in the satellite channel and sends a copy of the packet to each of them. The satellite channel module is configured through a parameter called *delay* which is set to 250 ms by default (this delay corresponds to the propagation delay). The satellite interface module has a *bitrate* parameter which is set to 64 Kbps. In the generic scenario, it is assumed that all the nodes have a satellite interface.

Summary

A generic scenario for MANET simulation is described in this chapter. The simulator version, the models and their parameters are identified.

The problem of simulating large networks is addressed by decreasing the number of nodes while keeping the distance between source and destination large enough so to guarantee the validity of simulation results. Finally, the utility of specific metrics is demonstrated by measuring the route length and the route lifetime between the source and the destination nodes of the proposed scenarios.

Chapter 5

Specific Scenario

As it has been discussed before, MANETs are convenient in many situations because they do not require an infrastructure, are easy-to-deploy and self-organized. Most of the scenarios reported in the MANET literature are generic. The nodes motion follows an entity mobility model as the random waypoint mobility model (see Section 2.3.1). However these scenarios are not realistic. For that reason, another scenario based on forest fire fighting is introduced with two objectives: provide a more realistic framework for MANET deployment and compare the results that will be obtained with the generic approach.

Fighting forest fires is an interesting context for deploying a MANET. Forests are a challenging environment for telecommunications. The firemen could be deployed in an area without the coverage of an existing telecommunication infrastructure or the fire could have destroyed it. Firemen need immediate communications in the early stage of the mission, and it is not possible for them to wait until an infrastructure is deployed. Finally, fire fighting operations are dynamic because of the fire evolution.

The organization of firemen is described in Section 5.1. Then, the rules and actions driving their deployment are detailed in Section 5.2. This information is used in Section 5.3.1 to implement a mobility model, the Fire Mobility Model. Finally Section 5.3.2 and Section 5.3.3 complete the specific scenario description with the details of the wireless and the satellite models.

5.1 Components

Information about forest fire operations was collected during interviews with personnel from the *"Direction de la Défense et de la Sécurité Civile"* of France. These interviews were consolidated from official training guides [60, 61].

The basic component in a forest fire mission is the intervention group (IG). It constitutes the elementary unit, theoretically indivisible. An IG is made of the following personnel and vehicles:

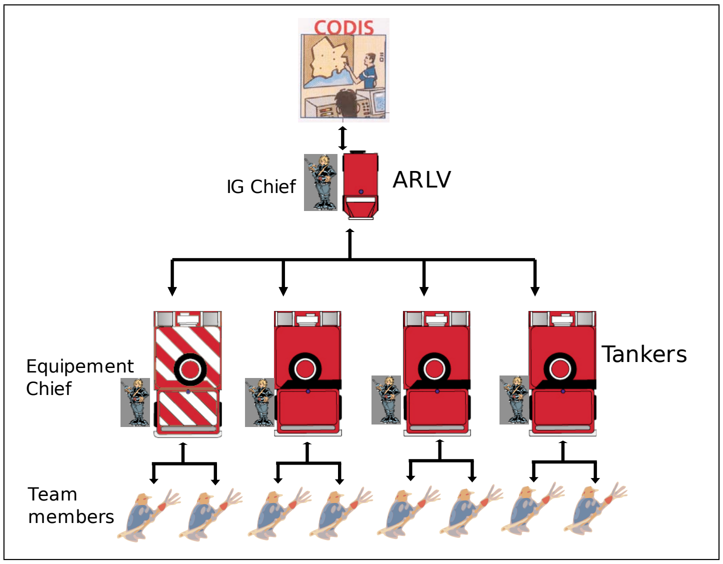

Figure 5.1: Intervention Group: basic component in forest fire missions [60].

- A group all-road light vehicle (GARLV) with an intervention group leader and driver.
- Four tankers with an equipment leader, driver and two team members for each of them.

That is 5 vehicles and 18 people (see Figure 5.1).

Depending on the magnitude of the fire, IGs could be organized into columns. A column consists of:

- Three intervention groups.
- A column all-road light vehicle (CARLV) with a column leader and a driver.

That is 16 vehicles and 56 people (see Figure 5.2).

When a fire requires more forces, columns are organized into sectors. A sector consists of three columns, a command and support elements. Figure 5.3 represents a diagram of the final state of a complex forest fire mission.

5.2 Maneuvers

Firemen follow a set of predefined rules for deployment and motion. The rules describe the organization of IGs in the following situations:

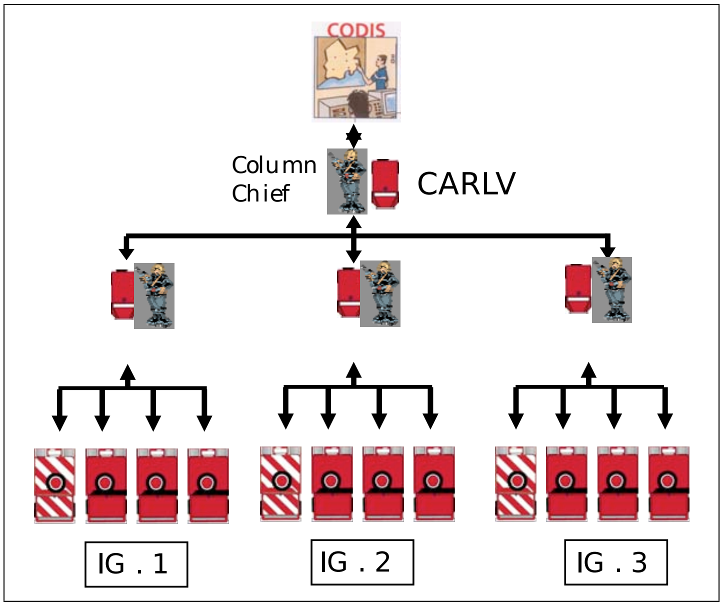

Figure 5.2: Column hierarchy in forest fire missions [60].

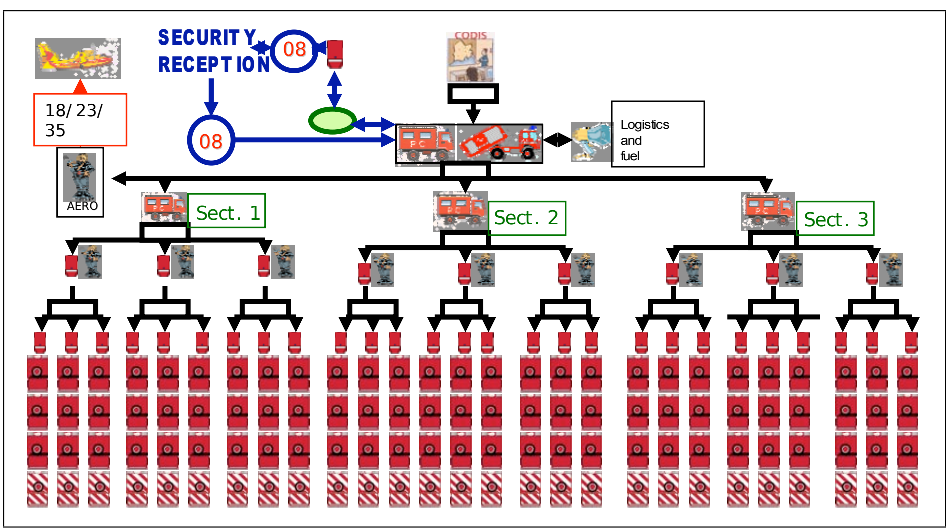

Figure 5.3: Diagram of a complex forest fire mission [60].

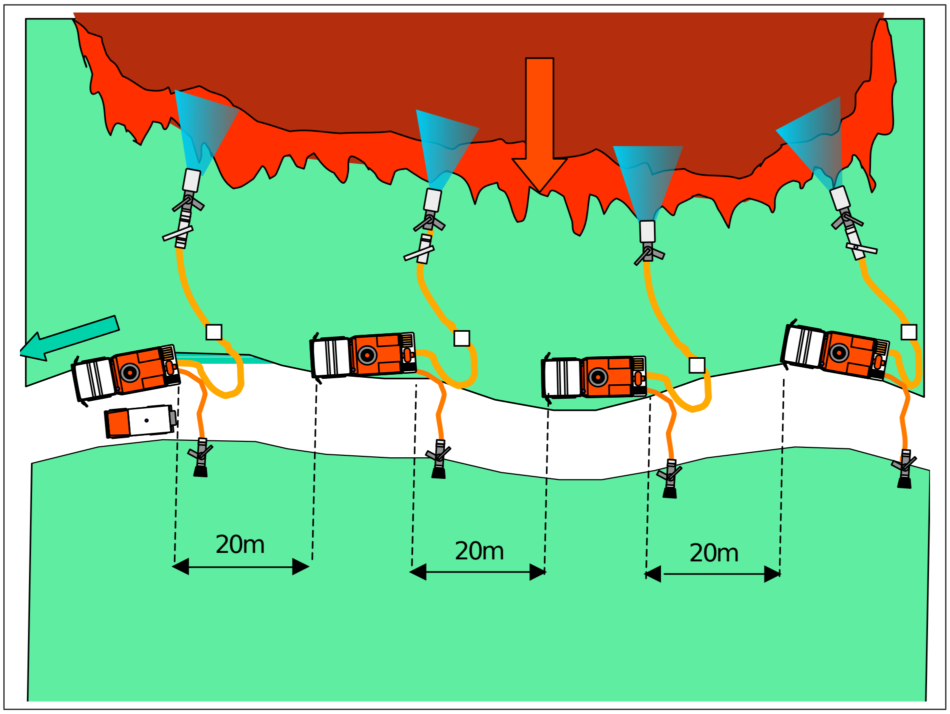

Figure 5.4: Execution of a defense support line [61].

Transit As IG is the theoretically indivisible unit, its components must approach their objective as a group. The maximum speed of the IG is set by the IG leader, with the GARLV leading the convoy. On road, the slowest vehicle or the one with the least capacity to maneuver is immediately after the GARLV. If the travel is on a track, the one with the least maneuver capacity should be the last one. The security distance among vehicles is 50 meters.

Defensive formation In a defensive formation, the IG adopts a position to wait for the fire and attack as soon as it arrives. There are two kinds of defensive maneuvers, the protection of strategic spots such as populated areas and the establishment of a support line.

Distance among vehicles in a static support line is 20 meters maximum. The team members of each tanker establish a hose and stay close to the group. A typical static support line is shown in Figure 5.4.

Offensive formation An IG could seek out the fire in an offensive maneuver. There are three kind of attacks: a front attack, a flank attack or a breakthrough attack. To perform these actions, there are four types of deployments:

- Four hoses up to 120 meters (Figure 5.5).

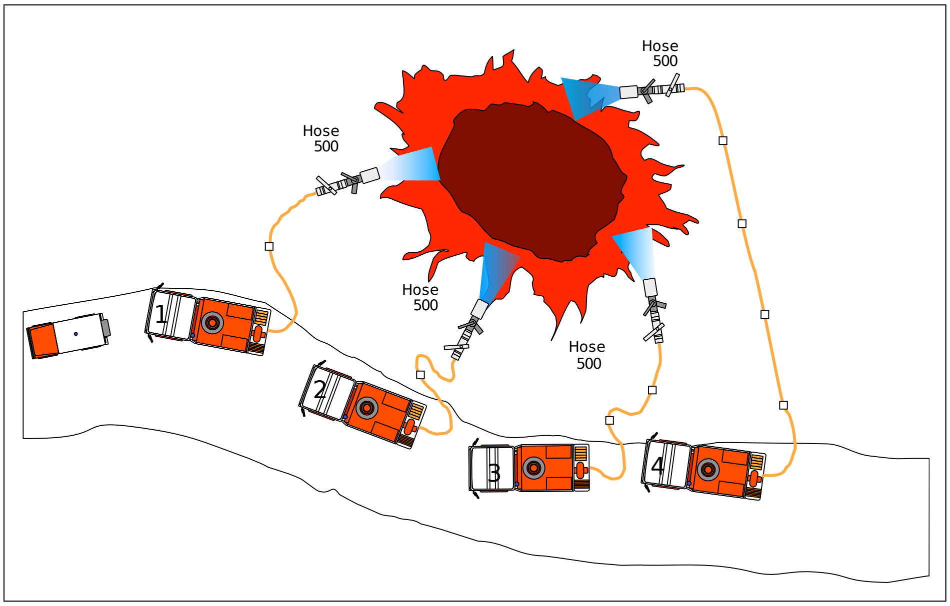

Figure 5.5: Offensive formation with four hoses [61].

- Two hoses up to 280 meters (Figure 5.6).
- One hose or two hoses up to 440m (Figure 5.7).
- Deployments for larger lengths.

5.3 A Forest Fire Fighting Specific Scenario

The forest fire fighting scenario is developed in the INETMANET framework of OMNET++ to complement the generic scenarios presented in Chapter 4. In this section, we describe the three main models of the specific scenario. Section 5.3.1 presents the fire mobility model, Section 5.3.2 discusses the relation to the wireless model and Section 5.3.3 covers satellite related models.

5.3.1 Fire Mobility Model

Modeling the motion of firemen is therefore a complex task. A coarse model called Fire Mobility is proposed to describe the basic behavior of the firemen, reflecting their hierarchy and group movements. The description of the fire mobility model is divided into two parts: deployment and motion. The former defines the way the units place themselves in the intervention area while the latter describes how they update positions during the operation.

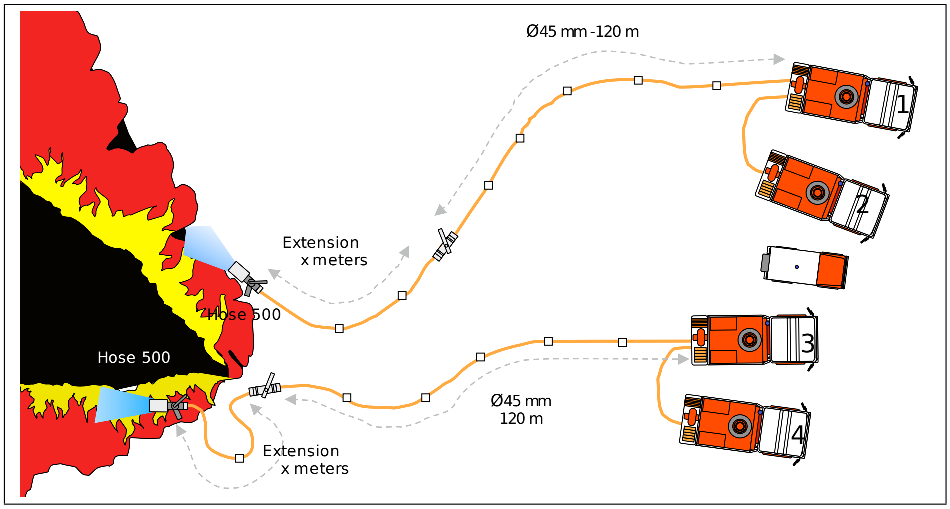

Figure 5.6: Offensive formation with two hoses [61].

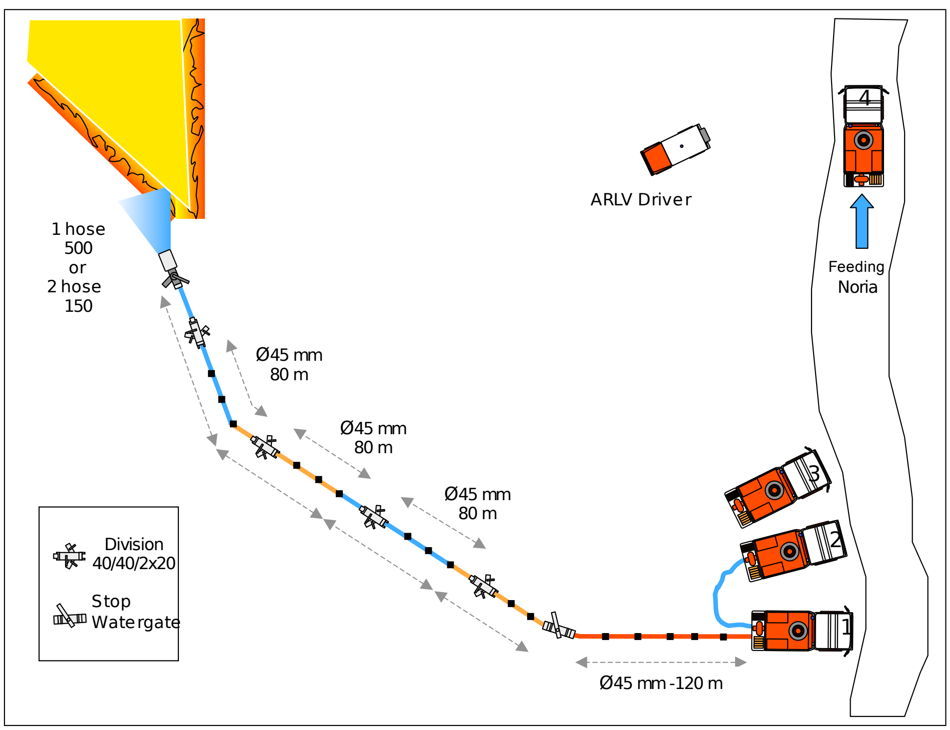

Figure 5.7: Offensive formation with one hose [61].

Deployment

Defining the firemen layout with regard to the fire is the first step to model their mobility. Firemen are deployed in groups, each one has a different mission to fulfill. This should be reflected in the mobility model. The reference point group mobility (see Section 2.3.2) is taken as a framework to define the deployment of the units. The method to calculate the location using the reference point is explained for each kind of unit and represented in Figure 5.8 . The fire mobility parameters used for the simulations are collected in Table 5.1.

Fire Fire is a difficult component to model. Its size, shape and movement depend on complex factors such as topography, weather and wind, kind of forest and terrain, etc. Forecasting the advance of a wild fire is a challenge nowadays. New sensors on-board satellites detect forest fires from the sky, and wireless sensor networks are designed to detect them from the ground. Also complex meteorological analysis are used. All these considerations are out of scope for this study, therefore a simplified model is chosen. The fire is modeled as a circle with variable radius. Also, a fixed direction is chosen to define the advance of the fire. The fire is not considered as an entity but as a virtual group center and it is used as reference point for some units. The following parameters characterize the fire:

- **fire_radius** It is calculated with the input parameters `RADIUS_MIN` and `RADIUS_VAR`, using a uniform distribution.
- **fire_center** It can be fixed with the `CENTER_X` and `CENTER_Y` parameter. If the parameter does not exist, the center of the playground is chosen.
- **fire_angle** It represents the direction of the fire advance. It is expressed using trigonometric convention. It can be fixed with the `FIRE_ANGLE` parameter. If it does not exist, the angle is randomly chosen.

Entities The entity position is related to its reference point (x_0, y_0). Therefore the position is defined by an angle θ and a distance d to the reference point.

$$x = x_0 + d \cdot \cos\theta$$
$$y = y_0 + d \cdot \sin\theta$$

In the following paragraphs the location of each entity is defined with (x_0, y_0), θ and d.

CARLV The column all-road light vehicle coordinates three intervention groups of the same area. It is deployed close to the IG that request its support. However it must take a safe position, farther from the fire than the IGs.

Its reference point is the fire center. The distance to the fire front is uniformly chosen using the parameters `CARLV_DIST_MIN` and `CARLV_DIST_VAR`. It presents the same angle offset regarding to the fire advance as the IG receiving its support.

$$
\begin{aligned}
(x_0, y_0) &= \textbf{fire\_center} \\
d &= \textbf{fire\_radius} + \texttt{CARLV\_DIST\_MIN} + U(0, \texttt{CARLV\_DIST\_VAR}) \\
\theta &= \textbf{fire\_angle} + \texttt{SUPPORTED\_IG\_OFFSET} + U(-\texttt{CARLV\_ANGLE\_VAR}, \texttt{CARLV\_ANGLE\_VAR})
\end{aligned}
$$

GARLV The all-road light vehicle should be close to the tankers it has to coordinate. It is also closer to the fire than the CARLV and it moves among the tankers to give them support.

Each intervention group is deployed with an angle offset regarding to the fire advance: the IG_OFFSET. It defines the attack angle used by the IG members. A front attack is established with $\texttt{IG\_OFFSET} = 0$ while flank attacks are set up with $\texttt{IG\_OFFSET} \neq 0$.

$$
\begin{aligned}
(x_0, y_0) &= \textbf{fire\_center} \\
d &= \textbf{fire\_radius} + \texttt{GARLV\_DIST\_MIN} + U(0, \texttt{GARLV\_DIST\_VAR}) \\
\theta &= \textbf{fire\_angle} + \texttt{IG\_OFFSET} + U(-\texttt{GARLV\_ANGLE\_VAR}, \texttt{GARLV\_ANGLE\_VAR})
\end{aligned}
$$

Tanker The tankers cover different angles around the IG_OFFSET. Four different angles are fixed with the TANK_OFFSET parameters to be used by the four tankers interchangeably. Consequently the angle of the tanker is defined as:

$$
\begin{aligned}
(x_0, y_0) &= \textbf{fire\_center} \\
d &= \textbf{fire\_radius} + \texttt{TANKER\_DIST\_MIN} + U(0, \texttt{TANKER\_DIST\_VAR}) \\
\theta &= \textbf{fire\_angle} + \texttt{IG\_OFFSET} + \texttt{TANKER\_OFFSET} + \\
&\quad + U(-\texttt{TANKER\_ANGLE\_VAR}, \texttt{TANKER\_ANGLE\_VAR})
\end{aligned}
$$

Team members Each team member is related to a tanker. Team members setup hoses and have the same reference angle as their related tanker. Teams are the entities closest to the fire.

$$
\begin{aligned}
(x_0, y_0) &= \textbf{fire\_center} \\
d &= \textbf{fire\_radius} + \texttt{TEAM\_DIST\_MIN} + U(0, \texttt{TEAM\_DIST\_VAR}) \\
\theta &= \textbf{fire\_angle} + \texttt{IG\_OFFSET} + \texttt{TANKER\_OFFSET} + \\
&\quad + U(-\texttt{TEAM\_ANGLE\_VAR}, \texttt{TEAM\_ANGLE\_VAR})
\end{aligned}
$$

Motion

Forest fires are dynamic elements. Firemen must follow the evolution of the fire and react consequently. All the elements of a column can be seen as an entire

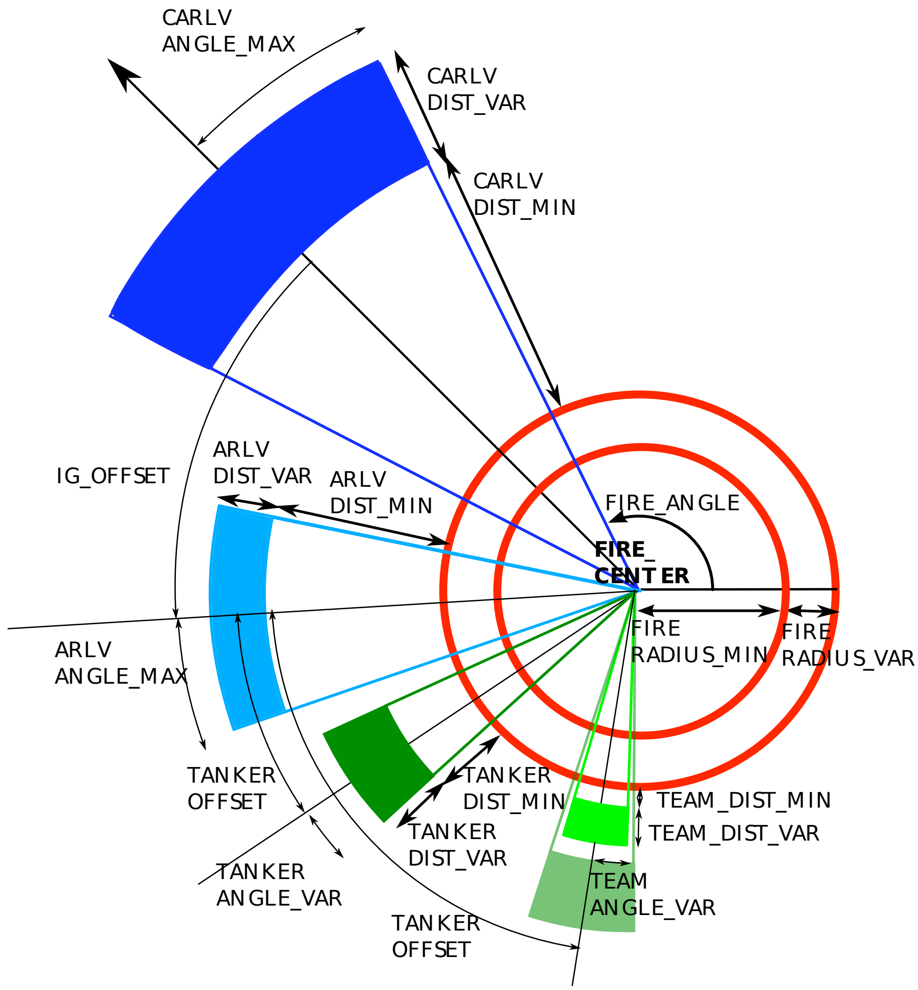

Figure 5.8: Example of deployment for each kind of entity in the fire mobility model.

Parameter	Value	Parameter	Value	Parameter	Value
RADIUS_MIN	40 m	CARLV_DIST_MIN	50 m	GARLV_DIST_MIN	50 m
RADIUS_VAR	10 m	CARLV_DIST_VAR	20 m	GARLV_DIST_VAR	10 m
FIRE_ANGLE	$\pi/2$ rad	CARLV_ANGLE_VAR	0 rad	GARLV_ANGLE_VAR	$\pi/4$ rad
CENTER_X	500 m	CARLV_OFFSET1	0 rad	IG_OFFSET1	0 rad
CENTER_Y	500 m	CARLV_OFFSET2	0 rad	IG_OFFSET2	$\pi/20$ rad
CENTER_Y	500 m	CARLV_OFFSET3	0 rad	IG_OFFSET3	$-\pi/2$ rad
Parameter	Value	Parameter	Value		
TANKER_DIST_MIN	30 m	TEAM_DIST_MIN	0 m		
TANKER_DIST_VAR	10 m	TEAM_DIST_VAR	10 m		
TANKER_ANGLE_VAR	$\pi/16$ rad	TEAM_ANGLE_VAR	0 rad		
TANKER_OFFSET1	$\pi/16$ rad				
TANKER_OFFSET2	$-\pi/16$ rad				
TANKER_OFFSET3	$3\pi/16$ rad				
TANKER_OFFSET4	$-3\pi/16$ rad				

Table 5.1: Fire mobility deployment parameters used in the simulations.

group following the same target, the fire. Since they move together, the motion of the entire column with the fire is discarded in the model, focusing on the relative positions among column members.

Entities of the mobility model are continuously changing between two states: *moving* and *waiting*. In the moving state, the entity chooses a new position following the rules explained in Section 5.3.1. Then it selects a speed and moves towards the destination. When it arrives, it waits until the next moving state. The WAIT_MIN and the WAIT_VAR parameters of each entity are used to calculate the waiting time. The SPEED_MIN and the SPEED_VAR parameters determines the motion speed. The mobility of the different entities and their relationship are explained in the following paragraphs and the parameters used for our simulations are collected in Table 5.2. The speed is determined by its absolute value (m/s) to reflect the behavior of firemen units, and not to create an optimized scenario to evaluate MANET routing protocols (like in the case of the generic scenarios). We can think that a speed of 10 and 15 m/s will create overly dynamic topologies. However this is not the case since the relative speed among the nodes is kept low.

Fire As it was previously seen, fire motion is not taken into account in the model. However the radius of the fire can change. A new fire radius is chosen each $\texttt{FIRE\_WAIT\_MIN} + U(0, \texttt{FIRE\_WAIT\_VAR})$ period.

CARLV The CARLV leads the three IGs that build the column. It must be fast and should stay close to an IG until another IG requests support.

In the mobility model, each time a CARLV finishes a waiting state, it choses an IG of the column and moves towards the new destination.

Parameter	Value	Parameter	Value	Parameter	Value
FIRE_WAIT_MIN	10 s	CARLV_WAIT_MIN	120 s	GARLV_WAIT_MIN	60 s
FIRE_WAIT_VAR	0 s	CARLV_WAIT_VAR	60 s	GARLV_WAIT_VAR	60 s
		CARLV_SPEED_MIN	15 m/s	GARLV_SPEED_MIN	10 m/s
		CARLV_SPEED_VAR	0 m/s	GARLV_SPEED_VAR	0 m/s
Parameter	Value	Parameter	Value		
TANKER_WAIT_MIN	120 s	TEAM_WAIT_MIN	1000000 s		
TANKER_WAIT_VAR	60 s	TEAM_WAIT_VAR	0 s		
TANKER_SPEED_MIN	10 m/s	TEAM_SPEED_MIN	10 m/s		
TANKER_SPEED_VAR	0 m/s	TEAM_SPEED_VAR	0 m/s		

Table 5.2: Fire mobility motion parameters used in the simulations.

GARLV As the CARLV moves among IGs, the GARLV commutes among the tankers of the IG. The difference is that GARLV does not explicitly choose a tanker to support. The `ANGLE_VAR` parameter implicitly lays the GARLV close to one of the tankers each time its position is refreshed.

Tanker Each tanker of a group selects a different angle offset among four different `TANKER_OFFSET` options. As the fire advances, a tanker position could be repositioned: its angle offset may change because of a maneuver restriction, or it could share the angle offset with another tanker that requests water supply.

To implement that, a flag is set in each possible offset to mark if it was previously selected by another tanker. Each time a tanker moves, it chooses an unselected offset and sets the flag. If there are not unselected offset options, all the flags are unset to make the four offsets available.

Team Team members are closely related to their tankers. Each time a tanker repositioning occurs, its respective team also updates its position. The `TEAM_WAIT_MIN` and the `TEAM_WAIT_VAR` parameters can be also used to model short individual movements of the team members while the tanker remains static.

5.3.2 Wireless Model

The wireless model is the same as in the generic scenarios: the *ChannelControlExtended* and the *802.11g* modules of the INETMANET framework. The input parameters are presented in table 5.3. The only difference between the generic and the specific wireless configuration is the α parameter. The difference is explained next.

Propagation Model

In a forest fire fighting operation, the wireless communications are impaired by trees and foliage. Therefore the free space path loss propagation model used in the generic scenario is not valid. Propagation models for forest environment are

Module	Parameter	Value
channelControl	pMax	1mW
channelControl	sat	-110 dBm
channelControl	alpha	3
channelControl	carrierFrequency	2.4 GHz
radio	transmitterPower	1.0 mW
radio	pathLossAlpha	3
radio	snirThreshold	4 dB
radio	bitrate	54 Mbps
radio	thermalNoise	-110 dBm
radio	sensitivity	-90 dBm
radio	phyOpMode	2 = 802.11g-only
radio	channelModel	1 = Rayleigh
radio	berTableFile	"per_table_80211g_Trivellato.dat"

Table 5.3: Simulation parameters for the wireless model.

studied in [62]. A common solution is to consider the Weissberger model [63] to account for the impairments introduced by foliage:

$$L_{\text{weiss}}(\text{dB}) = \begin{cases} 0.45 f^{0.284} x & \text{if } 0 \leq x \leq 14\text{m} \\ 1.3 f^{0.284} x^{0.588} & \text{if } 14 < x \leq 400\text{m} \end{cases}$$

With f the radio frequency in Gigahertz (GHz) and x the depth of foliage along the path in meters. The computational load of the model is demanding, with several powers and decibel conversions. The solution adopted is to use the path loss reception model with a higher α coefficient ($\alpha = 2$ means free space).

The Weissberger path loss model is compared with the free-space path loss model for several values of α coefficient in Figure 5.9. The curves are displayed for the frequency and transmitted power considered in the scenario ($f = 2.4\text{GHz}$, $p = 1\text{mW}$). All the path is considered impaired by the foliage ($x = d$). We notice similarities between the Weissberger path loss and the free space path loss with $\alpha = 3$ curves and close radio ranges.

So we decide to use the free space path loss with $\alpha = 3$ to model the radio propagation in a forest, simplifying the required computation of the Weissberger model.

Therefore the wireless radio range becomes:

$$R = \sqrt[\alpha]{\frac{p_{tx}\lambda^2}{p_{rx}16\pi^2}} = \sqrt[3]{\frac{0.001 \cdot 0.125^2}{10{-}12 \cdot 16\pi^2}} = 46.25 \text{ m}$$

5.3.3 Satellite Model

The specific scenario uses the same simplified satellite model as the generic scenario. However it presents some variations in the nodes configured with

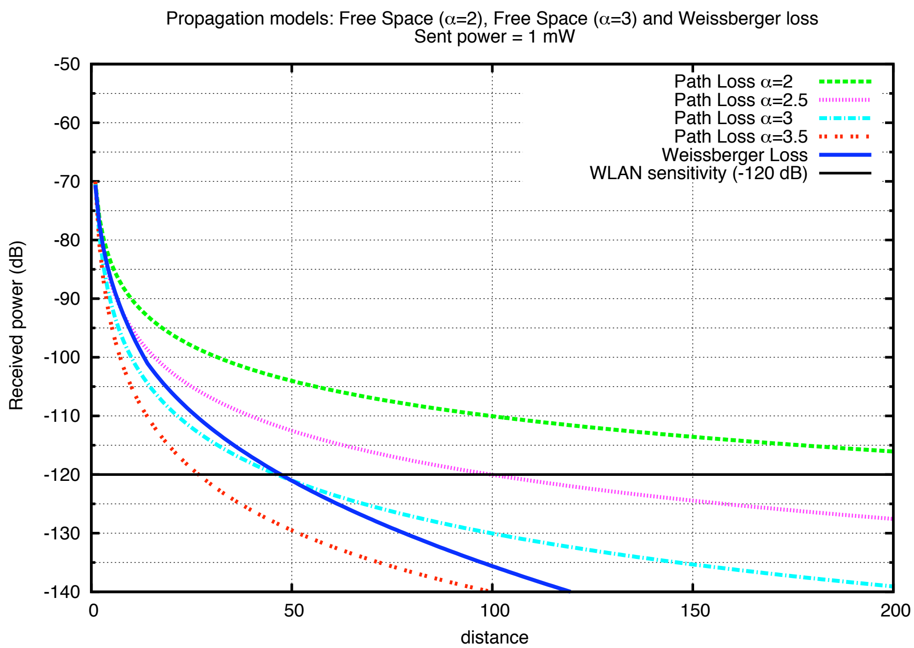

Figure 5.9: Received power against distance with several propagation models.

satellite interfaces. While all the nodes of the generic scenario feature a satellite interface, the specific scenario proposes an heterogeneous network closer to the reality where only a subset of the nodes have satellite capabilities.

The IETF draft on connectivity scenarios for MANET [64] discusses the connection of MANETs with external networks. It describes the gateway nodes, devices equipped with two or more network interfaces: a MANET interface and an interface typically connected to one or more non-MANET networks. MANET nodes exchange traffic among themselves using multi-hop paths and can reach remote hosts and the Internet through gateways. A MANET can have only one gateway or it can have multiple gateways. Besides guaranteeing a high degree of reliability and fault tolerance to the entire MANET, the presence of multiple gateways enables load balancing among the gateways themselves.

We consider a column (28 nodes) with several gateways with a MANET interface and a satellite interface. Three options are considered:

All units as gateways (r=n=28) All nodes can transmit and receive from the satellite interface. It is not a realistic scenario however the results serve as baseline. Also it is similar to the generic scenario.

Three gateway units (r=4) The column command car and the command cars of the three intervention groups can transmit and receive from the satellite interface. They are chosen because of their high position in the fireman hierarchy. These vehicles can be equipped with satellite dishes considering energy supply and antenna mounting constraints.

Seven gateway units (r=7) One tanker of each intervention group is equipped in addition to the command cars.

Summary

A specific MANET scenario was presented in this chapter. A forest fire fighting operation was chosen as a suitable scenario to deploy a MANET for firemen communications.

The first part of the chapter offered a brief outline of the forest fire fighting units, their hierarchy and their maneuvers. Then the scenario model was explained. The mobility of the fireman units is modeled with the fire mobility model, a coarse model that reflects the hierarchy of the firemen and their group movements. Then, the wireless model is described, focusing in the main difference with the generic scenario: the radio propagation. The free space propagation ($\alpha = 2$) of the generic scenario is changed to reflect the attenuation introduced by trees and foliage of the specific scenario. It is concluded that a good approximation to model this attenuation is to increase the path loss coefficient ($\alpha = 3$). Finally the distribution of the satellite gateways through the firemen units is shown. The command cars are the most likely units to embark a satellite interface.

Part III

Improvements in MANET Signaling

Chapter 6

OLSR Protocol Modifications

The optimized link state routing protocol is chosen as the protocol to be improved with a dedicated satellite signaling channel. This choice is based on the study carried out on Chapter 1. The most important MANET routing protocols were analyzed there and OLSR is selected because of its link state nature, its popularity and because it is standardized by the Internet Engineering Task Force (IETF).

This chapter presents how OLSR works with a special emphasis on the signaling broadcast: the multipoint relay broadcast mechanism and the `topology control` (`tc`) messages. Then, a first approach is described: OLSR Satellite broadcast (OLSR-SAT). It substitutes the default OLSR signaling broadcast with a satellite broadcast system. However, all nodes of an OLSR-SAT network must feature uplink and downlink satellite transmissions. OLSR Hybrid broadcast (OLSR-H) avoids this constraint combining OLSR and OLSR-SAT signaling broadcast systems. It can operate in heterogeneous networks where only a set of the nodes have satellite capabilities.

Finally an alternative route computation algorithm is introduced: the Extended Route computation Algorithm (EXTRA) which can be used with each of the previous protocol modifications.

6.1 Optimized Link State Routing Protocol

OLSR is a proactive routing protocol of the family of the link state protocols like the Open Shortest Path First (OSPF) protocol. Link state protocols perform two processes: link sense and link state broadcast. In the link sense process, the node obtains information about local links to its neighbors. Then, this information is circulated via the link state broadcast process. Each node calculates its routing table with the information obtained from both processes.

OLSR presents variations in these processes to match the ad hoc network properties like dynamics and bandwidth constraints. The link sense process is performed via `hello` message exchange and the link broadcast is performed via multipoint relays and `topology control` (`tc`) message broadcast.

6.1.1 Hello Message Exchange

The link sense process is achieved through the exchange of `hello` messages among neighboring nodes. The information contained in the `hello` message allows a node to discover its neighbors up to 2-hops far and also the state of the respective links. The resulting information about the local topology is then used by the nodes to select their multipoint relays (MPRs) and the contents of the `topology control` (`tc`) messages that they should broadcast over the network.

The hello message exchange is divided into two parts, creating `hello` messages and processing received `hello` messages.

Hello Message Creation An OLSR agent sends `hello` messages with a period fixed by the `HELLO_INTERVAL` parameter with a default value of two seconds. The agent lists three different types of neighbors in its `hello` messages: asymmetrical, symmetrical and multipoint relay neighbors.

- Asymmetrical neighbors are nodes that the agent hears but can not speak to.
- Symmetrical neighbors are the nodes with a bidirectional link with the agent.
- Multipoint relay neighbors are the neighbors chosen by the agent as its multipoint relays (see Section 6.1.2).

Hello Message Processing The `hello` messages are only processed by the OLSR agents, they are never forwarded. The originator of a `hello` message is classified by the OLSR agent receiving the message as:

- An asymmetrical neighbor when the agent receiving the message is not in any neighbor list of the `hello` message.
- A symmetrical neighbor when the agent is in any neighbor list of the message. In this case, the nodes inside the symmetrical neighbor list of the `hello` message are classified as 2-hop neighbors.
- A MPR selector neighbor when the agent is in the MPR neighbor list of the `hello` message.

6.1.2 Multipoint Relays (MPRs)

Traditional broadcasting mechanisms as flooding with duplicate control are not suitable in mobile ad hoc networks. They produce unnecessary packet transmissions and waste of bandwidth, a precious resource in a wireless context. OLSR optimizes the broadcasting of its signaling data (link state information) with a mechanism called multipoint relaying.

The idea of a multipoint relay is to avoid transmission redundancies. When a packet must be broadcast in a MANET, it is forwarded by several intermediate nodes to cover all the network. Transmission redundancies are present when a node forwards a broadcast packet when all its neighbors have been already covered by other forwarding nodes. Multipoint relaying avoids redundancies by identifying the forwarding nodes. Each node designates a set of its neighbors to forward its `tc` messages. The designated neighbors are called Multipoint Relays (MPRs). Therefore, a `tc` message from a node is only forwarded to its 2-hop neighbors by its multipoint relays. The other neighbors (those who are not MPR) process the broadcast packet but they never forward it.

Each node in the network must perform two tasks in order to take advantage of multipoint relaying broadcast: the MPR selection and the MPR notification.

In the MPR selection task, the node choses its MPRs among neighbors. Considering only bidirectional links, the multipoint relay neighbor set must cover all the two-hop neighbors. A minimum set is preferable to avoid unnecessary transmissions during the broadcast. Therefore, each node must store information about its neighbors up to two hops far. The previous section has explained how the hello exchange process provides this information. Figure 6.1 illustrates the MPR selection of the central node in the graph. The flooding and the MPR broadcasting mechanism are compared and the forwarding transmission reduction is shown.

Finally, the selected MPR neighbors must be notified by the node. This is performed during the `hello` message exchange. A node sends the list of its MPR neighbors inside its `hello` messages. Based on this, each node maintains a list of the nodes that it serves as MPR. It is called the MPR selector set. When a broadcast message arrives from a neighbor, the MPR selector set is looked up to decide if the message must be forwarded or not.

6.1.3 Topology Control (tc) Message Broadcast

The hello exchange process provides information up to two hops far from the nodes. This information is not enough to route packets to all destinations. The topology information needed to route these packets is obtained via the `tc` message broadcast. Each node includes a set of its local links inside its `tc` messages. Then, the advertised links are broadcast in the entire network taking advantage of MPRs.

Next, as in the `hello` message exchange, the `tc` message creation and the `tc` message processes are analyzed.

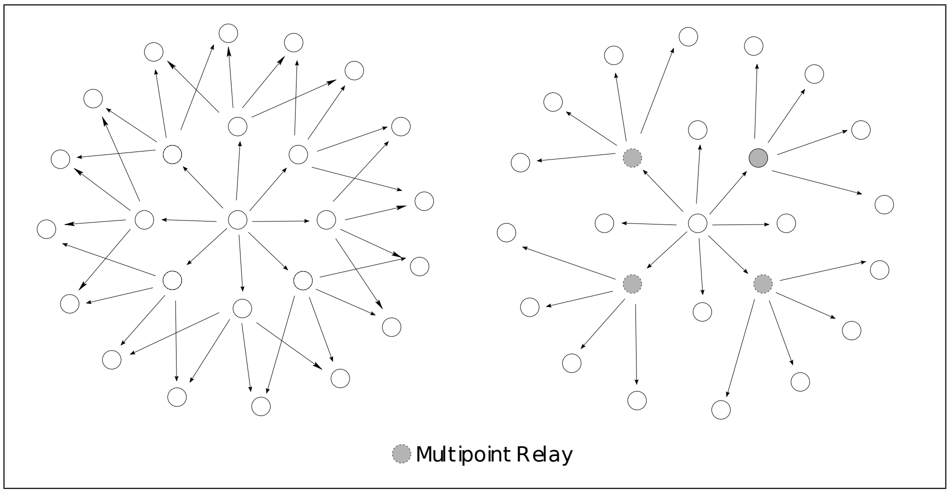

Figure 6.1: Example of Multipoint relay selection

Topology control message creation An OLSR agent sends `tc` messages with a period fixed by the `TC_INTERVAL` parameter, with a default value of five seconds. Traditional link state protocols share the state of all the local links to perform routing. OLSR proposes to send only a set of the local neighbors to save bandwidth. In order to provide sufficient information to enable routing, each node must at least disseminate the links between itself and the nodes in its MPR selector set. This is the default advertised neighbor set, however it can be configured in each node with the `TC_REDUNDANCY` parameter:

- `TC_REDUNDANCY` = 0. The default advertised neighbors, limited to the MPR selector set.
- `TC_REDUNDANCY` = 1. The advertised neighbors are the union of the MPR set and the MPR selector set.
- `TC_REDUNDANCY` = 2. The advertised neighbors are the full neighbor set.

Topology control message processing Nodes receiving a `tc` message obtain information on the network topology: the advertised neighbor set are reachable through the originator of the `tc` message. Each node stores the information of the received `tc` messages in a topology set as tuples *(T_last_addr, T_dest_addr)*. The *T_last_addr* corresponds to the originator of the `tc` message while the *T_dest_address* is the advertised neighbor.

6.1.4 OLSR Repositories

Each node has to store certain information for the operation of OLSR. The main OLSR repositories are:

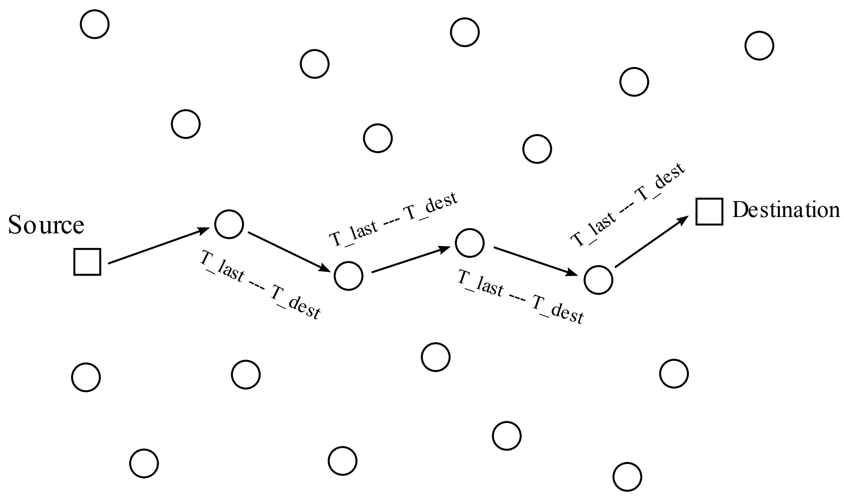

Figure 6.2: Building a route from the topology tuples on the topology set.

Link Set Stores information about links to neighbors. It is populated with the information of the received `hello` messages.

Neighbor Set Stores neighbor tuples to describe neighbors. It is populated via the `hello` message exchange process, when a symmetric link is detected.

2-hop Neighbor Set Stores 2-hop tuples with the address of the 2-hop neighbors and their corresponding direct neighbor.

Multipoint Relay Set Lists the neighbors selected as MPRs. The set is populated when the MPRs are computed using the information stored in the 2-hop neighbor set.

Multipoint Relay Selector Set Stores the neighbors that have selected the node as MPR. It is populated with the information of the received `hello` messages.

Topology Set Stores topology tuples *(T_last_addr, T_dest_addr)* obtained within the `tc` messages. It is used to compute the routing table.

6.1.5 Route Computing

With the information stored in the OLSR repositories, each OLSR agent is able to build a routing table. The routing table points out the next hop for each destination. For destinations that are one and two hops far, the routing table is filled using the neighbor set and the 2-hop neighbor set. Other destinations are known from the shortest routes computed from topology tuples *(T_last_addr, T_dest_addr)* as shown in Figure 6.2.

The routing table is recomputed each time the neighbor, 2-hop neighbor or the topology sets change. The default route computation algorithm is a shortest-path algorithm on the direct graph containing the edges:

- $X \rightarrow Y$, where Y is any symmetric neighbor of node X.
- $Y \rightarrow Z$, where Z is any 2-hop neighbor and Y is the corresponding direct neighbor.
- $U \rightarrow V$, where U is the *T_last_addr* and V is the *T_dest_addr* of any topology tuple of the topology set.

6.2 OLSR-SAT Signaling Broadcasting

The motivation of this thesis is to improve MANET routing performance by taking advantage of a satellite transmission channel to distribute signaling data. The most simple situation is first considered. We assume that all the network nodes have a satellite transmission/reception interface. This is an unrealistic situation however it is a good starting point to obtain baseline results.

The link sense process signaling (`hello` messages) can not be sent through the satellite interface since it is used to discover the links that will be used for data traffic transmission. As the satellite links are used only for signaling purposes, they must not participate to the link sensing process. On the other hand, satellite distribution is a straightforward solution for the links state broadcasting process. Therefore OLSR is modified to send the `tc` messages via the satellite interface, reaching all the nodes of the network in a single hop. The modified protocol is called OLSR-SATellite Broadcasting (OLSR-SAT).

One advantage of using satellite broadcasting is the avoidance of OLSR jitter. The OLSR jitter is a random waiting time generated by OLSR in each node when emitting control messages to avoid unwanted synchronizations hence signaling peaks and packet collisions. It is implemented as a uniform random variable between 0 and `MAX_JITTER`. The default value for `MAX_JITTER` is 250 ms. On the other hand, OLSR-SAT does not delay the `tc` messages before sending since the satellite system has its own multiple access method.

Another advantage is the saved bandwidth. OLSR-SAT removes the `tc` messages from the MANET and introduces it on the satellite segment. Also, this overhead is decreased on the satellite segment since a single transmission of each `tc` message is enough to reach all network nodes.

6.3 OLSR-H Signaling Broadcasting

OLSR-SAT was a first step because it supposes that all the nodes are equipped with a satellite interface. Let us now consider the case when only several nodes have a satellite interface.

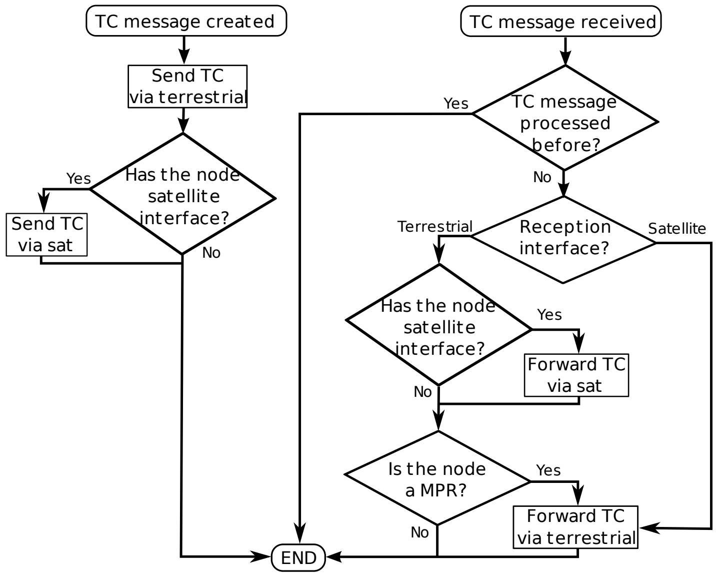

Figure 6.3: OLSR-H broadcasting flow chart.

The `tc` message distribution processes of OLSR and OLSR-SAT are combined to create the OLSR-Hybrid broadcast (OLSR-H). OLSR-H is an enhancement of the OLSR-SAT protocol. It is also equivalent to OLSR for nodes without a satellite interface, so OLSR nodes can be part of an OLSR-H network.

The simplest approach for combining both MPRs and satellite broadcasting is taken. A node originating a broadcast message always sends it via terrestrial wireless and satellite if possible.

When a node receives a broadcast message, it checks if the message was already processed (OLSR duplicate control). If yes, it is discarded. If no and the message was received via satellite, it is always forwarded via the terrestrial link. On the other hand, if it was received via the terrestrial link, it is forwarded through the terrestrial network if the node is a MPR and through the satellite if the node has a satellite interface. Figure 6.3 represents the flow chart of the OLSR-H broadcasting process.

We have remarked that OLSR-H is equivalent to OLSR for nodes without a satellite interface. On the contrary, assuming satellite interfaces in all nodes, the OLSR-H protocol is not equivalent to OLSR-SAT. OLSR-SAT assumes that a satellite broadcast arrives to all the network nodes and never forwards a `tc` message through the wireless interface. On the other hand, OLSR-H is designed to operate in hybrid networks so it will continue sending `tc` messages through the wireless interface, just in case one of neighboring nodes does not have access to the satellite channel.

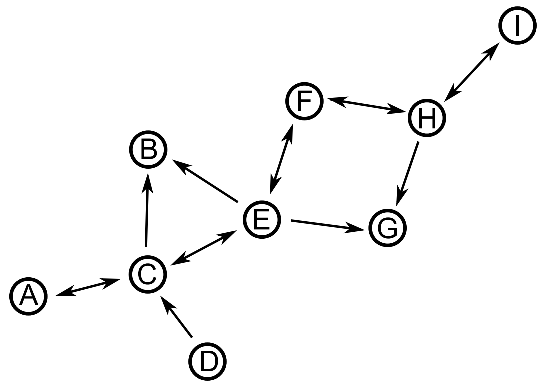

Figure 6.4: Resulting direct graph from the `topology control` messages in a 9 node network.

6.4 EXtended Route computation Algorithm (EXTRA)

EXTRA is a modification of the default OLSR route computation algorithm. It does not involve any changes in the protocol signaling nor in the routing information stored in the nodes. It uses implicit topology information to discover routes not considered by the default algorithm.

The default routing algorithm builds routes up to two hops far according to the local link information obtained through the `hello` message exchange. Then, the information from the broadcast `tc` messages is used to build a topology map of the rest of network. The topology map is a directed graph made from links used in multipoint relay broadcasting. That is, the links from node a to node b, where a is a multipoint relay of the node b. A route with the minimum hop count between any two network nodes can be found in this graph. An example of a directed graph for a network with nine nodes can be found in Figure 6.4.

Sometimes, only one of several possible shortest-routes between two nodes is reflected in the graph. this is due to the MPR optimization. If the information of a link from this route expires, no route to the destination and no alternative route will be present on the directed graph. Figure 6.5 represents that situation based on the previous graph.

However we know that OLSR operates only with bidirectional links. So EXTRA considers an undirected graph in the computation of the routing tables. Therefore some of the alternative shortest-routes will be present and more destinations in the routing table will be available after the route computation. Following the example of the network with nine nodes, Figure 6.6 shows one of these alternative routes.

This proposed change has a drawback. The EXTRA route computation does not take into account the willingness of the nodes. Each node has a parameter denoting the node's willingness to be a MPR, hence to participate in the sig-

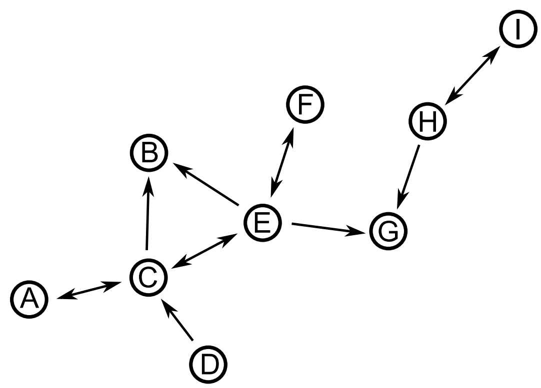

Figure 6.5: The expiration of the F-H link information in nodes A, B, C or D yields a route outage to H and I.

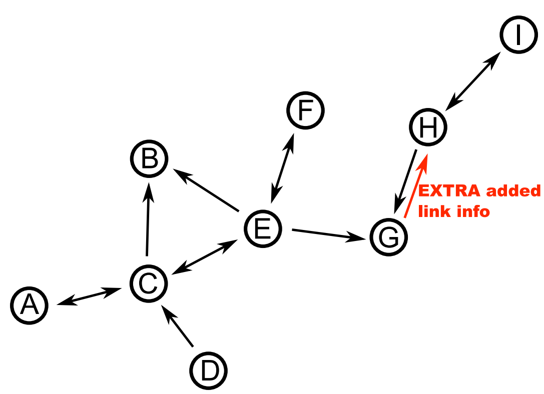

Figure 6.6: The EXTRA computation discover an alternate route to H and I through the H-G link because it knows it is bidirectional.

naling broadcast and the forwarding of data packets. This is specially useful for nodes with energy constraints.

EXTRA could select an alternative route with a non-MPR node in it. Then, a node with a willingness set to never, will not participate in the signaling broadcast but could participate to forwarding of data traffic. On the other hand, the algorithm is designed to only use these routes when the default routes are not available anymore.

The routes obtained with the EXTRA algorithm are similar to those obtained with the default algorithm if the redundancy of `tc` messages is set to 1 (`TC_REDUNDANCY` = 1). However, in this case, the advertised neighbor set contains not only the MPR selector set but also the MPR set of the `tc` message source node. The EXTRA modification does not require to explicitly broadcast any additional information in the `tc` messages, because it assumes that bidirectional links are considered between OLSR neighbors.

Summary

This chapter presented the optimized link state routing protocol. The link sensing, link state broadcasting and the route computation tasks are analyzed. Then, three modifications of the OLSR protocol are introduced: OLSR-SAT, OLSR-H and EXTRA. OLSR-SAT and OLSR-H are modifications of the link state broadcasting task so to use satellites.

OLSR-SAT uses solely satellites for the distribution of `tc` messages, so satellite equipment is needed by all the nodes. On the other hand, OLSR-H distributes `tc` messages over satellite but also using the multipoint relay mechanism of OLSR. Doing so, nodes without satellite interfaces can obtain the topology information needed to build routing tables.

Finally, the OLSR default route computation algorithm is modified to discover alternate routes. The proposed EXTRA computation algorithm can be used in OLSR, OLSR-SAT and OLSR-H.

Chapter 7

Simulation Results

The performance of OLSR, OLSR-SAT and OLSR-H has been measured in both the generic and the specific scenarios. However, some considerations must be taken when analyzing the simulation results. Section 7.1 presents the techniques that are used to ensure the validity of the simulation results.

Section 7.2 presents the performance results of the protocols. It starts comparing the data traffic delivery ratio of the routing protocols in each scenario. Then, the results are analyzed with a detailed study of the transmission errors. Also, the size of the routing tables are investigated. The main differences among the routing protocols are then highlighted with a study of their signaling, specially the `tc` message broadcasting system. The delay and the delivery of the `tc` messages in OLSR, OLSR-SAT and OLSR-H are exposed.

Finally Section 7.2.7 shows the differences on data delivery ratio between the default route computation algorithm and the EXTRA algorithm.

7.1 Output Analysis Techniques

With simulations, random variables are used to characterize the behavior of the system. The output of the simulation are thus realizations of random variables so, output analysis techniques should be performed to obtain concluding values. The duration of the simulation, the length of the transient state whose samples must be discarded and the number of simulation replications must be correctly set. The techniques used to obtain the topology metrics of the scenarios are explained in the following section.

Transient State The initial conditions of the model impacts the sequence of states that drives the simulation behavior. Generally, the simulation objective is to measure the properties of the system in steady state. For that purpose, a transient duration is determined. The simulation begins data collection after this transient duration, discarding all samples obtained so far. However, the determination of a valid transient time is not immediate. Abate and Whitt[65]

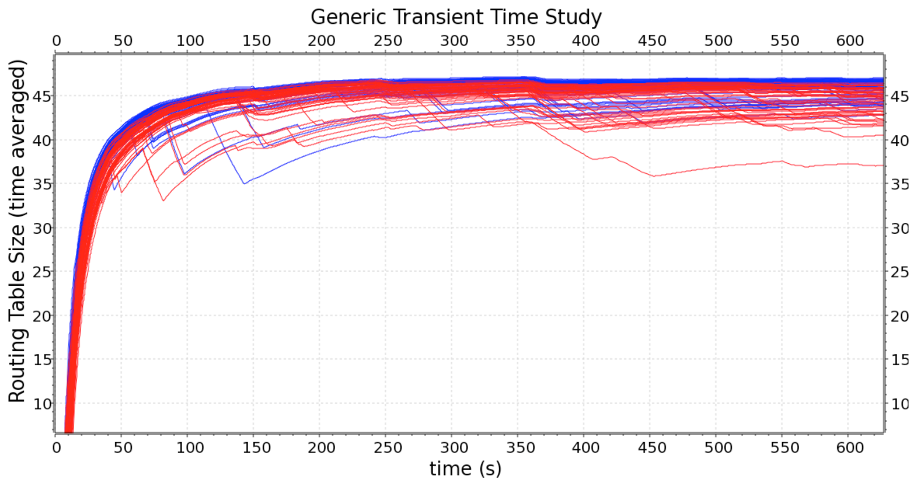

Figure 7.1: Average routing table size throughout time for the generic scenario.

provided an expression for the required time to reach the steady state of a M/M/1 queue system. But an analytical determination of the transient duration for more complex systems is not tractable. Consequently an inspection of the system properties throughout the time must be performed to identify a reasonable transient duration.

In our particular case we considered the routing table size of the network nodes as a good indicator of the transient duration. The routing tables are empty when the simulation starts. Then, the OLSR nodes start sensing the link states and distributing the information. New destinations are added to the routing tables when receiving link state information. So we consider the transient state is over when the routing table size is stabilized. Figure 7.1 shows the average size of the routing tables of all network nodes throughout time. A rapid increase of the routing table sizes is witnessed in the first 50 seconds of simulation when OLSR starts filling them and then the table contents are stabilized. At the light of this chart, a transient duration of 300 seconds is determined. The same method is applied for the determination of the transient duration in the specific scenario. A value of 500 seconds is derived from the Figure 7.2.

Useful information can be extracted from the transient state even from a qualitative point of view. It is interesting to know the behavior of the routing protocol when it starts to operate. For example, a common MANET scenario is the emergency situation. In that context, it is crucial to provide an operative network as soon as possible. The simulation transient state provides information of how fast the network is full-operative. In this work, the samples obtained during the transient state are not discarded but computed independently of the steady state samples.

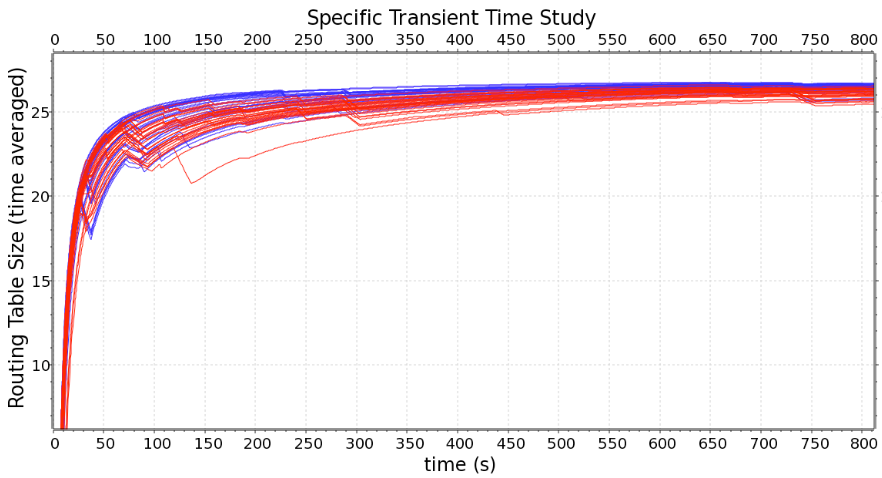

Figure 7.2: Average routing table size throughout time for the specific.

Replication To estimate performance, metrics are sampled during the execution of the model and the mean of the observations is calculated at the end of the run. Under general assumptions (ergodic process and wide-sense stationarity), this computed mean will converge to the performance criterion when the duration tends to infinity. Unfortunately, simulation duration is finite. It is thus necessary to estimate the accuracy of the results. Three methods are proposed: independent replication, batch means and regeneration.

If independent replication is used, the model is run m times in order to obtain m independent observations. The seed of the random number generator must be chosen to ensure independent runs.

The batch means method requires only one simulation run. A large period is simulated and divided in sub-periods of a fixed length. The mean of the observations in each period is computed. The period length should be long enough to consider that averages computed during each period are independent.

The regeneration method identifies instants when the system is regenerated. An example of regeneration point in the simulation of a queue system is the state when a queue becomes empty. The periods between regeneration points are considered independent.

Here, the independent replication method is used because of its simplicity. Also the run independence allows parallel simulations of several runs, taking advantage of the multi-core architectures of current computers. Finally, unlike the batch mean method where there is a single realization of the transient state, we simulate several transient states (one per replication) and therefore more detailed results are gathered for the transient study.

The *Law of the Large Numbers* method is applied to each independent replication. The confidence interval of the estimation is calculated for a level of confidence of 95% (the probability of the real value to be in the confidence

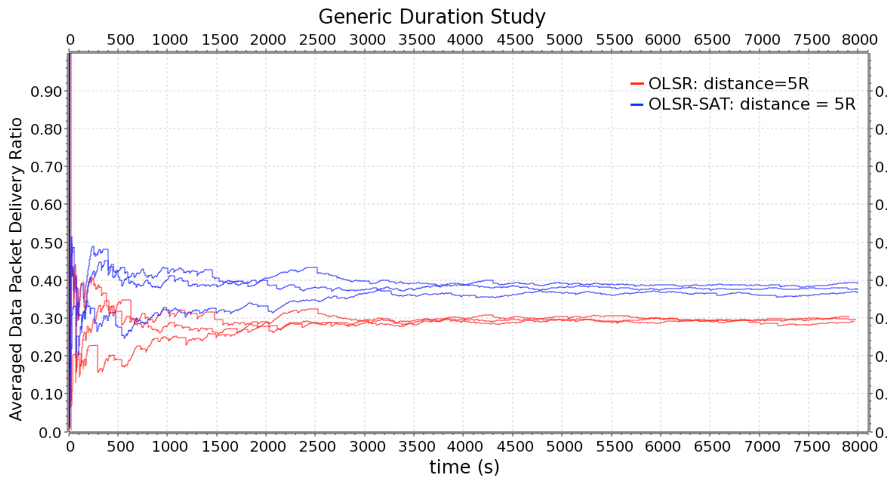

Figure 7.3: Generic Scenario: evolution of the average data delivery ratio for three simulation runs with a source-destination distance of 5 times the radio range.

interval). The formula used is:

$$\epsilon = 2\sqrt{\sigma^2(Z_T)}\frac{1}{\sqrt{n}}$$

Where ϵ is the confidence interval, Z_T is an estimation of the performance metric Z, $\sigma^2(Z_T)$ is estimated using the empirical variance and n is the number of simulation runs. It is inferred from the formula that an increase of the number of simulations produces smaller confidence intervals. A value of $n = 20$ runs is considered in our simulations.

Duration The simulation output is usually a collection of samples of the system parameters to study. Then the samples are averaged to obtain a representative value of the performance indicators. However there is a risk to obtain non representative results if the number of samples is not large enough. The duration of the simulation must be sufficiently long to obtain the samples needed to arrive to representative values.

As in the determination of the transient duration, an inspection of the evolution of the studied parameters throughout the time is performed to obtain a reasonable duration for the simulations. Figure 7.3 shows the evolution of the data delivery ratio in the generic scenario with a distance between source and destination of 5 times the radio range. Three different simulation runs are represented in order to compare the outputs based on different random variable seeds. The data delivery ratio stabilizes around 3000 seconds of simulation. A security margin is considered and a total duration of 5000 seconds is determined.

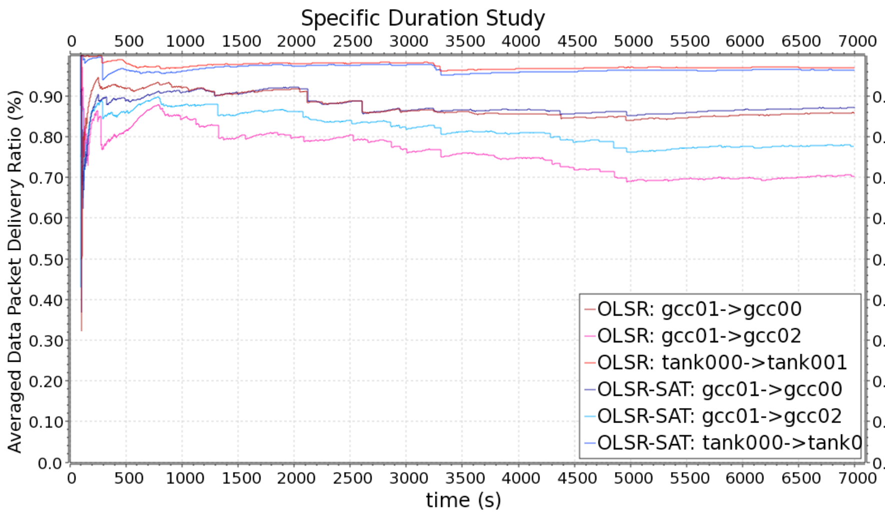

Figure 7.4: Specific Scenario: evolution of OLSR and OLSR-SAT average data delivery ratio.

Figure 7.4 addresses the specific scenario. A single run is represented with the average data delivery ratio for the three data streams. The ratio stabilizes around 5000 seconds. A simulation duration of 6000 seconds is chosen for the specific scenario.

7.2 Simulation Results

The most remarkable results are presented next.

First we present the topology properties of the simulation scenarios in Section 7.2.1. The performance of OLSR, OLSR-SAT and OLSR-H are measured using the data delivery ratio as metric in Section 7.2.2. Then, a deeper analysis of the transmission errors is carried out in Section 7.2.3. The properties of the routing tables of the protocols are inspected in Section 7.2.4. Finally, the routing signaling of the protocols is examined and the differences are highlighted in Section 7.2.5.

Each of the conducted studies are divided in two parts: the results of the generic scenarios and the results of the specific scenario. Some considerations about the scenarios must be taken into account when analyzing the results.

Generic Scenarios They are composed of 48 mobile nodes following the random waypoint model plus 2 static nodes. There are five generic scenarios, varying the distance between the two fixed nodes that are the source and destination of the data traffic. These scenarios are used to compare OLSR and OLSR-SAT protocols. OLSR-H is not used since it is discussable to operate a random

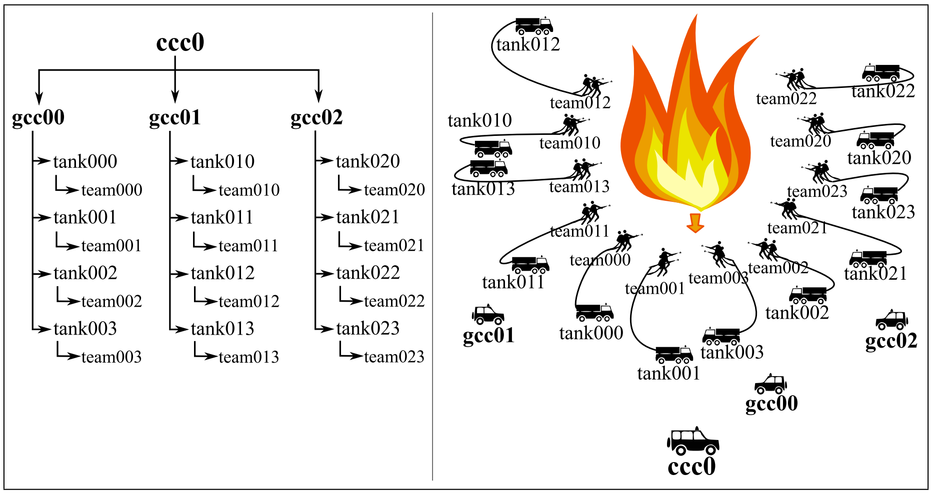

Figure 7.5: Specific Scenario: Firemen hierarchy and example of firemobility deployment.

election of nodes with satellite capabilities. OLSR-H should be evaluated in a scenario closer to the reality.

Specific Scenario The specific scenario is used to evaluate the routing protocols in an actual mobile ad hoc network. It is composed of a firemen column of 28 units: a column command car (ccc), 3 group command cars (gcc), 12 water tanker trucks (tank) and a 12 firefighter teams (team). Figure 7.5 represents the firemen hierarchy and an example of network topology. Several configurations of units with satellite capabilities have been proposed (see Section 5.3.3), so the specific scenario is also used to evaluate the OLSR-H protocol.

7.2.1 Topology Measurements

Before studying the routing protocol performance, an analysis of their topology properties is carried out with the metrics presented in Chapter 3. Table 7.1 summarizes the simulation results to obtain the topology metrics of the generic and specific scenarios. The specific route metrics between the data source and destination nodes are also included in Table 7.2.

The main interest of these measures is not the values themselves but the differences among the proposed scenarios. That will help us to analyze the impact of each property on the routing protocol performance.

The recommendation proposed by [40] for the average partitioning ($< 5\%$) is fulfilled for both generic and specific scenarios.

Regarding the length of the routes, we identify the generic scenarios with a distance between source and destination of 4 and 5 times the radio range (R) as the most suitable for the routing protocol performance evaluation (> 5 hops).

Metric		**Generic Scenario**	**Specific Scenario**
Partitioning	Average	5%	4%
	Std. Dev. (time)	6%	12%
Number of Neighbors	Average	7.5	5.5
	Std. Dev. (nodes)	3.7	2
Shortest-Path Hop Count	Average	3	3
	Std. Dev. (nodes)	1.5	1.6
Link Lifetime	Average	27 s	180 s
	Std. Dev. (links)	30 s	400 s

Table 7.1: General topology metric comparison between the generic and the specific scenarios.

	SRHC		**Route Lifetime**	
Source/destination	Average	Std. Dev.(time)	Average	Std. Dev.(routes)
1R	1	0	Inf	-
2R	3.1	0.3	7.6 s	7.3 s
3R	4.3	0.5	3.8 s	4.2 s
4R	5.7	0.7	2.7 s	3 s
5R	7.2	0.7	2 s	2.3 s
tank000-tank001	1.7	0.8	84 s	118 s
gcc02-gcc00	4.4	1.4	18 s	26 s
gcc01-gcc02	6.8	1.1	13 s	20 s

Table 7.2: Route specific topology metrics of the data stream node pairs for the generic (1R, 2R, 3R, 4R and 5R) and the specific (tank000-tank001, gcc02-gcc00 and gcc01-gcc02) scenarios.

In the case of the specific scenario, the most demanding data stream for the routing protocol is between the *gcc01* and the *gcc02* nodes (> 6 hops).

The main difference between the specific and the generic scenarios is the link lifetime. We could think that the high mobility of the firemen nodes ($0.2R$ m/s) compared to the generic nodes ($0.05R$ m/s) leads to lower link lifetimes. However, the hierarchical group motion of fire mobility produces a low relative speed among nodes. Therefore the specific scenario presents more stable links than the generic scenario. Also it shows larger link lifetime variations between the links among different groups and the links among nodes of the same group (which explains the large link lifetime standard deviation). Therefore, it is expected that the generic scenarios will be more demanding for the routing protocols, yielding lower performance.

7.2.2 Performance Measurements

There are several metrics to assess the performance of routing protocols. We decide to use the data delivery ratio. One data stream per generic scenario is configured between two fixed nodes and the distance between them is varied. The same analysis is performed in the specific scenario, with three data streams representing a short distance communication between two tankers (tank000 and tank001), a medium distance communication between two command cars of close intervention groups (gcc02 and gcc00) and a long distance communication between the command cars of the farthest intervention groups of the column (gcc01 and gcc02).

Generic Scenarios Figure 7.6 represents the data delivery ratio achieved with OLSR and OLSR-SAT with diverse distances between source and destination. A general decrease in the delivery can be noticed with an increase of the distance. As the distance between the source and destination increases, data should go through more hops and therefore the probability of errors (collisions, bit errors) increases.

However the impairment of delivery ratio in OLSR-SAT is weaker than in OLSR. OLSR-SAT outperforms OLSR by almost 10% when the distance between the source and the destination is five times the radio range.

Specific Scenario There are three data streams in the specific scenario: between two tankers of the same group (tank000 and tank001), two adjoining groups (gcc02 and gcc00) and two distant groups (gcc01 and gcc02).

The length of the routes computed by OLSR, OLSR-SAT and OLSR-H is represented in Figure 7.7. There are no difference between the protocols in this aspect; they build up routes with similar number of hops, so they display similar data delay. But as it was already noticed in the generic scenario, the data delivery ratio is improved with OLSR-SAT and OLSR-H. Figure 7.8 confirms the conclusions of the generic scenarios: OLSR-SAT outperforms OLSR ratio for long routes.

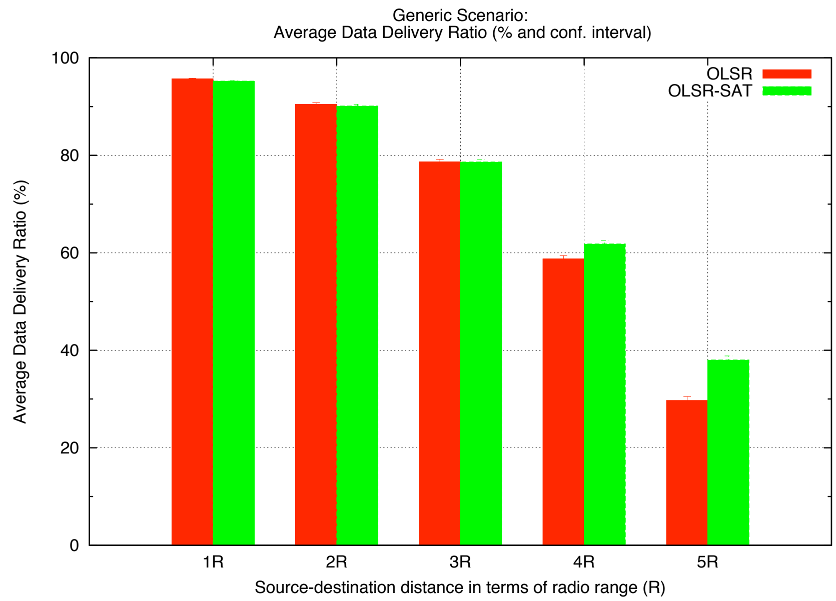

Figure 7.6: Comparison of OLSR and OLSR-SAT data delivery ratio in the generic scenarios.

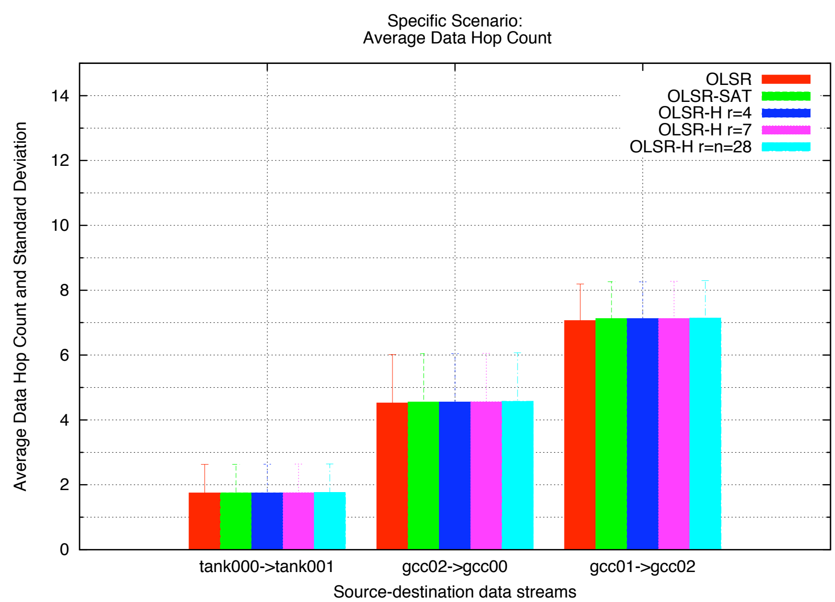

Figure 7.7: Average data hop count and standard deviation for OLSR, OLSR-SAT and OLSR-H (with four, seven and all nodes with satellite interfaces) in a forest fire operation scenario.

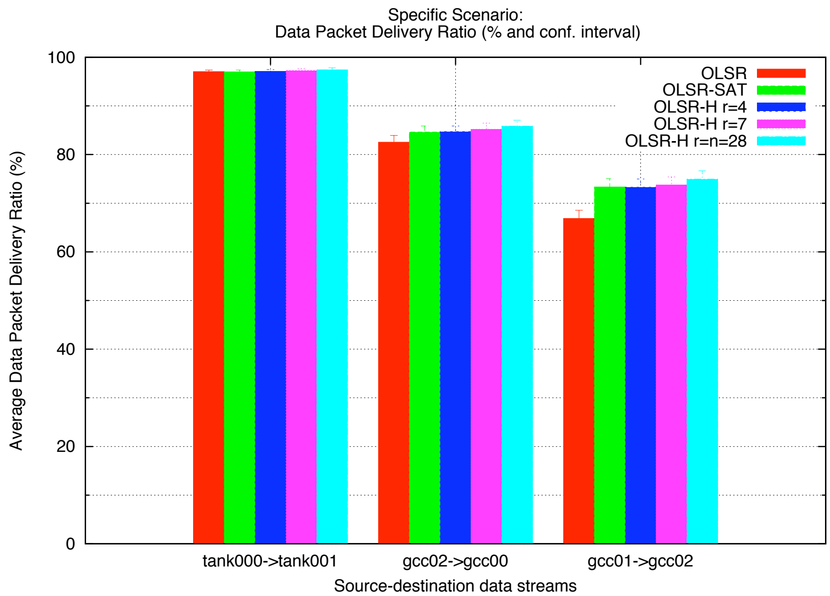

Figure 7.8: Data delivery ratio comparison of OLSR, OLSR-SAT and OLSR-H (four, seven and all nodes with satellite interfaces) in a forest fire operation scenario.

OLSR-H achieves a data delivery improvement similar to OLSR-SAT (more than 6%) but using four nodes with satellite capabilities (r=4) instead of all nodes as with OLSR-SAT. A slight increase of delivery ratio can be observed in the case of OLSR-H when all nodes have satellite capabilities.

The impact of the mobility model on the routing protocol performance can be noticed on the data delivery results. The firemobility model of the specific scenario organizes the nodes into groups, moving them together. That leads to more stable routes and therefore to a higher data delivery ratio higher than with the random waypoint mobility model of the generic scenarios. This is specially remarkable in the case of long routes (ca. 7 hops): we obtain 40% of data delivery in the generic scenario while the value tops to 70% in the specific scenario.

7.2.3 Transmissions Error Measurements

The first step to understand the previous results is to investigate the reasons for errors in the data delivery. These errors have different scopes: end-to-end and link layer level.

Generic Scenarios Figure 7.9 presents the percentage of data packets delivered and the percentage of packets that do not arrive to the destination because

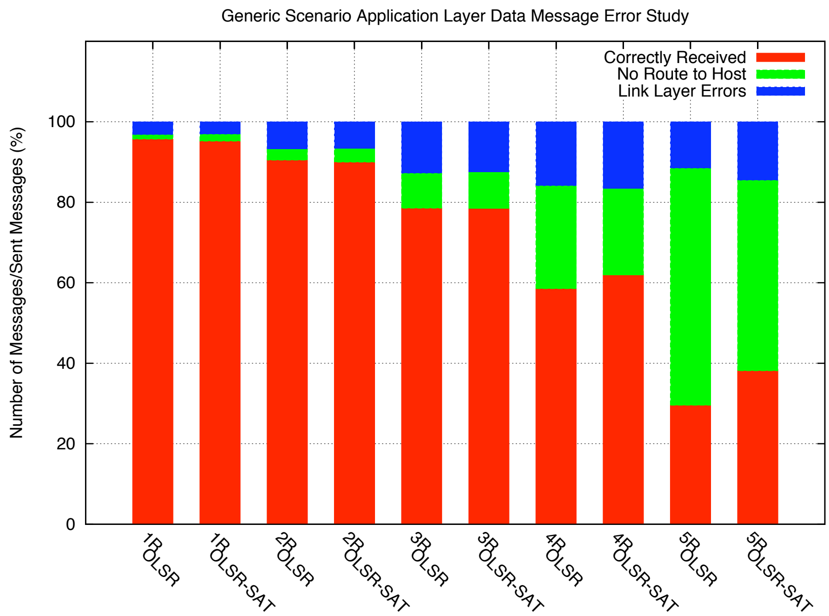

Figure 7.9: Data packet transmission results in the generic scenarios.

of a *no route to host* error: data packet can not be forwarded because the destination is not present in the routing table of some of the intermediate nodes. As expected, these errors increase with the number of hops between the source and destination. However we can observe a decrease of the OLSR-SAT *no route to host* errors compared with OLSR. Figure 7.10 shows the behavior of data frames at the link layer level. No difference between OLSR and OLSR-SAT can be noticed. So, from both graphs we conclude that the improvement of OLSR-SAT is due to a decrease in the *no route to host* errors, in other words, the routing tables of OLSR-SAT are more complete.

Specific Scenario The packets of the three data streams of the specific scenario are analyzed in Figure 7.11. As in the generic case, the increase of data delivery ratio is associated with a decrease of the *no route to host* errors. The difference is less significant that in the generic case because the data packets are analyzed together regardless of the number of hops they should go through. Figure 7.12 shows the results of the data frame transmissions. As in the generic case, OLSR-SAT and OLSR-H do not present differences at the link layer level. OLSR-SAT and OLSR-H improve data delivery ratio because the routing table of the nodes displays less gaps.

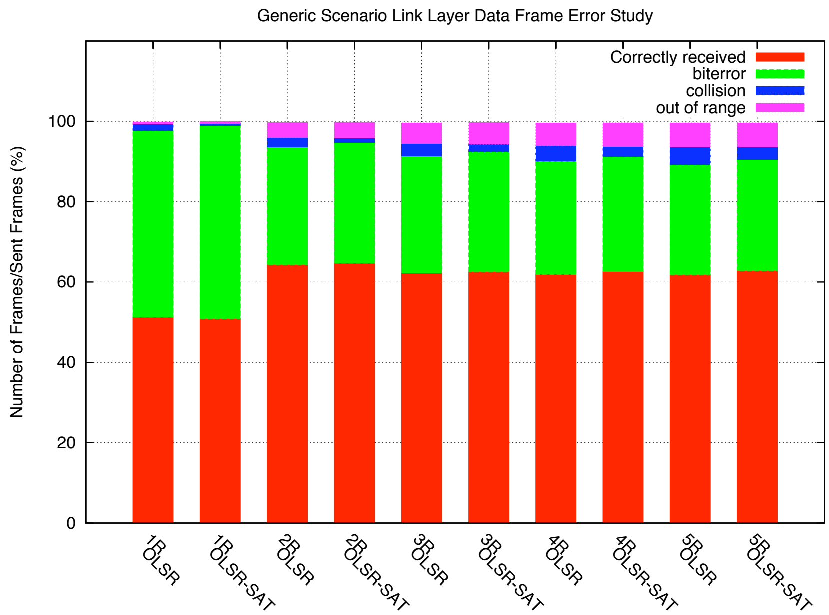

Figure 7.10: Data frame transmission results in the generic scenarios .

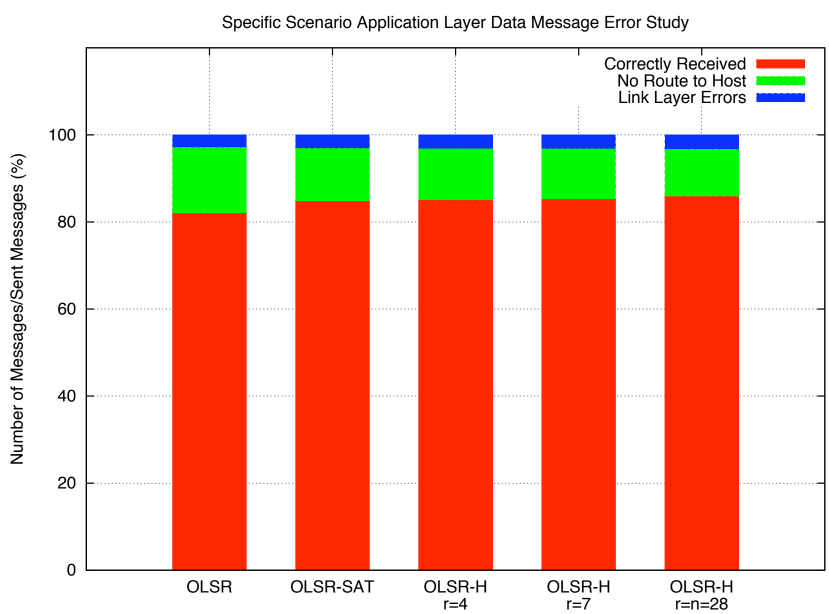

Figure 7.11: Data packet transmission results in the specific scenario.

Figure 7.12: Data frame transmission results in the specific scenarios.

7.2.4 Routing Table Measurements

The previous section concludes that the improvement brought by OLSR-SAT and OLSR-H is due to the fact that routing tables are more complete. This assumption is verified in this section by inspecting the average and standard deviation of the size of routing tables.

Generic Scenario Figure 7.13 represents the average and standard deviation of the size of routing tables in the generic scenario. The OLSR-SAT routing tables store only one destination more in average than OLSR. However the additional destinations that OLSR-SAT offers in its routing tables are usually far away nodes. This is the main reason why OLSR-SAT behaves better in the forwarding of data packets when the distance between source and destinations is several hops. Also, as it was indicated before, long routes increase the probability that some of the intermediary nodes do not include the destination in their routing table when OLSR is used.

Specific Scenario Like in the generic scenarios, Figure 7.14 displays larger routing tables when running OLSR-SAT and OLSR-H in the specific scenario. Although there is a slight difference among the protocols, the impact is significant on the forwarding of data packets, specially to distant destinations as mentioned in the case of the generic scenario.

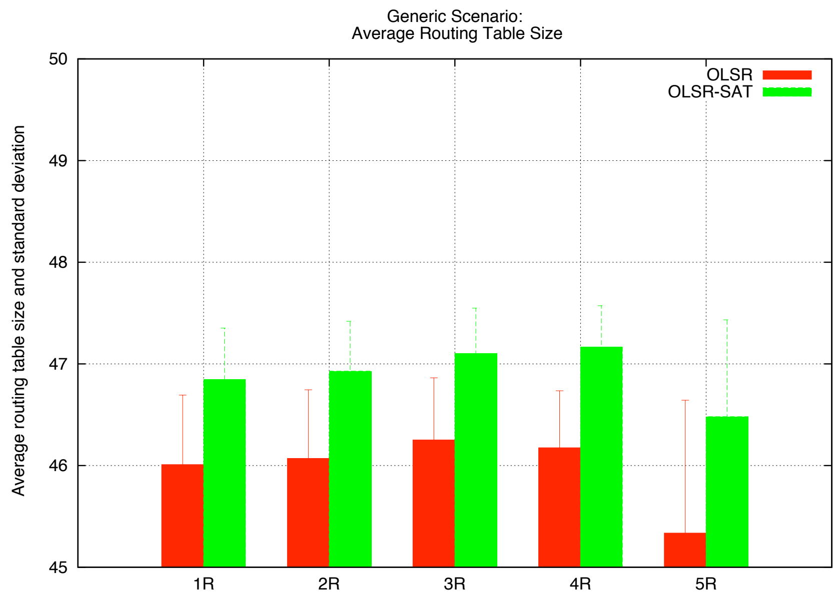

Figure 7.13: Average and standard deviation of the routing table size in the generic scenarios.

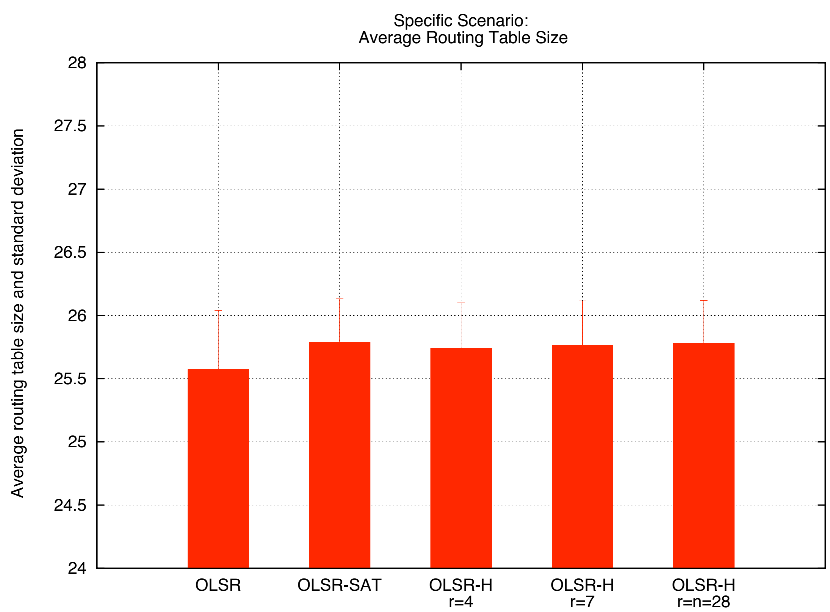

Figure 7.14: Average and standard deviation of the routing table size in the specific scenario.

7.2.5 Signaling Measurements

To understand the previous differences on the routing tables of OLSR, OLSR-SAT and OLSR-H, the signaling traffic of the protocols is analyzed. A general view of the signaling is offered with a study of the overhead due to the `hello` and the `topology control` (`tc`) messages. Then, we focus on the `tc` message broadcast mechanism properties since it is the distinctive point among the protocols.

Signaling Overhead

Generic Scenarios Figure 7.15 shows the `hello` and the `tc` message data rate for the OLSR and OLSR-SAT protocols in the generic scenarios. We notice no difference among the generic scenarios because the only difference among them is the position of the fixed source and destination nodes. The significant difference appears in the `tc` message rate between OLSR and OLSR-SAT. A `tc` message arrives to all network nodes with a single transmission using OLSR-SAT. On the other hand, OLSR should transmit several copies of the `tc` message to cover all network nodes in a multi-hop way. That is the reason of the reduction of the `tc` message rate in OLSR-SAT (ca. 20 times).

Specific Scenario The signaling of OLSR, OLSR-SAT and OLSR-H in the specific scenario is compared in Figure 7.16. The `tc` messages transmitted through the satellite (blue) are differentiated from the `tc` messages transmitted through the wireless LAN (green). OLSR-SAT results are similar to the generic scenarios. We now focus on OLSR-H results. The `tc` message rate in the wireless LAN is larger than in OLSR. This is caused by the multipoint relay mechanism of OLSR which is altered by the inclusion of an external factor, the nodes with a satellite interface. A node receiving a `tc` message through the satellite will always retransmit the message. Therefore, an increase of the WLAN `tc` message overhead happens as the number of nodes with satellite interfaces increases.

Topology Control Message Travel Delay

Each `tc` message should go through several hops when broadcasting in OLSR. The jitter introduced in each hop to avoid collisions produces high `tc` travel delays in the nodes that are far away from the source of the `tc` message. Using satellite transmissions decreases the number of hops needed to broadcast the `tc` messages and therefore their `tc` travel delay.

Generic Scenarios Figure 7.17 presents the travel delay of the `tc` messages at destination. The only contribution to the travel delay in OLSR-SAT is the satellite transmission delay of 250 milliseconds. On the other hand, OLSR presents a variable travel delay because of the variable number of hops the `tc` message must go through. Therefore, a node has more topical information about the topology of far nodes using OLSR-SAT and it contributes to better routing decisions.

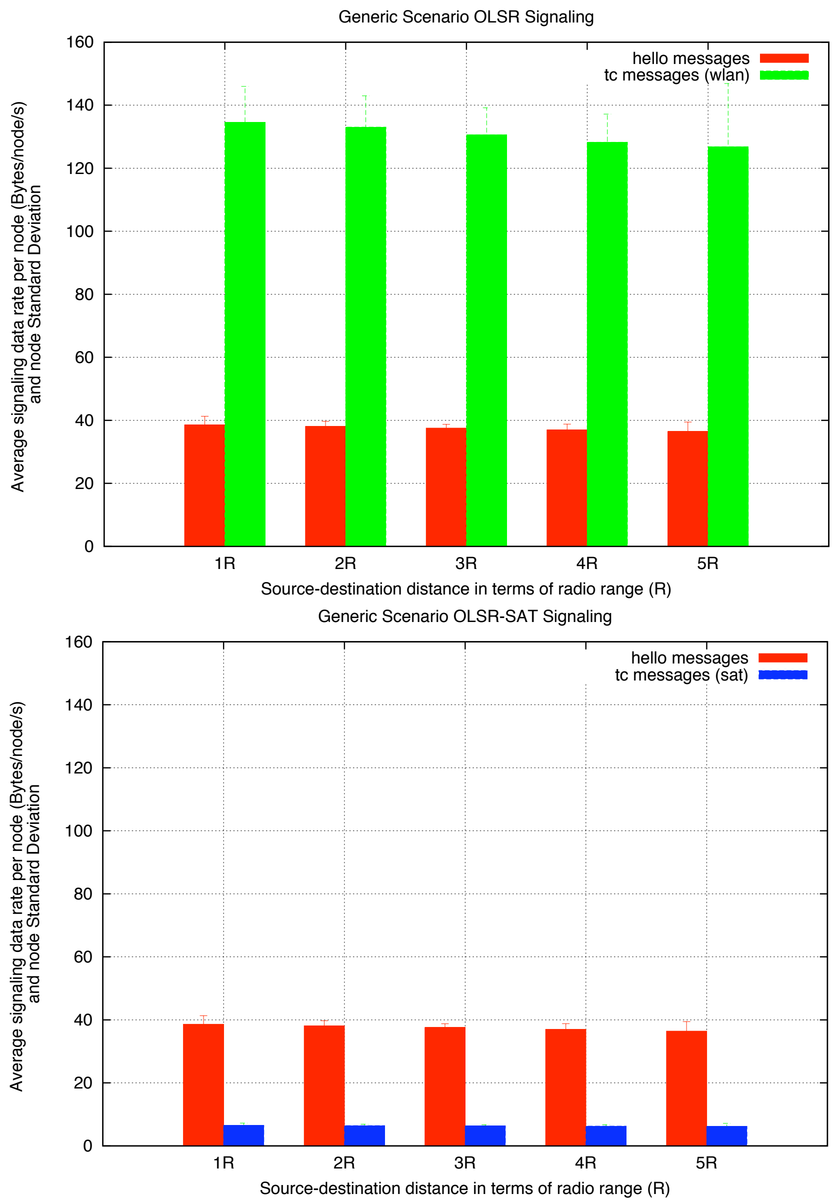

Figure 7.15: OLSR and OLSR-SAT signaling overhead in the generic scenarios.

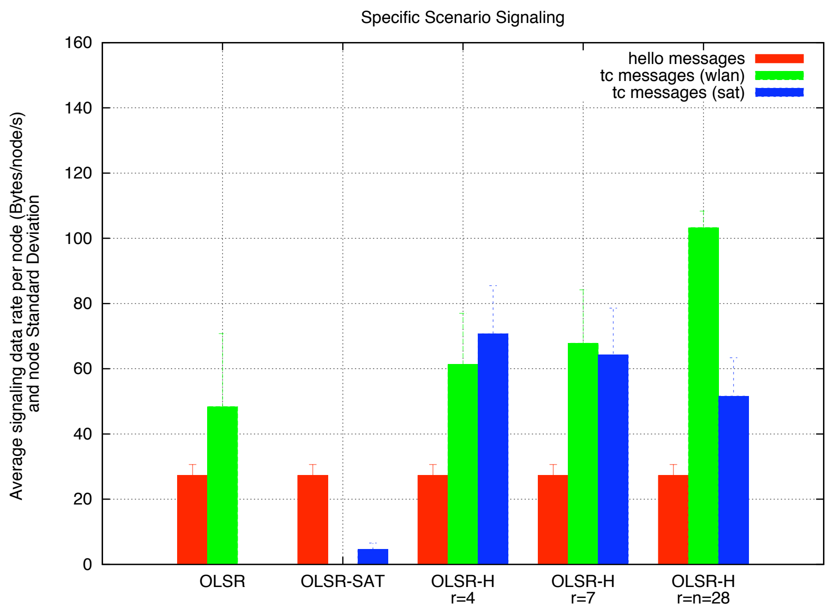

Figure 7.16: Comparison of the overhead of OLSR, OLSR-SAT and OLSR-H in the specific scenario.

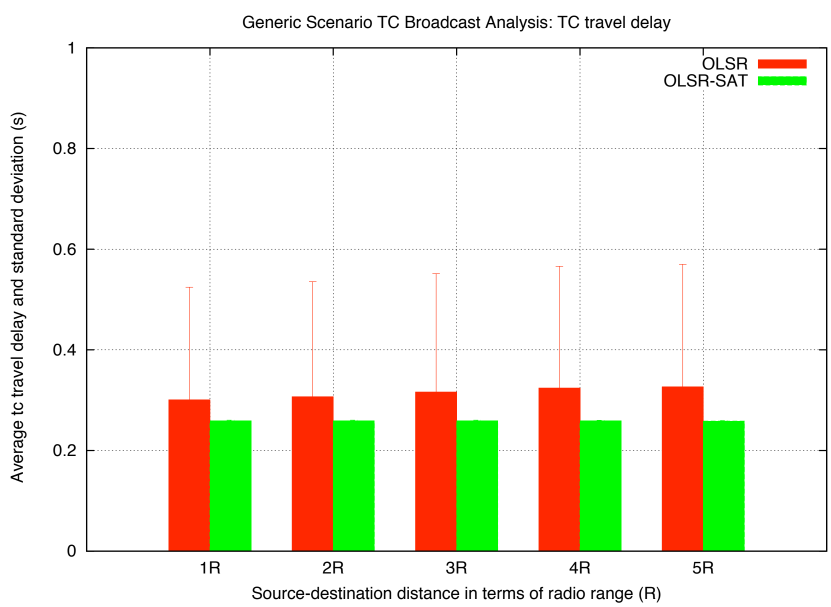

Figure 7.17: Average and standard deviation of the travel delay of the `tc` messages with OLSR and OLSR-SAT in the generic scenarios.

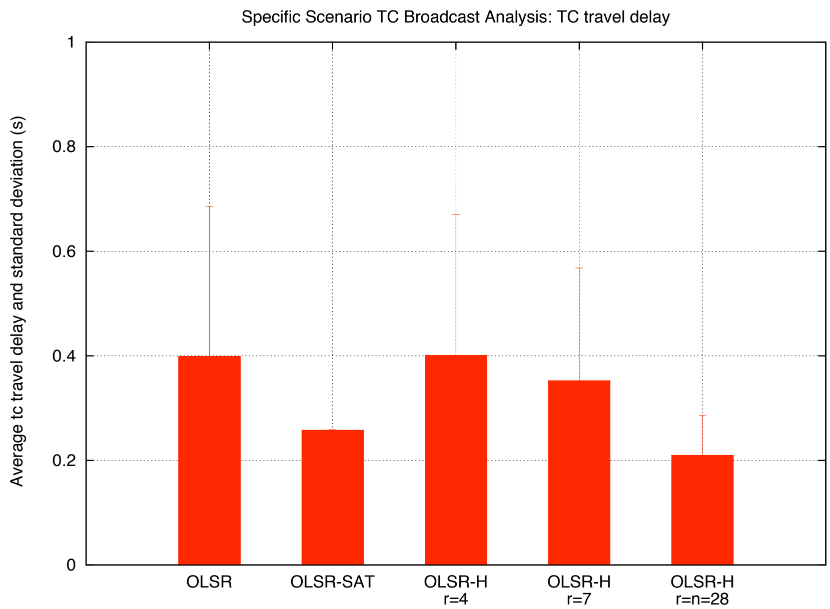

Figure 7.18: Comparison of the Average and standard deviation of the travel delay of the `tc` messages of OLSR, OLSR-SAT and OLSR-H in the specific scenario.

Specific Scenario The travel delay of `tc` messages for the specific scenario is analyzed in Figure 7.18. As in OLSR-SAT, an optimal `tc` travel delay is obtained when all the nodes have a satellite interface. Moreover, the travel delay is lower than in OLSR-SAT because it also take advantage of the short terrestrial travel delay for nodes that are close. However, when we decrease the number of nodes with a satellite interface (r=4 and r=7), the satellite contribution to the travel delay is not as significant as in the case of all nodes with satellite interface (r=n=28). Figure 7.19 presents a detailed view of the improvements in data delivery ratio obtained with OLSR-H. We notice similar values of data delivery ratio using 4, 7 or all nodes with a satellite interface. There must be another reason apart from the `tc` travel delay that impacts the quality of routing decisions.

Topology Control Message Delivery

We have the confirmation that the decrease of the `tc` message travel delay is not the only reason of the data delivery ratio improvement. The delivery ratio of `tc` messages should also be considered in order to analyze its impact on the data delivery ratio.

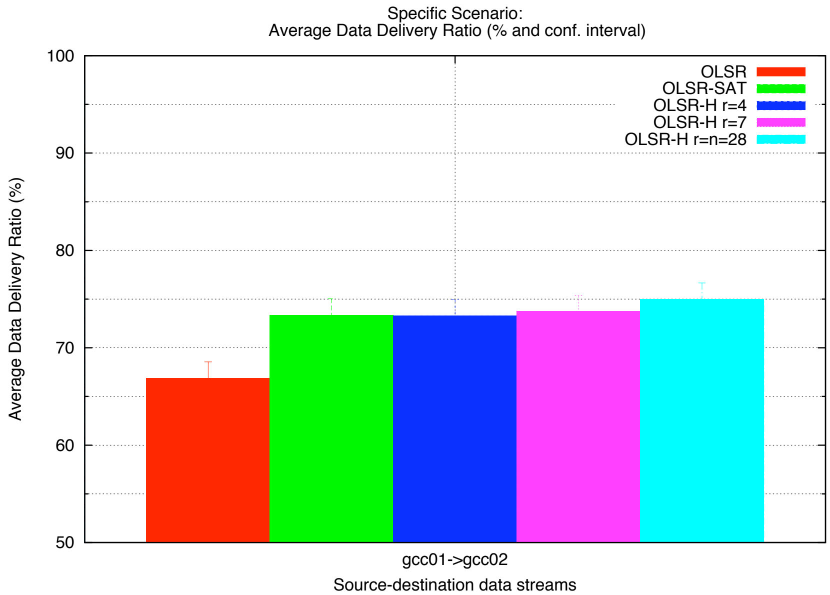

Figure 7.19: Detail of the data delivery ratio in the specific scenario with OLSR, OLSR-SAT and OLSR-H using different number of satellite terminals.

Generic Scenarios The `tc` message delivery is shown in Figure 7.20. The `tc` messages arrive to all network nodes with the OLSR-SAT broadcast mechanism achieving 100% delivery. No bit errors are considered in the satellite transmissions since advanced forward error correction techniques are generally applied. On the other hand, the broadcast mechanism in OLSR is impacted by the constraints of the wireless medium as was already seen in Section 7.2.3 for data packets, the `tc` messages are exposed to collisions and bit errors. Therefore, not all the nodes are reached when broadcasting a `tc` message over the WLAN interface. In average, 80% of the nodes receive a broadcast `tc` message. As a result, the use of satellite transmission in the broadcasting of `tc` messages has two impacts: the average travel delay of the `tc` messages is decreased and more nodes are reached at each broadcast. Therefore, OLSR-SAT has more and up-to-date information about the network topology which in turn yields more complete routing tables and better data delivery ratio.

Specific Scenario Figure 7.21 represents the delivery ratio of the `tc` messages for the specific scenario. We notice that the inclusion of 4 nodes with satellite interfaces gives an increase of the `tc` delivery ratio from the 83% of OLSR to the 96% of OLSR-H (r=4). The improvement of OLSR-H tops to 100% when all the nodes present a satellite interface (r=n=28). We can conclude that the main reason of the improvement of OLSR-SAT and OLSR-H is the increase in the delivery ratio of the `topology control` messages. Also, the decrease of

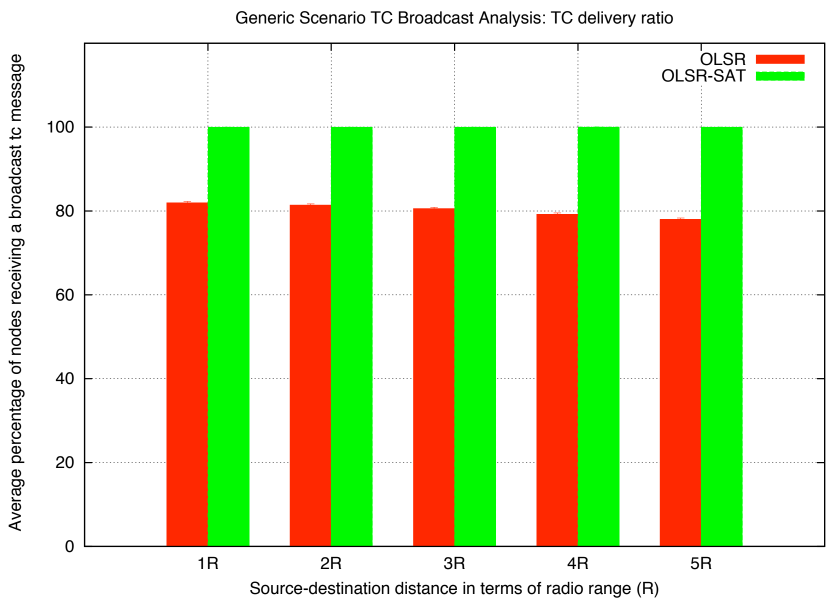

Figure 7.20: Comparison of the average percentage of nodes receiving a broadcast `tc` message using OLSR and OLSR-SAT broadcasting methods in the generic scenarios.

the travel delay of these messages contributes to improving the data delivery ratio which explains the slight improvement of OLSR-H (r=n=28) compared to OLSR-SAT.

7.2.6 Transient Study

The measures achieved during the transient time are not taken into account in the results presented so far. An analysis of the transient phase is performed in this section. The time required for the network to be operative is interesting.

Getting representative values of the transient period is a complex task. While the simulation of the steady state can be extended to get more samples and therefore more representative measures, the duration of the transient period is limited and the results are uncertain with the known impact on the analysis.

The evolution of the data delivery ratio for both scenarios is examined to determine the time each protocol needs to start forwarding data packets. Then the differences among the protocols are highlighted.

Generic Scenario The moment where the transient period finishes and the steady state begins can not be accurately determined, a conservative approach is used and longer transient time are considered. In such a way, we can ensure that no significant transient contribution in the steady state analysis. Conversely, we

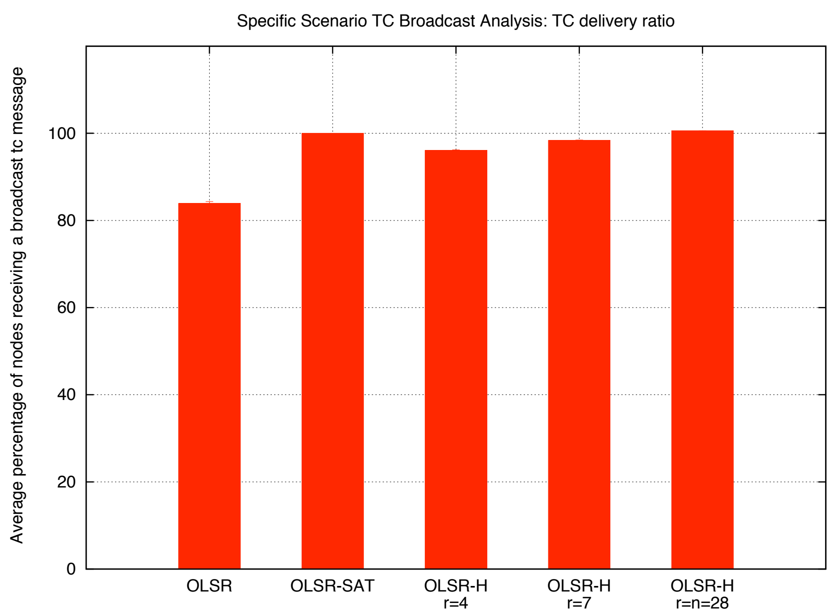

Figure 7.21: Comparison of the average percentage of nodes receiving a broadcast `tc` message using OLSR,OLSR-SAT and OLSR-H broadcasting methods in the specific scenario.

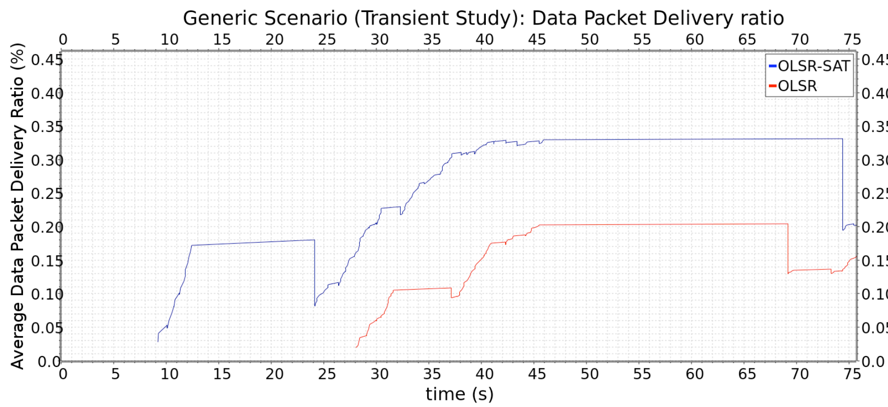

Figure 7.22: Data delivery ratio throughout the time for the generic scenario with a source-destination distance of 5 times the radio range.

will consider the system is in transient state when it is in fact in steady state.

Another approximation is taken in order to figure out the time that the protocols need to have converged. The evolution of the data delivery ratio throughout the time is represented in Figure 7.22. A simulation run of the scenario with the longest distance between source and destination is taken as an example, since long routes take more time to be discovered. The graph shows a faster route set up for OLSR-SAT which is able to forward the data packet to the destination sooner than OLSR. The lower travel delay when broadcasting `tc` messages in OLSR-SAT explains this behavior, so the topology information about remote links arrives sooner to the nodes in charge of route the data packets.

Specific Scenario We focus again on the evolution of the data delivery ratio throughout the time. Figure 7.23 shows the delivery ratio of the data packets transmitted between the two farthest group command cars. OLSR-SAT and OLSR-H with $r = n$ start to forward data packet sooner than OLSR and OLSR-H with $r = 4$ nodes with satellite capabilities. A relation between the speed of setting up the routes and the `tc` message travel delay can be noticed again. However, these differences are minimal.

In the simulation of OLSR-SAT and OLSR-H the time to deploy the satellite infrastructure was not taken into account. The nodes must point their satellite antennas and perform some registration operations before they can start to transmit over the satellite link. This is specially important in OLSR-SAT protocol because the nodes will not be able to compute long routes (more than 2 hops) without receiving the information transmitted over the satellite links (`tc` messages). On the other hand OLSR-H protocol performs like OLSR if the satellite links are not available, sending the `tc` message over the wireless LAN interface.

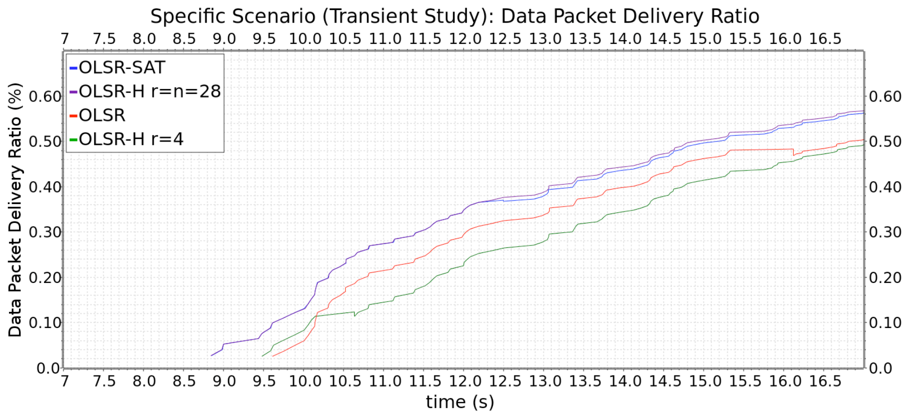

Figure 7.23: Data delivery ratio throughout the time for the communications between the two farthest group command cars of the specific scenario.

7.2.7 EXTRA Study

The Extended Route computation Algorithm is compared with the OLSR default route computation algorithm. Since the EXTRA route computation can be used in OLSR, OLSR-SAT and OLSR-H, the generic and the specific scenarios are simulated again using the EXTRA extension. The data delivery ratio is used as the performance metric.

Generic Scenario Figure 7.24 compares the data delivery ratio in the generic scenarios using the default and the EXTRA algorithm. The scenarios with the longest routes between the source and destination are represented. An improvement of 5% in the data delivery ratio can be noticed in both OLSR and OLSR-SAT protocols using the EXTRA extension. The improvement is almost 15% if we compare the default OLSR behavior with the combination of OLSR-SAT and EXTRA algorithm.

Specific Scenario The impact of the EXTRA extension in the specific scenario is shown in Figure 7.25. A general improvement on all OLSR variations is experienced with the EXTRA route computation. With the combination of EXTRA and the use of four satellite terminals in OLSR-H, we achieve an improvement of a 12% in the data delivery ratio for long routes compared to the OLSR default performance.

We can conclude that we improved two tasks of OLSR routing. The remote topology information is improved with the OLSR-SAT and OLSR-H satellite signaling distribution and the route computation is improved with the EXTRA algorithm. Then the combination of both improvements contributes to effectively handle networks featuring long routes.

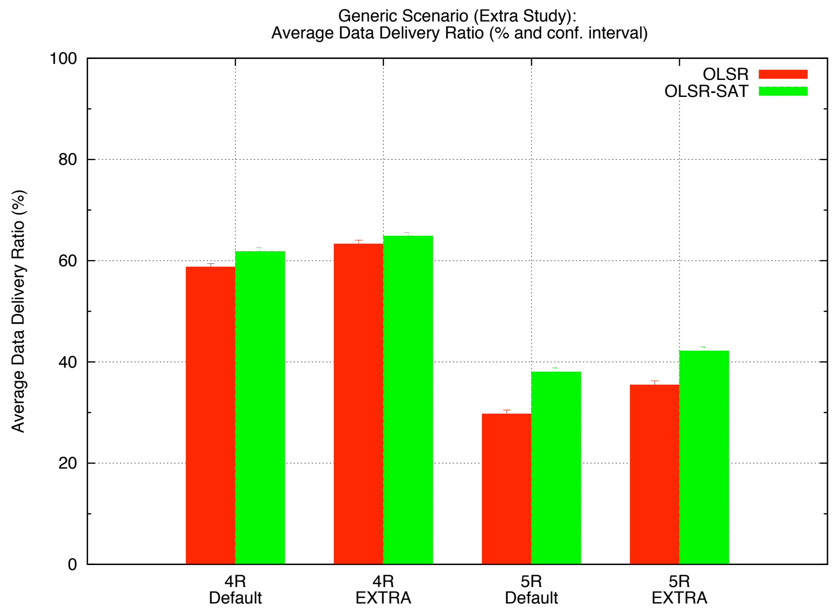

Figure 7.24: Data delivery ratio of the routing protocols with and without the EXTRA extension for the generic scenario.

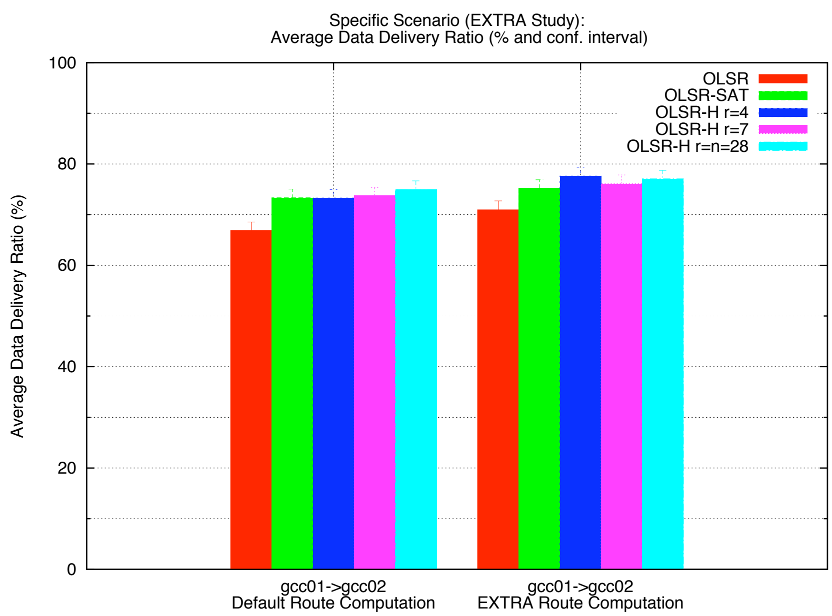

Figure 7.25: Data delivery ratio of the routing protocols with and without the EXTRA extension for the specific scenario.

Summary

This chapter presented the main simulation results of the devised MANET routing protocol in the proposed generic and specific scenarios. First, we covered the output analysis techniques to enforce the validity of the results. The duration of the transient state and the simulation length to arrive to representative results have been evaluated. Also, the replication method to compute the resulting confidence interval has been described.

The data delivery ratio of OLSR, OLSR-SAT and OLSR-H have been analyzed. An improvement close to 10% of data delivery ratio is achieved with the modified versions of OLSR. The most remarkable case is OLSR-H yielding these results with the use of only four satellite terminals out of 28 nodes (for the specific scenario).

A study of the source of errors in the data transmissions was performed in order to investigate the reasons for data delivery improvement. We have concluded that OLSR-SAT and OLSR-H perform better than OLSR because they store more destinations in the routing tables.

Then, the signaling of the routing protocols have been analyzed to explain this behavior. The use of a dedicated satellite channel in the broadcasting of `tc` messages increases their delivery ratio. Therefore, more topology information is available in OLSR-SAT and OLSR-H nodes favoring completeness during the route computation.

Also the travel delay of the `tc` messages is different when broadcasting over the satellite channel. The terrestrial transmissions contribute to the travel delay with the OLSR jitter delay while the satellite transmissions introduces 250 ms of fixed travel delay. When using OLSR-SAT or OLSR-H with all the nodes supporting satellite capabilities, the `tc` travel delay is minimized since a single hop is enough to cover all network nodes. This is reflected in the transient study: OLSR-SAT and OLSR-H (when all nodes have satellite capabilities) receive topology information sooner and they discover long routes around 3 seconds before OLSR.

Finally, the performance of the EXTRA route computation algorithm has been compared with the OLSR default route computation algorithm. An improvement of 5% of data delivery ratio is achieved using EXTRA instead of the default algorithm.

Conclusions and Outlook

This thesis addresses the routing problem on mobile ad hoc networks. The role of satellite communications in the distribution of MANET routing signaling information was analyzed. As far as we know, no other studies has taken this approach since the main use of satellite communications in MANETs is the forwarding of data traffic. Next, the contributions of each chapter are explained in more details.

Chapter 1 performs a study of the role of satellite systems in mobile ad hoc networks. The literature on MANETs shows satellite systems as a complementary technology to help in the distribution of data traffic (e.g., when the network is partitioned). Emergency situations are identified as a suitable scenario for our work. Finally, the most popular routing protocols are analyzed. It turns out that proactive link state protocols, reactive source routing protocols and location services of geographic routing protocols are candidates for taking advantage advantage of a satellite based signaling distribution.

Chapter 2 discusses the problems related to MANET simulations. The election of the OMNET++ network simulator is justified because of its open-source nature, facility to extend and smooth learning curve. Finally, the importance in the election of the mobility model is highlighted. The random waypoint mobility model is presented as the most popular generic mobility model for routing protocol evaluation. However the weaknesses of this mobility model to represent realistic situation are pointed out. The reference point group mobility is then proposed as a framework to describe more complex group mobility patterns.

Chapter 3 deals with the topology characteristics of MANETs. It shows that routing protocol behavior depends on the scenario and introduces a set of metrics to characterize it: network partitioning, network density, shortest-path hop count and link lifetime. These metrics impacts the behavior and performance of routing protocols. For example, short link lifetimes will incur route outages while networks with large diameters are more challenging for routing protocols because the higher the number of hops, the higher the chance to face a route outage.

However these metrics do not always explain the behavior of MANET routing protocols. The results do not solely depend on the network topology of the whole network but the properties of the routes followed by the data traffic. For that reason, two metrics to additionally characterize the routes between two specific nodes are proposed: the shortest-route hop count and the route lifetime. It is important to couple the previous metrics with the model of the MANET scenarios in order to understand the resulting routing protocol behavior.

Chapter 4 describes a typical scenario for generic MANET routing protocol evaluation. Like in most of MANET simulations found on the literature, we use the random waypoint mobility model. However a modification is introduced. The source and the destination nodes of data traffic are not mobile and the distance between them is parametrized in order to test how routing protocols cope with different route lengths.

Chapter 5 complements the generic scenario with a more realistic approach. A forest fire fighting operation is adopted as an example of a MANET based emergency scenario. The main contribution of this chapter is the development of a custom mobility model to describe the motion of the firemen units during the forest fire operation: the fire mobility model.

Chapter 6 presents the main contributions in the optimized link state routing protocol. A first approach is taken with the OLSR-SAT, an OLSR modification which substitutes the default multipoint relay broadcast mechanism of OLSR with a dedicated satellite broadcast channel. However, the nodes of an OLSR-SAT network must have all access to the satellite channel to obtain the broadcast signaling information. This is a not realistic solution and not compatible with the OLSR protocol. For that reason, the multipoint relay system of OLSR and the satellite broadcast system of OLSR-SAT are combined to create the OLSR-Hybrid (OLSR-H) protocol. The solution is compatible with the OLSR protocol, i.e., several nodes with satellite capabilities running OLSR-H can be introduced in a traditional OLSR network to improve the signaling distribution. The last improvement of the OLSR protocol deals with the computation of routing tables. We realized that the default OLSR route computation algorithm uses a directed topology graph but OLSR operates only with bidirectional links. This means that the opposite edges of the directed graph are also valid links of the network. Therefore, the EXTRA extension considers an undirected graph in the route computation offering more routes among the network nodes.

Finally, Chapter 7 shows the results of the simulations for the generic and the specific scenarios. We notice the importance of the data streams in MANET simulation. We obtain different values of data delivery depending on the length of the routes between the source and the destination nodes. We conclude that the election of these nodes has an impact on the protocol behavior. Regarding the OLSR signaling, the OLSR-SAT and the OLSR-H protocols avoid the wireless medium constraints in terms of bit errors and collisions. We notice an increase in the number of nodes covered by a signaling broadcast if we introduce satellite transmissions among several of the network nodes. Since more topology information is delivered, the routing tables display less gaps resulting in a decrease of the end-to-end data errors. A significant result is the improvement of around 8% of the data delivery ratio for long routes (ca. 7 hops) with the inclusion of only four satellite terminals in a MANET of 28 nodes. Regarding the route algorithm computation, the EXTRA extension also improves the data delivery ratio of about 4% in long routes for all the OLSR variations. However the EXTRA extension does not imply any modification in the signaling or the data stored in the nodes, only a change in the local computation of its routing tables.

Before describing the future directions for this work, the following paragraphs provide a summary of the contributions.

Our first contribution is to consider the use of satellite transmissions for optimizing the operation of a terrestrial network. Most proposals so far were focused on the data plane considering for example satellite-based backhauling or core network access. To our knowledge, using satellite for extending the control plane of a mobile ad hoc network was never studied before. Still, it is a sensible approach since the throughput considered are in the order to 100 byte/s per node which opens the way to low-cost, low-constraint satellite antenna design and transmissions.

Our second contribution is the Fire Mobility model which depicts the deployment and motion of firemen units during a forest fire fighting operation. This contribution is important for two reasons. First, MANET performance evaluation depends on the parameters of the scenario, therefore it is equally important to consider a close-to-reality network model for guaranteeing that results will be relevant. Second, the modeling of emergency situations from a network standpoint is barely addressed in the literature (mainly because it is a difficult issue requiring field know-how or knowledge transfer from end-users). It has been identified as a priority by the European Commission so to prepare for effective disaster management [66].

Our third contribution is the extension of the OLSR routing protocol with OLSR-H. By equipping a small amount of nodes (4 out of 28) with satellite facilities, an improvement of the delivery ratio up to 8 percent. The reasons for improvement were identified (namely the increased reliability of satellite-based `tc` message delivery). For the same reason, we also believe that the OLSR-H extension will sustain higher traffic loads or a larger number of nodes compared to OLSR.

Our fourth and final contribution lies in the proposal of OLSR-EXTRA which, without modifying the `tc` or `hello` signaling schemes, improves the robustness of the routing computation.

Finally, this PhD work has been a good opportunity to measure the difficulty of organizing reliable MANET simulation campaigns. The methodology that we used aims at achieving a good balance between simulation tractability, faithfulness to a context of deployment and validity of the results.

Outlook

The following paragraphs present further activities for this work. They are organized from short-term to long-term proposals.

Short-term The proposed routing solution could be evaluated in more situations. For example, we could test the routing protocol behavior in a loaded network increasing the number of data sources and/or their bit rate. In this situation we can expect an increase in the number of errors in the terrestrial signaling traffic. OLSR-H would therefore benefit from this situation.

The previous proposition opens another work line: improving the signaling overhead of OLSR-H. We experiment an increase in the overhead due to the broadcast of the `tc` messages in OLSR-H. We have concluded that the inclusion of an external factor (the satellite terminals) alters the multipoint relay mechanism of OLSR. Using information about the satellite terminals in the multipoint relay election could optimize the signaling overhead due to the `tc` message broadcasts.

Long-term We have focused in the optimized link state routing protocol in this work. However we pointed more MANET routing protocols as candidates to take advantage of satellite communication. For example, the dynamic source routing (DSR) could be modified to allow nodes to exchange known routes through the satellite. Also, location services could take advantage of satellite communications.

As of now, we have assumed that OLSR-SAT or OLSR-H would be implemented in the nodes taking part of the network. An alternate direction should be investigated where the network is kept as is but it is complemented by dedicated (satellite enabled) equipments contributing (i.e., capturing and circulating) signaling traffic. Those equipments would be located in strategic places of the network.

Bibliography

[1] N. Courville, H. Bischl, E. Lutz, A. Svigelj, P.M.L. Chan, E. Papapetrou, and R. Asorey-Cacheda. Hybrid satellite/terrestrial networks: state of the art and future perspectives. In *QShine Workshop: Satellite/Terrestrial Interworking (IWSTI07)*, pages 1–7. ACM, 2007.

[2] Y.N. Lien, H.C. Jang, and T.C. Tsai. A MANET based emergency communication and information system for catastrophic natural disasters. In *29th IEEE International Conference on Distributed Computing Systems Workshops (ICDS09)*, pages 412–417. IEEE, 2009.

[3] M. Luglio, C. Monti, C. Roseti, A. Saitto, and M. Segal. Interworking between MANET and satellite systems for emergency applications. *International Journal of Satellite Communications and Networking*, 25(5):551–558, 2007.

[4] K. Kanchanasut, A. Tunpan, M.A. Awal, D. K. Das, T. Wongsaardsakul, and Y. Tsuchimoto. DUMBONET: a multimedia communication system for collaborative emergency response operations in disaster-affected areas. *International Journal of Emergency Management*, 4(4):670, 2007.

[5] A. Oliveira, Z. Sun, M. Monier, P. Boutry, D. Gimenez, A. Pietrabissa, and K. Banovec Juros. On Optimizing Hybrid Ad-hoc and Satellite Networks the MONET Approach. In *Future Network and Mobile Summit*, pages 1–8. IIMC, 2010.

[6] E.M. Royer and C.K. Toh. A review of current routing protocols for ad hoc mobile wireless networks. *IEEE Personal Communications*, 6(2):46–55, 1999.

[7] M. Abolhasan, T. Wysocki, and E. Dutkiewicz. A review of routing protocols for mobile ad hoc networks. *Ad Hoc Networks*, 2(1):1–22, January 2004.

[8] H. Ehsan and Z. A. Uzmi. Performance comparison of ad hoc wireless network routing protocols. In *8th International Multitopic Conference (INMIC04)*, pages 457–465. IEEE, 2004.

[9] S. Buruhanudeen, M. Othman, and B.M. Ali. Existing MANET routing protocols and metrics used towards the efficiency and reliability- an overview. In *IEEE International Conference on Telecommunications and Malaysia International Conference on Communications (ICT-MICC07)*, pages 231–236. IEEE, 2007.

[10] I. Broustis, G. Jakllari, T. Repantis, and M. Molle. A Comprehensive Comparison of Routing Protocols for Large-Scale Wireless MANETs. In *IEEE Sensor and Ad Hoc Communications and Networks (SECON06)*, volume 3, pages 951 – 956. IEEE, 2006.

[11] R.V. Biradar and V.C. Patil. Classification and Comparison of Routing Techniques in Wireless Ad Hoc Networks. In *International Symposium on Ad Hoc and Ubiquitous Computing (ISAUHC06)*, pages 7–12. IEEE, December 2006.

[12] C. Perkins and P. Bhagwat. Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers. *Computer Communication Review (ACM SIGCOMM)*, 24(4):234–244, 1994.

[13] P. Jacquet, P. Mühlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot. Optimized link state routing protocol for ad hoc networks. In *5th IEEE Multi Topic Conference (INMIC 2001)*, page 62. IEEE, 2001.

[14] C. Perkins and E.M. Royer. Ad hoc On-Demand Distance Vector (AODV) Routing. In *2nd IEEE Workshop on Mobile Computing Systems and Applications (WMCSA99)*, pages 90–100, 1999.

[15] D.B. Johnson, D.A. Maltz, and J. Broch. DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks. *Ad hoc networking*, 5:139–172, 2001.

[16] R. Iyengar and B. Sikdar. Scalable and distributed GPS free positioning for sensor networks. In *IEEE International Conference on Communications (ICC03)*, pages 338–342. IEEE, 2003.

[17] S. Čapkun, Maher Hamdi, and J.P. Hubaux. GPS-free positioning in mobile ad hoc networks. In *34th Hawaii International Conference on System Sciences (HICSS01)*, pages 1–10. IEEE, 2001.

[18] A. Savvides, C.C. Han, and M.B. Strivastava. Dynamic fine-grained localization in Ad-Hoc networks of sensors. In *7th Annual International Conference on Mobile Computing and Networking (MOBICOM01)*, pages 166–179. ACM, 2001.

[19] D. Niculescu and B. Nath. Ad hoc positioning system (APS). In *IEEE Global Telecommunications Conference (GLOBECOM01)*, pages 2926–2931. IEEE, 2001.

[20] R. Nelson and L. Kleinrock. The Spatial Capacity of a Slotted ALOHA Multihop Packet Radio Network with Capture. *IEEE Transactions on Communications*, 2(1):9–14, 1984.

[21] H. Takagi and L. Kleinrock. Optimal Transmission Ranges for Randomly Distributed Packet Radio Terminals. *IEEE Transactions on Communications*, 32(3):246–257, March 1984.

[22] H. Ting-Chao and L. Victor. Transmission Range Control in Multihop Packet Radio Networks. *IEEE Transactions on Communications*, 34(1):38–44, 1986.

[23] G.G. Finn. Routing and addressing problems in large metropolitan-scale internetworks. *ISI Research Report*, 1987.

[24] I. Stojmenovic and X. Lin. Power-Aware Localized Routing in Wireless Networks. *IEEE Transactions on Parallel and Distributed Systems*, 12(11):1122–1133, 2001.

[25] I. Stojmenovic and X. Lin. Loop-Free Hybrid Single-Path/Flooding Routing Algorithms with Guaranteed Delivery for Wireless Networks. *IEEE Transactions on Parallel and Distributed Systems*, 12(10):1023–1032, 2001.

[26] E. Kranakis, H. Singh, and J. Urrutia. Compass Routing on Geometric Networks. In *11 th Canadian Conference on Computational Geometry (CCCG99)*, pages 51–54, 1999.

[27] J. Ghosh, S.J. Philip, and C. Qiao. Acquaintance Based Soft Location Management (ABSLM) in MANET. In *IEEE Wireless Communications and Networking Conference (WCNC04)*, pages 166– 171. IEEE, 2004.

[28] S.M. Woo and S. Singh. Scalable Routing Protocol for Ad Hoc Networks. *Wireless Networks*, 7(5):513–529, 2001.

[29] C.T. Cheng, H.L. Lembergy, S.J. Philipz, E. van Den Bergy, and T. Zhang. SLALoM: A Scalable Location Management Scheme for Large Mobile Ad-hoc Networks. In *IEEE Wireless Communications and Networking Conference (WCNC02)*, volume 2, pages 574– 578, 2002.

[30] S.J. Philip and C. Qiao. Hierarchical grid location management for large wireless Ad hoc networks. *Mobile Computing and Communications Review (ACM SIGMOBILE)*, 7(3):33, July 2003.

[31] J. Li, J. Jannotti, D. De Couto, D. Karger, and R. Morris. A scalable location service for geographic ad-hoc routing. In *6th International Conference on Mobile Computing and Networking (MOBICOM00)*, pages 120–130. ACM, August 2000.

[32] Y.B. Ko and N.H. Vaidya. Location-Aided Routing (LAR) in Mobile Ad Hoc Networks. *Wireless Networks*, 6(4):321, 2000.

[33] D. Cavin, Y. Sasson, and A. Schiper. On the accuracy of MANET simulators. In *2nd International workshop on Principles of Mobile Computing (POMC02)*, pages 38–43. ACM, 2002.

[34] E. Ben Hamida, G. Chelius, and J. Gorce. On the complexity of an accurate and precise performance evaluation of wireless networks using simulations. In *11th International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM08)*, page 395. ACM, 2008.

[35] J. Heidemann, N. Bulusu, J. Elson, C. Intanagonwiwat, K. Lan, Y. Xu, W. Ye, D. Estrin, and Ramesh Govindan. Effects of detail in wireless network simulation. In *Multiconference on Distributed Simulation*, pages 3–11. SCS, 2001.

[36] F. Bai, N. Sadagopan, and A. Helmy. IMPORTANT: A framework to systematically analyze the Impact of Mobility on Performance of RouTing protocols for Adhoc NeTworks. In *22nd Annual Joint Conference of the IEEE Computer and Communications (INFOCOM03)*, volume 2, pages 825–835. IEEE, 2003.

[37] K.M. Mcneill, Yun Zhao, Natalia Gaviria, Ralph Martinez, and John Deal. Scenario-Oriented Ad Hoc Networks Simulation with Mobility Models. In *Military Communications Conference, 2004. MILCOM 2004. IEEE*, volume 1, pages 113–119. IEEE, 2005.

[38] X. Hong, M. Gerla, G. Pei, and C.C. Chiang. A group mobility model for ad hoc wireless networks. In *2nd International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM99)*, pages 53–60. ACM, 1999.

[39] S Kurkowski, T Camp, and M Colagrosso. MANET simulation studies: the incredibles. *Mobile Computation Communication Review (SIGMOBILE)*, 9(4):50–61, 2005.

[40] S. Kurkowski, T. Camp, and W. Navidi. Two Standards for Rigorous MANET Routing Protocol Evaluation. In *International Conference on Mobile Ad Hoc and Sensor Systems (MOBHOC06)*, pages 256–266. IEEE, October 2006.

[41] András Varga and Rudolf Hornig. An overview of the OMNeT++ simulation environment. In *1st international conference on Simulation Tools and Techniques for Communications, Networks and Systems workshops (SIMUTOOLS08)*, pages 61–70. ICST, 2008.

[42] A. Ariza-Quintana, E. Casilari, and A. Triviño Cabrera. Implementation of MANET routing protocols on OMNeT++. In *1st international conference on Simulation Tools and Techniques for Communications, Networks and Systems workshops (SIMUTOOLS08)*, pages 81–84. ICST, 2008.

[43] J. Lessmann, P. Janacik, L. Lachev, and D. Orfanus. Comparative study of wireless network simulators. In *7th International Conference on Networking (ICN08)*, pages 517–523. IEEE, 2008.

[44] L Begg, W Liu, S Pawlikowski, S Perera, and H Sirisena. Survey of simulators of next generation networks for studying service availability and resilience. Technical report, Department of Computer Science and Software Engineering, University of Canterbury, 2006.

[45] L. Hogie, P. Bouvry, and F. Guinand. An Overview of MANETs Simulation. *Electronic Notes in Theoretical Computer Science (ENTCS06)*, 150(1):81–101, 2006.

[46] T. Camp, J. Boleng, and V. Davies. A survey of mobility models for ad hoc network research. *Wireless Communications and Mobile Computing*, 2(5):483–502, 2002.

[47] D. Johnson and A. Maltz. Dynamic source routing in ad hoc wireless networks. In *Mobile Computing*, pages 153–181. Springer, 1996.

[48] R.A. Guerin. Channel occupancy time distribution in a cellular radio system. *IEEE Transactions on Vehicular Technology*, 36(3):89–99, August 1987.

[49] Z.J. Haas. A new routing protocol for the reconfigurable wireless networks. In *6th International Conference on Universal Personal Communications (ICUPC97)*, volume 2, pages 562–566. IEEE, 1997.

[50] B. Liang and Z.J. Haas. Predictive distance-based mobility management for PCS networks. In *8th International Conference on Computer Communications (INFOCOM99)*, volume 3, pages 1377–1384. IEEE, 1999.

[51] M. Bergamo, RR Hain, K. Kasera, D. Li, R. Ramanathan, and M. Steenstrup. System design specification for mobile multimedia wireless network (MMWN) (draft). *DARPA project DAAB07-95-C-D156*, 1996.

[52] M. Sanchez. ANEJOS: a Java based simulator for ad hoc networks. *Future Generation Computer Systems*, 17(5):573–583, March 2001.

[53] W. Navidi and T. Camp. Stationary distributions for the random waypoint mobility model. *IEEE Transactions on Mobile Computing*, 3(1):99–108, January 2004.

[54] J. Yoon, M. Liu, and B. Noble. Random waypoint considered harmful. In *22nd Annual Joint Conference of the IEEE Computer and Communications (INFOCOM03)*, volume 2, pages 1312–1321. IEEE, 2003.

[55] V Davies. *Evaluating mobility models within an ad hoc network*. PhD thesis, Colorado School of Mines, 2000.

[56] S Corson and J Macker. RFC2501: Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations. *Internet RFCs*, 1999.

[57] P. Johansson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark. Scenario-based performance analysis of routing protocols for mobile ad-hoc networks. In *5th annual International Conference on Mobile Computing and Networking (MOBICOM99)*, pages 195–206. ACM, August 1999.

[58] B. Kwak, N. Song, and L.E. Miller. A Standard Measure of Mobility for Evaluating Mobile Ad Hoc Network Performance. *IEICE Transactions on Communications*, E86-B(11):3236–3243, April 2003.

[59] A. Munjal, T. Camp, and W.C. Navidi. Constructing rigorous MANET simulation scenarios with realistic mobility. In *European Wireless Conference (EW)*, pages 817–824. IEEE, 2010.

[60] Valabre Ecole D'Application De Sécurité Civile. *Le commandement d'une operation de secours*. Stage Chef de Groupe Feux de Forêts FDF 3, 2008.

[61] Direction De La Défense Et De La Sécurité Civile. *Guide national de reference: Manoeuvres feux de forêts*. Sous-direction des sapeurs-pompiers et des acteurs du secours, 2008.

[62] Y.S. Meng, Y.H. Lee, and B.C. Ng. Study of propagation loss prediction in forest environment. *Progress In Electromagnetics Research*, 17:117–133, 2009.

[63] M.A. Weissberger. An initial critical summary of models for predicting the attenuation of radio waves by trees. Technical report, Electromagnetic compability analysis center annapolis MD, 1982.

[64] S Ruffino, P Stupar, T Clausen, and S Singh. Connectivity Scenarios for MANET. *IETF MANET Internet-Draft*, 2006.

[65] Joseph Abate and Ward Whitt. Transient Behavior of the M/M/1 Queue via Laplace Transforms. *Advances in Applied Probability*, 20(1):145–178, 1988.

[66] European Commission. Towards a stronger European disaster response: the role of civil protection and humanitarian assistance. *Communication from the Commission to the European Parliament and the Council, (COM2010) 600 final*, 2010.

Routage MANET assisté par satellite

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Introduction

Les réseaux mobiles ad hoc (MANETs) constituent un domaine de recherche très dynamique au cours de ces dernières années. Malgré cette activité intense, peu de produits commerciaux ont vu le jour. Deux raisons peuvent être invoquées: (a) les opérateurs commerciaux n'aiment pas les réseaux non structurés qui, par définition, ne sont pas facilement contrôlables et (b) MANETs présentent encore de sérieux défis techniques.

Le paradigme ad hoc consiste en des réseaux sans infrastructure, où les hôtes ont de nouvelles capacités pour fournir la fonctionnalité de routeur de réseaux traditionnels. La mobilité apporte une complexité supplémentaire pour les hôtes en raison de la dynamique de la topologie, mais il étend la gamme des applications de ce type de réseaux. Leur indépendance vis à vis d'une infrastructure favorise leur utilisation là où les infrastructures terrestres de communication sont indisponibles. C'est le cas d'une attaque terroriste ou de catastrophes naturelles comme les tremblements de terre ou les ouragans. L'infrastructure pourrait même ne jamais exister, par exemple, dans le cas des équipes de secours ou des unités militaires lors d'opérations dans des environnements hostiles. Ils peuvent être également utiles lors d'événements en raison de leur spontanéité.

Toutefois, un réseau mobile sans infrastructure produit de nouveaux défis. Les MANETs ouvrent de nouveaux axes de recherche pour adapter les solutions traditionnelles à un environnement sans administration centrale. La sécurité, l'auto-organisation, le contrôle d'accès, le routage ou la qualité du service sont quelques questions ouvertes dans les MANETs.

La sécurité est affectée par le manque d'infrastructures. La division entre les dispositifs des utilisateurs et les équipements de l'opérateur disparaît et les données confidentielles doivent passer par plusieurs hôtes pour arriver à la destination. Les utilisateurs malveillants trouvent un moyen direct pour intercepter ces données ou même pour affecter le bon fonctionnement du réseau.

L'auto-organisation est une propriété souhaitée dans les réseaux mobiles ad hoc. Son principal objectif est de permettre aux hôtes de rejoindre ou quitter le réseau sans l'exigence d'une configuration préalable. Par exemple, la configuration automatique des adresses de réseaux traditionnels se trouve sur des serveurs centralisés (par exemple, le protocole DHCP). De nouveaux protocoles ont été développés pour fournir ces capacités de manière distribuée.

Les protocoles traditionnels de contrôle d'accès au support sont connus pour fonctionner en mode infrastructure. La norme IEEE 802.11 permet à deux hôtes de communiquer directement sans une entité routeur en mode ad hoc. Cependant ce n'est qu'une approche de base. Par conséquent, des protocoles de contrôle d'accès au support plus adaptés aux réseaux multi-sauts sans fil ont été proposés ces dernières années.

Le routage est également affecté par le manque d'infrastructure et la mobilité des hôtes. Dans les réseaux traditionnels, l'infrastructure est responsable des tâches de routage. Ces réseaux traditionnels gère la mobilité grâce à des procédures de *handover*. D'autre part, les hôtes doivent accomplir les tâches de routage dans les réseaux mobiles ad hoc face à des changements continuels dans la topologie. En outre, les solutions traditionnelles doivent être adaptées pour fournir une qualité de service pour assurer la gestion des ressources dans un réseau sans un administrateur central.

En résumé, des réseaux mobiles ad hoc sont des systèmes complexes qui conduisent à plusieurs domaines de recherche. Ce travail de thèse est centré sur le domaine du routage. Il se propose de pallier des problèmes de routage dans les MANET en distribuant la signalisation de routage à l'aide de transmissions satellite. Il offre une nouvelle perspective du rôle du satellite dans les réseaux mobiles ad hoc. Traditionnellement, les communications par satellite ont été proposées dans les réseaux mobiles ad hoc pour transférer trafic de données: comme passerelles reliant les MANETs à des réseaux externes (par exemple Internet); ou comme interconnexion d'hôtes ou de groupe d'hôtes isolés dans un MANET partagé. La motivation de ce travail est complètement différente: le segment satellite peut aider à la distribution de la signalisation afin d'améliorer le routage du trafic de données dans le MANET.

Par conséquent, le réseau satellite est utilisé comme un canal complémentaire pour aider à la distribution de signalisation de routage. Nous nous attendons à améliorer la distribution de cette signalisation et donc à obtenir de meilleures décisions de routage. Cependant, les transmissions par satellite induisent un retard important et le coût de la bande passante est élevé. En outre, tous les noeuds d'un MANET n'auraient pas accès au canal satellite. C'est pourquoi nous devons adapter le routage MANET aux réseaux hybrides terrestre-satellite et analyser si la signalisation de routage peut être améliorée dans ce nouveau contexte.

Tout d'abord, un tour d'horizon des protocoles de routage MANET doit être effectué. Il existe une grande quantité de publications sur le routage MANET et les solutions proposées doivent être classées et analysées. La répartition de la signalisation par satellite sera adaptable pour certains protocoles, mais inutile pour d'autres.

La solution proposée sera ensuite évaluée par simulation afin d'avoir accès à des mesures avec une granularité jusqu'au niveau des paquets. Mais la modélisation MANET pour la simulation n'est pas une tâche triviale. Par exemple, il existe un large éventail de scénarios où un MANET peut être déployé. La plupart des chercheurs utilise des scénarios avec le *random waypoint* (RWP) comme modèle de mobilité. Ce modèle crée des topologies dynamiques aléatoires pour tester les performances de routage du protocole. Toutefois, il ne peut être associé à aucune situation réelle. Pour évaluer les performances des protocoles de routage, il est judicieux d'utiliser des scénarios génériques, mais aussi des scénarios spécifiques correspondant à une situation réelle.

Une situation de lutte contre les incendies est proposée. Dans les premières heures d'une mission de lutte contre les incendies, quand il n'y a pas une infrastructure déployée, la communication est principalement composée de transmissions de voix sur des radios numériques mobiles professionnelles. Comme nous l'avons vu au début de cette introduction, il s'agit d'un scénario favorable pour déployer un réseau mobile ad hoc. Un MANET offrira des transmissions de données IP aux pompiers et de nouveaux services tels que la distribution des données cartographiques, le transport des données de capteurs, le suivi des unités de combat d'incendie, la voix sur IP, etc. Dans ce scénario, il est possible que certains des véhicules des pompiers portent des antennes paraboliques.

En travaillant avec deux scénarios distincts, il est possible d'analyser l'impact du contexte réseau sur les performances du routage. En outre, toutes les étapes de la simulation, du choix des modèles à l'analyse des résultats doivent être décrits. La complexité des simulations MANET sera prise en compte durant ce processus.

Objectifs

Comme aucune étude similaire n'a été proposée, ce travail présente les premières conclusions sur les possibilités de communications par satellite dans la distribution de la signalisation de routage MANET. Les améliorations sur les protocoles de routage MANET seront évaluées afin de déterminer s'il est intéressant ou non d'introduire ce nouveau rôle pour les satellites.

À cette fin, nous allons délimiter le contexte applicatif. Les réseaux mobiles ad hoc sont adaptés à un large éventail d'applications. Toutefois, la présence de terminaux satellite n'est pas toujours garantie. L'un des objectifs de ce travail est d'identifier les contextes applicatifs où la distribution hybride terrestre-satellite de signalisation est adaptée.

Un autre point est le protocole de routage lui-même. Un grand nombre de protocoles de routage MANET sont disponibles dans la littérature. C'est pourquoi nous avons besoin d'analyser les différentes solutions de routage afin d'identifier les plus adaptables à une distribution hybride terrestre-satellite de signalisation.

Enfin, nous avons l'intention de décrire les étapes et les points cruciaux dans l'évaluation des protocoles de routage MANET. Plusieurs tâches sont concernées: la modélisation du réseau, du scénario et des mesures de performance, les techniques d'analyse des resultats, etc. Par conséquent nous mettons en évidence la complexité de l'évaluation du routage MANET et les lignes directrices actuelles pour obtenir des résultats valables et représentatifs.

Plan

Le document est divisé en trois parties.

La première partie, l'état de l'art, présente le routage et la simulation des MANETs. Le chapitre 1 s'intéresse au rôle des satellites dans les réseaux terrestres et plus spécifiquement dans les MANETs. Ensuite, il analyse la manière dont un système de satellites peut contribuer à la distribution effective de la signalisation des protocoles de routage MANET. À cette fin, une classification des protocoles de routage MANET est effectuée et la possibilité d'adapter un système de satellite dans leur signalisation est étudié. Le chapitre 2 décrit les simulateurs et les modèles de mobilité utilisés dans la recherche MANET. Il présente également les problématiques associées à la simulation MANET.

La deuxième partie porte sur les scénarios utilisés dans la simulation. Deux scénarios différents sont utilisés, un générique et un spécifique. L'utilisation de plus d'un scénario est intéressant: cela nous permet de comparer les protocoles de routage dans des situations différentes, et d'analyser comment le contexte réseau influe sur les performances. À cette fin, un ensemble de métriques est introduit dans le chapitre 3 pour caractériser la topologie du réseau. Le chapitre 4 décrit le scénario générique en détail. Enfin, le scénario spécifique, une mission de lutte contre les incendies, est présenté dans le chapitre 5.

La troisième partie présente la solution de routage proposée. Le protocole OLSR est choisi en raison de sa nature à état des liens, sa popularité et parce qu'il est standardisé. Les bases de ce protocole sont présentées dans le chapitre 6 avec les adaptations nécessaires pour utiliser des satellites pour la distribution de la signalisation. Ensuite, les performances du protocole de routage sont testées dans le cadre des scénarios précités. Enfin, le chapitre 7 discute les questions de la simulation e.g., les intervalles de confiance, les mesures de performance, la durée de la simulation, etc. Ensuite, il présente une analyse des résultats.

Le document se termine par une conclusion et des perspectives.

Résumé

Chapitre 1: Réseaux Mobiles Ad-hoc et Satellites

Ce chapitre commence par une étude des communications par satellite dans les réseaux terrestres. La littérature présente deux rôles principaux des systèmes de satellites dans les réseaux mobiles ad hoc: pour joindre des noeuds isolés et pour connecter le MANET avec d'autres réseaux comme l'Internet. Par conséquent, l'utilisation principale du satellite dans les MANET est de transmettre du trafic de données. L'utilisation des communications par satellite dans la distribution de signalisation de routage n'a pas été considérée à notre connaissance. Au cours de l'étude de la littérature, nous avons également identifié des situations d'urgence comme le scenario MANET avec la plus grande probabilité d'impliquer des terminaux satellite: certains noeuds peuvent déjà avoir des interfaces par satellite pour interconnecter les MANET avec des réseaux extérieurs pour les transmissions de données. Nous pourrions profiter de cette infrastructure par satellite pour améliorer la distribution terrestre de signalisation.

Ensuite, le protocoles de routage MANET les plus populaires ont été décrits. Ils sont divisés en réactifs, proactifs et géographiques. La contribution possible des communications par satellite dans la distribution de leur signalisation a été étudiée pour chaque famille. Il a été montré que les protocoles proactifs à état de lien, les protocoles réactifs de routage par la source et les services de localisation sont les meilleurs candidats pour être modifiés pour utiliser les satellites dans la distribution d'informations de signalisation.

Chapitre 2: Simulation de Réseaux Mobiles Ad-hoc

Les principaux problèmes associés à la simulation des réseaux MANET ont été introduits dans ce chapitre. Il semble que, sans un cadre universel pour la simulation de MANET, le mieux que nous pouvons faire est de documenter tous les processus de simulation pour permettre à d'autres chercheurs de le reproduire. Pour cette raison, nous incluons le chapitre 4 et le chapitre 5 qui décrivent la configuration des scénarios MANET proposés pour ce travail. Ensuite, le choix du simulateur de réseau a été expliquée. OMNeT++ et l'extension INETMANET ont été choisis en raison de leur nature open-source, facilement extensible et de leur apprentissage rapide.

Enfin, l'importance de la mobilité dans la simulation MANET et sa modélisation ont été décrites. Le modèle de mobilité random waypoint a été choisi comme modèle représentatif. Le modèle de mobilité de groupe avec point de référence est décrite comme un exemple de modèle de groupe.

Chapitre 3: Métriques de Topologie

Plusieurs scénarios MANET seront proposés pour évaluer notre solution de routage. Ce chapitre présente des métriques de topologie pour classer les scénarios MANET et identifie les valeurs recommandées pour effectuer des évaluations rigoureuses du rendement du routage MANET. Un ensemble de mesures générales a été identifié dans la littérature pour caractériser les propriétés des scénarios MANET. Cet ensemble comprend: le nombre de noeuds, le nombre de voisins, le partitionnement du réseau, le nombre de sauts des chemins les plus courts et la durée de vie de lien.

Ensuite, la nécessité de mesurer les propriétés de certaines routes dans les réseaux est discutée. Deux mesures spécifiques sont adoptées à cet effet: le nombre de sauts de la route plus courte et la durée de vie de la route plus courte.

Chapitre 4: Scénario Générique

Un scénario générique pour la simulation MANET est décrite dans ce chapitre. La version du simulateur, les modèles et leurs paramètres sont identifiés.

Le problème de la simulation de grands réseaux est traitée en diminuant le nombre de noeuds tout en gardant la distance entre la source et la destination assez grande pour garantir la validité des résultats de simulation. Enfin, l'utilité de mesures spécifiques est démontrée pour mesurer la longueur et la durée de vie de la route entre les noeuds source et destination des scénarios proposés.

Chapitre 5: Scénario Spécifique

Un scénario spécifique MANET a été présenté dans ce chapitre. Une opération de lutte contre les incendies a été choisie comme scénario adapté pour déployer un MANET pour les communications entre les pompiers.

La première partie du chapitre offre un bref aperçu des unités de lutte contre les incendies, leur hiérarchie et leurs manoeuvres. Ensuite, le modèle de scénario a été expliqué. La mobilité des unités de pompier est modélisée avec le modèle *fire mobility*, un modèle grossier qui reflète la hiérarchie des pompiers et de leurs mouvements en groupe. Puis, le modèle de communication sans fil est décrit, en se concentrant dans la principale différence avec le scénario générique: la propagation des ondes radio. La propagation en espace libre ($\alpha = 2$) du scénario générique est modifié pour refléter l'atténuation introduite par les arbres et le feuillage du forêt. Il est conclu qu'une bonne approximation pour modéliser cette atténuation est d'augmenter le coefficient de pertes ($alpha = 3$). Enfin la distribution des passerelles satellite à travers les unités de pompiers est représentée. Les voitures de commande sont les unités les plus susceptibles d'avoir une interface satellite.

Chapitre 6: Modifications du Protocol OLSR

Ce chapitre présente le protocole *Optimized Link State Routing*. Les tâches de détection des liens, de la diffusion de l'état des liens et du calcul de routes sont analysées. Puis, trois modifications du protocole OLSR sont introduites: OLSR-SAT, OLSR-H et EXTRA. OLSR-SAT et OLSR-H sont des modifications de la tâche de diffusion de l'état de liens de sorte à utiliser les satellites.

OLSR-SAT utilise uniquement des satellites pour la distribution de messages `tc`, donc l'équipement satellite est nécessaire pour tous les noeuds. D'autre part, OLSR-H distribue messages `tc` par satellite, mais aussi en utilisant le mécanisme de *multipoint relays* du protocole OLSR. De cette façon, les noeuds sans interfaces satellite peuvent obtenir les informations de topologie nécessaires pour la construction des tables de routage.

Enfin, l'algorithme par défaut de calcul de routes d'OLSR est modifié afin de découvrir des routes alternatives. EXTRA, l'algorithme de calcul proposé, peut être utilisé dans les protocoles OLSR, OLSR-SAT et OLSR-H.

Chapitre 7: Résultats de Simulation

Ce chapitre présente les résultats principaux de simulation des protocoles de routage MANET proposés dans les scénarios générique et spécifique. Tout d'abord, nous nous sommes intéresés à la validité des résultats. La durée du régime transitoire et la durée de la simulation pour arriver à des résultats représentatifs ont été évaluées. En outre, la méthode de réplication pour calculer des intervalles de confiance dans les résultats a été décrite.

Le taux de délivrance des données avec OLSR, OLSR-SAT et OLSR-H ont été analysés. Une amélioration proche de 10 % de la délivrance des données est obtenue avec les versions modifiées du protocole OLSR. Le cas le plus remarquable est OLSR-H avec une amélioration similaire en utilisant seulement quatre terminaux satellite sur 28 noeuds (pour le scénario spécifique).

Une étude de la source d'erreurs dans les transmissions de données a été réalisée afin de chercher les raisons de l'amélioration dans la délivrance des données. Nous avons conclu que les protocoles OLSR-SAT et OLSR-H montrent de meilleurs résultats que le protocole OLSR car ils stockent plus de destinations dans les tables de routage.

Ensuite, la signalisation des protocoles de routage a été analysée pour expliquer ce comportement. L'utilisation d'un canal satellite dédié à la diffusion de messages `tc` augmente leur taux de délivrance. Par conséquent, plus d'informations sur la topologie sont disponibles dans les noeuds avec OLSR-SAT et OLSR-H favorisant l'exhaustivité au cours du calcul de routes.

En outre, le retard des messages `tc` est différent lors de la diffusion sur le canal satellite. Les transmissions terrestres contribuent au délai en induisant en outre de la gigue, tandis que les transmissions par satellite introduit un délai constant de 250 ms. En utilisant le protocole OLSR-SAT ou OLSR-H avec tous les noeuds supportant des communications par satellite, le retard `tc` est réduit au minimum, un seul saut étant suffisant pour couvrir tous les noeuds du réseau. Cela se reflète dans l'étude du régime transitoire: OLSR-SAT et OLSR-H (lorsque tous les noeuds ont des capacités de satellite) reçoivent des informations de topologie plus tôt et ils découvrent les routes longues environ 3 secondes avant OLSR.

Enfin, la performance de l'algorithme de calcul de routes EXTRA a été comparée à l'algorithme de calcul par défaut du protocole OLSR. Une amélioration de 5 % de taux de livraison des données est réalisée en utilisant EXTRA au lieu de l'algorithme par défaut.

Conclusions et Perspectives

Cette thèse aborde le problème de routage dans les réseaux mobiles ad hoc. Le rôle des communications par satellite dans la distribution d'informations de signalisation de routage MANET a été analysé. Autant que nous sachions, n'aucune autre étude a adopté cette approche; l'utilisation principale des communications par satellite dans les MANET est la transmission du trafic de données.

Le chapitre 1 effectue une étude sur le rôle des systèmes de satellites dans les réseaux mobiles ad hoc. La littérature sur les MANET montre les systèmes par satellite comme une technologie complémentaire pour aider à la distribution du trafic de données (par exemple, lorsque le réseau est partitionné). Les situations d'urgence sont identifiées comme un scénario adapté à notre travail. Enfin, les protocoles les plus populaires de routage sont analysés. Il s'avère que les protocoles proactifs à état de lien, les protocoles réactifs de routage par la source et des services de localisation des protocoles de routage géographiques sont candidats pour bénéficier de l'avantage de la distribution de la signalisation par satellite.

Le chapitre 2 aborde les problèmes liés à la simulation des réseaux MANET. Le choix du simulateur de réseau OMNeT++ est justifiée en raison de son caractère open-source, sa facilité d'extension et d'apprentissage. Enfin, l'importance du choix du modèle de mobilité est mise en évidence. Le modèle de mobilité random waypoint est présenté comme le modèle de mobilité générique le plus populaire pour l'évaluation de protocoles de routage MANET. Toutefois, les faiblesses de ce modèle de mobilité pour représenter des situations réalistes sont remarquées. La mobilité de groupe avec point de référence est alors proposée comme un cadre pour décrire des schémas de mobilité de groupe plus complexes.

Le chapitre 3 traite des caractéristiques de la topologie de MANET. Il montre que le comportement du protocole de routage dépend du scénario et introduit un ensemble de mesures pour le caractériser: le partitionnement du réseau, la densité du réseau, le nombre de sauts des chemins les plus courts et la durée de vie des liens. Ces mesures ont un impact sur le comportement et les performances des protocoles de routage. Par exemple, une durée de vie de lien courte entraînera des ruptures de routes tandis que les réseaux de grand diamètre sont plus critiques pour les protocoles de routage, car il y a plus de chance de faire face à une rupture de route avec un nombre élevé de sauts.

Toutefois, ces mesures ne peuvent pas toujours expliquer le comportement des protocoles de routage MANET. Les résultats ne dépendent pas uniquement de la topologie de l'ensemble du réseau, mais des propriétés des itinéraires suivis par le trafic de données. Pour cette raison, deux mesures pour caractériser les routes entre deux noeuds spécifiques sont proposées: le nombre de sauts de la route le plus courte et la durée de vie de la route. Il est important de coupler les mesures précédentes avec les modèles des scénarios MANET afin de comprendre le comportement du protocole de routage résultant.

Le chapitre 4 décrit un scénario typique d'évaluation générique de protocoles de routage MANET. Comme dans la plupart des simulations MANET trouvées dans la littérature, nous utilisons le modèle de mobilité *random waypoint*. Toutefois, une modification est introduite. Les noeuds source et destination du trafic de données ne sont pas mobiles et la distance entre eux est paramétré afin de tester la façon avec laquelle les protocoles de routage font face à des longueurs de route différentes.

Le chapitre 5 complète le scénario générique avec une approche plus réaliste. Une opération de lutte contre les incendies est adoptée comme un exemple d'un scénario d'urgence MANET. La contribution principale de ce chapitre est le développement d'un modèle de mobilité propre pour décrire le mouvement des unités de sapeurs-pompiers lors d'une opération des feux de forêt: le modèle *fire mobility*.

Le chapitre 6 présente les principales contributions dans le protocole *Optimized Link State Routing*. Une première approche est prise avec le protocole OLSR-SAT, une modification OLSR qui substitue au mécanisme par défaut de diffusion *multipoint relay* du protocole OLSR un canal de diffusion par satellite dédié. Cependant, les noeuds d'un réseau OLSR-SAT doivent tous avoir accès au canal satellite pour obtenir les informations de signalisation diffusées. Il s'agit d'une solution irréaliste et incompatible avec le protocole OLSR. Pour cette raison, le système *multipoint relay* du protocole OLSR et le système de diffusion par satellite du protocole OLSR-SAT sont combinés pour créer le protocole OLSR-hybride (OLSR-H). La solution est compatible avec le protocole OLSR, c'est à dire, plusieurs noeuds avec des capacités satellite en exécutant OLSR-H peuvent être introduits dans un réseau OLSR traditionnel afin d'améliorer la distribution de la signalisation. La dernière amélioration du protocole OLSR traite du calcul des tables de routage. Nous avons constaté que l'algorithme par défaut de calcul de routes de OLSR utilise un graphe orienté, mais OLSR fonctionne uniquement avec des liens bidirectionnels. Cela signifie que les liens opposés du graphe orienté sont également des liens valides du réseau. Par conséquent, l'extension EXTRA considère un graphe non orienté dans le calcul d'itinéraire offrant plus de routes entre les noeuds du réseau.

Enfin, le chapitre 7 montre les résultats des simulations pour les scénarios générique et spécifique. On remarque l'importance des flux de données dans la simulation MANET. Nous obtenons des valeurs différentes de délivrance des données en fonction de la longueur des routes entre les noeuds source et destination. Nous concluons que l'élection de ces noeuds a un impact sur le comportement du protocole. En ce qui concerne la signalisation du protocole OLSR, les protocoles OLSR-SAT et OLSR-H évitent les contraintes de la transmission terrestre sans fil en termes d'erreurs de bits et de collisions. Nous remarquons une augmentation du nombre de noeuds couverts dans la diffusion des messages `tc` si on introduit les transmissions par satellite entre plusieurs des noeuds du réseau. En outre, plus de renseignements sur la topologie sont donnés, les tables de routage affichent moins de lacunes résultant en une diminution des erreurs dans la transmission de données de bout en bout. Un résultat significatif est l'amélioration de l'ordre de 8 % dans le taux de délivrance des données pour les routes longues (environ 7 sauts) avec la présence de seulement quatre terminaux satellites dans un MANET de 28 noeuds. En ce qui concerne l'algorithme de calcul de routes, l'extension supplémentaire améliore également le taux de livraison de données d'environ 4 % dans les routes longues pour toutes les variances d'OLSR. Cependant l'extension EXTRA n'implique aucune modification de la signalisation ou des données stockées dans les noeuds, seul un changement dans le calcul de ses tables de routage locales apparaît.

Avant de décrire les orientations futures de ce travail, les paragraphes suivants présentent un résumé des contributions.

Notre première contribution est d'examiner l'utilisation des transmissions par satellite pour optimiser le fonctionnement d'un réseau terrestre. La plupart des propositions présentées jusqu'à présent ont porté sur le plan de données. À notre connaissance, utiliser le satellite pour l'extension du plan de contrôle d'un réseau MANET n'a jamais été étudié auparavant. Pourtant, il s'agit d'une approche sensée car le débit considéré est dans l'ordre de 100 octets par seconde et par noeud, ce qui ouvre la voie à des transmissions satellite à faible coût et à faibles contraintes dans la conception des antennes.

Notre deuxième contribution est le modèle de mobilité *fire mobility* qui représente le déploiement et le mouvement des unités de pompiers au cours d'une opération de lutte contre les incendies. Cette contribution est important pour deux raisons. Premièrement, l'évaluation des performances MANET dépend des paramètres du scénario. Il est donc tout aussi important de considérer un modèle de réseau proche de la réalité pour garantir que les résultats seront pertinents. Deuxièmement, la modélisation des situations d'urgence d'un point de vue réseau est à peine abordée dans la littérature (principalement parce que c'est une question difficile, qui exige un savoir-faire sur le terrain ou le transfert des connaissances auprès des utilisateurs finaux). Il a été identifié comme une priorité par la Commission Européenne afin de se préparer à la gestion efficace des catastrophes [66].

Notre troisième contribution est l'extension du protocole de routage OLSR avec OLSR-H. En équipant une petite quantité de noeuds (4 sur 28) avec des installations satellites, on obtient une amélioration du ratio de délivrance jusqu'à

8 pour cent. Les raisons de cette amélioration ont été identifiées (à savoir la fiabilité du satellite dans la remise des messages `tc`). Pour la même raison, nous croyons également que l'extension OLSR-H permettra d'écouler des charges plus élevées de trafic ou avec plus grand nombre de noeuds par rapport au protocole OLSR.

Notre quatrième contribution réside dans la proposition du protocole OLSR-EXTRA qui, sans modifier la signalisation de `tc` ou `hello`, améliore la robustesse du calcul de routes.

Enfin, ce travail de thèse a été une bonne occasion de mesurer la difficulté d'organiser des campagnes de simulation MANET fiables. La méthodologie que nous avons utilisée vise à atteindre un bon équilibre entre simulations maniables, fidélité à un contexte de déploiement et validité des résultats.

Perspectives

Les paragraphes suivants présentent des perspectives pour ce travail. Elles sont organisées en propositions à court terme et à long terme.

Court terme La solution proposée de routage peuvent être évaluées dans plus de situations. Par exemple, nous avons pu tester le comportement du protocole de routage dans un réseau chargé en augmentant le nombre de sources de données et / ou de leur débit. Dans cette situation, on peut s'attendre à une augmentation du nombre d'erreurs dans le trafic terrestre de signalisation. OLSR-H pourrait donc profiter de cette situation.

La proposition précédente ouvre une autre piste de travail: l'amélioration de la surcharge de signalisation du protocole OLSR-H. Nous subissons une augmentation de la surcharge due à la diffusion des messages `tc` dans OLSR-H. Nous avons conclu que l'inclusion d'un facteur externe (les terminaux satellite) modifie le mécanisme de *multipoint relay* du protocole OLSR. Utiliser des informations sur les terminaux satellite dans le choix de relais multipoint permet d'optimiser la surcharge produite pour la diffusion des messages `tc`.

Long terme Nous nous sommes concentrés sur le protocole *Optimized Link State Routing* dans ce travail. Cependant nous avons souligné d'autres protocoles de routage MANET en tant que candidats pour profiter de communications par satellite. Par exemple, le *Dynamic Source Routing* (DSR) pourrait être modifié pour permettre aux noeuds d'échanger des routes connues par le satellite. En outre, les services de localisation pourrait profiter de communications par satellite pour partager la position des noeuds.

Jusqu'alors, nous avons supposé que OLSR-SAT ou OLSR-H serait mis en oeuvre dans les noeuds qui font partie du réseau. Une autre direction devrait être étudiée où le réseau est maintenu tel quel, mais il est complétée par des équipements satellite dédiés contribuant (i.e., capture et circulation) au trafic de signalisation. Ces équipements seraient situés dans des endroits stratégiques du réseau.