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A Novel Ferry Assisted Greedy Perimeter Stateless Routing Protocol (FA-GPSR) for *Ad-hoc* Networks in Remote Locations

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Copyright statement

I would like to dedicate this thesis to my loving Mother, Wife and to my father's soul who died during my study and now he is not here to share the happiness of my graduation.

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List of Publications

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Abstract

Network functionalities play a major role in the connectivity and routing in an *Ad-hoc* networks because end user devices must contribute in routing and therefore maintain connectivity. In dynamic environments with mobile nodes, routing becomes very challenging; this challenge becomes even more burdensome if a network is deployed in larger areas. Therefore, in order to avoid centralisation and bottlenecks, routing algorithms in *Ad-hoc* networks should not depend on any specific node. Furthermore, these algorithms should be able to support routing in sparse topologies when the density of the nodes is very low in a large deployment area.

The rationale behind this research project stems from the lack of sufficiently effective solutions for wireless networks deployed in large areas where the node's mobility creates what is called the Loosely Coupled Nodes Problem. Therefore, this gap in knowledge needs to be addressed by developing a novel and scalable routing protocol, which can utilise application characteristics to stabilise routing between loosely coupled nodes in a large deployment area. This research proposes a new routing protocol to address this gap by increasing the number of packets delivered to their final destinations in an *Ad-hoc* networks.

As another gap, very few current approaches deal with realistic situations, based on real-life case scenarios, in order to evaluate and enhance the accuracy of their *Ad-hoc* network protocols, and thus they cannot accurately approximate common real world environments [1]. Therefore, this project addresses research issues directly linked to evaluation of protocols and architectures in use cases and applications in real life scenarios.

The novel routing algorithm, Ferry-Assisted Greedy Perimeter Stateless Routing (FA-GPSR), proposed in this thesis demonstrates the

benefits of extracting information from the application to support communication between the nodes in the network topology. In addition, this approach highlights the advantages and disadvantages of the efficiency and reliability of communication in open large areas of deployment.

A simulation model of the proposed algorithm has been implemented and its features investigated through simulation runs. The communication between nodes in the topology show that FA-GPSR outperforms the other routings in terms of packet delivery ratio, especially in sparse networks, where the density of nodes is low. The mobility of the destination nodes affected the packets delivery ratio by decreasing the ratio, compared to other cases because of the changes in the location and node velocity. By increasing the number of packets and source nodes, FA-GPSR outperformed the other algorithms because of the efficient use of the patrol node (ferry). Thus, the comparison of FA-GPSR to these algorithms supports the conclusion that FA-GPSR is suitable for use in large open areas with the effect of node density and packet load.

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Acronyms

AODV	***A**d-hoc* **O**n-demand **D**istance **V**ector
AOR	**A**rea **O**f **R**esponsibility
BATMAN	**B**etter **A**pproach **T**o **M**obile ***A**d hoc* **N**etwork
BZGFS	**B**uffering **Z**one **G**reedy **F**orwarding **S**trategy
C2C	**C**ar-to-**C**ar Communications
C2I	**C**ar-to-**I**nfrastructure Communications
C4I	**C**ommand, **C**ontrol, **C**omputer,**C**ommunication and **I**ntelligent
DP	**D**ivisional **P**erimeter
DREAM	**D**istance **R**outing **E**ffect **A**lgorithm for **M**obility
DSDV	**D**estination **S**equence **D**istance **V**ector routing
DSR	**D**ynamic **S**ource **R**outing
DTN	**D**elay **T**olerant **N**etwork
DT-DYMO	**D**elay **T**olerant **D**ynamic **M**ANET **O**n-demand routing
EAR	**E**fficient **A**daptive **R**outing
FA-GPSR	**F**erry **A**ssisted **G**reedy **P**erimet**S**tateless **R**outing algorith
GeoDTN+NAV	**G**eographical and **D**elay **T**olerant **N**etwork with **NAV**igation assistance

GeOpps	**G**eographical **O**pportunistic routing
GF	**G**reedy **F**orwarding
GPCR	**G**reedy **P**erimeter **C**oordinate **R**outing algorithm
GPS	**G**lobal **P**ositioning **S**ystem
GPSR	**G**reedy **P**erimeter **S**tateless **R**outing algorithm
ICT	**I**nformation and **C**ommunication **T**echnology
ITC	**I**ntelligent **T**ransportation **S**ystem
MAC	**M**edium **A**ccess **C**ontrol
MANET	**M**obile ***A****d hoc* **Net**work
MF	**M**essage **F**erry
NS2	**N**etwork **S**imulator **II**
NS3	**N**etwork **S**imulator **III**
OLSR	**O**ptimised **L**ink **S**tate **R**outing
SCF	**S**tore **C**arry **F**orward
SMON	**S**tructured **M**esh **O**verlay **N**etworking
STAR	**ST**orage **A**ware **R**outing
VANET	**V**ehicular ***A****d-hoc* **Net**work
VNI	**V**irtual **N**avigation **I**nterface
WMN	**W**ireless **M**esh **N**etworks

Chapter 1

Introduction

1.1 Mobile *Ad-hoc* Network

For better understanding of the requirements of sparsely distributed nodes deployed in large environments, we need a detailed investigation of the characteristics and features of mobile *Ad-hoc* networks . In an ordinary computer network, a group of stationary computer devices are connected via network links to exchange data. The wired or wireless mediums can be used to establish network links and connect the nodes in a stationary computer network. However, when the devices are mobile, establishing a reliable connection between nodes becomes challenging. These type of devices require infrastructure-less environment support to establish a network, such as Mobile *Ad-hoc* Network (MANET).

MANET research includes different areas, such as a Vehicular *Ad-hoc* Network (VANET) and mobile networks. As another area, the use of Information and Communications Technology (ICT) in Intelligent Transportation System (ITS) requires the development of an advanced communication model that enables all participants in the traffic to talk to each other. There are European projects focusing on different types of ITS information systems' paradigms, known as the Car-to-Infrastructure (C2I) communications, which develop models for message delivery to/from cars and the Car-to-Car (C2C) communication for enabling cars to exchange data. C2C research is still lagging behind in developing a stable wireless communication environment [6].

Figure 1.1 shows a typical Mobile *Ad-hoc* Network (MANET), which is characterised by roaming node, freely entering and leaving the network, leading to short lived routes and dynamic topologies. In MANET, support from existing infrastructure is often presumed to be insignificant or non-existing which is in contrast with wired and infrastructure-supported wireless networks. Researching efficient routing methods which are able to maintain routes in such a challenging setting has been the main focal point of study in MANET literature[7]. In MANETs, mobile nodes typically collaborate, acting both as forwarders and consumers of messages, in order to achieve connectivity and support services. Military applications has been a motivation for MANET technology, because in most military applications the situation necessitates infrastructure-less environments. The use of such highly dynamic networks, if operating adequately, can be very useful in many cases, such as surveillance and reconnaissance missions, where an established (e.g. cellular) infrastructure is unavailable or unusable. An *Ad-hoc* network with

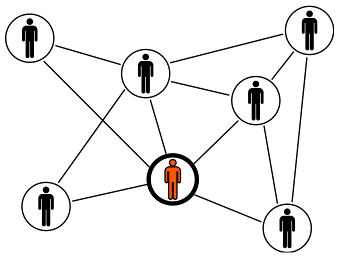


Figure 1.1: *Ad-hoc* network.

very low density of nodes suffers from regular dis-connectivity [8] due to limited transmission range of a node and poor density of nodes. A destination node may not be able to reach the source transmission range all the time. This network is called a partially connected network or sparse ad hoc network.

Network functionalities play a major role in the connectivity and routing in an *Ad-hoc* network because end user devices can contribute in routing and therefore maintaining the connectivity. In dynamic environments with mobile nodes, routing is a challenging problem. The routing algorithms in *Ad-hoc* networks, in order to avoid centralisation and bottlenecks, should not depend on any specific node. In an *Ad-hoc* network, the development of a new and complex structure must happen through the network system itself to enhance the decentralised process. Moreover, the network should organise itself and be able to readjust in a case of a failure to maintain the perfromance of the network. Furthermore, the routing algorithms should be self-healing which is the procure of recovery to rapidly overcome any failures. This process, in particular increases the network performance because it assists with maintaining the network connections. These characteristics are essential for evaluating the routing algorithms in an *Ad-hoc* network.

The Global Positioning System (GPS) and its usage introduced an important evolution in communication technology by providing the location information and universal timing of nodes. The idea of geographical routing is based on the knowledge of the location of the destination to deliver the messages, and it uses the location instead of the network address in the routing process. The destination node location support the idea of using geographical routing to transfer the messages by using the location information rather than the network address scheme in the delivering process. The methods that geographical routing use to deliver the packets are as follows [3] :

- Single-path which means one copy of the packet travel over the network through single known path to the destination node. The techniques used in this type of routing are Greedy Forwarding(GF) or face routing. GF technique has a critical problem, which is called the GF empty-neighbour-set problem where a node cannot discover any neighbour closer to the destination than itself so, the forwarding process achieves a dead-end. To overcome the dead-end problem in GF recovery methods, such as FACE routing, have been proposed in some geographical routing algorithms. The FACE routing is a distributed geographical routing algorithm. The name face comes from the concept of graph-theory for the plan graph where each side of the graph can be viewed as a face.

- Multipath which means few copies of the messages are generated and different routes defined to use for these copies to transmit to the destination nodes.

- Flooding which means that a large number of the messages are generated and broadcasting through the network.

In MANETs, the graph of the network topology is expected to form a bidirectional communication, which indicates that the path of the connection is known to support the forwarding process. On the contrary, Delay-Tolerant Networking (DTN) presumes that the end-to-end path is not available because of high mobility nodes or regular disconnections. Therefore, each paradigm apply different forwarding techniques [9]. MANET and DTN routing protocols are different in terms of their operations [9]. MANET routing applies a control packet to support the build of unicast connection where a single copy of each packet is transmitted. DTN on the other hand, replicates a packet to transmit it to a group of nodes at the same time. The source node stores a number of packet copies in a secondary memory and forwards each copy to any node which is within its transmission range.

1.2 Problem specification

The MANET must be able to accommodate changes in its topology and, if needed, to increase packet delivery [10]. The nodes in the network also need to cooperate to support packets' delivery [10]. In MANETs, maintaining the links between nodes and in advance estimation of packet delivery time is very challenging because the number of nodes in the topology can change the scale of the network and it requires an appropriate algorithm for message delivery [11]. The existing routing in MANET assume that the network density is high so, there is always a connection between nodes [12]. However, lower number of nodes in the topology can add more challenges to the routing process.

Some networks are categorised as sparse networks in which few nodes are distributed in a large area; the packet delivery approach in these networks is completely different from where there is a high number of nodes distributed in the same area, i.e. when the density is higher. The different number of nodes, i.e. different node densities, can add new challenges in MANET routing, especially the aspects related to the work domain, forwarding capability and network traffic. In addition, deployment of a network in a large area adds another challenge in MANET routing. In the communication between the nodes, for example, due to node location changes it can cause a regular disconnection between nodes and a link break.

The rationale behind this research project stems from the followings:

- the lack of sufficiently effective solutions for wireless network deployment in large areas where the node's mobility creates what is called the Loosely Coupled Nodes Problem. Therefore, this gap in knowledge needs to be addressed by developing a novel and scalable routing protocol, which can utilise application characteristics to stabilise routing between loosely coupled nodes in a large deployment area. The utilisation of the application characteristics to support the cooperative work between nodes to enhance a network performance, to our best knowledge, has not been yet studied. The research addressed this gap and in particular this new routing protocol aims at increasing the number of packets delivered to the final destination.

- The fact that very few current approaches deal with realistic, based on real-life case scenarios, situation models in order to evaluate and enhance the accuracy of their *Ad-hoc* network protocols, and thus they cannot accurately approximate common real world environments [1]. Therefore, this project addresses research issues directly linked to evaluation of protocols and architectures in use cases and applications in real life scenarios.

Validation use-case scenario

Information plays a major role in the modern battlefield since the introduction of the concept of battlefield digitalisation by controlling a determining stake for the armed forces. To achieve the requirements of a digital battlefield, we should have an architecture of wireless network, which automatically adapts to variable topologies and performs auto-configuration and dynamic routing. This architecture should work in the situations where there are node mobilities, the absence of nodes, and nodes temporal presence in a network. As an example, we can consider the architecture of a mobile ad hoc-network – one of the networks that tries to develop such requirements in different environments. The increasing need for interoperability for data transmission architecture in the battlefield for joint and allied forces has made the use of commercial off-the-shelf technologies and products in telecommunications protocols an important resource for Defence C4I (command, control, communication, computer, and intelligence) systems [13]. An architecture with distributed control is essential, and centralised functions should be limited to optimisation capabilities. Autonomous packet radio networks are essential because of their ability to be operational rapidly and without any infrastructure. Military requirements and constraints make MANET more pertinent relative to the brigade-and-below tactical unit levels for example, the battalion.

Despite military application being the preferable environment for an evaluation of MANET routing, the real military scenario to validate routing protocol does not exist. Military applications have unique characteristics [14] that influence the network topology. These characteristics include:

- Chain of commands in the deployment field should be followed. This has a direct effect on the design of MANET topology.
- The military mission is the basis of the deployment of any military unit. This requires unit members to cooperate to complete a mission successfully. Military mission specification can be used to predict a unit's member movement in the topology.

1.3 Aims and Objectives

While the general principals of MANETs are well known, when it comes to specific types of applications the principles behind providing support for such applications are not well investigated. This is especially true for application that employ collaborative approach in achieving the intended results.

The main aim of this project is to propose and evaluate a novel hybrid routing protocol for wireless mobile *Ad-hoc* networks deployed in a wide area to lessen the effect of the loosely coupled node problem. This is especially useful when we consider remote locations where the only services available reside within the nodes themselves. The project aims to investigate the possibility of gaining *Ad-hoc* cooperation information generalisation, and determine how the functionality of the *Ad-hoc* node affects the quality of the wireless traffic information systems when collaboration is involved. It will investigate the possibility of designing, implementing and modelling the routing protocol of such an intelligent *Ad-hoc* network support that will be at the same time active participant in the formation, routing and specialised collaborative application network support for MANETs. Furthermore, the investigation will consider the use of knowledge derived from the application characteristics to improve the performance of the network. The work presented in this thesis focuses on the communication between stationary nodes, the communication between mobile nodes, and the communication between stationary and mobile nodes; it also studies the essential cases of real-life communication scenarios.

The objectives of this research project have been identified as follows:

- Review the existing protocols and research studies in the area of mobile *Ad-hoc* networks;
- Evaluate the existing routing protocols with a comparative study on their performance in the area of mobile *Ad-hoc* networks;
- Optimise geographical routing protocol named Greedy Perimeter Stateless Routing protocol (GPSR) [15] in a real military scenario to achieve high network performance and to increase packet delivery ratio using predefined knowledge from the military unit deployment.

These research efforts are expected to lead to the creation of a clear technical basis for dealing with the aforementioned problems regarding node connectivity in MANETs.

1.4 Methodology

The research process in this thesis is designed in four stages. Firstly, a number of metrics will be defined which will be used for measuring the performance of routing algorithms in MANET.

In the second stage, these metrics will be used to evaluate and compare similar routing approaches which are already available for MANET. To achieve this stage described above, the research work will implement a real case scenario inspired by military unit deployment in a network simulator (NS3) and this implementation will be used to compare the performance of three state of the art GPSR [15] [5] [4] routing protocols using a real case scenario. The factors that influence algorithms performance and cause a degradation in the network performance will also be defined. The performance of these routing protocols are expected to be poor because of the large simulation area and limited number of participating nodes as a result of a sparse network. This stage can shed the light on identifying the problem of routing in MANET and thus proposing/designing a new approach to address them.

Third stage in this thesis is the actual implementation of the proposed algorithm and evaluating it against similar approaches in MANET. This will help in identifying the limitations of the new routing algorithm. A new model will be implemented that uses the knowledge derived from the application characteristics to establish the routes through network nodes. The new implemented optimisation will be based on a real military application scenario and can be used to demonstrate if it performs any better than previous approaches. The new idea will involve using the patrol node as a special node to disseminate messages when needed.

We propose a novel hybrid routing protocol in which the packets that would be dropped due to route failure are delivered expediently through the network until they reach a node that it is able to establish connection to create an end-to-end path to the destination node. Therefore the approach leverage's the potential partial end-to-end routes that can be created in the mobile network. This hybrid protocol not only improves the packet delivery ratio of end-to-end routing protocols, it will also improves the efficiency of MANET protocols.

In particular, this thesis proposes a ferry-assisted version of GPSR to overcome the recovery mode problem caused by regular disconnection. The proposed algorithm extends the default GPSR protocol to use a message retention mechanism and re-attempts to forward packets when the regular forwarding options have failed. This new GPSR function is based on knowledge derived from the structure of the military topology and makes use of patrol units that exist in it.

Moreover, the combining bidirectional routing algorithms and Delay/disruption Tolerant network algorithms have been tested with other reactive routing protocol such as AODV [16]; and has been shown to deliver promising results and improve clustered-based routing algorithms[17] [18]. In addition, the technique is used to optimised proactive routing algorithms[19] and others[20].

The new approach will involve knowledge of nodes whose position is already known from unit deployment (approximately), such as guard posts and surveillance patrol nodes. The thesis will introduce the new optimisation using ferry nodes which are involved in deployment, can protect the network from the constant disconnection, help in increasing the packets delivery rate and minimise the end-to-end delay. Then, the thesis will simulate the new model network using NS3 simulator, evaluate the new model using the real scenario case study and compare the results with the existing routing algorithms available in the literature.

Considering that the topology parameters reflected a realistic scenario, we focused on discovering a routing protocol optimisation tailored to the particular conditions rather than proposing changes in the military operational parameters.

In the final stage, the new algorithm will be optimised to reduce the limitations imposed by the new design and the optimised solution will be evaluated.

1.5 Original Contributions

OC1: **Novel approach to utilising information derived from application characteristics to increase path stability for loosely coupled nodes in MANET**

This novel approach requires close study of applications to identify the characteristics which can help to develop a new routing algorithm and these characteristics closely linked to real-case scenarios.

The use of real-case scenario is a contribution of this thesis to evaluate the performance of the existing routing in the literature for validation and evaluation.

Each application has its own characteristics that distinguish it from other applications. Defining these characteristics requires the implementation of real-case scenario to study and analyse the application characteristics. As mentioned in Section 1.3, there are few studies use case scenarios in the literature and most of the existing routing algorithms have not been validated and evaluated by using a real-case senario [21]. These characteristics could affect the nodes behaviour in the topology, resulting a regular disconnection and changing in the topology.

Military is one of the most important application of mobile ad hoc networks [22]. In this application, there is a chance that the application characteristics are major factors to support or frustrate the communication between elements. The contribution here is the implementation of real-case study inspired from the deployment of a military unit in the battlefield (Chapter 3) to demonstrate how the application characteristics can enable such possibilities. This thesis considers the use of a real case study to show how the application characteristics influence node's behaviour, which can potentially affect the routing performance in wireless ad hoc networks.

In addition, this case-study is used to evaluate a well known geographical routing algorithm and two of its variants to validate the possibility of the effect of application characteristics to the routing in MANET. The geographical routing algorithms are used in this thesis because these algorithms support the use of location information for routing purposes. In the military domain, the units are usually equipped with communication devices that support GPS technology. Furthermore, the military unit elements, in the case of any device failure in determining the location, are able to use paper maps to define a location. Dealing with and reading paper maps are considered as essential knowledge in a military domain.

OC2: **Designing Ferry-Assisted Greedy Perimeter Stateless Routing protocol (FA-GPSR)**

The novel approach described above leads to the design of FA-GPSR algorithm. The FA-GPSR algorithm (Chapter 4) is a new hybrid geographical routing protocol designed for loosely coupled nodes in MANET, as shown in Figure 1.2. Obviously, the algorithm contributes to achieving the goal of increasing message delivery and efficiency and reliability of transmission by addressing the problem of regular disconnection caused by node deployment in large areas and the application characteristics. To optimise network performance, the protocol fully exploits the application characteristics for the

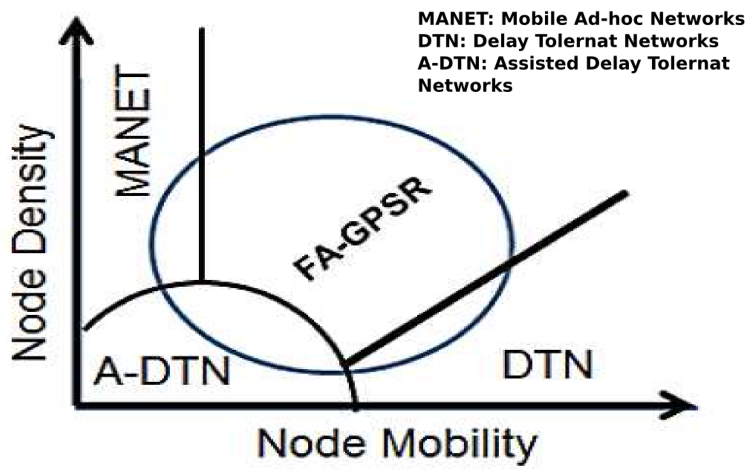


Figure 1.2: Defined network pardigim based on mobility and density where FA-GPSR can apply.

benefit of forwarding the messages in case of a dead-end problem. Novelties incorporated in the algorithm include:

- **Employs the Store-Carry-Forward (SCF) principle to support GPSR protocol**
  The FA-GPSR is a hybrid geographical algorithm proposed to use a node that can support the cooperative work because its duty is to travel around the topology area. In military, there is an element responsible for monitoring a unit area's of responsibility and supporting the security aspects, such as controlling the rotation of the guards in the battlefield. This element can support communication between nodes in a cooperative manner by carrying a message that cannot be forwarded due to network partitions.

- **Incorporate SCF scheme without an effect on the duties of the nodes**
  The SCF paradigm or Message Ferrying (MF) is one of the techniques used in Delay Tolerant Networks (DTN). The principle of MF is to take advantage of the predictability in device movement to deliver data [23]. A node that needs to contact a ferry prioritises the message forwarding

or receiving process over its duty. FA-GPSR apply the MF scheme without forcing the nodes to leave their duties by updating the message header with the ferry node address. In the same time, the original destination node address is saved to be used by the ferry to deliver the messages.

OC3: **Designing and implementation of real case scenario and simulation model for the evaluation of FA-GPSR**

The real-case study implemented in network simulator (NS3) as a platform for the evaluation and validation of the routing algorithms. The GPSR variants introduced by Wei et al. [4], which employs a strategy termed the Buffering Zone Greedy Forwarding Strategy (BZGFS) and by Guoming et al. [5], which is a Divisional Perimeter (DP) forwarding algorithm are not available for public use, so they are implemented from scratch in NS3 in this thesis for comparison purposes. Moreover, the novel algorithm is implemented and validated against the geographical routing in NS3. These implementations are done to establish a complete model to evaluate a mobile *Ad-hoc* wireless network based on a real-case scenario.

1.6 Thesis Structure

The thesis is structured as follows:

Chapter 1 (this chapter) introduces the research area and outlines the research problems that are addressed in this project. It also defines the aims and objectives of this research and lists all major research contributions of this work.

Chapter 2 provides an overview of the fields of *Ad-hoc* networking and its relationship to the military domain as well as the related work and essential literature for the following chapters. First, a general overview and introduction to routing protocols in mobile *Ad-hoc* networks (MANETs) along with a taxonomy are presented. Second, we introduce GPSR protocol, including the subsequent optimisation performed on the original GPSR techniques to increase performance. Third, it provides an overview of DTN routing and illustrate a SCF paradigm used in DTN. This chapter also provides an overview of the work done in terms of combining MANET and DTN techniques to take advantage of the strengths in each network type. Finally, there are current simulation issues delivered, including various simulators and methodology explanations.

Chapter 3 introduces the military real-case scenario and presents the command hierarchy and military unit features. In addition, GPSR variants (GPSR-DP, GPSR-BZGFS) are implemented and analysed against the default GPSR in real case scenarios. Then we present the result of the evaluation to compare the three routing algorithm's performance. The chapter discusses the results of how the application characteristics and node's behaviour affects the network. The final section of this chapter focuses on application information and discusses the utilisation of such information to enhance routing in MANET.

Chapter 4 presents the technical details of FA-GPSR algorithm. The intent of this algorithm is to increase the packet delivery ratio by utilising the information derived from the application to optimise the GPSR routing protocol. The SCF mechanism is described with several events to explain terminology, procedure definitions and algorithm presentations. In addition, simulation experiments conducted and their results are presented in this chapter to evaluate the proposed algorithm and compare it with the algorithms described in Chapter 3.

Chapter 5 introduces experiments conducted to calibrate the proposed algorithm to minimize end-to-end delay. The proposed algorithm is based on the use of the ferry node, so increasing the number of ferries and the ferry buffer is investigated in this chapter.

Chapter 6 presents the abridged essential results and concludes the research presented in the previous chapters and proposes a baseline for future works.

Chapter 2

Related Work

2.1 Overview

The first part of this chapter is a brief review of *Ad-hoc* networking and military tactical communication, in order to augment the understanding of the work reported in this thesis. The chapter then presents a review of routing protocols in Mobile *Ad-hoc* Networks (MANETs) and their taxonomy. Greedy Perimeter Stateless Routing protocol (GPSR) along with the subsequent techniques for optimisation applied on the original GPSR are also reviewed in this chapter.

In addition, it covers the Delay Tolerant Networking (DTN) and opportunistic routing in such network and outlines a store-carry-forward paradigm used in DTN. Furthermore, this chapter introduces the previous works in terms of integrating MANETs and DTNs to take advantage of the strengths in each of these networks resulting in a hybrid routing algorithm that can work in different types of networking architecture. In the final sections, the integration between MANET and DTN is considered to show that the combination of the two types could increase the performance in new algorithms.

2.1.1 *Ad-hoc* network

An ad hoc network is 'the cooperative engagement of a collection of mobile nodes without the required intervention of any centralized access point or existing infrastructure' [24]. From this definition we can recognise that the two most important characteristics of ad hoc networks are the cooperation between nodes and the autonomous management. This section will provide a brief overview of ad hoc network types, their characteristics, the standards and current approaches, the routing protocols and the applications.

2.1.1.1 *Ad-hoc* network types

Wireless Mesh Networks (WMNs) One of the general form of ad hoc networks is the mesh network that is made up of mesh routers and mesh clients, as shown in Figure 2.1. Mesh routers are connected to each other in a multi-hop manner, resulting a comparatively stable network. The clients communicate with the routers via wireless or wired links. The routers in wireless mesh networks most commonly act as relays to other routers or as Internet gateways.

The wireless mesh networks were quickly developed to provide a few miles connectivity, and as such, are better suited as a solution for metropolitan area networks [2]. One of the benefits of WMNs is the possibility of increasing the number of mesh routers, resulting in more coverage in an area. Researchers have been motivated to develop the characteristics of WMNs and to examine their performance. WMNs make use of transceivers using the IEEE 802.11 standard because they are affordable and easy to deploy; these characteristics have stimulated rapid growth in WMNs. Future research will continue to use other standards such as WiMAX [25] and 3G/4G to develop WMNs over 802.11. One of the most important research topics in WMN is their routing protocols and the self-configuration of their nodes.

Mobile *Ad-hoc* Networks

Mobile Ad hoc Networks (MANETs) are similar to WMNs in terms of general form of ad hoc networks. Both use the same communication technology to establish the network. Research on MANETs is mainly focused on the mobility of the nodes, which affects the performance of the network. Importantly, the mobility of the node will not help in building a solid backbone as in WMNs. All nodes in a MANET work together to manage network communication by establishing routing protocols for sending packets to others [3], whilst taking into consideration that the device's heterogeneity could be limited. Most research on MANETs relates to

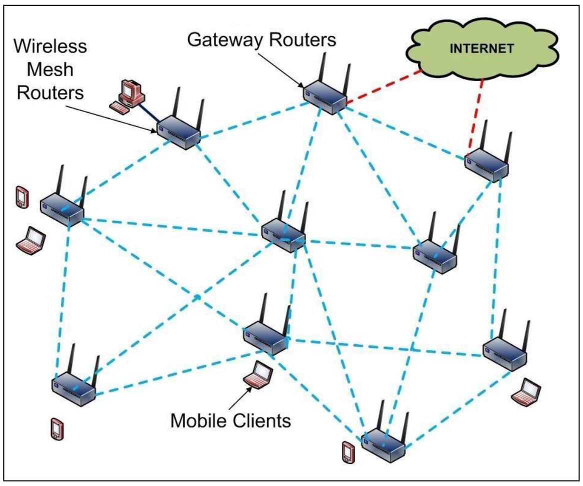


Figure 2.1: Wireless mesh network architecture [2]

routing protocols and mobility models.

2.1.1.2 Characteristics of MANETs

Recently, the research and development of infrastructureless networks has become increasingly important. MANET is one of the popular examples of wireless networking that work without the support of wired infrastructure. It is a group of mobile nodes communicating through wireless communication. Direct communication between the nodes is only possible via the neighbouring nodes. Therefore, connecting to remote nodes is based on multiple-hop fashion. The key characteristics that differentiate a MANET from other wired and wireless networks are:

- ***Infrastructureless*:** In MANETs, mobile nodes typically collaborate, acting both as forwarders and consumers of messages in order to achieve connectivity and support services. There is no prior organisation or any base station requirements. The role of a node in such a network is based on situational needs, and, as such, nodes can work as routers or gateways to support the processes participating in a network [26].

- ***Dynamic Topology*:** The nodes in MANET's are free to move; therefore, certain nodes can be in or out of the transmission range of the others and so links and topology can change, resulting in disconnection between nodes [26].

- ***Low and Variable Bandwidth*:** The links that nodes use to communicate with each other in a MANET are more limited than the ones used in stationary networks due to the effects of multiple access, multi-path, fading, noise and environment and signal interference [27]. The throughput in wireless networks could be less than the radio's maximum capacity. The communication capabilities are also limited due to battery power restrictions; the networking activities in light mobile devices consume nearly half of the overall power consumption [28].

- ***Short Range Connectivity*:** Connectivity is the representation of the available path for communication using short range technologies. It depends on the radio radius, the density of the nodes and the changes in the topology. The nodes need to be located close together to communicate with each other. Remote nodes that lie outside the transmission range need to use multi-hop routing techniques to overcome the short range problem.

- ***Self-contained*:** A MANET is self-contained, therefore each node is responsible for discovering other nodes with which it can communicate in a dynamic topology. The nodes in a MANET organise themselves to establish mobile ad hoc networks. Each node administrates its own resources and participation in forwarding the packets to other nodes.

2.1.1.3 MANET Challenges

There are several important challenges arising from the characteristics of MANETs. These include challenges in designing, implementing and deploying MANETs in some applications and are derived from specific application requirements. Military applications, for instance, have a number of specific requirements, such as privacy, tolerance, accuracy and flexibility [29].

Applications with sensitive data must not be accessible to the outside world when using MANETs, otherwise, they may be destroyed or the success of a mission may be jeopardised. Moreover, because the effectiveness of deploying such a system in the field is associated with the life of the device's battery, power consumption may be an issue in terms of creating a tolerant network. Furthermore, accuracy is vital, as inaccurate information may result in the making of erroneous decisions.

The most important challenges affecting the design and deployment of a MANET in general and in the military context in particular are listed below. Later in the chapter, details will be provided for the most important one which is routing protocols:

- ***Routing:*** The process of discovering the route from source node(s) to the destination node(s). The most common problem in routing protocol is the mobility of the nodes [28].
- ***Security:*** In special applications, such as in the military, communications security is an important issue. A MANET is an open architecture that could be employed in an open area, leading to a dynamic network topology using a shared wireless medium. This characteristic can pose significant challenges in designing secure MANETs in military applications that require increased protection and achievable network performance [30].
- ***Multicasting:*** In MANETs, there are single source(s) and single destination(s) or multiple sources and multiple destinations when packets are exchanged and some nodes work as routers between them. Multicasting is a way to transmit packets to more than one destination. If there are multiple senders in a group multicast, the multicast protocols may fail due to certain MANET characteristics, such as dynamic topology, resulting in inconstant updating of the delivery path, thereby changing the group membership [31].
- ***Medium Access Scheme:*** Medium access control (MAC) performs an important role in coordinating channel access among the MANET nodes to get packets get through from one node to another. However, in MANETs, wireless channel MAC coordination is not always reliable as it suffers from path loss and interference. The dynamic characteristics of a MANET result in continuous topology changes that cause route breakages requiring re-routing [32][33].

- ***Management:*** The domain of management covers different aspects. Quality of services is a way to prioritise different applications, users, or data flow, or assure a degree of performance level when the network capacity is in low density, especially for near real time applications [34]. Energy management and the size of device employed in a MANET leads to the use of a small battery with a short life, and consequently, short participation time in a network forwarding scheme. Self-organisation [35] and scalability [36] are other aspects related to the management challenges in a MANET.

- ***Transport Layer Protocols:*** The unique characteristics of MANETs affect the Transport Control Protocol (TCP), which is responsible for maintaining and setting up the end-to-end connections. TCP is not capable of differentiating between mobility and network congestion [37].

2.1.1.4 Standards and Current Approaches

The rapid development of ad hoc networks has been mirrored by increased activity from the Institute of Electrical and Electronics Engineering (IEEE) and the Internet Engineering Task Force (IETF) towards the standardisation of the technologies that are used. In particular, the IEEE 802 family of standards covers the networks that use variable-sized packets. Wireless communication standards, such as IEEE 802.11 (wireless local area networks), IEEE 802.15 (wireless personal area network) and IEEE 802.16 (wireless broadband), reflect a sizeable and ambitious standardisation effort.

Packets routing and self-configuration are the main issues in standardising in ad hoc networks. Three important working groups in the IETF have taken responsibility for standardising the technologies in ad hoc networks [38] : 1) the Ad hoc Network AutoConfiguration group (autoconf), which works with issues related to self-configuration characteristics, i.e. assigning address for devices that join the network; 2) the Mobile Ad hoc Network (MANET), which deals with routing protocols; and 3) Routing Over Low power and Lossy networks (roll), which handles routing standard in specialized scenarios.

2.1.1.5 Applications of MANETs

MANETs are potentially useful and promising networks in many areas. These areas can be classified into business and public safety and the military [3][28][39][40]. Some examples of these two types are illustrated below.

- **Business Applications:** Exchanging information in urban traffic has attracted attention of researchers. In this area, vehicles play the main role in establishing wireless mobile communication through modem in-car devices. A networking system in this setting is termed Vehicular Ad hoc Network (VANET) [41]. The use of this system introduces the ability to monitor and control a vehicle's mechanical components. Moreover, it makes it possible for cars to communicate to exchange road information or safety warnings.

  Personal Area Networks (PANs) is another example of business applications. This is an ad hoc system for communication between mobile devices or between mobile and stationary devices, such as students exchanging files or presentations on university campuses. Other examples include sharing information or files inside conferences or family members playing games within a household. Linking with Telecom networks or the Internet provides a PAN with the additional characteristics of extension networks. The concept of ubiquitous computing is a good example of this type of linking, where participants, either transparently or not, interact closely and dynamically with devices in the surrounding environment. Notably, linking to larger networks makes PANs even more useful.

- **Public safety and military applications:** In cases of natural disasters or war, the infrastructure could be destroyed, necessitating the use of a network like a MANET. Emergency and rescue operations could use MANETs for immediate deployment in the destroyed area(s), due to such systems' characteristics of self-configuration, flexibility and mobility to support the rapid cooperative activities. These special characteristics of MANETs make them a considerable favourite in such situations.

  In modern warfare, fighters and unmanned ground or airborne vehicles may be equipped with computing devices to report changes in the battlefield situations and communicate important observations to operational planners and commanders in the field. Such communication plays a major role in intelligence, surveillance, field assessment and tactical operations. Organising agents and soldiers into small groups in order to provide or support a wireless communication network(s) facilitates the relay of information or reconnaissance for enemy movements in the field.

2.1.1.6 MANET Architecture

Using a reference model that describes the layers of hardware and software is a way to represent a network architecture for transmitting data between pairs of devices or enabling the operation of multiple devices in a network. Reference models are used to increase the compatibility between different manufacturers' devices in the network [42][43]. The International Organisation for Standardisation (ISO) proposed the Open Systems Interconnection (OSI) reference model, which consists of seven layers [44].

The OSI layers are ordered from layer 1, which is the lowest, to layer 7, which is the highest, as shown in Figure 2.2. The physical layer is the first or lowest layer followed by a data link layer, a network layer, a transport layer, a session layer, a presentation layer and the highest layer, or layer 7 as application layer.

The Physical layer is responsible for transmission unstructured bits-stream over a communications channel (physical medium). Accessing the physical medium requires dealing with the mechanical, electrical and procedural characteristics. The data link layer is responsible for the coordination of accessing shared medium by different nodes, transferring data as frames with headers to treats as a self-contained entity because if any errors occur in a frame, it will be discarded without affecting others frames, and using a sub-layer called Medium Access Control (MAC) for addressing purpose.

The function of the network layer is routing the data from node to node by creating, maintaining and ending the network connections. Moreover, it responds to generate Internet Protocol (IP) addresses.

The transport layer works as the interface between the three lower layers (physical, data link, network) and the upper three (session, presentation, application) layers. It provides an error-free connection, if so desired, and assures that the data is received as it was originally sent from the source. It offers services for recouping the different quality of services provided by the network layers that are linked to particular types of networks.

The session layer organises and synchronizes the dialogue between two applications layers and manages the data exchange between those layers. The presentation layer is responsible for representing the data during the transferring mechanism between the two nodes. The application layer forms the user interface as application program or distributed information services. The network layer maintains the communication between the nodes in the network and manages any frequent disconnections occurring in the network.

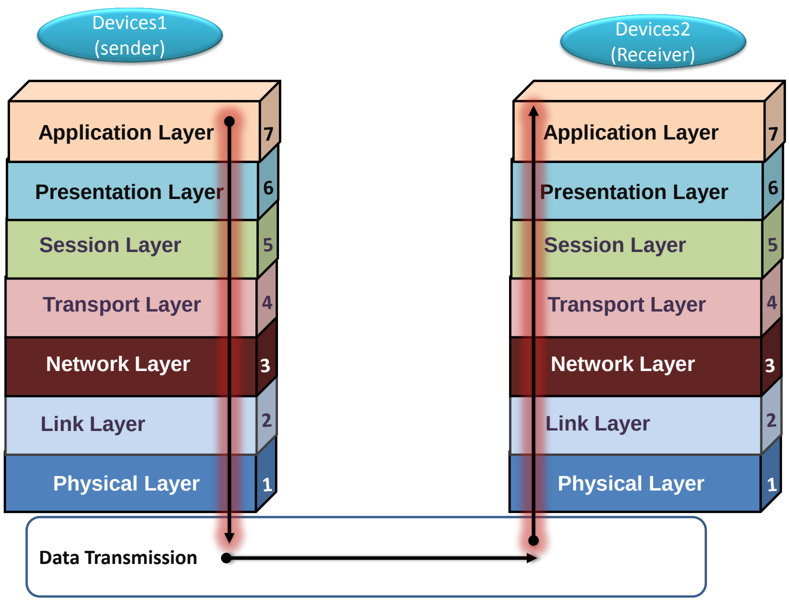


Figure 2.2: ISO-OSI reference model.

The most recommended architecture of MANET in the literatures is based on a 5-layer reference model [45] as shown in Figure 2.3. The layers are as follows:

- Radio layer instead of physical layer in ISO-OSI reference model;
- Link layer;
- Network layer;

- Transport layer;
- Applications layer.

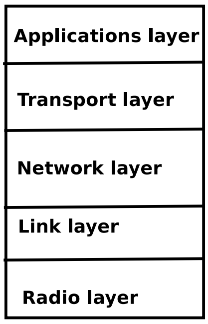


Figure 2.3: MANET reference model.

Basagni et al. merged the layers 5,6 and 7 in ISO-OSI model in one layer in MANET's reference model which is the link layer. The layers 1,2 and 3 are similar without any changes except they have more challenges due to the MANETs nature.

2.1.2 Military networks

Sharing information under conditions of war is an important issue that results in a new paradigm in a modern military concept called Network-Centric Warfare (NCW), which augments military force through communication networks and sharing of information. The NCW philosophy depends on the preponderance of information on the battlefield, the delivery of Internet-like capability in operational areas and on the provision of continuous connection to networks for anytime and anywhere communication.

The most important issues in military networks are security, jamming, changing topology, bandwidth and delay. These issues define the differences between military networks in the battlefield and commercial networks. Indeed, military networks are built to achieve certain goals and objectives, which can be affected by the previously mentioned issues [46].

New forms of military communication play a major role in modern warfare [47]. Military networks have unique characteristics that distinguish them from other types of networks such as :

- They consist of different linked subsystems that are valid and obtainable for providing a light network for the safe exchange of information.

- They have the ability to integrate with different simulation systems to establish a powerful networking environment that can recognise resources and share information in various situations, such as in training or in actual wartime.

- They are capable of using and integrating different types of communication technologies.

2.2 Routing Protocol in MANET

Network functionalities play major roles in connectivity and routing in ad hoc networks. End users can perform routing in addition to maintaining connectivity. Routing poses a significant challenge in dynamic environments with mobile nodes. A critical challenge for researchers lies in increasing the efficiency of routing protocols in MANETs. The role of routing in MANETs is to find and maintain the connectivity between nodes in a dynamic topology. As mentioned in 2.1.1.2 MANETs possess unique characteristics that may affect the efficiency of routing and introduce a challenge to improving routing protocols [3]. One of these important characteristic is the mobility of the nodes, which results in highly dynamic networks with regular changes in topology. Consequently, there may be rapid disconnection between nodes in sparse networks in large topology [26].

To evaluate the performance of routing in an *Ad-hoc* network, it should have the following characteristics:

- *Decentralized:* there is no specific central node controlling routing decisions.

- *Self-organisable:* in case of failure, nodes need to re-organise themselves to improve network performance.

- *Self-healing:* routing needs to be self-dependent, which means routing could be applied to a process for recovery in case of failure.

Routing algorithms can be categorised into three types as follows:

Flat routing schemes, which consists of two types of protocols, similar to those found in wired networks: 1) proactive or table-driven routing protocols, and 2) reactive or on-demand routing protocols.

Hierarchical routing The increasing size of wireless networks has become challenging to flat routing because of the link and processing overhead. To resolve this issue and produce a scalable and efficient solution, hierarchical routing algorithms have been introduced. The idea is to form nodes in small groups and allocating different functionalities to the nodes. Using geographic information to support the establishment of a hierarchical group to design a cluster for each group. Each cluster has a cluster-head node which is the node that can communicate with other nodes outside the cluster

Geographic position assisted routing Introducing the usage of Global Positioning System (GPS) led to an important evolution in communication technology by providing location information and universal timing of nodes. The idea of geographical routing is based on the knowledge of the location of the destination to deliver the messages and using the location instead of the network address in the routing process. Later in this chapter, there are further explanations of geographic position-assisted routing and a well-known routing algorithm called Greedy Perimeter Stateless Routing algorithm (GPSR). GPSR uses two techniques to forward messages to avoid disconnection between the forwarding node and the destination node, which is suitable for military applications [48].

Recently, the challenges posed by MANETs have necessitated the introduction of a new taxonomy in routing protocols. Alotaibi et al [3] present a taxonomy for routing protocols in MANET based on the evolution of routing protocols, in which introducing the unique characteristics of such networks led to novel algorithms, as shown Figure 2.4. This taxonomy includes classical categorisation and introduces Geographical, Multi-casting, Geo-casting, Hierarchical, Flow-aware, Power-aware, Multi-path, Hybrid, and Mesh routing algorithms. The following section presents only the proactive, reactive and geographical routing protocols in detail because this work focuses explicitly and specifically on geographical routing protocols. Proactive and reactive routing protocols are presented here because they are the standard types of routing used in MANETs.

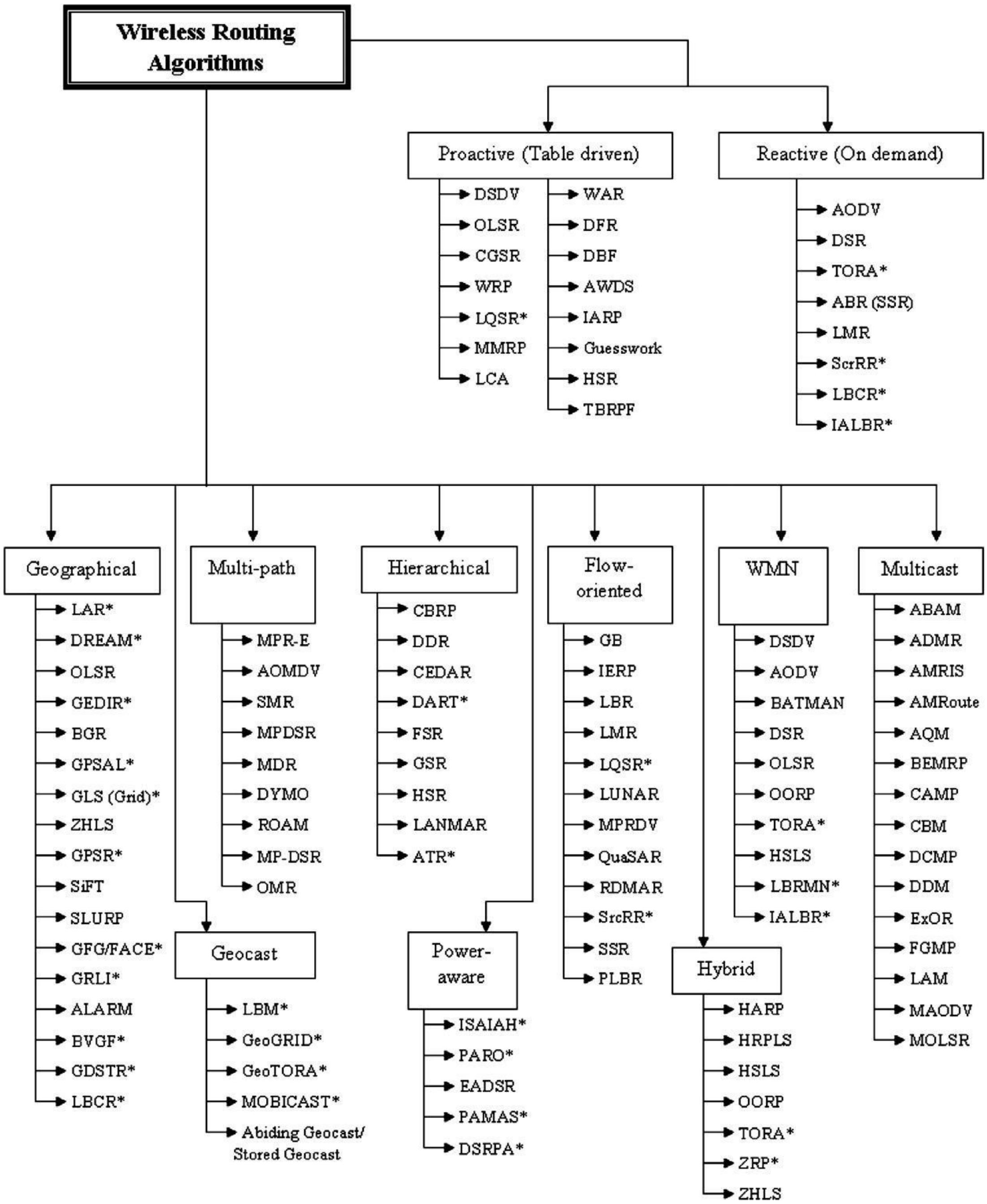


Figure 2.4: A taxonomy of routing algorithms in MANETs [3].

2.2.1 Proactive Routing

Proactive routing is also called table driven routing. This is a method in which each node can create a table that includes updated information on the routes of each node to all destinations in the network. Dissemination of updated routing information through the network is propagated on a continuous basis to update the table information at each node. Transmission process in this type of routing protocols is based on a sender consulting its own table to define the path to the destination node.

However, updating the information table for each node in the network requires high overhead traffic and sufficient bandwidth. In highly dynamic topology, this type of routing approach is not recommended because the need to maintain the consistency and currency of the routing information table requires additional control overhead messages, which may not be possible due to high mobility.

There are many well-known proactive routing protocols in the literature, such as Destination Sequenced Distance Vector Routing (DSDV)[49] and Optimized Link State Routing (OLSR)[50].

DSDV

Destination Sequenced Distance Vector Routing (DSDV) is a well-known protocol in the proactive family [49] that uses the Bellman-Ford algorithm to calculate paths. The number of hops that the packets need to travel to reach the destination node is used as a metric of the cost in DSDV. DSDV routing is a proactive routing algorithm, therefore, it maintains a routing table that stores all the available destinations, cost metrics and sequence numbers assigned by the destination node to avoid a protocol loop. Periodic mechanisms are used to propagate changes in the routing table regularly.

In the case of the occurrence of an update event, the sequence number must be incremented by a node. In a normal update, the sequence number must be an even number; each time there is an update, the node increments its sequence number by 2 and adds this update to the routing message. Nodes cannot change the sequence number of other nodes. If a node wants to announce an expired route to its neighbours, it only increments the sequence number of the disconnected node by 1. Each node receiving this update will check the sequence number and if it is an odd number, it will be removed from the routing table [51].

OLSR

Optimised Link State Routing (OLSR)[50] is a proactive routing protocol that applies discovery and maintains route mechanisms before sending messages from the source node to the destination node. OLSR discovers and broadcasts link state information that is gathered by HELLO as well as topology control messages. Each node in the network receiving this information can define the next hop destinations for all other nodes in the network. HELLO messages contain two hops neighbour information and select a set of multipoint relays (MPR). MPRs are the nodes that broadcast messages and build the link state in the network. HELLO and topology control messages by OLSR frequently flood over the network to ensure that all nodes are synchronised with link state information [51].

2.2.2 Reactive Routing

Reactive routing is also called on-demand routing, which means that the route will be established on demand only. In this protocol, there is no need to pre-create a table of information as in proactive routing. The routing process in reactive routing protocols requires low control overhead because it occurs only when it is necessary to establish a route. Due to node mobility in dynamic topologies, maintaining routing between nodes is a complex challenge. Thus, reactive routing protocols are more efficient than proactive routing protocols in dynamic topologies. The disadvantage of this approach is that the nodes need to wait until the discovery of the routing process is complete. Therefore, there is a greater delay in transmitting packets between nodes. The most well-known examples of reactive routing are *Ad-hoc* On-Demand Distance Vector Routing (AODV)[24] and Dynamic Source Routing (DSR)[52].

AODV

Ad hoc On-Demand Distance Vector Routing (AODV)[24] is an on-demand routing, which means it is established and maintained upon request from the source node.

AODV is similar to OLSR in terms of using sequence numbers to avoid the routing loop. In addition, AODV is self-starting and can be scaled to accommodate a large number of mobile nodes. AODV uses three types of messages to establish a route between the source and destination: route requests (RREQs), route replies (RREPs) and route error messages (RERRs). The source node broadcasts the RREQ message to its neighbours in order to discover a route to the destination node. If the intermediate nodes do not have any previous information about the requested route in their table, they will rebroadcast the RREQ.

Each node receiving an RREQ stores the route information in its own routing table. Once the RREQ is received by the destination node or an intermediate node which has route information to the destination node, they respond by unicasting an RREP message to the last RREQ sender. The RREP will follow a reverse path to the source node and each node receiving the RREP will update their routing table by setting up the forwarding entries by indicating the node from which they received the RREP message [51]. However, in case of link breaks, the node that discovered this disconnection sends RERR message to inform the source node.

DSR

Dynamic Source Routing (DSR)[52] is a reactive routing protocol based on a method known as source routing. DSR formats the route based on a request from the source node; therefore, it is an on-demand routing, similar to the AODV routing algorithm. DSR is different from AODV in that in DSR, the intermediate node adds its own address identifier to the list carried in the packet. An RREP message generated by the destination node, including the list of received node addresses, is sent through a reverse path to the source node. DSR has a route maintenance mechanism through a node confirmation message when the next node successfully receives the packets. The node confirmation messages could be acknowledgements through the link layer or specified by DSR. As mentioned above, DSR is source routing, which means when there is a break in the link by a node that cannot receive an acknowledgement message from the next hop it will generate a route error message transmitted to the source node [51].

2.2.3 Geographical Routing

Research has shown that geographical location information can improve routing performance in ad hoc networks [53]. Additional attention must be paid in mobile environments, i.e. locations may not be accurate by the time the information is used. Position-based algorithms work in tandem with location services[3], which are tasked to inform nodes of each others' positions.

There are many examples of geographical routing algorithms. In [54], which was one of the first routing protocols using geographical information to support the decision for the next hop, the authors proposed the Distance Routing Effect Algorithm for Mobility (DREAM) as a geographical routing built on the basis of minimising the flooding area size by choosing the neighbour that can forward route request messages. DREAM manages the routing updates and message lifetimes to minimise the routing overhead by what the author calls *distance effect* and *mobility rate* [54]. Distance effect is where the distance between two pairs is reflected by the importance of this pair to the others. For example, if the distance is large, then the location update to the others occurs less frequently than for nodes closer together; this means that the greater the distance separating two nodes, the slower they appear to be moving with respect to each other.

In mobility, node speed is used to determine how often a node needs to update its location to other nodes. High-speed nodes need to update more frequently because they are moving faster and their locations are constantly changing. Using distance effect and mobility, DREAM can utilise bandwidth and energy more efficiently. Nodes can periodically broadcast their location information to other nodes in the ad hoc network using control messages. The location information stored in the location table in each node is used to keep nodes up to date on the mobility of other nodes in the network. However, because DREAM is based on flooding, it may excessively use network resources.

The following section will cover other examples starting with the most well-known algorithm in geographical routing.

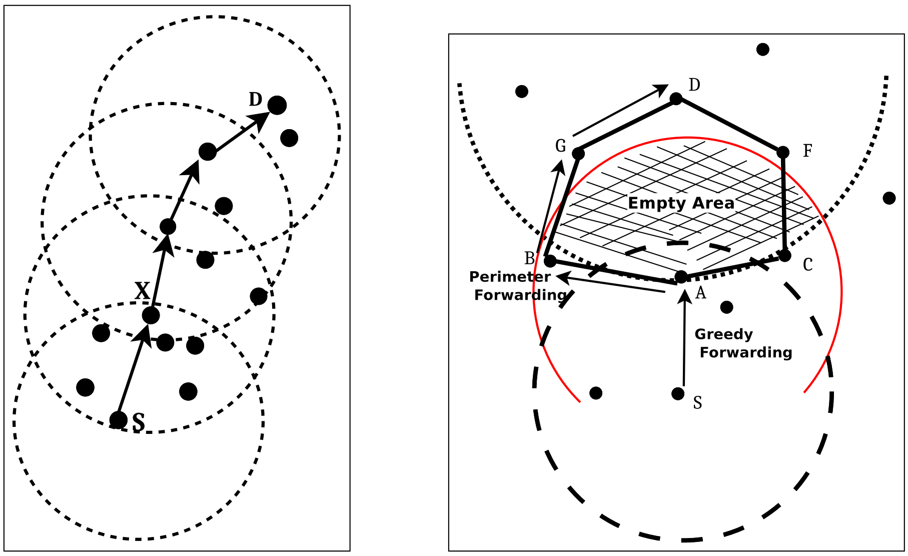
2.3 Greedy Perimeter Stateless Routing

There are many examples of geographical routing algorithms in the literature [3]. In this section, we will focus on Greedy Perimeter Stateless Routing (GPSR) [15]. Following the original GPSR proposal, several variants have been proposed in the literature, such as Divisional Perimeter (DP) [5] and Buering Zone Greedy Forwarding Strategy (BZGFS) [4], to improve its performance in particular settings. These protocols will be used with the vanilla GPSR to measure the performance of the new algorithm proposed in this thesis.

Greedy Perimeter Stateless Routing (GPSR) [15] is one of the best known position-based protocols in the literature. GPSR, as a greedy routing protocol, does not need to maintain a routing table and works best in a free open space scenario with regularly distributed nodes [48]. The protocol virtually operates in a stateless manner and has the capability of multi-path routing [55]. Typically, GPSR uses a greedy forwarding strategy to forward the packets from a source to an immediate neighbour that is located closest to the destination. When the local optimisation problem occurs, for example a neighbouring node closer to the destination does not exist, the node instead uses perimeter forwarding to forward messages. The two techniques are explained as follows:

- ***Greedy forwarding (GF)*** is the main method for forwarding packets to their destinations in GPSR algorithms [15]. It is one of the techniques on which single-path (only one route can be discovered from the source to its destination) routing relies on forwarding the data packet to a single neighbour instead of broadcasting the packet to all neighbours. As mentioned above, the source node knows the geographical position of the destination node. The destination node position will be added to the packet header so that each node receiving the packet will know the position of the destination node. Each forwarding node will consult its local table to check which neighbour is geographically closest to the destination node. The closest node will receive the packet and repeat the process until the packet is received by the destination node. Figure 2.5a shows the greedy forwarding process; the node S as the source wants to send packets to the destination node D.

  The greedy forwarding method ensures that the shortest path from the



(a) Forwarding packet process through a greedy forwarding technique

(b) Forwarding packet process through a perimeter forwarding technique

Figure 2.5: Illustrating GPSR operation in two techniques.

source node to the destination will be used as long as it is possible to forward packets to the destination node. However, when the forwarding node is faced with an empty area, which means there are no neighbours closer to the destination than the forwarding node itself, the greedy forward will fail to forward packets. Karp et al. [15] explained that this problem is the limitation of the greedy forwarding method and they proposed a recovery mode to solve the empty area problem.

- ***Perimeter Forwarding*** is used when the forwarding node fails to find a neighbour closer to the destination than itself. This changes the forwarding mode to perimeter, as a recovery method to bypass the empty area, along with the location when the greedy forwarding mode has failed. Perimeter mode is based on the FACE routing methods explained above. First, it determines a planner graph using the Relative Neighbourhood Graph (RNG) [56]. Second, the right-hand rule is used to traverse the planner graph.

  Figure 2.6 shows an example of the right-hand rule. Node S sends a packet to node X, which, in turn, will send the received packet to the first link finds'

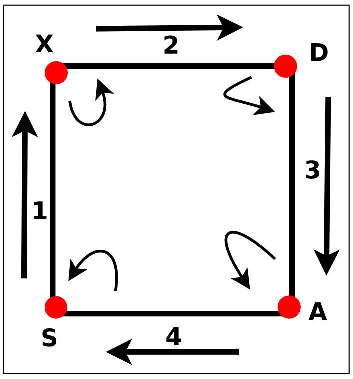


Figure 2.6: Right-hand rule interior of the polygon.

counter-clockwise around X from the edge (S, X). It is known that the right-hand rule traverses the interior of a closed polygon in clockwise order [15]. In Figure 2.5b the dash arc around node D represents the distance to node A. The red arc around node A shows the radio range of node A. Finally, the dash circle is the radio range for node S. When node S wants to send packet to node D, first it will use a greedy forwarding method to transfer the packet to node A. The destination node D is out of the radio range of node A and there are no neighbours through which to forward the packet to node D using the greedy forwarding method. In this case, node A will change the forwarding mode to perimeter mode. Node A has two paths to the destination node: (A, B, G, D) or (A, C, F, D). Based on the right-hand rule to route around the empty area using the cycle traverse properties, the cycle will be $(A, B, G, \mathbf{D}, F, C, A)$. In this manner, GPSR can forward the packet around the void area to reach the destination node.

However, there are a number of drawbacks to the transmission process in GPSR, which have led to the proposal of many variants in the literature. In the following section, we will examine some of these variants based on the shortcomings of the two techniques.

2.3.1 Optimising GPSR Greedy Forwarding Methods

In this section, we will show how GPSR has been optimised to resolve the issues experienced using greedy forwarding methods.

Buffering Zone Greedy Forwarding Strategy

A GPSR variant introduced by Wei et al. [4] employs a strategy termed the Buffering Zone Greedy Forwarding Strategy (BZGFS). Its application in GPSR is called GPSR-BZGFS and it deals with greedy forwarding failures and the right-hand rule. In this case, the perimeter forwarding strategy is the same as in GPSR, however, nodes that are on the edges of the transmission range are not considered for follow-up transmissions as they are deemed more likely to go out of range shortly. As such, a 'buffer zone' is defined at the edges of the transmission range where nodes contained therein are not chosen for forwarding purposes.

The main idea for this algorithm is to address the temporary communication problem (TCP) [57], which means that the next hop node is not in the transmission range because of node mobility. The algorithm defines a buffer zone that introduces a suitable radius at the radio margin, as shown in Figure 2.7. The forwarding node will search in its neighbour list for a node within its radio range with the condition of not being in the buffering zone, and which is geographically closest to the destination location. If the selected node moves to the buffering zone during the period between the two HELLO messages, it will be available to participate in the forwarding procedure because it will not move out of the transmission range, even at maximum speed. When the selected node moves to the buffering zone, it will be recognized by the node that planned to use this selected node as the next hop by the HELLO message and will be replaced by another node based on the BZGFS protocol. The node planning to forward the packet can choose another node before the selected node is moved out of its transmission range by the buffer zone.

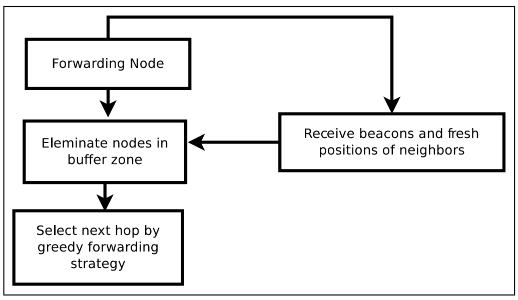
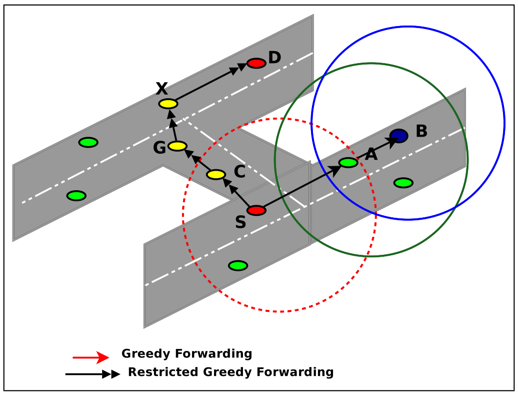


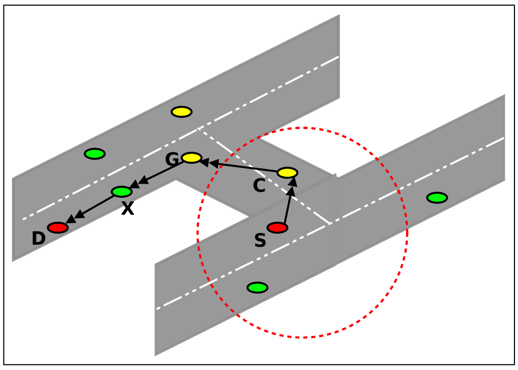
Figure 2.7: Buffering Zone Forwarding Strategy flow chart [4].

Greedy Perimeter Stateless Routing with Lifetime for VANETS (GPSR-L)

Roa et al. [58] consider the problem of poor linking between the forwarding node and its neighbours because of high mobility which leads to changes in the position of the nominated node to forwarding the packet to the destination node. They proposed a new variant of the vanilla GPSR by adding a lifetime to the packet header. The lifetime is calculated between the forwarding node and its neighbours and the timer value is set to the value of the lifetime. In the case of selecting the closest node to the destination node from the node neighbour list, the forwarding node checks the timer if it is not equal to zero, and then checks the link quality by comparing different neighbour timers to select the next hop [58]. The author claims that GPSR-L improves the packet delivery ratio by $20\% - 40\%$ compared to the original GPSR.



(a) Greedy forwarding vs.Restricted Greedy Forwarding in GPCR



(b) GPCR repair method to solve the local minimum problem

Figure 2.8: Illustrating GPCR operations using two techniques.

Greedy Perimeter Coordination Routing

In [59], the authors proposed a new algorithm to overcome the obstacles faced the radio transmission range in a city topology. The algorithm consists of two techniques: restricted greedy forwarding and a repair method, as shown in Figure 2.8. Figure 2.8a shows that node S is the source node that needs to send a packet to node D. Following the normal greedy forwarding method, S will send the packet to node A and then B, which is a dead-end node, then the packet will be dropped because there is no way to reach the destination node. The author proposed a different method called 'restricted greedy forwarding'. In this method, the node in the junction will be called a *coordinate node*, which will broadcast its role to all nodes. When node S is close to the junction as shown in Figure 2.8a it knows that node C is the coordinate node and it is the first node that should receive the packet to complete the forwarding process and reach the destination node. Figure 2.8b shows the repair methods using the right-hand rule similar to the vanilla GPSR to avoid the local minimum problem that appeared in the position of node S; the algorithm then follows restricted greedy forwarding to transmit the packet to the destination node D.

The new algorithm is based on the use of street junctions as a form for the planner graph without using any external information, such as a street map. However, this depends on the junction nodes, which could fail on the curve road and on sparse network where the distance between nodes could affect the transmission range and lead to the loss of packets [60]. Moreover, the node in the junction could face the problem of local minimum, which forces the node to drop the packets. As previously mentioned, the decision on the next hop in GPCR is made by the coordinate node at the junction; therefore, this node could present a bottleneck in routing the packets.

In [61], the author proposed a new schema called GPSRJ+. As previously mentioned, the decision on the next hop in GPCR is made by the coordinate node at the junction; therefore, this node could present a bottleneck in routing the packets [61]. The main idea of GPSRJ+ is to improve the perimeter mode in [59]. GPSRJ+ is used to exchange beacon messages to detect coordinate nodes at the junction area. It uses information from two hop neighbours to detect and identify a routing path. The GPSRJ+ authors claim that the new strategy they used improved the packet delivery ratio of GPCR [59], and reduced the number of hops in the recovery mode of GPSR [15] by 20%. It should be noted that the use of GPSRJ+ [61]could overload the network. The authors used a line trajectory to evaluate the routing performance. However, a real urban scenario could follow a more complex trajectory.

2.3.2 Optimising GPSR Perimeter Forwarding Methods

In this section, we will show how GPSR can be optimised to resolve the issues encountered when using the perimeter forwarding method.

Divisional Perimeter

Work in [5] proposed a Divisional Perimeter (DP) forwarding algorithm, called GPSR-DP, which improves GPSR by using both a right-hand and a left-hand rule. Specifically, in GPSR-DP, a forwarding node in the case of the local optimisation problem is chosen either on the left-hand or right-hand side of the transmitting node, depending on a heuristic. As in GPSR, the proposed algorithm does not change forwarding behaviour when reaching a dead-end; the packet is simply discarded. The GPSR-DP protocol improved GPSR by combining the right-hand rule with the left-hand rule.

Figure 2.9 shows that if node X faces an area where there are no nodes capable of forwarding a packet to a destination following the greedy mode, then node X will decide to change to recovery mode to avoid the empty area. Node X will choose node a because there are no nodes in the left region, so node a will continue in recovery mode. Node a, if it follows the right-hand rule, will choose node b, and so on. The path following the right-hand rule will be $(X \rightarrow a \rightarrow b \rightarrow c \rightarrow d \rightarrow e \rightarrow f \rightarrow g \rightarrow D)$; this route seems a very long path to the destination node , so the author combined the left-hand rule by node a. Instead of choosing node b as the next hop, it will choose node e because it will follow the left-hand rule. The path following the left-hand rule in this case will be $(X \rightarrow a \rightarrow e \rightarrow f \rightarrow g \rightarrow D)$. It is clear that the number of hops has decreased by using the left-hand rule.

2.3.3 Optimising Overall GPSR Performance

In this section, GPSR will be optimised to increase performance without considering any specific problem in the forwarding methods.

In order to improve the accuracy of GPSR, Granelli et al. introduced a Movement Aware GPSR variant called GPSR-MA [62]. GPSR-MA is meant for

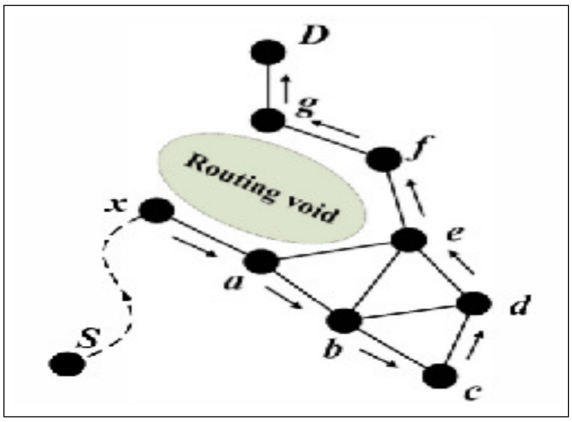


Figure 2.9: Divisional Perimeter Protocol concept taken from [5].

use in Vehicular *Ad-hoc* Networks (VANETs) and adds speed and direction to the basic GPSR packet header format to improve the next forwarding node decision. As such, it extends the routing protocol's awareness of the nodes' mobility state; additional information is used in subsequent routing decisions.

In [63], the authors improve GPSR [15] for use in city scenarios and highways. This algorithm uses the positions of the nodes; each node can determine the intersection node by comparing its position with the table of neighbours' positions and using this information to determine the intersection node that will be used to overcome the obstacles problem in the city scenario. However, the author assume that all nodes are equipped with GPS to define the node position, yet GPS can be made ineffectual by obstacles such as buildings and tunnels. Moreover, the use of this algorithm typically increases the packets' collision with these obstacles because the change in the position in the city scenario can be quick and sudden, meaning that nodes increase the number of broadcasting messages to inform others of their new location.

In [64], the authors propose a new variant from GPSR, namely, On-demand GPSR (OD-GPSR). This is a data-driven geographical routing protocol customised to work in wireless sensor networks. OD-GPSR addresses the problems that could face GPSR in wireless sensor networks, such as when a wireless sensor network is not a symmetric link (bidirectional), the location of the home node in a sensor network is outside the boundary of the perimeter node, or there are changes in the home node location caused by mobility. However, the accuracy of the use of

GPS to define the location in OD-GPSR could be affected by the topology of the sensor networks, and that will result in the loss of packets.

In [65], the author proposes two schemes to be applied on top of GPSR to control the routing overhead and minimise the MAC layer collision to allow for the use of more resources. The first scheme is Neighbour Awareness position Update (NAU), which uses the number of neighbours and their positions to set the position update interval dynamically. The second scheme used is Beacon assist Geographical Forwarding (BGF), which allows the forwarding node to consider the next hop by comparing the neighbour's beacon interval stored in its neighbour list.

2.4 Delay/Disruption Tolerant Networking (DTN)

The massive and rapid evolution in the techniques used by smart devices with short range wireless communication technology has stimulated developments in MANETs during the last few years. However, the concept of bidirectional networks, which is the basis of MANET, is not guaranteed due to the regular disconnection in the network caused by node mobility and low-density networks. MANET routing algorithms, which are discussed above, are not common in the networks suffering from frequent disconnection. This type of network is called a challenged network or a Delay Tolerant Network (DTN). Following is a brief history of the DTN, which will outline the most commonly used techniques for routing messages in a DTN, based on the Store-Carry-Forward paradigm.

In the late 1990s, the Interplanetary Internet project (IPN) became the spark that prompted an investigation into the possibility of using the Internet approach in deep space communications [66]. The particular characteristics of space minimise the time that the path between two pairs is available; outside of this window, it will not be available at all. Research into IPN has created the opportunity to introduce DTN as a new communication model to be used in deep space communications. Fall in [66], this type of network is classified as a challenged network and is characterised by an unstable connection, a low packet delivery ratio and heterogeneity. Networking techniques used in such difficult situations could be applied to ground communication, for instance, in wireless communications that experience various causes of delay, such as communication disruptions. When an end-to-end path is not guaranteed or if it is unstable or unpredictable, the network is considered a disrupted network, which is one form of DTN. The IETF formed the DTN Research Group (DTNG) in 2002 to implement the concept of DTN as an architecture. There are many causes of disruption that need to be addressed by DTN, including the followings [67]:

- ***Mobility***: The nodes are free to move on the topology, and this movement causes regular disconnections between two pairs, resulting in the disruption of the whole network.
- ***Line of sight***: Nodes cannot detect other in the topology because of natural obstacles (e.g., mountains or other land topography).
- ***Device incompatibility***: Communication between heterogeneous devices could result in an inability to communicate because of the differences in their specifications.
- ***Short radio range***: Mobile devices equipped with short range communication tools that lead to the farthest nodes will be out of the transmission range.

2.4.1 DTN classification

When the end-to-end connectivity is not available, e.g. in the case of a sparse network, that means low number of nodes are available in the transmission ranges and it causes the topology to split into numerous non-connected sectors. This typically is the domain of Delay Tolerant Networking (DTN). DTN can further split into two types [68]: the assisted DTNs (A-DTN), when the mobility of the nodes is very low, or Unassisted DTNs (U-DTN), where the mobility of the nodes is high and this type correspond to traditional DTN paradigm.

Routing in A-DTN involves the use of special nodes known as message ferries to relay the messages between the disconnected sectors [69]. The use of ferry node is based on store-carry-forward scheme, which is explained in the following section.

2.4.2 Store-Carry-Forward Paradigm

The Store-Carry-Forward Paradigm (SCF) is a classical paradigm for DTN in which messages are stored and carried until there is an opportunity to forward them to the destination node. The routing protocols that are followed in this technique can be classified into two groups based on the assumption made regarding the available knowledge of the networking topology [70].

In the first group, routing algorithms require minimal information about the topology, or non-knowledge. In such algorithms, a number of message copies are generated and distributed in the network. The source node or the forwarding nodes store copies of the message and forward a copy each time there is a node within transmission range. Consequently, there are $(n-1)$ copies of the message in a network with n number of nodes, which means a node could have multiple copies of the message, thereby increasing the probability of delivering the message to the destination node and requiring the minimum time to deliver. The primary aim is therefore to establish control rules regarding the number of message replications. However, this method does waste nodes' resources because they participate in storing copies without any guarantee that they will be in the destination node transmission range.

The routing algorithms that follow this technique for forwarding messages are known as Epidemic routing algorithms [71][72][73][74][75]. Yet in high-traffic networks, these algorithms are at a high risk of dropping a message, which affects the routing performance [76][73]. To control the number of copies made, different techniques are applied in routing algorithms such as keeping the number of copies constant regardless of the network size and forward the message to dedicated relay nodes or sending a copy to a node that does not have a copy, which is defined by historical encounter-based metrics.

The second group is composed of routing algorithms that require knowledge about the network topology. The routing algorithms assume that the topology is divided into different zones, and each zone contains nodes that connect well together; however, the zones themselves are not connected to each other. The need to connect these zones inspired researchers to use a special node, called a *ferry*, to travel around the deployed area to collect messages from each zone of connected nodes. Knowledge of topology is not limited in most algorithms following this method, so one copy of the message is carried by a ferry and forwarded to the proper zones based on location information; the main concern in this method, then, is how to evaluate ferry movement and delays in message delivery and collection. Much research has been completed on other aspects of routing in DTN (see [70] and [77]).

Yet these algorithms force the node to be in the ferry transmission range to receive messages or to send messages to the ferry node. The node needs to prioritise between its duty and the sending or receiving procedure. The decision of which is a higher priority will affect the delivery of messages. For instance, if the duty of the node in the topology is of higher priority than the sending or receiving procedure, the node will not move into the ferry node transmission range, and that will lead to a dropped packet.

2.5 MANET and DTN Integration

The combination of the MANET and DTN paradigms could solve some of the problems from which each paradigm suffers. MANET routing algorithms are unable to forward packets in link break networks, which suffer from a regular disconnection, while DTN routing algorithms are not efficient in well-connected networks and have high delay times [78]. This is confirmed by the framework[9] , which argues that the uncertainty of the link and the connectivity of the network could organise the topology to recognise which MANET routing, DTN routing, and flooding are the appropriate ways to communicate. The following sections outline the work that has been done to integrate MANET routing and DTN routing in the last few years. The research was classified based on the MANET routing type described above.

2.5.1 Classical MANET Routing Integrated with DTN

A hybrid algorithm that combined AODV and DTN bundle protocol [79] was proposed by Ott et al. in [80]. The proposed work is based on extending AODV routing to include nearby DTN routers during a route search mechanism to obtain routing hints. The default routing is AODV, whenever possible, but if there is no end-to-end link, DTN-based routing is applied. In this hybrid algorithm, the application can dynamically choose which mechanism is preferable based on its situation. This approach requires that the nodes in the network should support the bundle protocol.

Moreover, in [81], the authors propose a similar approach by combining AODV with DTN through a scheme applied by the sender only to allow it to dynamically choose the routing type. The decision between MANET or DTN routing is based on local information, such as message size, or can be determined through inferred data, such as node density or available bandwidth. The forwarding node does not participate or change the decision made by the source node. DTN routing protocol could be used in the presence of an end-to-end path in the case that the time delivery when using MANET routing is larger than that when using DTN routing. The authors claim that their work is different from the previously mentioned approach because it applies a more extensive evaluation and uses more realistic mobile networks.

The author of [82] extends this, introducing a reactive routing protocol named Better Approach To Mobile Ad hoc Networking (BATMAN)[83] that has a Store-and-Forward protocol (SF-BATMAN). A node buffers the messages to decrease the number of dropped packets in the following cases of bad links:

- The path to the destination node is not determined.
- The next hop node sent the control packets recently but it is not active at the time that the forwarding node wants to use it.

The nodes that receive control messages update or validate the entry table then send the buffered messages. The BATMAN protocol is modified to use store-and-forward techniques without changing any of its control messages, so SF-BATMAN works in a way that is similar to BATMAN, but with an added feature. It uses the reactive routing protocol approach also proposed by [84] and [85].

Pant et al. [86] enhance the performance of OLSR [50] by integrating it with a DTN-based mechanism. The new algorithm, namely DTS-OLSR, is a recent routing and discovery mechanism based on the Structured Mesh Overlay Network (SMON) to provide discovery, registration and routing functionality. The authors extend OLSR routing with DTN to register the nearest and a more stable DTN node by utilising the number of hops and the link quality. Using the modified control messages in OLSR, nodes can build and maintain a hierarchical network overlay that uses bundle routing in DTN [79] to deliver the messages. A node that does not support bundle protocol could use the nearest node that does support bundle through what the author calls a "lite" bundle. The messages in DTS-OLSR are encapsulated into bundles or lite bundles before transmission, resulting in an increase of communication overhead. In the well-connected network, the increase of communication overhead in DTS-OLSR decreases its performance when compared to OLSR.

In the Storage Aware Routing (STAR) protocol [87], the knowledge of the available storage with OLSR routing and modified control messages [50] to define short-term and long-term link cost are used when choosing between buffering or forwarding the messages. If the cost of the long-term link is lower thn the short-term link, the available storage for the next hop is not enough or the end-to-end path does not exist, the packets will be stored instead of forwarded in STAR. However, STAR has a large delay for some packets because they are buffered for one of the above reasons, while its packet delivery ratio outperforms the vanilla OLSR.

The author of [88] uses the number of connected nodes to distinguish between sparse and cluster networks. The proposed algorithm uses the DSDV [49] for intra-cluster delivery, and in the case of inter-cluster communication, the proposed algorithm uses the message ferry technique. The source node is the only node that allows the use of DSDV routing to communicate with the gateway node, which is responsible for communicating with the ferry node.

The use of proactive distance vector MANET routing protocol in combination with custodian selection and message buffering from DTN was also used by Musolesi et al. [89] to propose Context-Aware Adaptive Routing (CAR). The MANET routing is used to exchange information related to networks such as the change of rate in connectivity and the connection status between pairs. A context framework is used to predict the probability of delivery between nodes to decide which node is best-suited for delivering the message. These results are added to the routing table for use in the case of a partitioned network. In the case of a connected network CAR, a proactive MANET protocol is used to transmit the messages.

Kretschmer et al. [90] introduced the Delay Tolerant Dynamic MANET On-demand Routing protocol (DT-DYMO). This is an integration of the probability model in the Dynamic MANET On-demand Routing (DYMO) [91] and the DTN custodian scheme. In well-connected networks, DT-DYMO works in a way that is similar to the vanilla DYMO as described in [91], while in a partitioned network, the messages are forwarded to a node that has a high probability of meeting the destination node based on the probability model built in DYMO. The nominated node will buffer the messages until it has a link with the destination node. To perform an accurate delivery likelihood estimation, nodes need to exchange their delivery probability periodically, which is not a feature in the default DYMO because it is a reactive routing; this therefore introduces an additional beaconing mechanism.

In [92], Liu et al. propose an adaptive routing protocol, named Efficient Adaptive Routing (EAR). EAR is a combination between DSDV [49] and the spray and wait method used in DTN [73]. A group of nodes that can communicate with each other form a logical cloud in EAR. However, the number of nodes in a cloud is limited because EAR protocol limits the bandwidth used by a node for maintaining the use of the DSDV shortest paths technique. The communication between nodes in the same logical cloud is used to maintain the shortest path inside the cloud. Moreover, for communicating between clouds, nodes use spray and wait routing protocol.

Whitbeck et al. [93] propose a hybrid DTN-MANET routing protocol (HYMAD). The authors use the concept of cluster networks to divide a network into small clusters. The routing inside the intra-group is handled by a simple distance vector algorithm. For inter-group communication, HYMAD uses the spray and wait method. However, HYMAD is based on the assumption that the nodes form groups, so it seems more suitable for networks in which some level of "natural" grouping occurs.

2.5.2 Geographical Routing in MANET Integrated with DTN

Several geographical routing protocols have been proposed for MANET, but the majority cannot be applied to sparse networks or large areas. The geographical routing presented in [3] cannot deal with small numbers of nodes deployed in large areas, such as military units deployed in a remote location for training or other scenarios.

In contrast, geographical routing following the carry-and-forward of DTN was proposed to applied for road-based scenarios in a VANET [94], which is a type of network, be used to provide communication between cars and between cars and fixed infrastructure. This type of network has its own characteristics that distinguish it from other types of MANET [95] [96]. However, VANETs are outside of the scope of this work.

Motion Vector (MoVe) routing, proposed by Lebrun et al.[97] predicts a node's future location and sends a packet to the node when it is expected to be within the node transmission range. The routing protocol uses a request mechanism in which the node wants to send a packet to create a HELLO message and awaits a response from any nodes in its transmission range; then, nodes begin to exchange their information to determine if the responder is able to carry the message and whether it is expected to be closer to the destination than the sender.

Geographical Opportunistic Routings (GeOpps) were proposed by Lee et al. [98]. GeOpps assume that all modern cars have a navigation system, including a GPS device, maps, and the function to calculate a suggested route. A navigation system is assumed to have the ability to calculate the route to estimate the time it will take to move from a current position to a requested destination; this can be used to determine the route of messages to a destination area. The car then follows the route suggested by its navigation system to reach its destination, calculated based on the nearest point that it must go through to reach the destination area. The forwarding node, in this case, will use the nearest point and its map in a utility function to estimate the minimum time the packet needs to be delivered to the destination area. The node that can send the packet quicker and closer to the destination becomes the next carrier. This protocol could only be applied in

VANET if we assume there are pedestrians participating in such network; it is neither logical nor practical for them to carry a navigation system.

GeoDTN [99] is a routing system that uses geographical information in DTN. GeoDTN is a distribution scheme based on nodes' mobility, and it consists of three schemes to route messages: distance, rescue and scoring modes. Distance mode is used to compare the distance of each node to the destination node and to compare the results with a fixed threshold. The node that is at the shortest distance is used as the forwarding node. If a message faces a local minimum problem, the algorithm applies rescue mode. Finally, the scoring mode is used to calculate the probability of the nodes being at a common location between other nodes and the destination. A node that has a higher neighbour score with the destination node will be considered a better forwarding node. The algorithm assumes that the node score will be based on updated information about the destination node mobility, which is not a practical assumption with regard to security and privacy.

In [100], Cheng et al. propose the Geographic and Delay Tolerant Network with Navigation Assistance (GeoDTN+NAV). It is a combination of DTN mode and non-DTN mode. The switch between the two modes is based on a Network Partition Detection Method that is proposed by the authors to evaluate the correct forwarding mode for each packet to increase the possibility of delivering packets to their destinations. In general, this method is based on the road connectivity. In DTN mode, the authors propose a Virtual Navigation Interface (VNI) to choose the delay tolerant forwarding node in case of partitioning networks by providing the mobility information for neighbouring vehicles to confirm which one is the most proper to deliver the packets. In non-DTN mode, the algorithm uses two techniques, namely greedy and perimeter, similar to GPSR [15]. However, the latency in this protocol is high in sparse networks, resulting in a decrease in performance. In addition, the packets delivery ratio is low compared with other routing protocols [60].

In [94] and [101], the authors propose geographical routing protocols for vehicular delay-tolerant networks called GeoSpray and Graph Relay (PGR) respectively. Those routing protocols also use a path prediction mechanism and the knowledge of the road to choose to hand over packets to a vehicle if it is predicted to come closer to the destination than the vehicle holding the packet. Moreover, GeoSpray uses limited replication to explore different paths to the destination. In addition, LAROD [102] relies on greedy forwarding, and when that is not possible, it waits until node movement makes continued forwarding possible.

2.6 Simulation Techniques

For accurate evaluation of routing protocols, a real test environment is required. However, evaluating routing protocols in a real environment is costly, so most evaluations are performed based on simulated applications. When there is a need to evaluate a routing protocol in a simulator, it is important that the simulator is easy to understand and use so that the system environment can be described accurately. Simulation is a tool used to design a changeable model of a theoretical networking system to reflect a real system or to work in specific conditions to evaluate results used for other purposes [103]. To completely analyse any system, it needs to be simulated [104], to investigate any difficulties that might occur during implementation that would result in hardship at the analysis stage. Simulation offers researchers a tool for analysing complex systems through virtual environments. In this section, we will briefly describe the most well-known network simulators described in the literature. The present study was conducted using the NS3 simulator, which will be described later in this section.

2.6.1 Network simulators for MANET-based networks

Recently, various simulators have been developed to analyse routing protocols in academia and industry. The majority of network simulation tools in the literature are based on the paradigm of discrete event based simulation [105][106][107]. This paradigm is based on scheduling an event, such as a node sending a packet to another node, and sorting the events in a queue, depending on the event execution time. The simulation tool performs the events from the queue successively. NS2 [108] is one of the approaches applied in the discrete event based simulation paradigm. At least virtually, it has become a standard for network simulation [106]. As evidence for this, protocol model is available to the public in the NS2 simulator off-the-shelf, so it does not need to be implemented from scratch. NS2 has undergone a number of redesigns for improvements and to overcome deficiencies in performance, which has resulted in the availability of several designs. One of these is NS3 [109], which focused on design alterations to improve performance and allow for easy extensibility [110].

Most works appearing in the literature classify the existing simulation models as open source and commercial simulators and the models are compared to show the advantages and disadvantages of each one [111][112][113]. An outstanding example of an open source model, in addition to NS, is OMNeT++ [114] ; the most well-known example of commercial simulators is OPNET [115].

NS2:

NS2 is one of the most popular simulators in the academic field. It is an extended version of a network simulator (NS), which is based on REAL network simulator [116]. It was developed at the University of California-Berkley. NS2 is object-oriented and uses two programming languages namely C++ and Tcl (Tcl script language with object-oriented extensions developed at MIT). NS2 is used to model network architecture or to design new routing protocols and to evaluate the performance of a network or innovative routing protocols. It takes a long time to learn and understand the mechanism used by the simulator [111], while it is easy to modify existing routing, which may take a long time to execute.

NS3:

NS3 is not an updated version of NS2. It is a new, discrete-event simulator. It no longer uses OTcl and the simulation can be implemented in NS3 using C++ with an option to use Python if needed. There is a tracing and statistical framework to enable customisation of output instead of rebuilding the simulation core. The models used by NS3 are updated and the protocol entities are built to be extremely close to those of real computers [112]. In addition to it being an open source code, the use of C++ language was one of the aspects that guided the researchers to use NS3 as the main simulator in the present work.

OMNeT++:

OMNeT++ is another discrete-event simulator. Its main application is the simulation of communication networks. However, its generic features and flexible architecture enable it to simulate other areas, such as complex IT systems, queuing networks or hardware architectures. Therefore, it is not a network simulator by definition when compared to previous simulators [106].

OPNET:

OPNET is an example of a commercial network simulator. It provides high level, event-based, network level simulation. The GUI and the documentation in OPNET make it an attractive simulator. It is more costly to purchase the complete set of OPNET to have more features [117].

2.6.2 Mobility Model

The key component of a simulator is a model describing the node movement in a topology. MANET research has shown that the node mobility plays an important role that could affect routing performance [118][119][120]. Because of the difficulties involved in using a real model to evaluate routing protocols in MANET, researchers have to use simple synthetic models to describe node movement. This can be done by generating trace files and having each one represent one movement in a scenario, such as military deployment. In the end, we have multiple files that can be used in the statistical model for evaluation.

Mobility models can be divided into two types [121]. The first type of model reflects how a node moves in the topology, which can be done by observing and tracing a node's movement in a real environment. However, a trace model is costly and not always possible, so it poses a complex and difficult task if it has not already been created. The second type of model is one that reflects how the node shell moves and realistically represents the node's behaviour in the topology. The difference between the two types is their verification methods; the first one is verified against the real scenario that it describes, while the second method is verified against the nodes' roles in the topology, or in other words, against the nodes' achievements [120].

To create a valid mobility model, we need to know that the application we intend to simulate exists and that its behaviour is known. If such information is not available, then the recommended modelling is synthetic modelling [120]. Many synthetic mobility models have been developed that could be used to reflect a scenario's behaviour and to evaluate a routing protocol. The most common of these in the computer network research community are the Random Waypoint (RWP) and Random Walk (RW) models [119]. Further detail about the mobility models for MANET research can be found in [122]. Next, we describe the two synthetic mobility models that have been used in the evaluations in this thesis.

Waypoint-based Mobility Model

Each node determines its velocity and position at a given time. Each node starts from a defined first waypoint travelling towards a last waypoint, passing defined waypoints on route. When a node is between two waypoints, it moves with a constant velocity if it is between waypoint times. Waypoints can be added at any time, and setting the current position of a node sets its velocity to zero until the next waypoint time.

Random Walk

Nodes randomly choose their directions and speeds to move from their current locations to new locations. The speed is defined in the range between the minimum and maximum speeds. The movement in this model is based on either a constant time interval or a constant distance travelled. Many derivatives of the Random Walk Mobility Model have been developed, including the 1D, 2D (as used in this work) and 3D walks.

2.7 Summary and Discussion

This chapter presented a review of MANETs covering their characteristics, applications, challenges, and a reference model for MANETs. Specific routing issues were discussed with more details in Section 2.2 as they are within the general scope of this research. Routing aspects covered in this section are characteristics, issues, requirements, and classification of routing protocols in MANETs including proactive, reactive, and geographical protocols. A review of state-of-the-art greedy perimeter stateless routing was also presented in Section 2.3 covering all design issues and optimisation in this type of routing in MANETs. A novel aspect of this review is that the optimisation in the GPSR based routing protocols in MANETs are classified into new two types. This classification is based on analysing the most significant aspects and properties of greedy perimeter stateless routing in MANETs. The features and the differences between the proposed routing protocols were also discussed in this review.

In this chapter, a review of Delay/Disruption Tolerant Networking techniques was also presented in Section 2.4, which covers the routing algorithms in this paradigm. The integration between MANET and DTN was furthermore described in Section 2.5.1 to illustrate that their integration could improve the performance of the network.

In the next chapter, an experimental study is presented to evaluate the performances of geographical routing protocols in MANETs. The evaluation is conducted for three geographical routing protocols, namely GPSR, GPSR-DP, and GPSR-BZGFS against each other using a real case scenario.

Chapter 3

Loosely coupled nodes use – case scenario – path stability issues

3.1 Introduction

This chapter introduces a real-life loosely coupled nodes communication scenario which, as implemented in NS3, shows that the existing routing algorithms do not utilise application-related information and this may result in a poor network performance in some cases. Later in this thesis it is shown how utilising application-related information could increase path stability for such cases of loosely coupled nodes and improve network performance.

Wireless *Ad-hoc* networks, as mentioned in Chapter.2, have special characteristics such as self-configuration, autonomy, and adaptability, which make them particularly suited for military applications. Notably, as the bandwidth in such networks is limited, appropriate multi-hop routing mechanisms can be used to distribute the work-load through the network.

Most of the current studies on MANET routing are not based on real-life scenarios and as such do not reflect a realistic environment [21]. Emergency rescue organisations and military are among the most important applications of mobile *Ad-hoc* networks. In such settings there is a possibility of embedding information that indicates the presence or lack of support for communication between nodes. To demonstrate how the application information can enable such possibilities, we consider the use of a real case study to show how it can affect the routing performance in wireless *Ad-hoc* networks.

Overall, this chapter introduces a real-life scenario which reflects the deployment of military units. In this study, NS3 is utilised to simulate well-known geographical routing protocols in order to evaluate the network performance for all deployments in the battlefield.

3.2 Case study of real-life scenario

In this section, we define the military requirements with regards to tactical networks. Our description focuses on a military battalion and its topology deployment. We provide a brief overview of the elements of an actual battalion formation and outline how these are reflected in a parametrised topology scenario.

The concept 'battlefield numerisation plays a vital role in helping information control become a dominant player in the armed forces. This concept could apply to specific architectures, including MANETs, to make them adaptable in different topologies. Moreover, it adds the capability of determining the presence and the absence of nodes in the network. However, the determining requirements are considered fertile area for research [13].

In military operations, due to the inherent nature of radio propagation and the distance between communicating units, most of the time there is no guarantee that nodes are at one-hop distance from each other. The multi-hop architecture in MANETs may effectively be deployed to solve node connectivity problem. Disseminated control and non-centralised functionality are essential in such architecture for communication to be possible. Using MANETs in a military tactical space requires knowledge of the deployed military unit type and the communication needs. Characteristics of these platforms have a significant effect on the design of the required solution. In any type of military operation, there may be dismounted soldiers, ground vehicles, and mobile or temporary fixed commands headquarters [46]. In such settings there is also command and control, communication, computers and intelligence (C4I) and surveillance assets that may be fixed or mobile.

As shown in Figure 3.1, it becomes relatively more important for units below

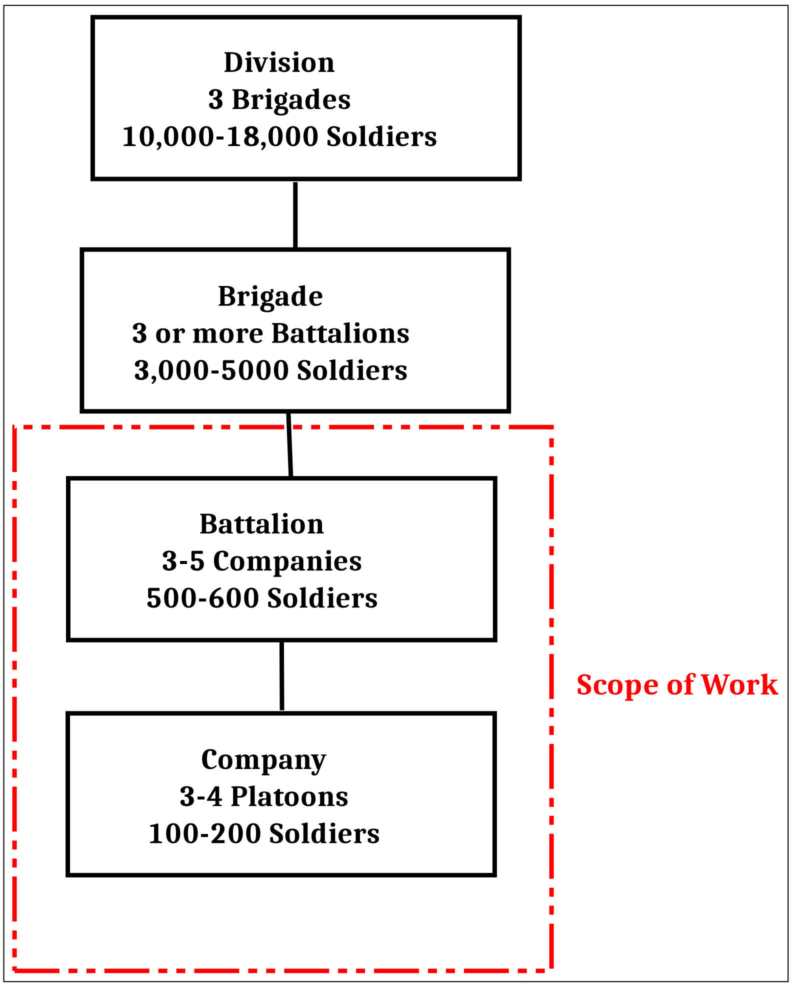


Figure 3.1: The organisation of Army operational units down through divisions, brigades, battalions and companies

the brigade level of communication to use a MANET because the need of a network that could work in different situation without any centralisation mode. This network should not allow contact to be dependent on specific nodes. In addition, to enhance the network and in order to support network optimisation, it should not allow any centralisation. Finally,this network should be capable to work in autonomous environments and in infrastructure-less situations. [13]. The battalion unit is used in this work as an example of a unit whose organizational level is just below the brigade echelon.

3.2.1 Battalion Elements

A military battalion generally consists of three companies, in addition to a command post company which consists of a military police platoon responsible for security and a signal platoon for battalion communication [123]. This hierarchy is the basis upon which battalion elements are set, whether in a field of operations or during regular training time. Figure 3.2 depicts a typical chain-of-command structure. Note that a deployed battalion is assigned an Area Of Responsibility (AOR)[124], as determined by the high command. Each battalion's AOR covers a physical area of a certain size depending on the type of military battalion; for example, an artillery battalion or an armour battalion has larger AOR than an infantry battalion because they are different types of arming battalions. The average AOR for an infantry battalion is nearly 20 square kilometres plus an area of reconnaissance, which is approximately 2 kilometres in front of the AOR. At the front of a battalion's AOR, the surveillance and reconnaissance units monitor the movement of the enemy and provide commanders with up-to-date information, which can help decision-makers to quickly make changes in the field operation.

In general, we distinguish four types of participants across companies. First, the commander and his/her staff are responsible for planning, leading and taking appropriate actions when prompted by changes in the situation on the battlefield[125]. Commanders (both company commanders and the battalion commander) reside in tents and are generally immobile upon deployment as their locations must be easily discoverable by other elements for orders diversion. Second, there are officers and soldiers who are responsible for the implementation of the actions dictated by the commander on the battlefield. Their movements are mission based so, they could be mobile or immobile. Third, there are guards which are soldiers tasked with controlling a small area and checking the identity of trespassers. Their motion is very limited and only within their particular area for the duration of their guard duty. Finally, there are patrol elements who are on the move along a predetermined route and tasked with certain duties along their area of responsibility.

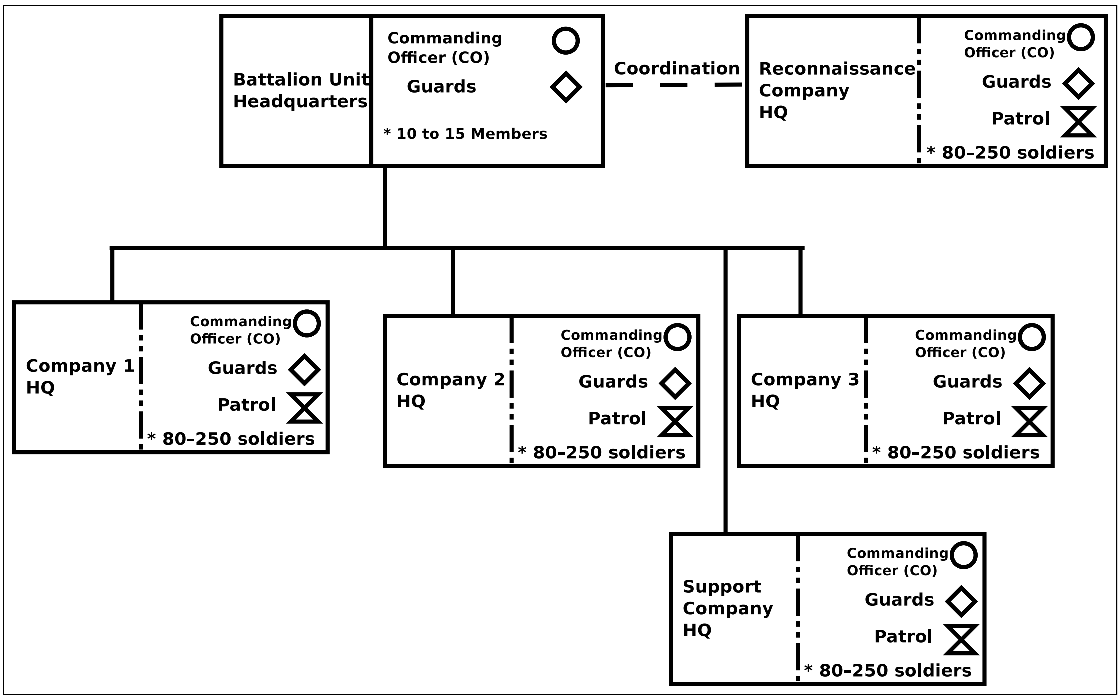


Figure 3.2: Typical chain-of-command structure in a battalion. Here we consider commanding officer, guard, patrol and free roaming (soldier) node types. The latter is not depicted here but is included in all companies.

3.2.2 Battalion topology

In this work, we consider the mobility patterns observed in an infantry battalion deployment, following the blueprint introduced in Section 3.2.1 as depicted in the topology shown in Figure 3.3. Such a deployment typically reflects a real-life scenario from [124] during a military training course.

The size of the deployment area is set to $4500m \times 7500m$. The battalion has an orientation, with the forward section (the top area as shown on Figure 3.3) being the reconnaissance area and the rest its area of responsibility. There are 6 command nodes located at pre-arranged locations. The surveillance [126] and support company command headquarters (or centres) are located at the rear. The three main companies (the main fighting elements) have headquarters in the forward-most location of the area of responsibility. These headquarters are immobile [127].

There are 12 guard nodes located near the command centers and 6 guard nodes at the reconnaissance area. The guard nodes have a linear back and forth pre-planned path of 600m length with uniformly distributed speed between $2 - 4$ m/sec, which changes at the edge of the patrol path, i.e. when they change direction.

There are 3 patrol nodes in the topology which represent vehicle patrols in real-life deployments. The patrol nodes follow a pre-assigned rectangular path covering a wide area shown in Figure 3.3 with average speed randomly and uniformly distributed between $5 - 20$ km/h that changes every 10 minutes.

Throughout the AOR, there are several free roaming nodes representing soldiers on various duties. These are randomly placed in the area and move according to the random waypoint mobility model with no pause time. The number of free roaming nodes in this work varies from $50 - 200$ elements (the only parameter in the battalion topology).

3.3 Performance evaluation of three geographical routing protocols in a military setting

We conducted simulations using NS3 to evaluate the performance of Greedy Perimeter Stateless Routing algorithm(GPSR), Divisional Perimeter (GPSR-DP) and Buffering Zone Greedy Forwarding Strategy (GPSR-BZGFS), which are described in Sections 2.3, 2.3.2, 2.3.1 respectively, over the topology described in Secton 3.2.2. The implementation used for GPSR is derived from the fourth patch set of GPSR under code review for inclusion in NS3. We created the GPSR-DP and GPSR-BZGFS implementations from scratch as they were not publicly available.

3.3.1 Simulation set-up

The node topology mirrors the topology described in Section 3.2.2 and shown in Figure 3.3. Note that in this topology we assume a flat open area terrain scenario which does not have any natural or constructed obstacles that may have effects

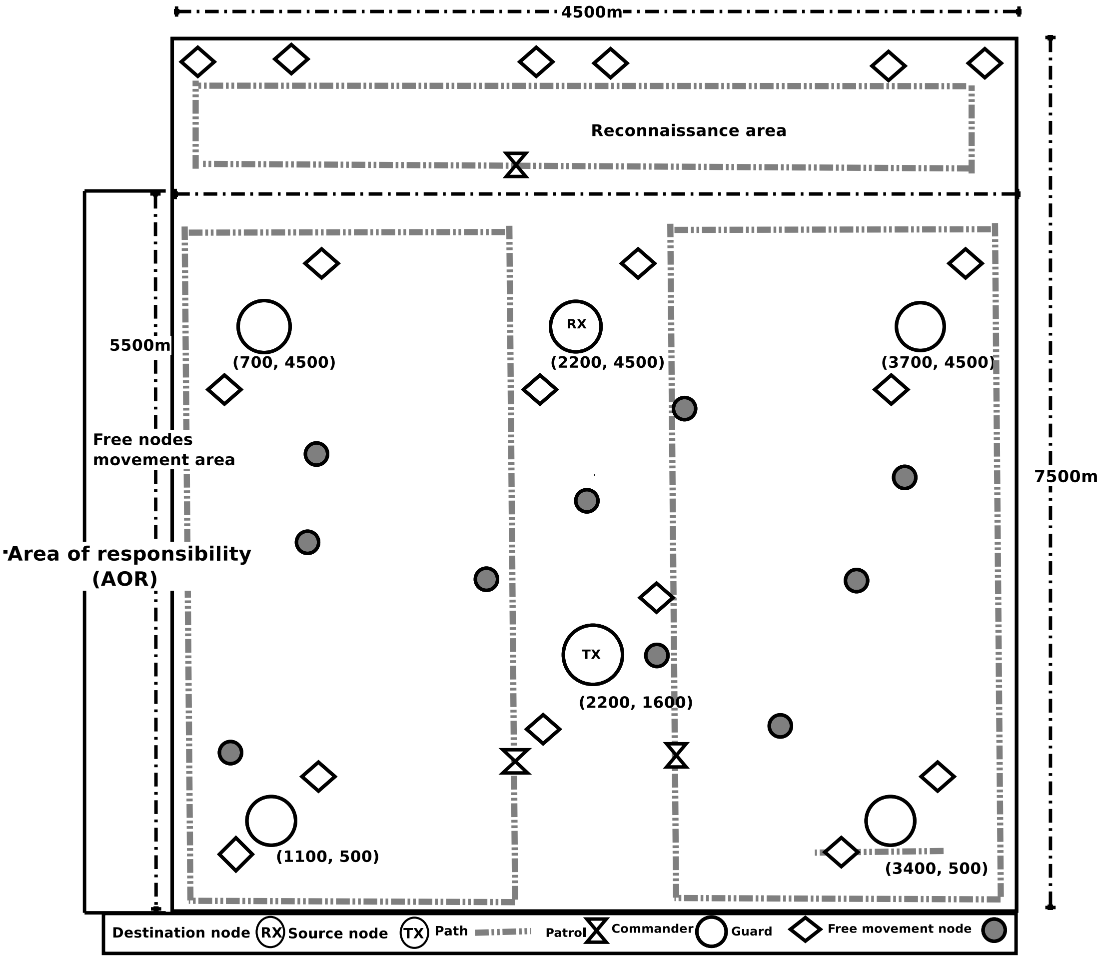


Figure 3.3: Battalion topology and mobility patterns. The number of free roaming nodes (soldiers) is the only parameter in this layout and ranges from $50 - 200$.

on communication signals. In all simulations, there are 6 fixed nodes representing the commander nodes, 18 nodes acting as guards and surveillance units and 3 patrol nodes moving according to a predefined patrol path. There are between $50 - 200$ free moving nodes representing regular soldiers within the AOR. This range represents the penetration rate of communication technology, i.e. we assume that only a portion of the elements (soldiers) are equipped with communication equipment.

In every simulation run, there is a single, perpetual User Datagram Protocol (UDP) based application running on the battalion commander node (marked Tx in Figure 3.3). The simulation considers the following cases:

- A stationary (source and destination) perpetual UDP application running on the battalion nodes. This case is used to investigate the communication between the commanders in the AOR area to exchange the orders and any updated information. We will refer to this as case 1.

- Stationary source and mobile destination perpetual UDP applications running on the commander nodes. This case is used to investigate the communication between the commanders and nodes that are mobile in the reconnaissance area to request updated information. We will refer to this as case 2.

The application sends a single 512-byte packet every second to a commander node in the area at the front of the battalion (marked Rx in Figure 3.3). This exchange lasts for 6000 seconds, then the simulation ends. Then, we note the performance of the routing protocol in terms of the following metrics:

Packets delivery ratio (PDR)

PDR is defined as the ratio of the number of packets received by the destination against the number of packets sent by the source. PDR is computed as shown in the Equation 3.1.

$$\boxed{PDR = \frac{\sum P_R x}{\sum P_T x} \times 100\%} \tag{3.1}$$

Where:

- $P_R x$: **The packets that were successfully received by the destination node**

- $P_T x$: **The packets generated by the source node**

Delay

This is the time taken for a packet originating from a source to reach its ultimate destination. For completeness, it should be mentioned that this metric refers to physical layer timings (i.e. it does not include MAC-layer processing times). The timer starts when the packet is transmitted by the transceiver at the source and only ends when the packet has been successfully received by the transceiver at the destination. Delay is computed as shown in the equation 3.2.

$$\boxed{D_T = T_R - T_S} \tag{3.2}$$

Where:

- D_T: **The individual time interval that the message travelled from a sender to its destination**
- T_R: **The time that the destination node receives the message**
- T_S: **The time when the message was originally transmitted to the network**

Number of hops

This term refers to the length of the transmission path that the packet needs to travel from the source node to the destination node. A greater number of hops indicates a higher probability of using more forwarding nodes to transmit the packets from source to destination nodes. The number of hops is computed by tracing the packet's ID and counting all nodes that participated in the forwarding process from the source to the destination nodes.

Packet drop ratio

This term refers to proportional packet drops between communicating nodes. Packet loss is caused by the lack of communication and long packet size, which may make the wireless channels busy with a long delay. Packet drop ratio is computed as shown in the Equation 3.3.

$$\boxed{Drop = \frac{\sum P_T x - \sum P_R x}{\sum P_T x} \times 100\%} \tag{3.3}$$

Where:

- P_Rx: **The packets successfully received by the destination node**
- P_Tx: **The packets generated by the source node**

The simulation is carried out 15 times for a particular number of free motion nodes, and the performance with respect to the above metrics is recorded. As there is sparse network traffic, it is expected that there will be packet loss due to network segmentation or poor forwarding choices by the routing protocol. The simulation parameters for the scenario are presented in table 3.1.

Parameter	**Value**
Simulation area	$4500m \times 7500m$
Free mobile nodes	$50 - 200$
Command nodes (static)	6
Patrol nodes (path motion)	3
Guard nodes (path motion)	18
Guard nodes speed	$2 - 4$ m/s
Patrol node speed	$5 - 20$ km/h
Mobility model for free nodes	random waypoint model 2-4 m/sec
Zone buffer size (GPSR-BZGFS)	$150m$
Packet size	512 bytes
Transmission rate	1 pkt/sec
Simulation runs	Each number of nodes run 15 different seed numbers
Simulation time	6000 second

Table 3.1: Simulation parameters

3.3.2 Results and discussion

Packet delivery ratio

Figures 3.4 and 3.5 show the average packet delivery ratio observed for different numbers of free roaming nodes. For each observation, we also plot a 95% confidence interval based on the assumption of normal distribution of the variation observed. Evidently, as the number of participating nodes increases, more packets are

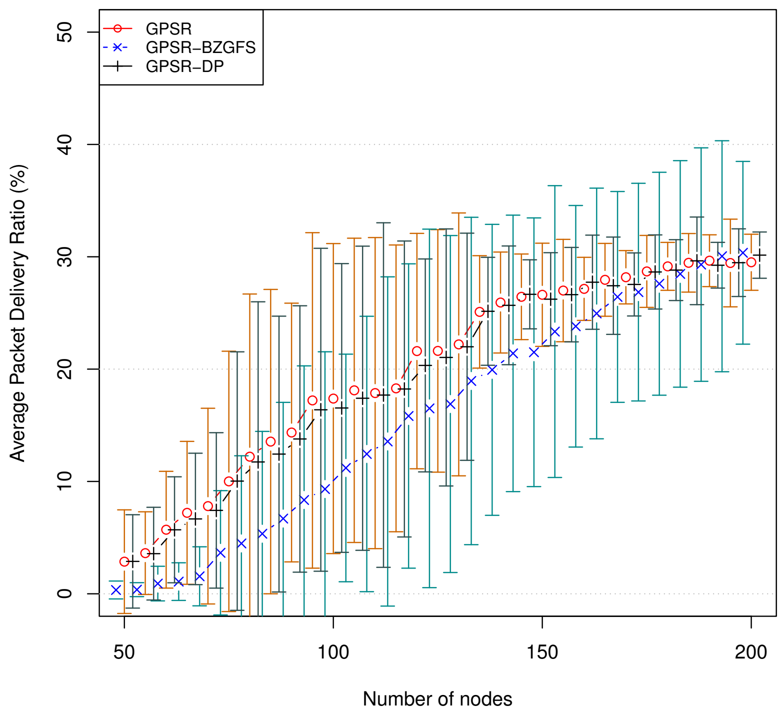


Figure 3.4: The average packet delivery ratio in case of station source and destination nodes.

successfully delivered to their destination for all routing protocols examined. The increase is explained by the increased connectivity afforded to the network by the presence of extra nodes. Intuitively, as the number of participating nodes rises, there is a higher probability of a forwarding node being present between the source and the destination and a higher probability that a viable route exists at all.

Notably, GPSR-BZGFS(Buffering Zone Greedy Forwarding Strategy) underperforms in terms of delivery ratio by up to 11% and 20% compared to vanilla GPSR and GPSR-DP(Divisional Perimeter) in both cases, respectively. This can be understood in terms of the more selective forwarding method of the buffering zone strategy. In its attempt to maintain more stable routes, GPSR-BZGFS assumes that nodes inside the buffer zone are less likely to be reliable and so does not re-use them for follow-up transmissions. However, by doing so, in a sparse network, the algorithm foregoes a valid route choice to try to find an alternative - which often does not exist. When the number of participating nodes reaches

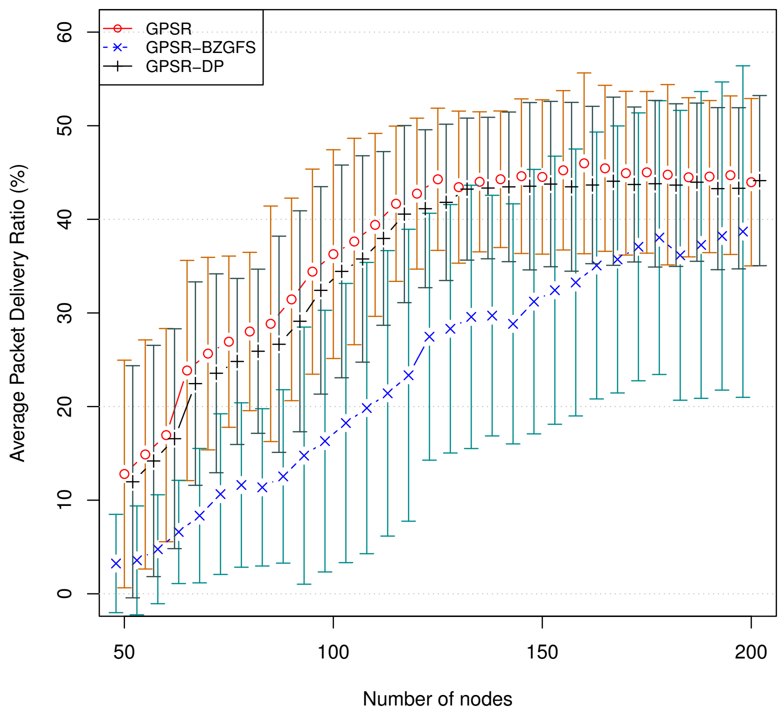


Figure 3.5: The average packet delivery ratio in case of a station source node and a mobile destination.

about 150, in case 1, alternatives do exist and the packet delivery ratio observed in GPSR-BZGFS reaches a similar level to the other two algorithms. While in case 2, it remains lower even if the number of nodes becomes 200.

Overall, the observed delivery ratio is quite low for all protocols ranging from 1.8% – 28% in case 1, and from 17% – 43% in case 2 for plain GPSR and a very similar observation for GPSR-DP. GPSR-BZGFS shows the lowest performance among the protocols with 0.3% – 29% and 1% – 35% of average packet delivery for case1 and case2, respectively. This is attributed to the frequent network segmentation present due to the large deployment area and relatively few participating nodes. Moreover, the restriction on the movement of the free roaming nodes and the patrol nodes in the topology also affect the packet delivery ratio.

Finally, the routing protocols considered here performed better in case 2 because of the probability that the destination comes within the range of the forwarding nodes during its movement compared to the fixed location in case 1.

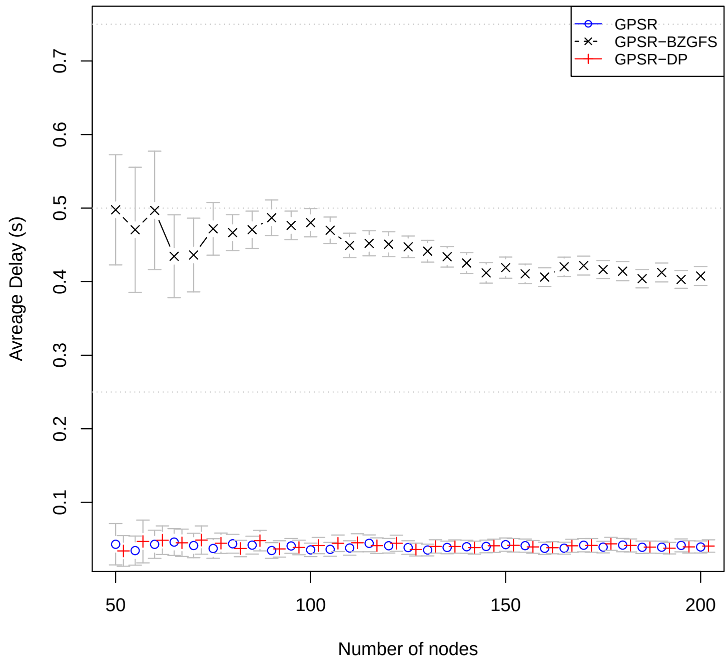


Figure 3.6: The average delay in case of station source and destination nodes.

GPSR does not include a 'message retention' mechanism and relies, like other general known routing protocols, on packet retransmissions from the application to ensure delivery. A mechanism for local route repair could prove to be useful in this instance, although it would have to be adapted for use with a position-based routing algorithm.

Average end-to-end delay

Figures 3.6 and 3.7 show the average delay time required by the packets to reach the destination nodes for each routing protocol during simulations. The 95% confidence intervals shown are, as before, based on the assumption of normal distribution of the variation observed. Note that the delay metric does not consider the case when a route is not discovered and a packet is not delivered; only successfully delivered packets contribute to the results.

As may be expected, the observed average delay is constant for each protocol as

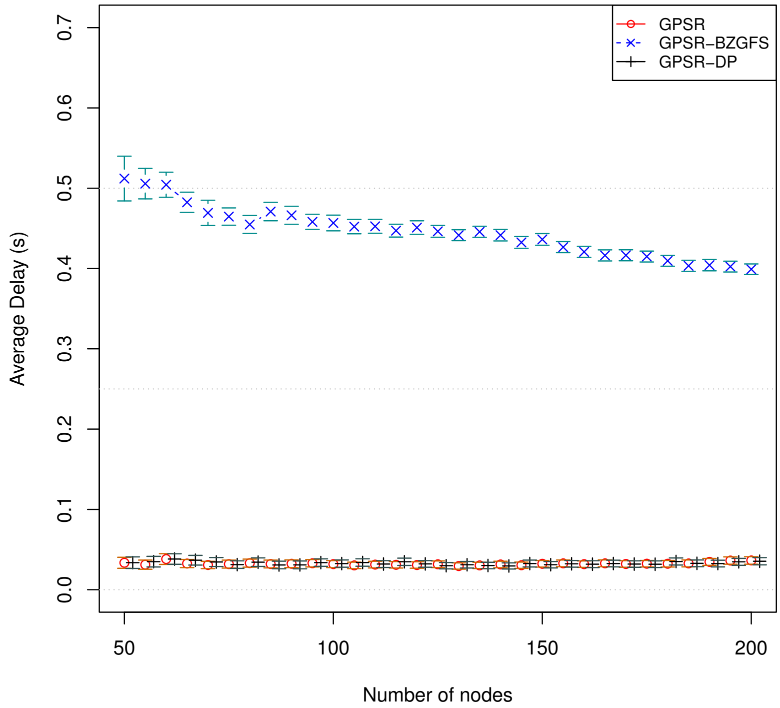


Figure 3.7: The average delay in case of a station source node and a mobile destination node.

the number of free nodes increases. In the case of plain GPSR, it ranges between $31.8ms$ and $54ms$ in both cases. In GPSR-DP, it ranges from $32ms - 56ms$ in both cases. GPSR-BZGFS ranges from $420ms - 500ms$ in all cases. Communication, in this scenario, occurs only between the two commander nodes which, accounts for the stability in the delay metric. However, note that there is increased variance in all protocols, especially in GPSR-BZGFS, as alternative routes through the perimeter are sought out and sometimes found in the sparser cases. In denser topologies (such as those with over 100 nodes), there is a more straightforward route available which is chosen in subsequent transmissions.

The delay observed when buffer zones are employed (GPSR-BZGFS) is substantially higher by a factor of $8 - 14$ times. The reason, again, lies in the rejection of nodes within the buffer zone as viable forwarding nodes; instead, alternative routes are employed which are longer (if at all available). It should be noted here that a different setting in buffer zone size could yield substantially better results. However, the discovery of such is left as a prospect for future work.

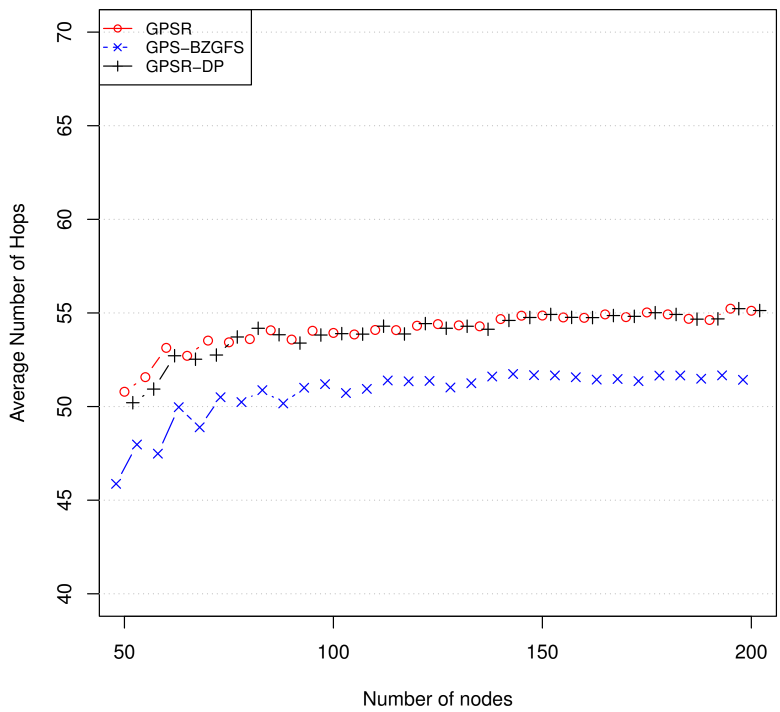


Figure 3.8: The average number of hops in case of station source and destination nodes.

Overall, the delay in all algorithms in case of low density, which represents a sparse network, is quite low. However, at the same time, the number of packets that are successfully delivered is also quite low. Intuitively, it is important in this case to focus on the reasons behind low packet delivery before attempting to decrease delay.

Number of hops

Figures 3.8 and 3.9 depict the number of hops measured for each routing protocol during simulations in both cases. Each point also includes a 95% confidence interval as before. The number of hops in all algorithms is large, between 45 and 53 as minimum hops respectively, and this is explained as follows: Firstly, the area of the topology is larger in a work context so the network diameter is substantially larger compared to the smaller scenario areas. Secondly, the recovery method described in Section 2.3 is applied in this scenario because there is frequently no shortest path from the source node to the destination node; applying this method

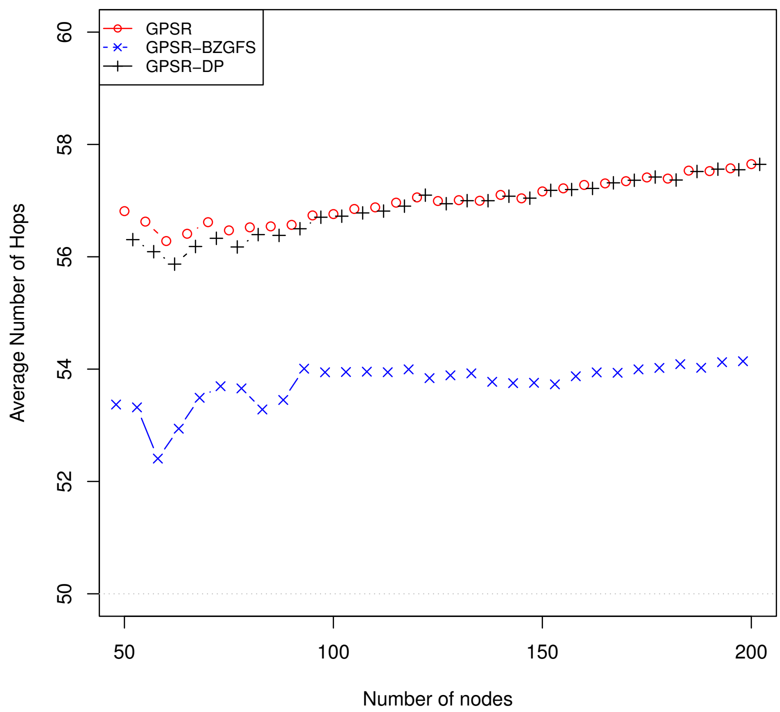


Figure 3.9: The average number of hops in case of a station source node and a mobile destination.

increases the number of hops as mentioned in [15]. In our experiments, GPSR and its variants exhibited the lower number of hops because these routing protocols drop the packets if a dead end is encountered. The variants that appeared in case 2 are a result of the calculation of the average number of hops that the messages used to reach the destination node.

The GPSR-BZGFS method had the lowest average number of hops by 45% in case 1 as shown in Figures 3.8 and 53% in case 2 as shown in Figure 3.9 compared to the other variants because of the use of a buffering zone to select the forwarding nodes. GPSR-BZGFS expects nodes inside the buffer zone to be less reliable and, thus, not reusable for the next hop transmissions.

Following GPSR-BZGFS in terms of the minimum number of hops are GPSR and GPSR-DP by the nearly similar percentages of 52% and 57% in both cases, respectively. Using the recovery mode in this case increases the number of hops, while the number of packets delivered to the destination still remains low, as shown in Figures 3.4 and 3.5.

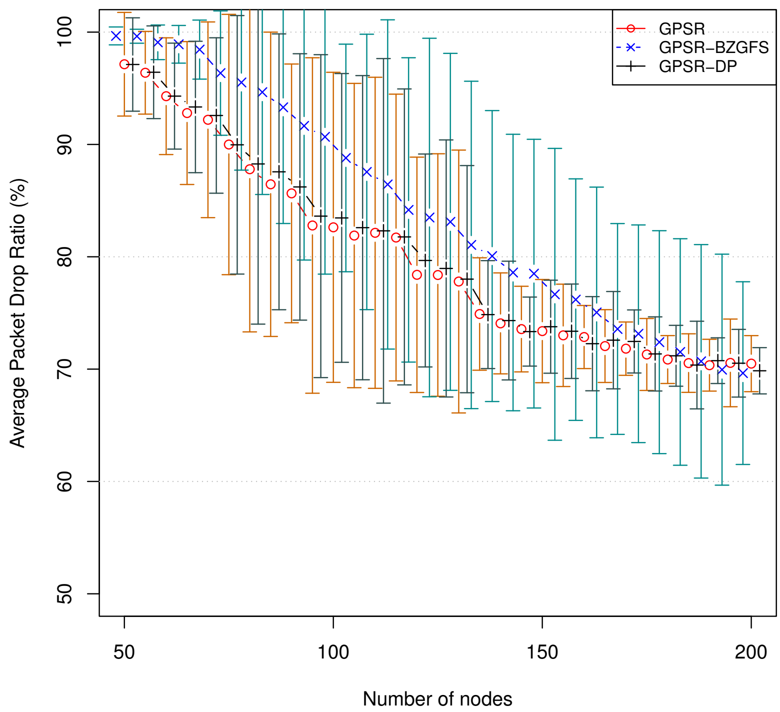


Figure 3.10: The average dropped packets in case of station source and destination node.

Average packet drop ratio

Figures 3.10 and 3.11 show the average packet drop ratio observed for different numbers of free roaming nodes. For each situation, we also plot a 95% confidence. Evidently, as the number of participating nodes increases, fewer packets are dropped for all routing protocols examined. The decrease is explained by the increased connectivity afforded to the network by the presence of extra nodes. Intuitively, as the number of participating nodes rises, there is a higher probability of a forwarding node being present between the source and the destination and a higher probability that a viable route exists at all.

As expected, the rate of dropping messages in GPSR-BZGFS is higher than in other protocols, especially when the number of nodes in the network are few due to the use of a buffering scheme. It is also clear that an increase in the number of nodes leads to a decrease in the number of packets dropped, which in turn leads to an increase in the effectiveness of the network in case of a large number of nodes.

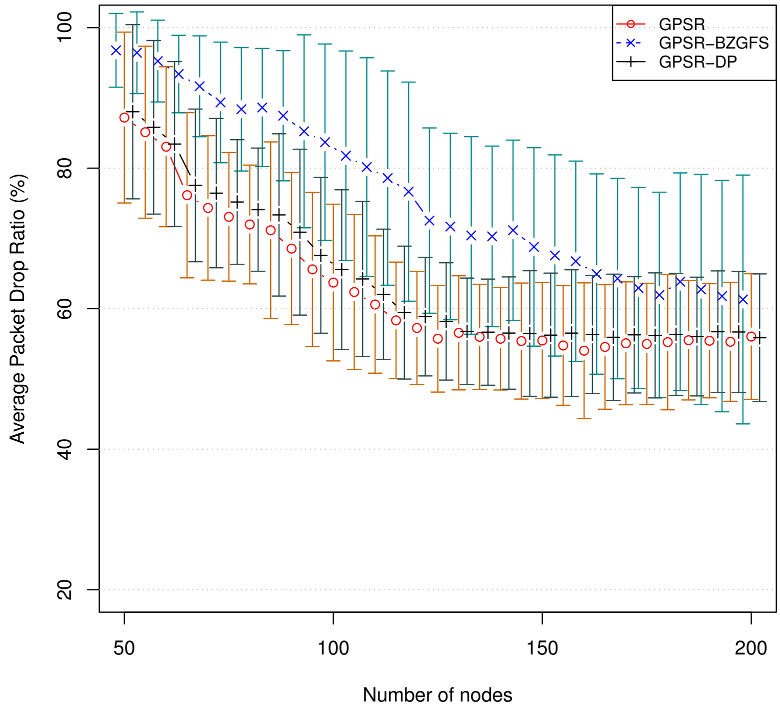


Figure 3.11: The average dropped packets in case of a station source node and a mobile destination.

GPSR and GPSR-DP dropped the lowest number of messages in both cases and are close significantly, the dropped ratio are between 98% and 72% in case 1, as shown in Figure 3.10, respectively. In case 2, as shown in Figure 3.11, the drop ratios are between 88% and 60% respectively. In theory, lower drop occurs in case 2 because the movement of the destination node increases the probability of having a connection between the nodes to deliver the packets and prove that the number of the receiving packets in Figure 3.5 is greater than in a fixed location case, as in Figure 3.4. GPSR-BZGFS had the largest number of packets dropped in both cases by 99% -70% and 98%- 75%. Finally, it is clear that the military rules restrict the movement of the nodes and since the underlying protocols have no information about the special nodes' path, they do not utilise the nodes based on their roles in the topology. This is due to the lack of communication between the nodes in a large geographical area and the restriction of movement in military applications which causes significant packet loss (approximately 90% as shown in Figures 3.10 and 3.11), especially in the case of a sparse network.

3.4 MANET application information

We have introduced a use case scenario of an application running on a real-life military operation scenario topology based on a potential infantry battalion deployment in order to examine the network performance of three GPSR-based routing algorithms. Our results from the investigation indicate that even though communication between nodes is possible using a position-based routing paradigm, the overall performance is quite poor with respect to packet delivery ratio, delay, and drop ratio as well as number of hops if buffer zones are employed.

The analysis of the use-case scenario application that use MANETs as preferable networks for communication between nodes have shown that there is some built-in information that can support the communication networks. This information may include elements in the developed topology such as the communication message's generator and the receivers, the node's deployment location in the topology, the time that the node is available in the topology, the path(s) that the nodes should follow during their appearance in the topology and the roles and duties of nodes. Specifically, knowledge of these roles and duties may help when forwarding the messages to their final destinations.

3.4.1 Identifying application information for better communication

We will present a general definition of plans that are prepared in advance in some applications to demonstrate that these plans have useful information to construct the methods of communication between nodes. We will use the scenario described in 3.2 to extract this information.

A plan is a prearranged document to explain the procedures during emergency situations or military operation missions. An emergency evacuation system is an example of an emergency plan that contains information such as the layout of the building, the number of rooms and doors and the population in the building [128].

A definition of a military plan is given in [125] as the means by which a leader views certain desirable outcomes and determines effective ways of achieving successful results. The final planning product should:

- Enhance the command task through clear explanation of the commander's needs;
- Appoint subordinates' duties;
- Allocate or reallocate resources;
- Contain a minimum of coordination procedures necessary to synchronise the process;
- Direct the support work and define the time or conditions for implementation.

It is clear from the above that the number of people and vehicles are equally as important resources in military planning. The behaviour of these resources during the implementation of the plan may be used to increase the performance of routing in MANETs. Moreover, the duties of these resources could be used to increase the stability of routing in MANETs as described in the following section.

3.4.2 Utilising application information

The military scenario described in Section 3.2.2 shows that there is a predefined path used to complete the patrolling duty. Each element in the scenario has a duty that does not affect other roles during a mission. Effective cooperation of the nodes is necessary for a mission to be adequately completed without having any known impact on assigned duties. Moreover, there are some rules such as movement restrictions in the battlefield that cause a regular disruption between the nodes in the topology. Thus, the nodes in such a large area seem loosely coupled with each other because of the distance between the elements aiming to build a network.

We aim to utilise the above information to increase the stability of the routing process between nodes in the topology. The patrol node, in which a vehicle goes around the topology for monitoring duties, will be used to carry the messages from the node that is located in an area with poor or no connectivity options. Nevertheless, this extra role assigned to a patrol node will not affect the patrol node's duty so as not to compromise its operational use. In the process of receiving messages, the patrol node will continue its duty without the need to move from its path to receive the messages. In addition, in the process of sending messages from the patrol node, the destination node or any other participating node will not have to move to be in the patrol node transmission range.

3.5 Summary

This chapter has conducted the first performance analysis of three geographical routing protocols, namely GPSR, GPSR-DP and GPSR-BZGFS, in order to assess their performance in a military network based on a real-life scenario. The first part introduced the real case study based on real-life deployment of a military unit. The second part described the analysis which was conducted through studying the effects of different network densities in terms of deploying different numbers of nodes over a large topology area.

The results revealed that, for a given network set up with a given network density and node mobility, communication between nodes can be achieved in terms of packets successively delivered. The large area and the node movement degraded the overall network performance in terms of network packet delivery ratio and end-to-end packet delay, because the node movement restriction in a military application caused a regular disconnection in the network. The use of information derived from the application itself was not utilised well in the existing routing algorithms, resulting in poor network performance. The military plan has information that can increase the network performance in terms of raising the number of packets that were successfully delivered to the final destinations.

In the following chapter, we present a message retention mechanism which improves message delivery performance for the specific network in a military scenario. We also investigate local route repair functions in this context by introducing suitable heuristics to decide when these should be employed. Moreover, we explore special use of pre-planned patrol node route information to fill gaps in the communication fabric where possible.

Chapter 4

Designing a Ferry-Assisted Greedy Perimeter Stateless Routing Protocol

4.1 Introduction

Based on the results presented in Chapter 3, we can conclude that the application characteristics and nodes behaviours are reasons for the degradation of the routing performance in MANETs.

In this chapter, a new algorithm is proposed which solves most of problems out lined above. It aims to increase the packet delivery ratio by using the information derived from the application to optimise the Greedy Perimeter Stateless Routing algorithm(GPSR) routing protocol. It works by extending the forwarding process when a dead-end path is encountered through the use of a patrolling node. This chapter is organised as follows. First, a brief overview of the ferry scheme is given in Section 4.2. Sections 4.3 and 4.4 provide the design of the new algorithm, including the description of all functions that support the proposed algorithm. The evaluation of the proposed work, compared to the other routing algorithms described in Chapter 3 is conducted in Sections 4.6, 4.7 and 4.8. Finally, Section 4.9 provides a summary of this chapter.

4.2 Ferry Scheme

Partitioned networks are a specific area of research on *Ad-hoc* networks, where previous studies have proposed solutions to overcome the disconnection problem in Delay/Disruption Tolerant Networks (DTN). One such solution used is a ferry scheme.

The name "ferry" was inspired by the transport method in which ferries are used to carry people across valleys or straits. In the ferry technique, a subset of nodes, which are called ferry nodes, is used to transmit information across the gap between the disconnected parts of the network segments. However, the nodes that are not members of the ferry subset are called ordinary nodes. One of the major challenges in the ferry scheme is to determine the destination of the ferry nodes where the ferries should modify their paths to move to the node positions to enhance packet delivery. it is assumed that ordinary nodes in MANET are stationary or only have restricted mobility [129]. Thus, a ferry node will operate its route according to the locations of the ordinary nodes. Nonetheless, the mobile node is a common phenomenon in real-life applications. An updated location is needed to guide the ordinary nodes and direction of movement. Kuo-Feng et al. [130] used a central control to define the optimised location of a ferry. However, the cost of communication is very high. Chia-Ho et al. [131] used the concept of a First-In-First-Out (FIFO) queue to store all possible locations of the ferries. The ferry will then move from one location to another until it finds an empty location that is not occupied by any other ferry. However, the high number of ferries required by this scheme negatively affects its performance. Moreover, this scheme suffers from long delay in packets delivery. Tariq et al. in [69] used the prediction methods of the location of ordinary nodes. This scheme is not distributed and not scalable to the increased number of nodes.

Zhao et al [23] proposed a message ferry approach using two methods: Node-Initiated Message Ferrying (NIMF) and Ferry-Initiated Message Ferrying (FIMF). The ferry node has a predefined path known by others nodes, so in NIMF, a node will move to be close to the ferry's path to transmit or receive data as shown in Figure 4.1 [23]. In the FIMF approach, the ferry node will broadcast its location periodically to be used by the nodes if they plan to send or receive a message through the ferry. Figure 4.2 [23] shows the process of the FIMF in which a node sends a service request message to the ferry node via long-range radio. The message includes node location information. The ferry node will change its route to be in the range of the requested transmission. When the transmission is completed, the ferry node will return to its predefined route.

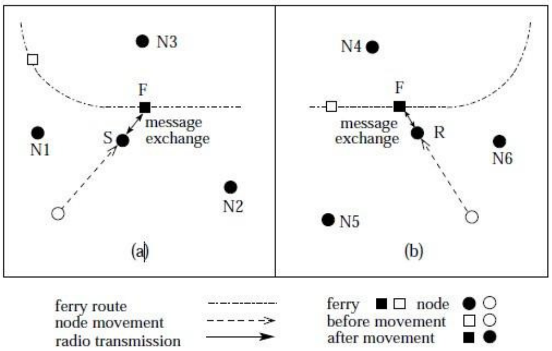


Figure 4.1: An example of Node-Initiated Message Ferrying schem (NIMF). The ferry moves according to a specific route which is predefined.

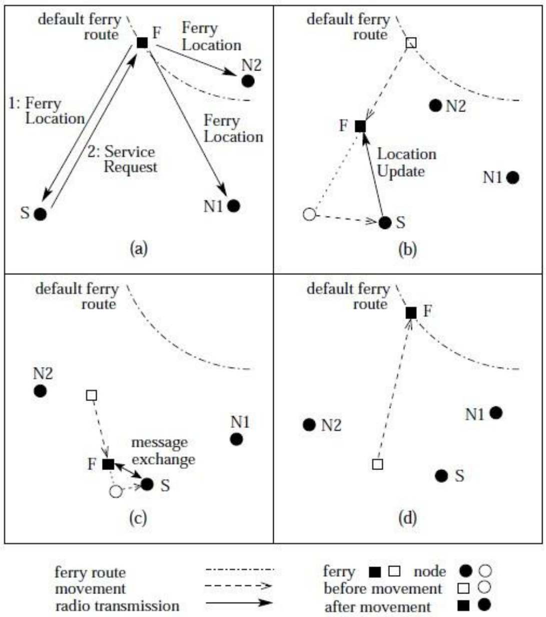


Figure 4.2: An example of Ferry-Initiated Message Ferrying (FIMF). The ferry takes proactive movement, which means it will leave the predefined route, to meet up with nodes for communication purposes.

4.3 Ferry-Assisted GPSR

As detailed in Chapter 2, GPSR is a position-based routing algorithm that uses the position of the source node and destination node to forward packets. Each node needs to know its own location, and the source node needs to know the destination node's location information [3]. The GPSR routing algorithm consists of two techniques to forward packets, namely Greedy and Perimeter forwarding. Greedy forwarding is used as the first choice, whereas Perimeter forwarding is used when a node in Greedy forwarding mode cannot choose a neighbour closer to the destination than the node itself. Both techniques are used in the prosed novel algorithm. When a node in Perimeter forwarding (Recovery mode) faces the case where no nodes in its table list are able to forward a packet either by the Greedy or Perimeter techniques, it will simply drop it. In the proposed ferry-assisted GPSR variant (FA-GPSR), the packet is not dropped but is instead forwarded towards a special patrolling node that takes over the forwarding task. In particular, patrolling nodes already exist in the military scenario and are used by FA-GPSR as ferry nodes to fill the gap when there are disconnections between the nodes in the topology. The FA-GPSR process is illustrated in the following Figure 4.3:

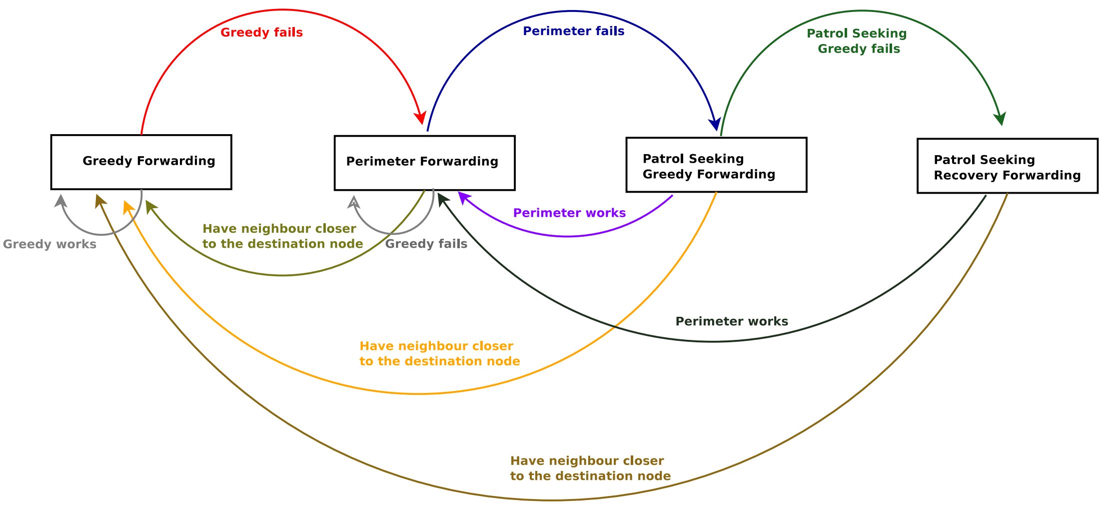
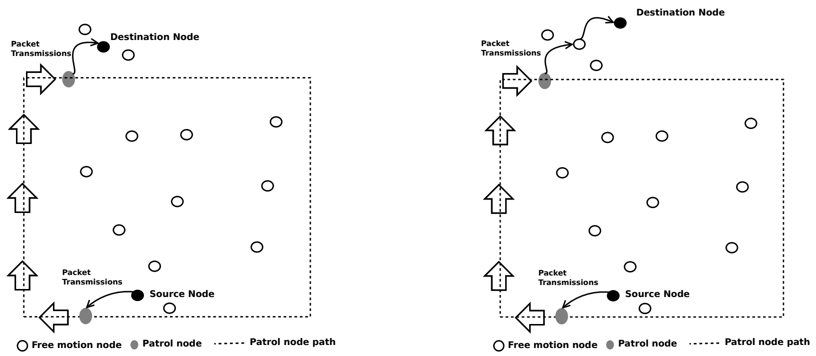


Figure 4.3: Ferry-assisted GPSR concept



(a) Forwarding packet process through patrol node only

(b) Forwarding packet process through patrol node and an intermediate node

Figure 4.4: Illustration FA-GPSR operation

Specifically, Figure 4.3 shows that when the Perimeter mode fails, the FA-GPSR algorithm enters a third mode of operation called the **Patrol Seeking Mode** in which the node does not drop the packet but instead forwards it to an appropriate patrol node, which is termed the ferry node. In effect, the patrol node becomes a new destination, and the original destination is stored in a special field. The new mode involves two forwarding techniques, namely the Ferry-Greedy and Ferry-Recovery Forwarding. These mirror the process of the normal Greedy/Perimeter mode GPSR techniques and are used to forward the packet to the patrol node. If during this forwarding there is another Perimeter mode failure, then the packet is discarded.

When the packet reaches the ferry node, it is cached and stored in a queue. The patrol node moves along its predefined path and reaches a point where it is closest to the destination. Once this point is reached, the patrol node forwards the packet directly to the original destination if the destination node is within its transmission range, as shown in Figure 4.4a. Otherwise, the patrol node forwards the packet to an intermediate node using the standard GPSR process as shown in Figure 4.4b. It should be further noted, that a packet may only use the ferry (patrol) node once; if a Perimeter mode failure occurs subsequently, the packet is discarded. Such a measure prohibits extensive forwarding loops. The new mode is described by using the following definitions:

- R - is the node receiving a packet p for destination D
- N - is the set of one-hop neighbours of R
- n - is a node of the set N that is used to forward the packet
- D - is the destination of the packet
- Pat - is the patrol node that is used to forward the packet

The following pseudocode describes the operation:

Algorithm 4.3.1: FA-GPSR(R, N, n, D, Pat)

```
if ∃n ∈ N : Distance(n, D) < Distance(R, D)
  then { procedure GREEDY FORWARDING(N, D)
         n=MinDistance(N, D)
         FORWARD PACKET(p, n)
         return
  else if R is Local Maximum
      comment: use right hand rule
  then { procedure RECOVERY MODE()
         if n = RightHandRule(N)
           then FORWARD PACKET(p, n)
         return
  else if N is empty
  then { procedure PATROL SEEKING MODE()
         if CAN REROUTE TO PATROL NODE(p)
           then { SELECT(Pat)
                  FORWARD PACKET(p, Pat)
                  MANAGEMENT PROCESS(p, D)
                  FORWARD PACKET(p, D)
         return
  else DROP(p)
```

As mentioned previously, the most important new feature is the forwarding of packets to a patrol node when both traditional GPSR techniques (Greedy forwarding and Recovery mode) fail.

4.4 Patrol Seeking Mode

The first step in the new mode is to check whether the packet has a header with the information about the destination location. This check is essential because the use of destination location is a core functionality in the geographical routing protocols. If the packets fulfil this condition, then it will change its mode to the Patrol Seeking Mode and start following the procedures to transmit packet to the target node or location. Some functions support the work of the new mode. The following subsection describes all functions in detail in order to present the new variant process.

4.4.1 Patrol node selection

To avoid increasing the length of the packet's path to the patrol node, the FA-GPSR in the beginning allows a node that faces a dead-end to determine the patrol node that is closest to the destination node. Each node can use the predefined route information for the patrol nodes and the destination location information from the packet's header to detect which patrol node is closest. The assumption in this algorithm is that the path of the patrol node is a geometric shape composed of four points defining the beginning and end of each line in this shape and each line between two points is a segment. The pseudo code in algorithm 4.4.1 shows the calculation of the distance between a segment and the destination node. It defines the point in the segment that is the shortest distance to the destination node.

This is undertaken by testing the angles of intersection between the segment, defined by $P0$ and $P1$, and the destination node D as shown in Figure 4.5.

- The dot product of the segment and the vector from point $P0$ to the destination node D is found and reserved in vector A. If the result is less than or equal to zero then the $P0$ lies closest to the destination node D as

D is positioned outside of the segment and the distance is found between them.

- If the result is greater than zero the dot product of the segment with itself is found (reserved in vector B) and compared to A to determine if D lies on the other side of the segment and so is closer to $P1$.
- If B is less than or equal to A, then point $P1$ is closer to D as it is positioned outside of the segment.
- If A is less than B, then the destination node D is between $P0$ and $P1$ and the point of intersection Di is found by starting at $P0$ and moving along it in the direction set by the vector of the segment scaled by the ratio of A to B.
- Finally, the algorithm returns the distance between the destination node and the point of intersection with the segment.

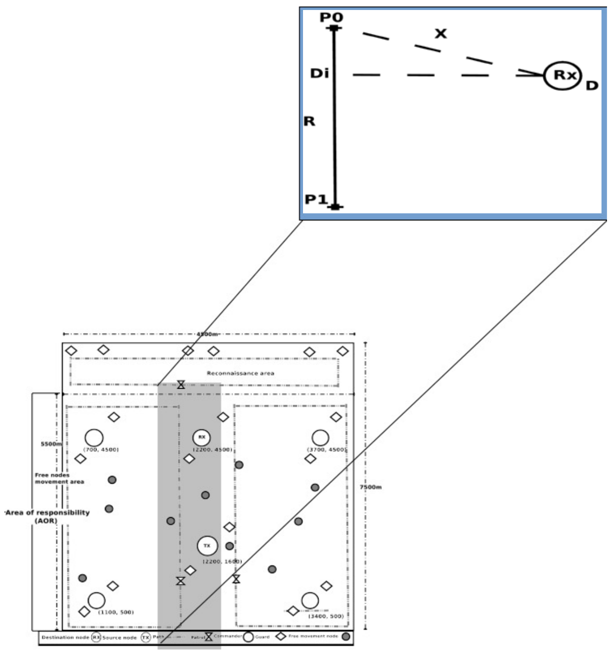


Figure 4.5: Battalion topology and mobility patterns.

Algorithm 4.4.1: CALCULATE DISTANCE FROM POINT TO SEGMENT(D, S)

Comment: *get the distance and the nearest point from destination node D to segment S, which starts at point $P0$ and ends at point $P1$.*
input: *destination node D and segment S*
return: *location and the distance of nearest point in segment S to node D*

procedure FIND SHORTEST DISTANCE(D, S)
- $vectorR \leftarrow P1 - P0$
- $vectorX \leftarrow D - P0$
- $A \leftarrow R.X$ **comment:** A is a temporary variable
  - **if** $A \leq 0$
    - **then return** $dist =$ CALCULATE DISTANCE$(D, P0)$
  - $B \leftarrow R.R$ **comment:** B is a temporary variable
    - **else**
    - **if** $A \leq B$
    - **then return** $dist =$ CALCULATE DISTANCE$(D, P1)$
  - **else**
  - $C \leftarrow A/B$ **comment:** C is temporary variable
  - $Di = P0 \times (C \times R)$
  - **return** $dist =$ CALCULATE DISTANCE(D, Di)
- **return** $dist$

The algorithm 4.4.1, defines the location in each segment, which means that each patrol path has four locations, and returns these locations and the destination between each location and the destination nodes.

This information will be used in the function described in algorithm 4.4.2 to choose the patrol node that has the shortest distance to the destination node. In algorithm 4.4.2, we used a mathematical structure to calculate the shortest distance from the patrol path to the destination node. The algorithm will use the patrol node path that has the shortest distance, and the function will determine the position in the chosen path at which the patrol node will transmit the packets. This position in the patrol path is the closest to the destination, as shown in algorithm 4.4.2:

- PP - Patrol Node;
- D - Destination Node Position;
- S - Segment (P0,P1);

Algorithm 4.4.2: CHOOSE PATROL NODE(D)

$d \leftarrow DefaultDistance$
Comment: *the assumption is that the default distance is a large number greater than the length of the topology*

for $\forall$PP
  do for $\forall S \in PP$
    do {
      $(Distance, Point) \leftarrow$
      DISTANCE FROM POINT TO SEGMENT(D, S)
        if $Distance \leq$d
          then {
            $d \leftarrow Distance$
            $MinimumDistance \leftarrow Distance$
            $ShortestPoint \leftarrow Point$
            $TargetPatrol \leftarrow PP$

When the patrol node is detected, the node facing the dead-end will add to the packet header the IP address for the patrol node chosen. The node then starts forwarding the packet to the patrol node using the Patrol Seeking Greedy forwarding method (PS-Greedy). Any intermediate node facing a dead-end with no access to the patrol node changes the method to Patrol Seeking Recovery (PS-Recovery) to avoid the dead-end area. The algorithm 4.4.3 describes the patrol node selection and the forwarding process from the ordinary nodes to the patrol node.

Algorithm 4.4.3: SEND PACKET TO PATROL(p, Pat)

```
CHOOSE PATROL NODE(D)
p.Header.Destinationnode ← Pat(IP)
if ∃n ∈ N : Distance(n, Pat) < Distance(R, Pat)
  then { procedure GREEDY FORWARDING(N, Pat)
           n=MinDistance(N, Pat)
           FORWARD PACKET(p, Pat)
           return
  else R is Local Maximum
       comment: use right hand rule
       { procedure RECOVERY MODE()
           if n = RightHandRule(N)
             then FORWARD PACKET(p, Pat)
           return
```

4.4.2 Patrol node packet management

If a packet is received by the patrol node, it will then be buffered with the extra information, such as the point that the patrol node will use to transmit the packet. However, the patrol node will use the original destination position to identify the destination node because the packet will have the original destination position as shown in algorithm 4.4.4.

Algorithm 4.4.4: PROCESS AT PATROL NODE(p, Pat)

---

if $p.Hder.Dest.IP = Pat.IP$ **and**
$pckHdr.Mode = PatrolSeekingMode$
then {
  procedure PATROL NODE BUFFERING(p)
  return $(TRUE)$
}
else
  return $(FALSE)$
  comment: Drop the packet

4.4.3 Packet transmission to destination node

The patrol node continues to operate without being influenced by the process of receiving the packets because the transmission process to the patrol node does not require any change in the path or waiting at a certain point for the reception. This is an important feature of the FA-GPSR protocol, and it differs substantially from previous uses of the ferry scheme [23]. Moreover, the transmission and receiving process do not require a prioritising comparison between reception or transmission and duty.

The patrol node needs to make sure that the message is received at the correct address by comparing the IP address in the message with its local address. When they are identical, the patrol continues to carry out its pre-scheduled duty. The message contains extra information, as explained previously in subsection 4.4.1, and specifically the location that the patrol node will start to transmit when it reaches this point because it is the closest location to the destination node in the patrol path. The message can be transmitted directly to the destination node if it is in the patrol node transmission range or through an intermediate node if it is closer to the destination node than the patrol node.

4.5 Simulation Scenario

This section presents the performance evaluation of the new proposed protocol using the same simulation model and parameters outlined in Section 3.3. The performance metrics used to conduct the performance evaluation include the packet delivery ratio, end-to-end delay and number of hops. These metrics have been defined in Section 3.3.

The results are compared against Greedy Perimeter Stateless Routing algorithm(GPSR), Divisional Perimeter (GPSR-DP) and Buffering Zone Greedy Forwarding Strategy (GPSR-BZGFS), which have been described in Section 2.3. The simulation scenarios consist of three different settings, each of which is specifically designed to assess the impact of a particular network operating condition on the performance of the protocols. First, the effects of various loads of packets generated by different numbers of source and destination nodes at fixed locations are evaluated. The second simulation scenario investigates the same effects but the source and the destination nodes are mobile nodes. The third simulation scenario investigates the same effects, but the source nodes are station and the destination nodes are mobile, as illustrated in Table 4.1.

Table 4.1: Simulation scenarios

Simulation scenario	Number of source and destination	Packets load size	Value
Inter Commanders	1-6	Low load packet	1p/s
		Medium load packet	5 p/s
		High load packet	10 p/s
Inter Elements	10-15	Low load packet	1p/s
		Medium load packet	5 p/s
		High load packet	10 p/s
Mixed elements	1-5	Low load packet	1p/s

The communication among the commanders on the battlefield is an important issue because if this communication path is stabilised, it leads to an increase in the number of successfully received packets. Moreover, the communication between the commanders and other active elements on the battlefield is important such as the surveillance team that needs to update the commanders with recent information. In addition, the commanders sometimes need to communicate with highly mobile elements in the field.

The performance of the communication among the commanders and between the commanders and the soldiers are evaluated using the four protocols. As shown in Table 4.1, the packet load is divided into three types in order to evaluate the performance of the network in different situations. First, we set a low packet load in which only one packet in a second is generated by each source node. Second, medium packet load is set to five (5) packets per second generated by each source node. Finally, high packet load is set to ten (10) packets per second generated by each source node. For each simulation trial, the source and destination nodes are selected based on the distance between them, which is the farthest distance between any two nodes on the battlefield. The number of source and destination nodes is between 1-15, as shown in Table 4.1. The simulation scenarios in Table 4.1, will be used for investigate the impact of the following:

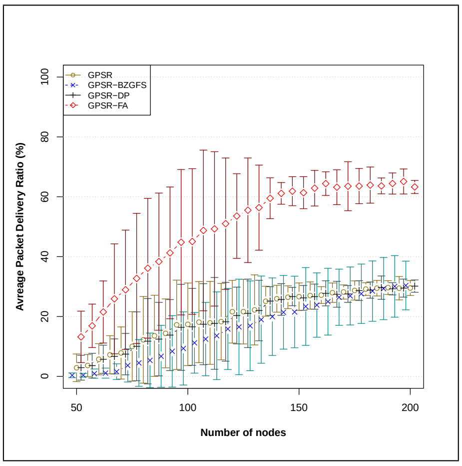
- **Inter commanders** to investigate the impact of communication between station nodes
- **Inter elements** to investigate the impact of communication among mobile nodes
- **Mixed elements** to investigate the impact of communication between station and mobile nodes

The next sections will present and discuses the results for each impact.

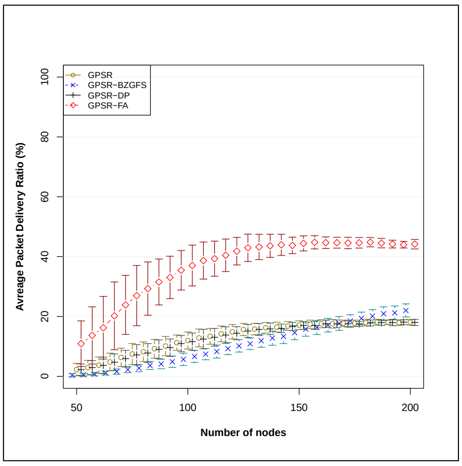
4.6 The Impact of Communication between Stationary Nodes

Communication between the Battalion commander and officers in the battlefield is essential to receive commands and operation orders during the mission. As stated in Section 3.2.1 they are immobile elements so, in this section the thesis will investigate the network performance in the situation that the source and destination nodes locations are fixed.

4.6.1 Packet delivery ratio



(a) One source node and one destination node



(b) Five source nodes and five destination nodes

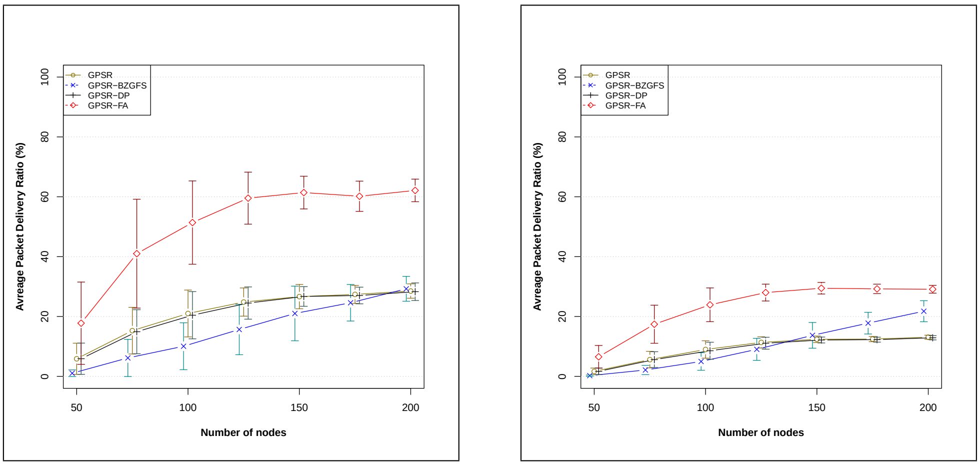
Figure 4.6: Average low load packet delivery ratio using different numbers of source and destination nodes [1]

A) In the case of low load packets, Figure 4.6 shows examples of the average packet delivery ratio observed for different numbers of free roaming nodes. For each observation, we also plot a 95% confidence interval. The results show that as the number of participating nodes increases, more packets are successfully delivered to their destination in all routing protocols examined.

In all cases the proposed algorithm FA-GPSR outperforms the other variants in all numbers of free motion nodes. When the number of nodes in the network is between 50 and 100, which represents a sparse network in the topology, GPSR and its variants do not successfully deliver many packets because of connectivity failures; often a route between the source and the destination does not exist.

[1] This group of figures just shows an example where the number of source and destination nodes changes. Figures are shown in Appendix A.1.

FA-GPSR delivered 18% – 60% of the packets to the destination node. The use of ferry nodes in this case increases the delivery ratio from 1% to more than 10%, in 50 nodes, without affecting the duty of the patrol nodes (ferries) and the activities of the soldiers who participate in the packet forwarding process. The confidence interval values show that the worst case performance of the FA-GPSR algorithm is better than the best case performance of GPSR and its variants. The difference in the number of packets successfully delivered to the destination node by FA-GPSR compared to the existing algorithms rises from 70 nodes onwards. In the proposed algorithm, the delivery ratio of the packets stabilises between 150 – 200 nodes, as is the case for GPSR and GPSR-DP, while GPSR-BZFS shows a linear increase.



(a) One source node and one destination node

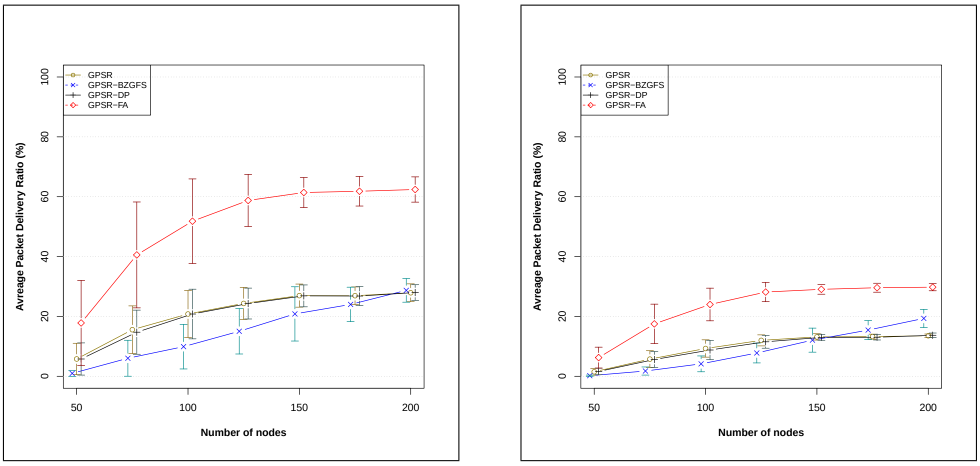
(b) Five source nodes and five destination nodes

Figure 4.7: Average medium load packet delivery ratio using different number of source and destination nodes [2]

It can be noted that increasing the number of source and destination nodes does not affect the performance of the proposed algorithm; FA-GPSR maintains this advantage against the existing algorithms in all cases. In the case of using five sources instead of one, the packet delivery ratio increased in FA-GPSR by 15% – 40% when the number of nodes increased from 50 to 200 nodes, respectively.

[2]This group of figures shows an example where the numbers of source and destination nodes changes. The figures are shown in Appendix B.1.

B) The medium load of packets (Figure 4.7) show some examples of the average packet ratio when medium loads of packets are used (full figures available in appendix B.1). These examples are considered turning points in the effectiveness of the routing performance, compared to other graphs shown in appendix A.2. In this type of experiment, the number of free roaming nodes starts at 50 nodes and increases incrementally by 25 (instead of by 5 as in the previous experiments) in order to minimise the noise while the graphs are plotted.



(a) One source node and one destination node

(b) Five sources node and five destination nodes

Figure 4.8: Average high load packet delivery ratio using different numbers of source and destination nodes [3]

FA-GPSR continues to outperform the other routing algorithms, and the packet delivery ratio increases when the number of free movement nodes is increased. When one source and 50 free-roaming nodes are used, the packet delivery ratio in FA-GPSR is higher by 20%, compared to 15% when five sources are used. While the number of nodes increases, the packet delivery ratio increases until the number of nodes is 150. The ratio is relatively stable until the number of nodes reaches 200 because of the presence of enough number of nodes in the topology to deliver packets to their final destinations.

The packet delivery ratios in GPSR and GPSR-DP start from less than 15%

[3] This group of figures shows an example where the number of source and destination nodes changes. The figures are shown in Appendix C.1.

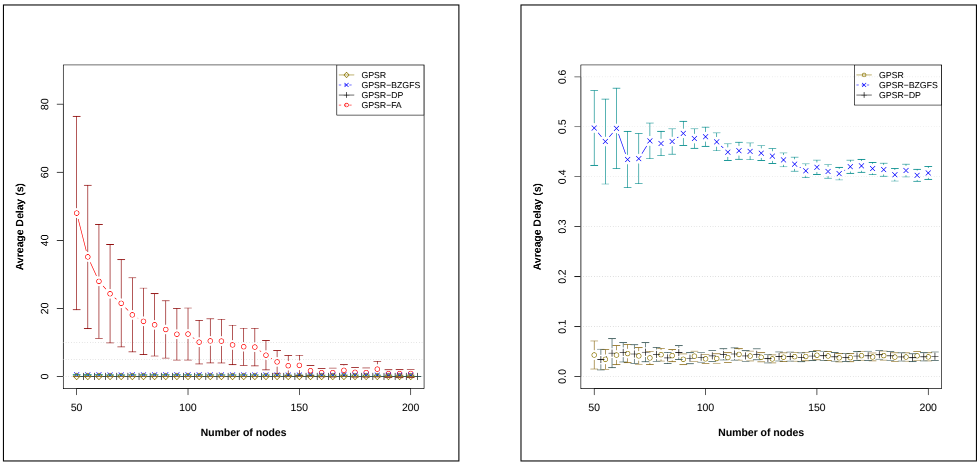
when one source node is used. While the number of free roaming nodes becomes 125, the packet delivery ratios in the two algorithms stabilise around 20% in the case of using one source node. GPSR-BZGFS shows the lower packet delivery ratio by nearly 1% in the cases of low density nodes, which represent a sparse network. Then it starts increasing when the number of nodes is increased. GPSR-BZGFS shows a linear increase, whereas the number of nodes is increased.

Figure 4.8 shows examples taken from appendix C.1 for the results of examining high load packets when the number of sources is changed. The use of one source load remains the performance equivalent to the cases of low and medium load packets, as explained above. Increasing the number of source nodes to five affects negatively to the proposed algorithm by declining the average ratio by nearly 50% comparing to the uses of one source node. This is because of the presence of a large number of packets and the patrol node starting its duty resulting in a continual change in the location. Moreover, packets generated when more than one source is used will affect the buffer queue in the forwarding node(s). This will result in the need to drop many packets in order to insert the newly arrived packets.

However, FA-GPSR still outperforms the other routing algorithms. GPSR-BZGFS does not exceed 20% when there are 200 free roaming nodes and 0% in 50 free roaming nodes. GPSR and GPSR-DP did not go beyond 10% in the high density network and they are nearly 1% when 50 free roaming nodes are used.

4.6.2 Average end-to-end delay

Delay refers to the time needed for the packets to traverse the network to be successfully received at the destination. This is the time from the generation of the packet by the sender to the time the packets are received at the final destination. It subsequently includes all delays in the network such as buffering queues, transmission time and MAC control activity. The 95% confidence intervals shown are based on the assumption that the variation observed is normally distributed. Note that the delay metric does not consider the case when a route is not discovered and a packet is not delivered; only successfully delivered packets contribute to the results.



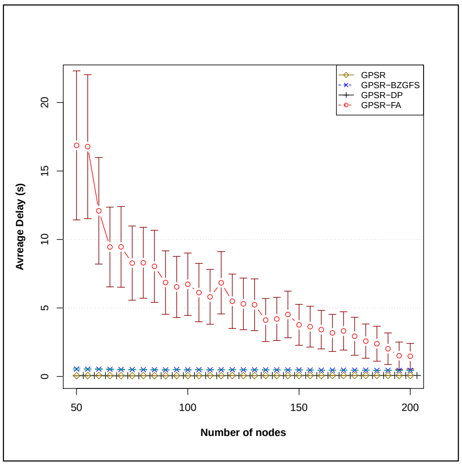
(a) Using one source node

(b) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS

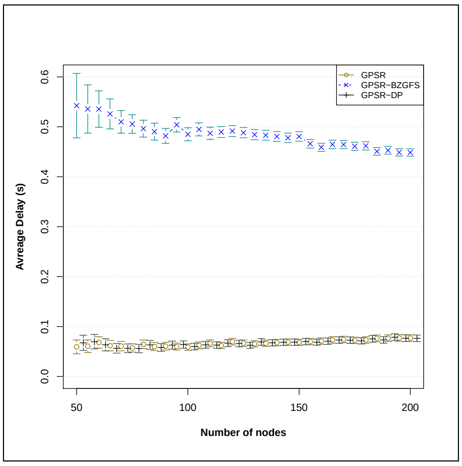
Figure 4.9: Average low load packet end-to-end delay using a single number of source and destination nodes

A) Figure 4.9 shows the end-to-end delay from the source to the destination node. Using one source node, FA-GPSR needs more time to deliver the packets to the final destination when there are 50 free roaming nodes. The time required is 50 seconds, compared to less than 0.1 seconds required by the default GPSR and GPSR-DP as shown in Figure 4.9b. The FA-GPSR delay starts decreasing when the number of free roaming nodes is increased. By using 150 free movement nodes, the FA-GPSR delay becomes similar to that of GPSR-BZGFS, as shown in Figure 4.9a. The highest delay occurs when FA-GPSR is used because of the long path that the patrol node follows to complete its duty. However, this delay will be accepted, especially in the case of a sparse network, such as when 50 free roaming nodes are used the packet delivery ratio in this case is higher than the others as shown in Figure 4.6a.

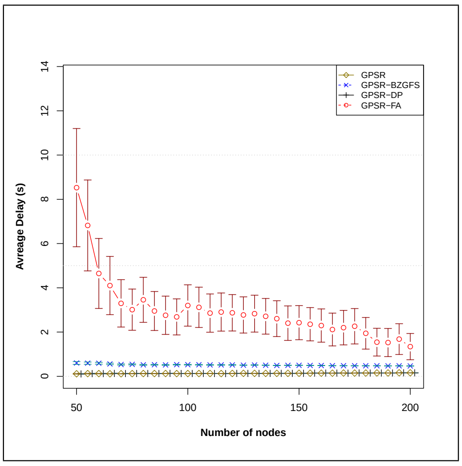
Figures 4.10 shows that the increase in the number of source nodes results in a decrease in the delay when the FA-GPSR algorithm is used. When 5 source nodes and 50 free roaming nodes are used, the average delay is 8.5 seconds. In contrast, in the other protocols increasing the number of source nodes has led to increased delay at a rate of 0.5 seconds. In addition, GPSR's and its variants' delay remain stable when the number of free roaming nodes increases, whereas FA-GPSR shows



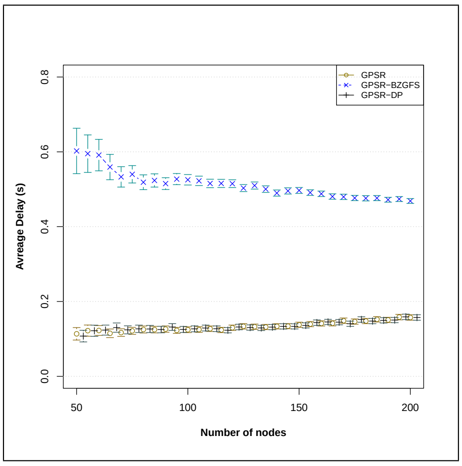
(a) Using two sources



(b) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS using two sources



(c) Using five sources

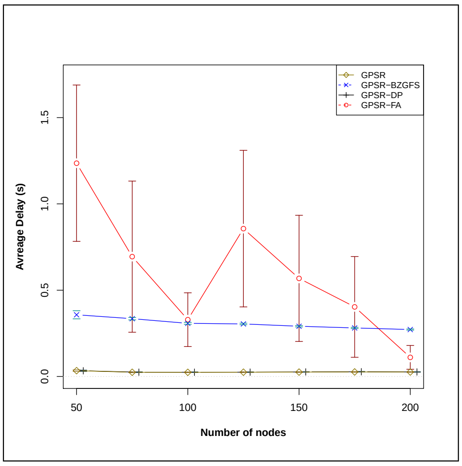


(d) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS using five sources

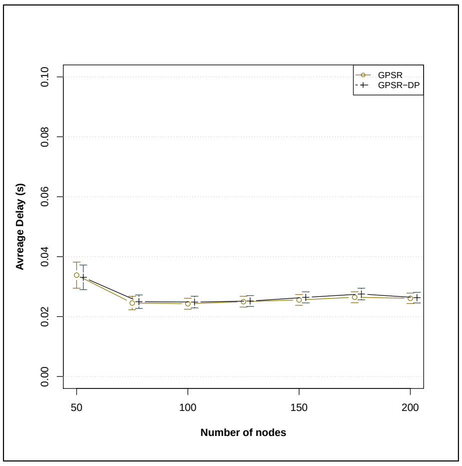
Figure 4.10: Average low load packet end-to-end delay using two and five source and destination nodes

some decreases in the delay. This decrease occurs because the increase in the number of free roaming nodes increases the probability of communication to the patrol node. This conclusion is supported by the increase in the packet delivery ratios shown in Figure 4.7b.

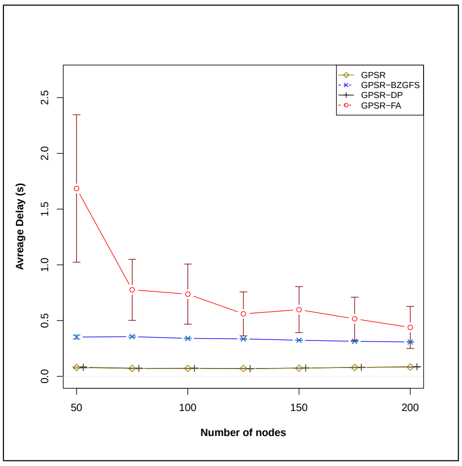
B) The number of packets is increased to 5 packets/second in order to evaluate the performance of routing algorithms in a medium load of packets. Figure 4.11



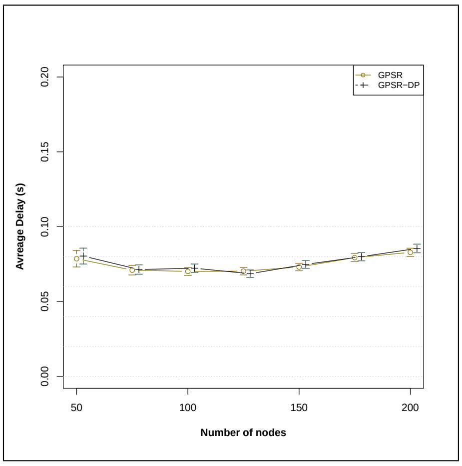
(a) Using one source node



(b) A zoomed graph of GPSR and GPSR-DP



(c) Using five source node

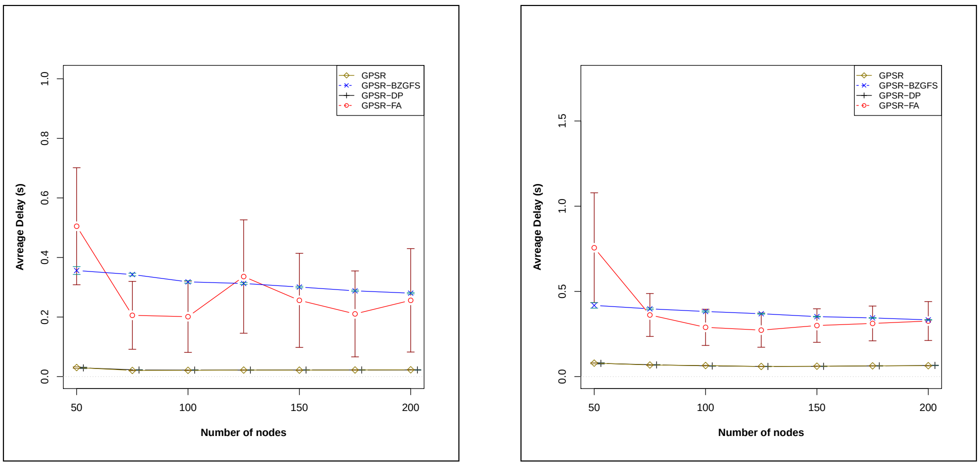


(d) A zoomed graph of GPSR and GPSR-DP

Figure 4.11: Average medium load packet end-to-end delay using a single and multiple number of source and destination nodes

shows the results of using one and five source nodes. The proposed algorithm has the greatest delay compared to GPSR and its variants, as packets are buffered for long periods, which is the case because the patrol node follows a pre-defined path at low speed to complete its duty. The algorithms GPSR and GPSR-DP have the lowest delay, which are almost equivalent to 0.04 seconds. Their delay decrease when the number of nodes increases to stability to 0.02 seconds. GPSR-BZGFS follows the previous two with a constant time less than 0.5 seconds. The figure also shows that FA-GPSR has a low delay compared with the case of using low load packets as shown in Figure 4.9a. This is because of the use of the patrol nodes, which have the ability to buffer more packets to be delivered to the final destination. When there are 100 nodes in the topology, the delay of FA-GPSR is similar to that of GPSR-BZGFS - nearly 0.5 seconds. This time is increased when the number of free roaming nodes increases to 125 because the deployment of the nodes in the simulator is randomised. It may be that during transmission, no nodes are close enough to the forwarding node to participate in the transmission procedure.

When five sources are used, the delay is more stable than when one source is used, as shown in Figure 4.11c. The delay decreases by less than one second when there are 75 free roaming nodes in the topology. It becomes stable when the number of nodes is increased. Default GPSR and GPSR-DP slightly increase when there are more than 150 nodes because of the use of recovery mode, as shown in Figure 4.11d. GPSR-BZZGFS is more stable than the others by less than 0.5 seconds, as shown in Figure 4.11c



(a) One source node

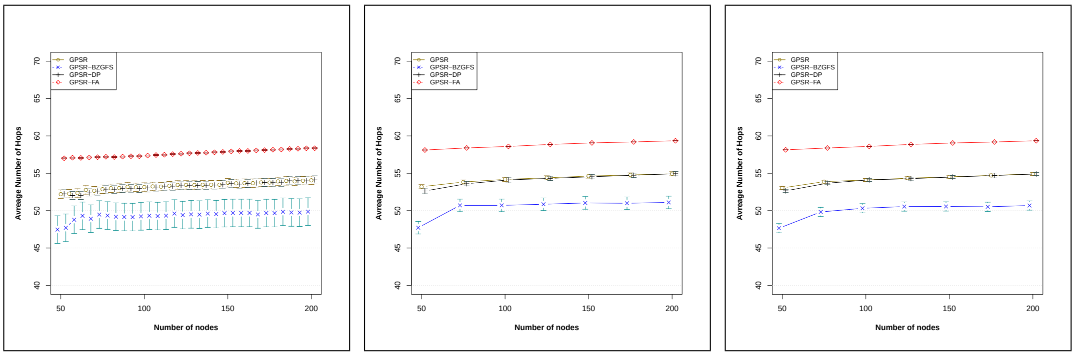
(b) Five sources nodes

Figure 4.12: Average delay using different number of source and destination nodes 4

C) The number of packets generated by the source nodes is increased to 10 in order to evaluate the performance of the routing algorithms in heavy load network.

As shown in Figure 4.12, FA-GPSR delay is decreased, compared to the low and medium load of packets. This is an indication that FA-GPSR works better in heavy load networks. The delay is limited between 0.5 seconds and 0.3 seconds. The default GPSR and GPSR-DP remain the best routing algorithms in terms of delay. However, this low delay is just one aspect of performance and taking into consideration the packets delivery ratio compared to FA-GPSR, they deliver less than 1% when 50 free roaming nodes are used in the topology while FA-GPSR achieves more than 15%, as shown in Figure 4.8.

4.6.3 Number of hops



(a) Using two source nodes and one packt/s (b) Using one source node and five packets/s (c) Using one source node and ten packets/s

Figure 4.13: Average medium load packet end-to-end delay using single number of source and destination nodes[5]

Figure 4.13 shows the number of hops measured for each routing protocol during simulations in the case of one and two sources. The 95% confidence intervals shown are, as before, based on the assumption of normal distribution of the variation observed. The number of hops in all algorithms is large and this is explained as follows: Firstly, the area of the topology is large so the network diameter is substantially larger compared to the smaller scenario areas. Secondly, the recovery method is applied in this scenario because there is frequently no shortest path from the source node to the destination node; applying this method

[4] This group of figures shows an example where the number of source and destination nodes changes. The figures are shown in Appendix C.2.

increases the number of hops as mentioned in [15]. In our experiments, GPSR and its variants exhibited the lower number of hops compared to the proposed algorithm because the use of the ferry node in FA-GPSR keeps the packets from being dropped if a dead end is encountered.

The GPSR-BZGFS method has the lowest average number of hops in the range of 46% – 51% compared to the other variants because of the use of buffering zone to select the forwarding nodes. GPSR-BZGFS expects that nodes inside the buffer zone are less reliable and so does not re-use them for next hop transmissions.

GPSR and GPSR-DP are second in terms of minimum number of hops by the nearly similar percentage of 52%. Using the recovery mode in this case increases the number of hops while, as mentioned above, the number of packets delivered to the destination still remains low.

The FA-GPSR algorithm exhibits the highest number of hops by 57%. This is explained by the additional hops required to reach a ferry node and the subsequent retransmission from the ferry node to reach the destination. Although the number of hops observed is the highest, it is useful to recall that the side-effect is, as shown above, that the highest packet delivery ratio of all the algorithms is observed.

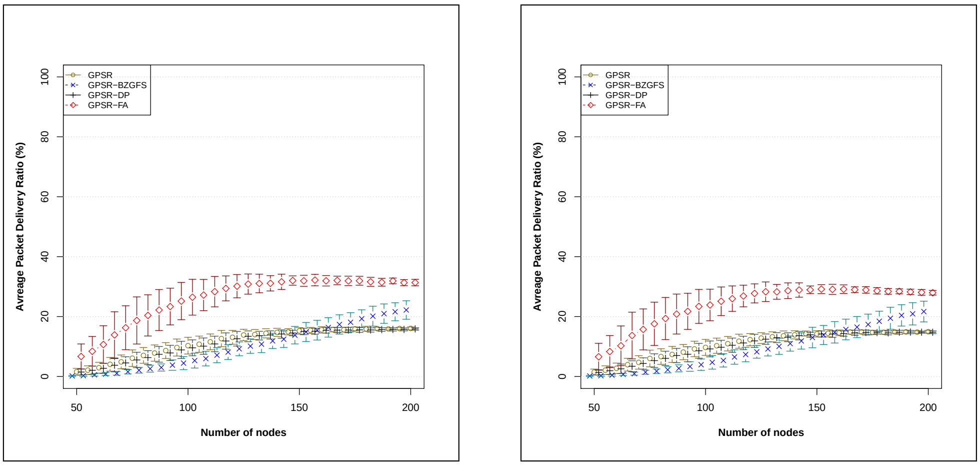
4.7 The Impact of Communication among Mobile Nodes

Normally, some soldiers in high ranks have the authority to communicate with other soldiers to coordinate the work and gather the information to deliver to the commanders. In addition, such soldiers are mobile elements that communicate with mobile soldiers in the battlefield.

4.7.1 Packet delivery ratio

[5] This group of figures shows an example where one source node used and packet load changes. The full figures are in Appendices A.3, B.3 and C.3.

[6] This group of figures shows an example where the numbers of source and destination nodes changes. The figures are shown in Appendix A.1.



(a) 11 source nodes and 11 destination nodes

(b) 15 source nodes and 15 destination nodes

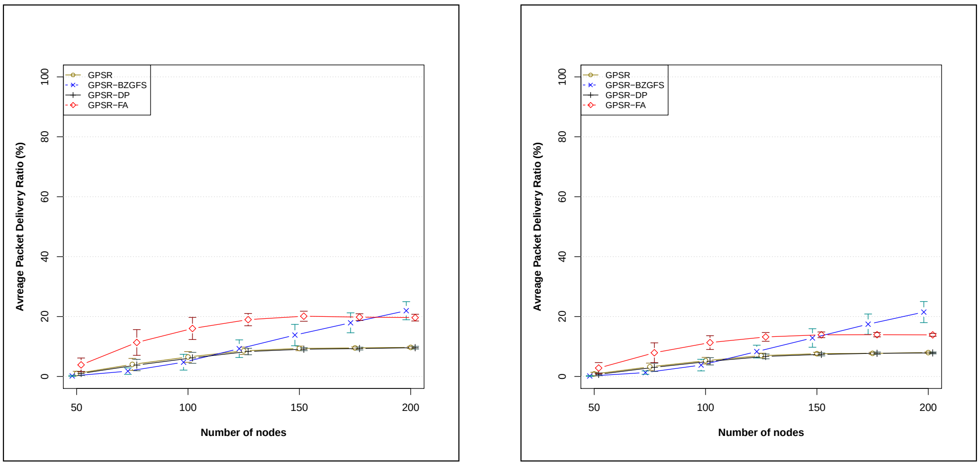
Figure 4.14: Average low load packet delivery ratio using different number of source and destination nodes [6]

Figures 4.14a and 4.14b show the packet delivery ratios in low packet loads. For each observation, we also plot a 95% confidence interval. The results show that as the number of participating nodes increases, more packets are successfully delivered to their destination in all routing protocols examined. When there are 10 or fewer sources, the packet delivery ratios are more than 40%. Increasing the number of sources to more than 10 will degrade this ratio by 10%-15% in nearly all cases.

However, the increase in the number of source nodes shows that the GPSR-BZGFS algorithm performs well, outperforming the default GPSR and GPSR-DP algorithms. When the number of source nodes is more than three and there are almost 100 free roaming nodes, the GPSR-BZGFS buffering strategy works effectively to ensure that communications to the destination node(s) are stable.

In the case of raising the number of sources to nine or more and there is a medium packet loads, as shown in Figure 4.15, GPSR-BZGFS outperforms the other algorithms. In this example the number of free roaming nodes is 175 compared with FA-GPSR and 125 compared to GPSR and GPSR-DP. This

[7] This group of figures shows an example where the number of source and destination nodes changes. The figures are shown in Appendix B.1.



(a) 9 source nodes and 9 destination nodes

(b) 15 source nodes and 15 destination nodes

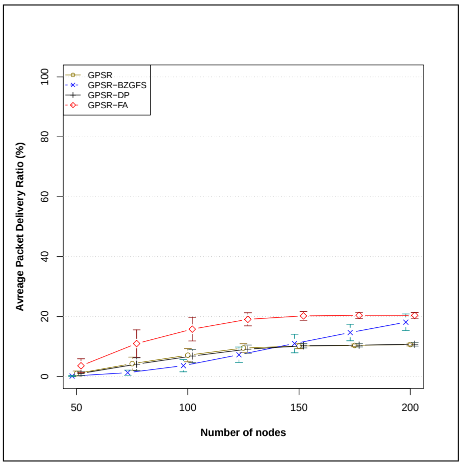
Figure 4.15: Average medium load packet delivery ratio using different number of source and destination nodes [7]

superior performance is due to the use of a buffering zone, which ensures that the forwarding nodes communicate with the next hop node. However, this technique succeeds only when there is a high number of nodes in the topology. It will not work well in sparse networks because of the low number of nodes in a large area. In addition, FA-GPSR remain perform better in sparse network by nearly 5% in case of using 50 nodes in the topology.

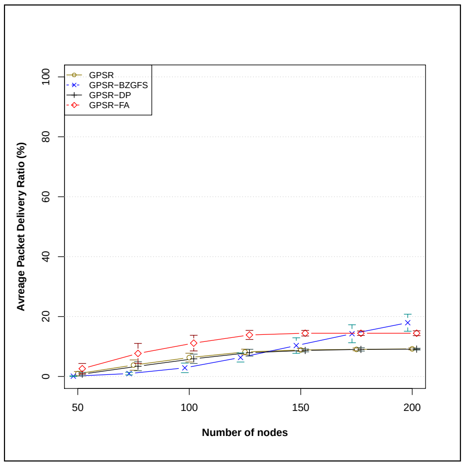
In the scenario of using high packet load and 9 source nodes, FA-GPSR is still better than others by 4% in the case of 50 free movement nodes used in the topology. The packet delivery ratio is dramatically increased to 20% when the number of free roaming nodes is 200.

GPSR and its variants exhibit very low performance especially in the case of having 50 free roaming nodes where the delivery ratio noted is 0% and only increase slightly as the number of free roaming nodes increased. Using 150 nodes, the packets delivery ratios for GPSR and its variants are nearly similar by 15% packets successively delivered to their destinations. However, GPSR-BZGFS packet delivery ratio continues raising to almost 19% when there are 200 free

[8]This group of figures shows an example where the numbers of source and destination nodes change. The figures are shown in Appendix C.1.



(a) 9 source nodes and 9 destination nodes



(b) 15 source nodes and 15 destination nodes

Figure 4.16: Average high load packet delivery ratio using different number of source and destination nodes [8]

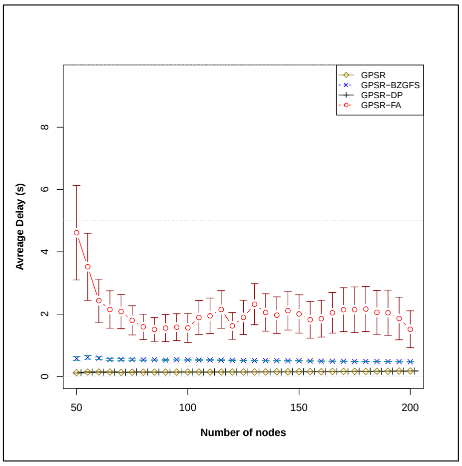
roaming nodes because the buffering strategy was used, which helped the algorithm to communicate with the next hop node.

When the number of sources is above 9 with low density of free roaming nodes, FA-GPSR performs better than GPSR and its variants until the number of free movement nodes increases to 190 then GPSR-BZGFS outperform all algorithms. Nonetheless, this relative superiority does not reduce the effectiveness of FA-GPSR, which is characterised by when the number of nodes has lower density in a large area.

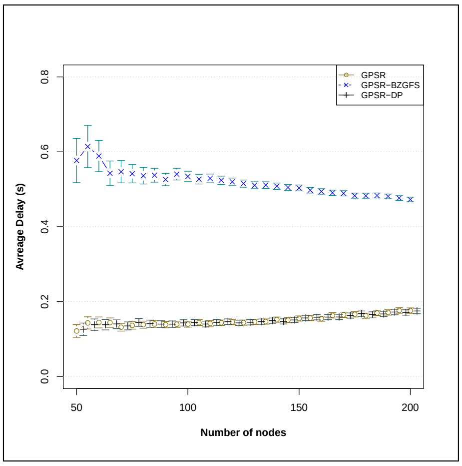
4.7.2 Average end-to-end delay

Figure 4.17 is an example taken from appendix B.2 showing that the increase in the number of sources with low load packets positively affects the delay in FA-GPSR. The 95% confidence intervals shown are based on the assumption that the variations observed are normally distributed. Note that the delay metric does not consider the case when a route is not discovered and a packet is not

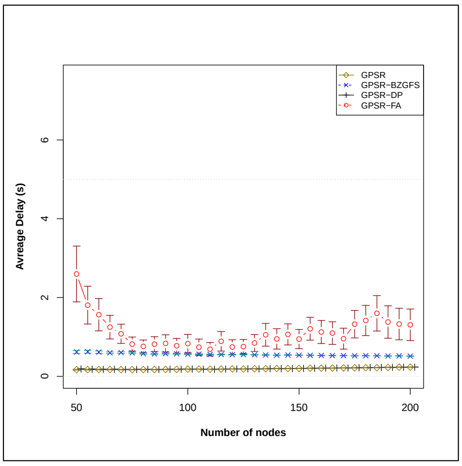
[9]This group of figures shows an example where the number of source and destination nodes are changes. The figures are shown in Appendix A.2.



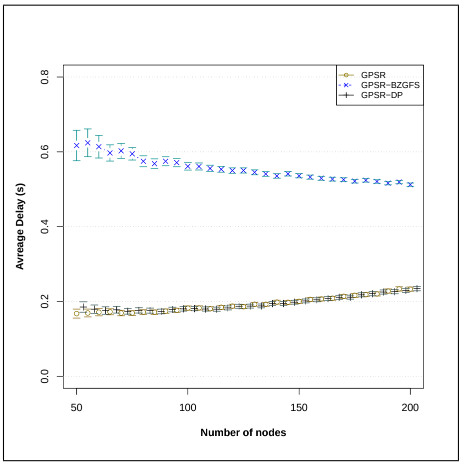
(a) Using 6 sources



(b) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS using 6 sources



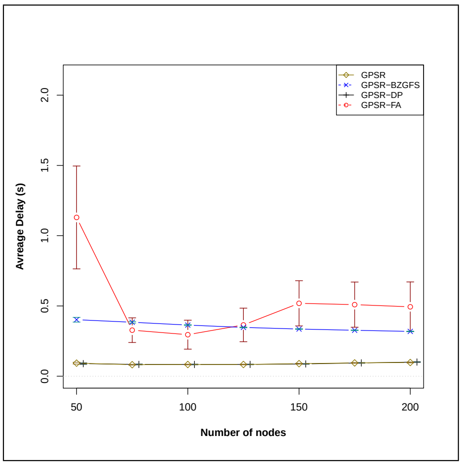
(c) Using 15 sources



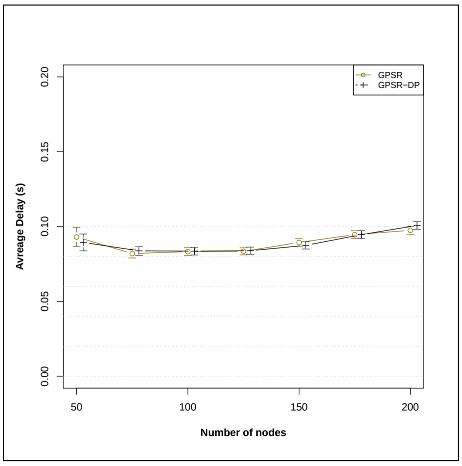
(d) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS using 15 sources

Figure 4.17: Average low load packet end-to-end delay using 6 and 15 source and destination nodes [9]

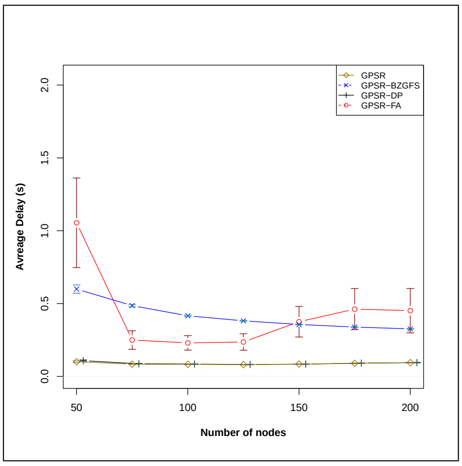
delivered; only successfully delivered packets contribute to the results. The delay start stabilising around one second when the number of nodes reaches 75. On the contrary, the delay of GPRS and GPSR-DP slightly increase when the number of free roaming nodes increases. This increase occurs because the forwarding node(s) made increasing use of the recovery mode, which increased the time in GPSR and GPSR-DP. However, GPSR-BZGFS shows a minor decrease in the delay because buffering zones were used, which were affected by the increase in the number of free roaming nodes.



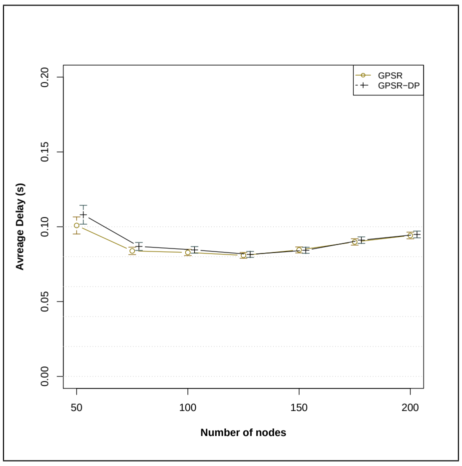
(a) Using 9 source node



(b) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS



(c) Using 15 source node



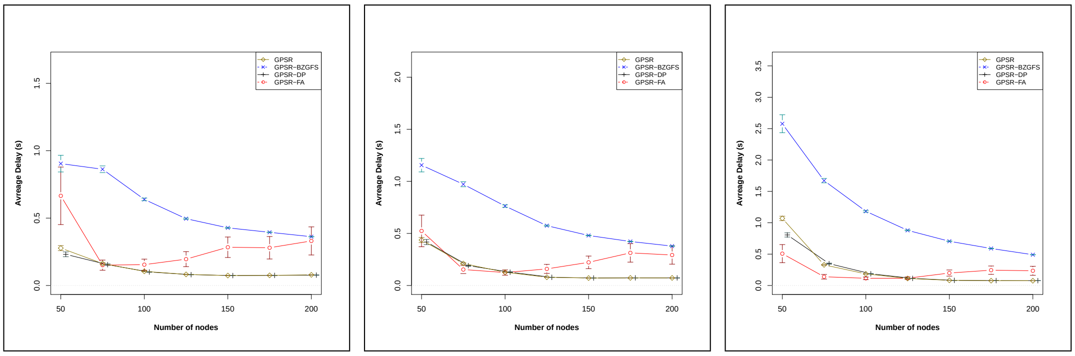
(d) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS

Figure 4.18: Average medium load packet end-to-end delay using a single number of source and destination nodes[10]

Regarding the use of medium load packets, Figure 4.18 shows that the delay is stable and almost identical for all algorithms. FA-GPSR shows some improvement

[10]This group of figures shows an example where the number of source and destination nodes changes. The figures are shown in Appendix B.2.

in minimising the delay when there are only 50 nodes with five and nine sources, by 1.7 and 1 seconds, respectively. This is because the patrol node can buffer more packets and deliver them successfully to the final destinations. However, in compensation there is an increased ratio of successful packet delivery in the proposed algorithm, as shown in Figure 4.7.



(a) 9 source nodes

(b) 11 source nodes and 11 destination nodes

(c) 15 source nodes and 15 destination nodes

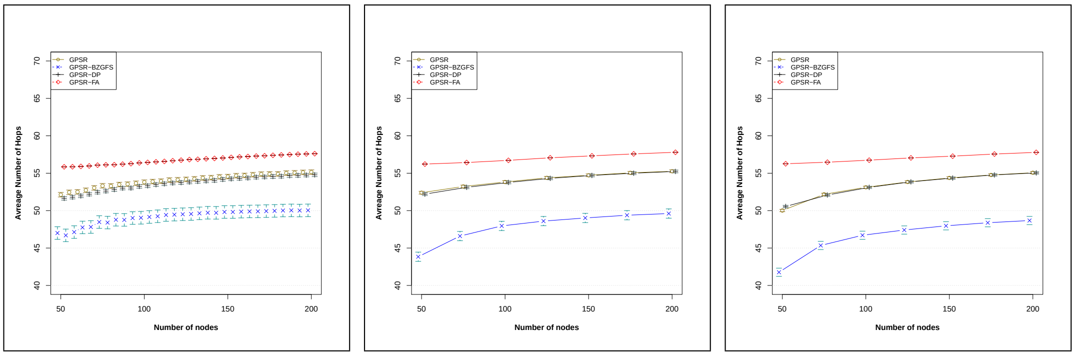
Figure 4.19: Average delay using different numbers of source and destination nodes [11]

However, as shown in Figure 4.19 when 11 source nodes or more are used with high packet loads, FA-GPSR is similar to the vanilla GPSR and GPSR-DP and lower than GPSR-BZGFS, especially when there are 50 free movement nodes in the topology. Taking into account the average packet delivery ratios of FA-GPSR and the other routing algorithms investigated in this thesis, the metric of the packet delivery ratio of FA-GPSR clearly outperforms those of the other routing algorithms.

4.7.3 Number of hops

Figure 4.20 shows the number of hops measured for each routing protocol during simulations of 15 sources. The 95% confidence intervals shown are based on the assumption that the variations observed are normally distributed. The number of

[11] This group of figures shows an example where the number of source and destination nodes changes to examine the delay of high packets load. The figures are shown in Appendix C.2.



(a) Using 15 sourc nodes and 1 packt/s (b) Using 15 source nodes and 5 packets/s (c) Using 15 source node and 10 packets/s

Figure 4.20: Average medium load packet number of hops using single number of source and destination nodes[12]

hops in all algorithms is large for the following reasons: First, the impact of the topology area was explained previously in subsection 4.6.3.

Second, the recovery method used resulted in increase in the number of hops [15]. In our experiments, GPSR and its variants exhibited a lower number of hops compared to the proposed algorithm because the ferry node used in FA-GPSR keeps the packets from being dropped if a dead end is encountered.

The GPSR-BZGFS method resulted in the lowest average number of hops, between 43% and 47% in all packets load cases, compared to the other variants, because a buffering zone was used to select the forwarding nodes. GPSR-BZGFS expects the nodes inside the buffer zone are less reliable and therefore does not re-use them in the next hop transmissions.

GPSR and GPSR-DP are second in terms of the minimum number of hops with nearly equal percentages of 50% and 52%. The use of the recovery mode in this case increases the number of hops. However, the number of packets delivered to the destination still remains low.

The proposed FA-GPSR algorithm exhibits the highest number of hops by 57%. This is explained by the use of the ferry node, adding more hops and the subsequent retransmission from the ferry node to reach the destination.

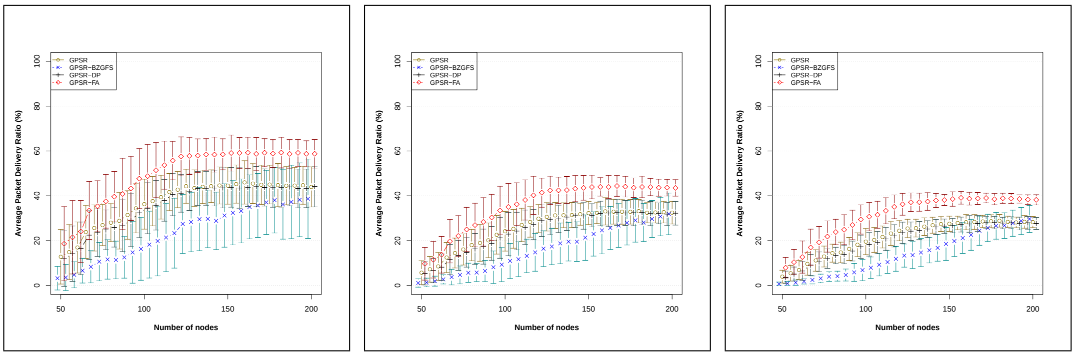
[12]This group of figures shows an example where the number of source and destination nodes changes. The figures are shown in Appendices A.3, B.3 and C.3.

4.8 The Impact of Communication between Station and Mobile Nodes

Communication between officers and soldiers is crucial for the transmission of orders, information about special operations, or intelligence. Therefore, stable communication is an issue in the ability to increase the number of packets.

Some experiments are conducted to evaluate the GPSR and its variants and the proposed algorithm in the case of communication between fixed location nodes and mobile nodes. The number of free roaming nodes in the topology begins at 50 and increases in increments of five nodes in each experiment, following the simulation parameters explained in Table 4.1.

4.8.1 Packet delivery ratio



(a) Using one fixed location sourc node and one mobile destination node

(b) Using three fixed location sourc nodes and mobile destination nodes

(c) Using five fixed location sourc nodes and mobile destination nodes

Figure 4.21: Average packets ratio in the communication between fixed node(s) and mobile destination node(s)

Figure 4.21a shows the average packet delivery ratio when one fixed location source node is used. The 95% confidence intervals shown are based on the assumption of normal distribution of the variation observed. FA-GPSR outperforms from 15% to more than 40%, compared with 1% to 28% for the other protocols. The mobility of the destination node affects FA-GPSR in terms of the packet delivery ratios and minimises the ratios when there are 200 free roaming nodes from nearly

60%, as shown in Figure 4.6a to nearly 40%, as shown in Figure 4.21a. Figures 4.21b and 4.21c show that the number of sources is changed to three and five, respectively. There are no changes compared with one source, except in the case of five sources, where GPSR and its variants performed better than in the cases of the station source and the destination nodes, as shown in 4.6b.

GPSR and its variants are not affected by the changes in the destination mobility because the changes in the destination location are updated in the packet header, in contrast to FA-GPSR in which the packets hide the origin destination information. Moreover, FA-GPSR uses the patrol node address if a dead-end is encountered during the recovery period.

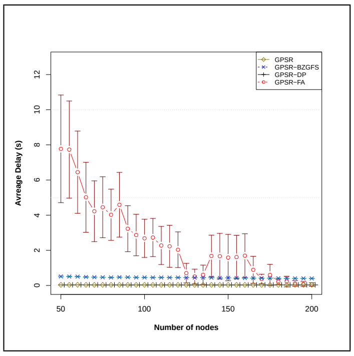
4.8.2 Average end-to-end delay

Figure 4.22 shows the delay for all algorithms when the fixed location node and mobile destination node are used. The 95% confidence intervals shown are based on the assumption that the variations observed are normally distributed. While the number of source nodes increases, FA-GPSR remains the protocol needs more time then followed by GPSR-BZGFS, GPSR and GPSR-DP. Increasing the number of free roaming nodes minimises the delay of FA-GPSR. For example, by using one source node and 185 free roaming nodes, it needs the same amount of time as GPSR and GPSR-DP by 0.05 seconds. This applies to the use of three or five sources. Increasing the number of free roaming nodes enhances the probability of communication between the forwarding nodes and the patrol node (ferry).

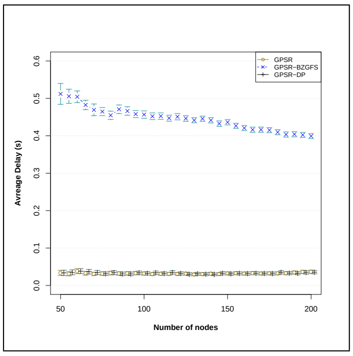
In GPSR and its variables, when the number of source nodes is increased, the delay increases. Moreover GPSR and GPSR-DP are quite similar in term of end-to-end delay needed. For example, the use of one source node GPSR-BZGFS needs 0.5 seconds; GPSR and GPSR-DP require 0.05 seconds. When five sources are used, they required 0.6 and 0.1 seconds, respectively.

4.8.3 Number of hops

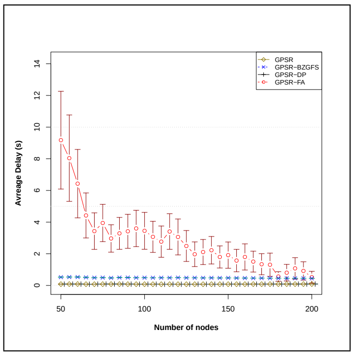
Figure 4.23 shows the number of hops measured for each routing protocol during the simulations of single and multiple sources. The 95% confidence intervals shown



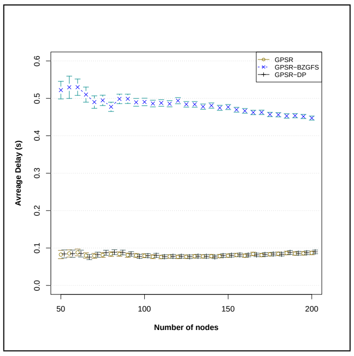
(a) Using one fixed location source node and one mobile destination node



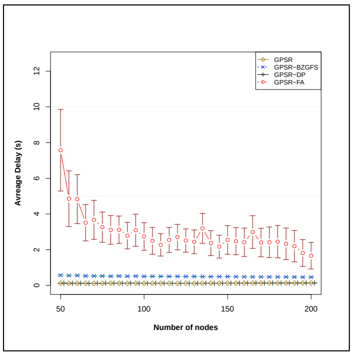
(b) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS using one sources



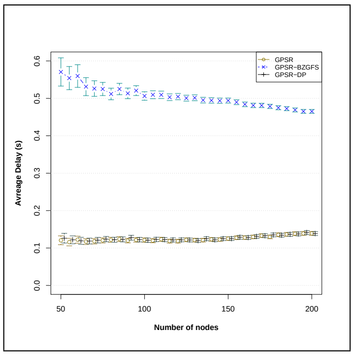
(c) Using three fixed location sourc nodes and three mobile destination nodes



(d) zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS using three sources



(e) Using five fixed location sourc nodes and mobile destination nodes



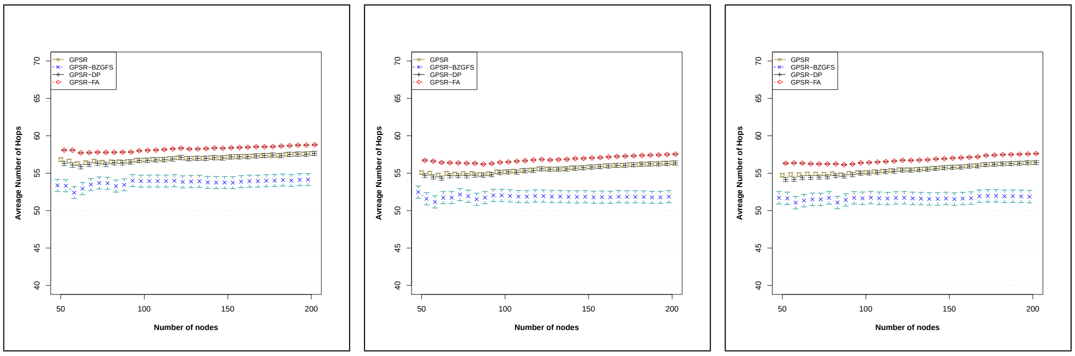
(f) zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS using five sources

Figure 4.22: Average delay in the communication between fixed node(s) and mobile destination node(s)

are based on the assumption that the variations observed are normally distributed. The number of hops in all algorithms is large, which was explained previously.

Packets using FA-GPSR and one source node need 58 hops to reach the final destination. The increase in the number of free roaming nodes did not affect the number of hops, as shown in Figure 4.23a. Figures 4.23b and 4.23c show that FA-GPSR improved slightly in terms of minimising the number of hops to 56 because the patrol node seems close to the forwarding nodes in such scenarios.

The GPSR-BZGFS method has the lowest number of hops (at 53), compared to other variants because the buffering zone was used, as explained previously.



(a) Using 1 source (b) Using 3 sources (c) Using 5 sources

Figure 4.23: Average number of hops in the communication between fixed node(s) and mobile destination node(s)

GPSR-BZGFS expects that the nodes inside the buffer zone are not trustworthy, so it will not use them in the next hop transmission.

GPSR and GPSR-DP are second in terms of the minimum number of hops by similar hops 55. The use of the recovery mode negatively affected all algorithms by increasing the number of hops, which was caused by the large area of topology. The nodes deployment in such large area suffers from the regular disconnection. Compared to the other simulation scenarios explained above, in this scenario the mobility of the destination node does not affect the number of hops.

4.9 Summary

This chapter proposes a novel routing algorithm which demonstrate the benefits of extracting information from the application to support communication between the nodes in the topology. In addition, this approach highlighting the advantages and disadvantages to the efficiency and reliability of communication in open large area environment. A simulation model of the proposed algorithm has been built and its features demonstrated through simulation runs.

The experiments, performed using different parameters for the protocols, show that existing protocol performance depends on the characteristics area of interest and in most cases is better than the similar algorithms. The protocol proposed by Karp et al. [15] (GPSR) works well in the open areas and increases communication between nodes, resulting in improvements in communication performance. Furthermore, the optimisation done by Guoming et al. and Wei et al. in [5] and [4], respectively to the default GPSR to improve the shortcomings of the Recovery and Greedy modes in MANET, by using the left-hand rule and the buffering strategy, respectively. Thus, the comparison of FA-GPSR to these algorithms supports the decision that FA-GPSR is suitable for use in large open areas with the effect of node density and packet load.

The metric packet delivery ratio was used in the evaluation of efficiency. The communication between nodes in the topology shown in Figures 4.6, 4.7 and 4.8 show that FA-GPSR outperforms the other routings in terms of packet delivery ratio, especially in sparse networks, where the density of nodes is low. The mobility of the destination nodes affected the packets delivery ratio by decreasing the ratio, compared to other cases because of the changes in the location and node velocity. By increasing the number of packets and source nodes, FA-GPSR outperformed the other algorithms because of the efficient use of the patrol node (ferry).

The long delay in the FA-GPSR algorithm was minimised by increasing the number of source nodes. The number of hops in all algorithms is large for the following reasons: First, because the area of the topology is large, the diameter of the network is substantially larger than the diameters of smaller areas. Second, the recovery method is applied in this scenario because frequently there is no shortest path from the source node; therefore, the application of this method increased the number of hops [15]. In our experiments, GPSR and its variants exhibited a lower number of hops, compared to the proposed algorithm because the use of the ferry node in FA-GPSR keeps the packets from being dropped if a dead end is encountered.

Chapter 5

The effects of network parameters on FA-GPSR

5.1 Introduction

Utilisation of multiple ferries in the topology could be vital as, a rule to increase network performance and robustness. Zhao et al. [132] refer to the following reasons for this need. First, the movement capability and topology are affected by the capacity of one ferry. Second, single ferry is a bottleneck issue, especially in case of failures or attacks. The main role of the ferry in the Zhao et al. algorithm [132] is to connect the areas and deliver the packets, so any failure will affect the network performance. Because of this, Zhao et al. focused on designing the path(s) of the ferries in the topology.

The use of the ferry approach in Ferry Assisted-Greedy Perimeter Stateless Routing algorithm(FA-GPSR), however, is different from the approach used by Zhao et al. [132]. The ferry in FA-GPSR is not only a node connecting the disconnected nodes in the topology, but also does main duty as a normal unit in the topology. It connects a function carried out in order to cooperate with other nodes in delivering services and supporting communication stability. The ferry node has a major duty in the battlefield, so any failures will result in the replacement of the vehicle because failure does not affect the ferry in FA-GPSR. Moreover, the ferry path in FA-GPSR is based on a military plan, so FA-GPSR does not force the ferry to follow a specific path(s) or consider designing a special path(s) for the ferry. As FA-GPSR utilises the information delivered from the application, all communications based on that information and FA-GPSR will not force nodes to do certain works that support the communication.

Alternatively, using multiple ferries may enhance the algorithm's performance, if it is controlled well to avoid the loop problem and minimise the delay time. This chapter will investigate the impact of using single or multiple ferries in the proposed algorithm (FA-GPSR) in terms of packet delivery ratio, delay time and number of hops.

5.2 Controlling the use of ferry node

When facing a dead-end problem, FA-GPSR considers different modes for delivering messages to the final destination node(s). FA-GPSR has four ways to transmit a packet to the next hop. The first two strategies, Greedy and Recovery, are inherited from the default Greedy Perimeter Stateless Routing algorithm (GPSR) [15]. The other two are newly developed in FA-GPSR and are named Patrol Seeking Greedy (PSG) and Patrol Seeking Recovery (PSR). FA-GPSR modified the packet header to accept the four strategies. Number 1 refers to Greedy mode, 2 refers to Perimeter mode (recovery), 3 is PSG mode and 4 is PSR mode.

A node facing a dead end in perimeter mode will change the mode to PSG by changing the mode field in the packet header to number 3, and start forwarding the packet to the patrol node (ferry). If there is another dead end, the forwarding node will change the mode to PSR by changing the mode number to 4. When the patrol node receives a packet, it will continue to work as normal until it reaches the shortest point to the destination node in its path. At this point, the patrol node will start transmitting the packet to the destination node if it is in its transmission range, or to a neighbour that is nearer to the destination node than the patrol node.

FA-GPSR does not allow any exchanging packet between the patrol nodes to avoid either Lost Link (LLNK) or loop in packet delivery (LOOP) problems [133]. Node mobility is the reason behind the LLNK problem, which is related to the link connection with neighbouring nodes, and the LOOP issue,which is identified with the erroneous location of the destination node(s). Patrol node will check the mode field in the packet header if it is 3 or 4 then the packet will be discarded.

In the next sections, the performance of FA-GPSR using one and multiple ferries is evaluated. The goal is to investigate the impact of using single or multiple ferries on the delay time, not the packet delivery ratio. Using multiple ferries in the topology means that the forwarding node faces a dead end, and the packet received in the following perimeter mode has the chance to choose from multiple ferries in the topology. In theory, that will minimise the time as the number of ferries increases. Using one ferry means that only one ferry travels around the whole topology. Using two ferries mean each ferry covers half of the topology and using three ferries means each ferry covers one-third of the topology.

5.3 The impact of changing the destination node location

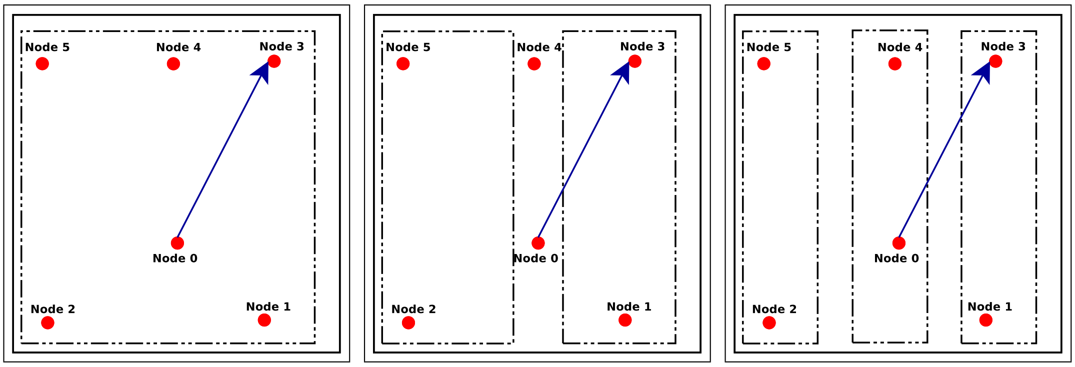
This section describes the scenarios used to evaluate FA-GPSR routing in cases of single and multiple ferries. Moreover, the results are discussed in this section to show the effect of increasing the number of patrol nodes.

5.3.1 Simulator Scenarios

Experiments are conducted to evaluate the effect of using single or multiple patrol node(s) in the topology of the proposed routing algorithm.

5.3.1.1 Scenario 1

Figure 5.1 shows that the source node (0) is located in the rear of the topology, and that the destination node (3) is located in the top right corner of the topology. The source node sends one packet per second to the destination node. This set of experiments is divided into three types: first, one patrol node in the topology and the source and destination nodes defined as in Figure 5.1a; second, increasing the patrol nodes in the topology and dividing the area into two parts with each patrol node covering one part with the same source and destination nodes as shown in



(a) Using one patrol node (b) Using two patrol node (c) Using three patrol node

Figure 5.1: The sceinario of using single and multiple ferries

Figure 5.1b; and third, three patrol nodes, each one covering nearly one-third of the area as shown in Figure 5.1c.

The destination node is changed in the next set of experiments as follows: first, node (4) is the next destination. The number of patrol nodes increases as the previous experiments shown in Figures 5.1a, 5.1b and 5.1c. Second, node (5) is used as the destination node and patrol nodes increases in the topology as shown in Figures 5.1a, 5.1b and 5.1c.

The simulation parameters used are explained in Table 3.1 except for changing the time of the simulator to 11000 seconds because this set of experiments assumed that one patrol node needs that amount of time to complete one trip around the whole topology. The number of free roaming nodes starts at 50 increases by increments of 5 to 100 nodes because the focus of this chapter is to evaluate the proposed routing algorithm in sparse networks.

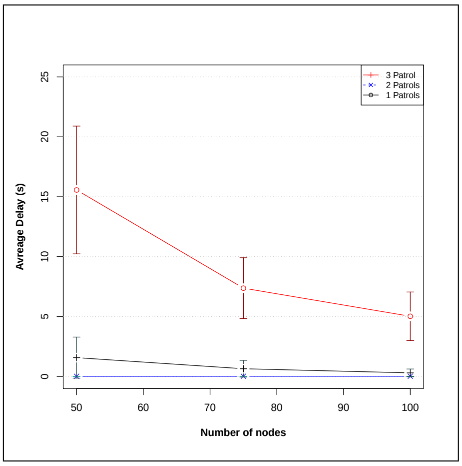
5.3.1.2 Scenario 2

In this set of experiments, the scenario follows method described in section 4.6. For each simulation trial, the source and destination nodes were selected on the basis of the distance between them, which is the farthest distance between any two nodes on the battlefield. The number of source and destination nodes is between 1-5.

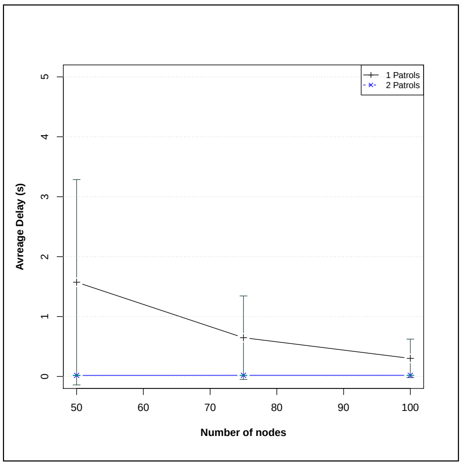
5.3.2 Results and Discussion for Scenario 1

This subsection will present and discuss the results of the impact of change the number of patrol nodes in the cases of changing the location of the destination node and using the same source node. These cases to examine the effect of the destination node locations change and who this related to the usage of one or more ferries.

5.3.2.1 End-to-End Delay



(a) Delay time in the case of using multiple ferries



(b) A zoomed graph of using one and two patrols

Figure 5.2: Average end-to-end delay using single and multiple ferries. The source node is NODE 0 and the destination node is NODE 3, as shown in Figure 5.1

Figure 5.2 shows the end-to-end delay time for the scenario in which the source node is NODE 0 and the destination node is NODE 3, as shown in Figure 5.1. Using three patrol nodes result in more time than in the case of one patrol and in more time than two patrol case. A packet needs nearly 15 seconds to reach the final destination in the case of 50 free roaming nodes in the topology. That compares to less than two seconds and less than one second in during the use of one or two patrol node (s) respectively, as shown in Figure 5.2b. As the number of free roaming nodes increases, the delay time decreases in the cases of two patrol nodes. Using two patrol node, however, results a stable delay time, as the number of free roaming nodes is increased. This is due to the availability of nodes to connect the forwarding node that faced a dead end to the patrol nodes. Moreover, the recovery modes used in the FA-GPSR algorithm cause an increase in the time that the packet needs to be received by the final destination.

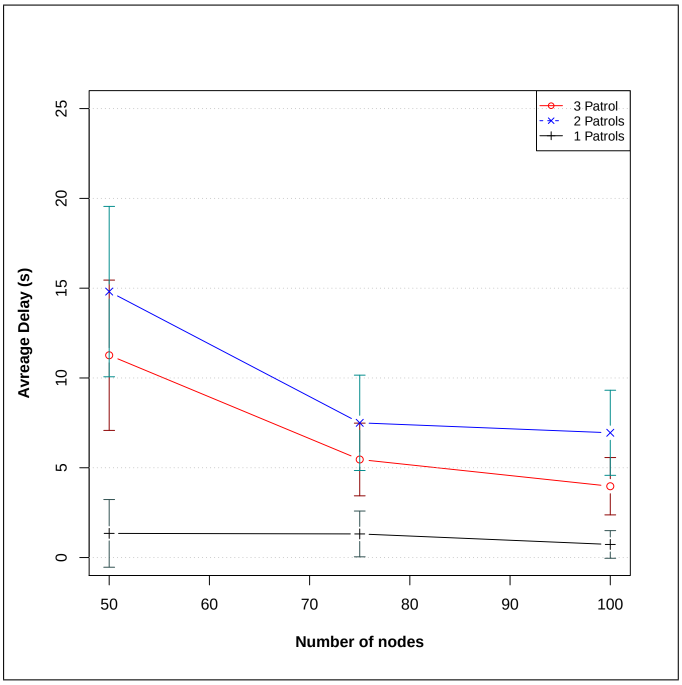
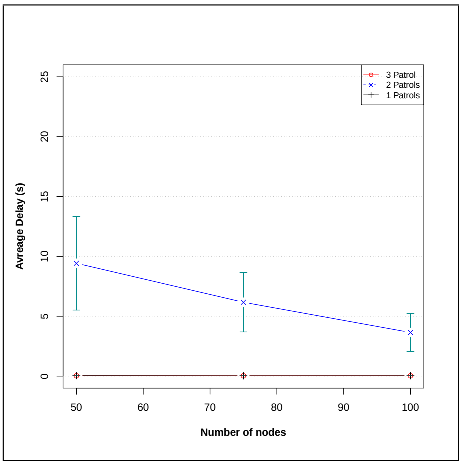
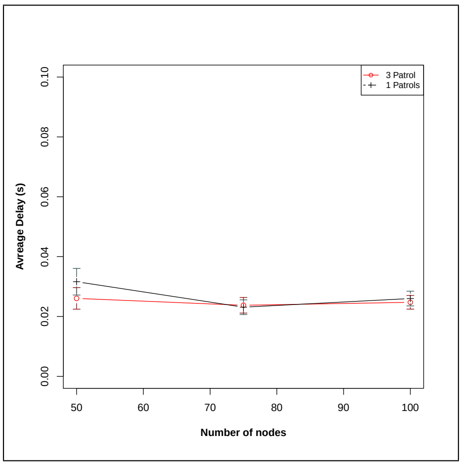


Figure 5.3: Average end-to-end time using single and multiple ferries when the source node is NODE 0 and the destination node is NODE 4, as shown in Figure 5.1

Figure 5.3 shows the case of changing the destination node to NODE 4, as shown in the Figure 5.1. In this case, using one patrol node is better than using two or three patrol nodes because receiving the packets during the recovery modes with one patrol node is faster than the other cases. Two patrol nodes has the highest delay time, of 15 seconds, which is decreased as the number of free roaming nodes is increased. The location of the destination nodes in this case affects the delay time, because the destination node is outside the patrol nodes' paths, as shown in Figure 5.1. In this case, intermediate nodes needed to connect the patrol node with the destination node to support the forwarding process using PSR mode, which increases the time from the source to the destination nodes. The use of one or three patrols with their paths covering the destination area results in less delay than the use of two patrols. The use of one patrol node is the case in which the packets need less than one second to reach the final destination, and that time is stable as the number of free roaming nodes is increased.



(a) Delay time in the case of using multiple ferries



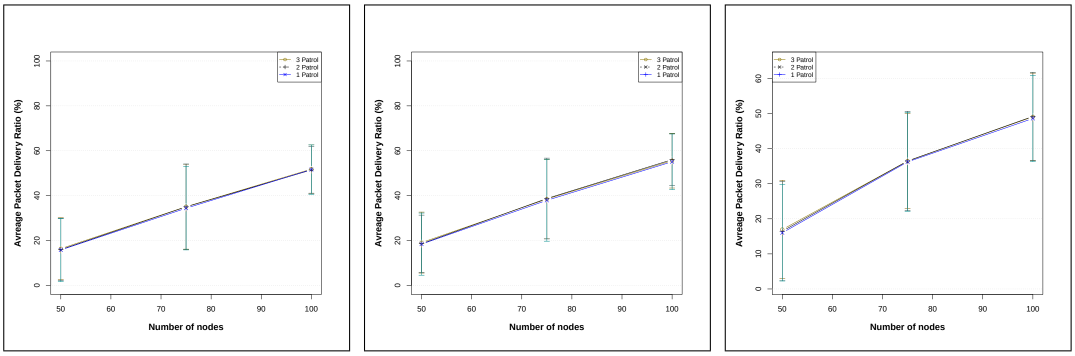
(b) A zoomed graph of using one patrol and three patrols

Figure 5.4: Average end-to-end time using single and multiple ferries when the source node is NODE 0 and the destination node is NODE 5 as shown in Figure 5.1

Figure 5.4 shows the delay time in the case when the destination node is NODE 5 and it is located in the upper-left corner, as shown in Figure 5.1. In this case, the patrol node will visit the destination before the other locations in the forwarding area, so the delay time will be less than in the other scenarios. Using one patrol or three patrol nodes, the end-to-end delay time is low compared to using two patrol nodes. When 50 free roaming nodes are used, the delay time is nearly 0.03 second when using one or three patrols. The deployment of the free roaming nodes in the topology is randomised, so when two patrol nodes are used, an increase in that time may be observed.

5.3.2.2 Packet Delivery Ratio

Figure 5.5 shows the average packet delivery ratio observed for different numbers of free roaming nodes. For each observation, we also plot a 95% confidence interval based on the assumption of normal distribution of the variation observed. The



(a) Source node is node 0 and the destination node is node 3 (b) Source node is node 0 and the destination node is node 4 (c) Source node is node 0 and the destination node is node 5

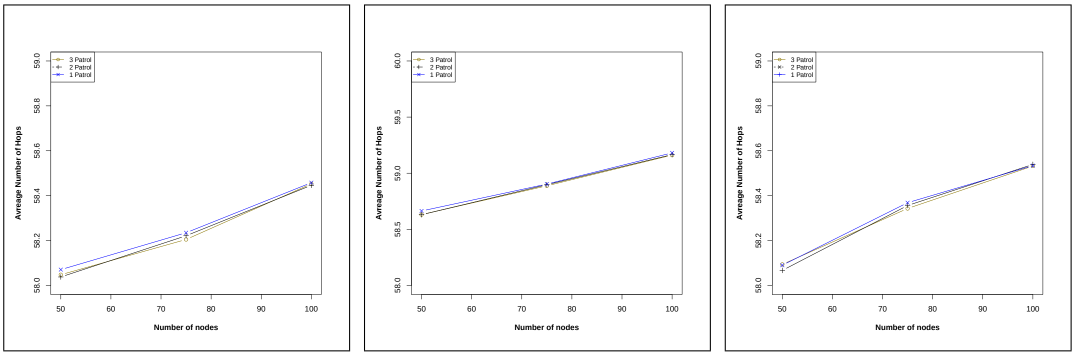
Figure 5.5: Average packet delivery ratio using single and multiple ferries

results show that as the number of participating nodes increases, more packets are successfully delivered to their destination in all cases of using patrol nodes that examined in this section.

As FA-GPSR does not allow the packet exchange between the patrol nodes to avoid the loop problem, the packet delivery ratios in all cases are expected to be similar to what is shown in Figure 5.5. In the situations where the destination node is located in the left or right corner, the packet delivery ratios are nearly identical. In the case where the destination node is in the middle of the forwarding area, as shown in Figure 5.5b, however, the packet delivery ratio is slightly better (2%) than the others and the packet delivery ratio increased as the number of free roaming nodes increased in all scenarios.

5.3.2.3 Number of Hops

Figure 5.6 shows the number of hops measured for each case of increasing the patrol nodes during simulations in the case of one source. The 95% confidence intervals shown are, as before, based on the assumption of normal distribution of the variation observed. The number of hops in all cases is large; this is explained as follows: First, the area of the topology is large so the network diameter is substantially larger compared to the smaller scenario areas. Second, the recovery method is applied in this scenario because frequently there is no shortest path from the source node to the destination node; applying this method increases the



(a) Source node is node 0 and the destination node is node 3 (b) Source node is node 0 and the destination node is node 4 (c) Source node is node 0 and the destination node is node 5

Figure 5.6: Average number of hops using single and multiple ferries

number of hops, as mentioned in [15].

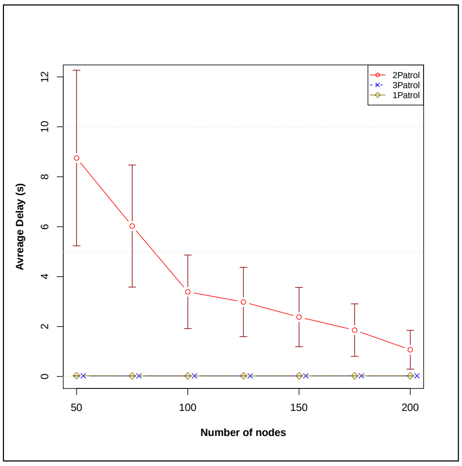
There are no significant differences among all cases. When the destination nodes are located in the topology corners, the number of hops increased by 0.2, as the number of free roaming nodes increased as shown in Figures 5.6a and 5.6c. In the case of 50 free roaming nodes, the number of hops is nearly 58.1 for the two scenarios. Using three patrol nodes lowered the number of hops to 58 for the two scenarios. Using 75 free roaming nodes increased the number of hops to 58.1 and 58.3 respectively. The number of hops starts to increase when there are 100 free roaming nodes. The number of hops increased to 85.5 in the scenario where the destination node is located in right corner and to 85.4 in the scenario where the destination node is located in left corner.

In the case where the destination is located in the middle of the topology, the number of hops increased slightly, by nearly 0.1 hops compared to the other scenarios as the number of free roaming nodes increased as shown in Figure 5.6b. The number of hops is 58.6 when 50 free roaming nodes used and increased to 59 when there are 100 free roaming nodes in the topology.

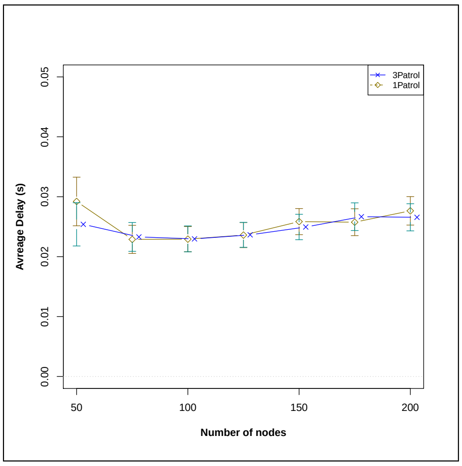
As FA-GPSR has two recovery modes that will used in the cases of the forwarding nod(s) face a dead-end problem. The use of these tow techniques will increase the number of hops as explained above, however, the number of hops is expected to be relatively high because the previous reason and also because the nodes are distributed in large topology. These reasons effect the number of hop in FA-GPSR and as the number of free nodes increased the number of hop will increased as shown above.

5.3.3 Results and Discussion for scenario 2

As explained in Table 3.1, the simulation parameters involved changing the time of the simulator to 11000 second because this set of experiments assumes that one patrol node needs this duration of time to complete one trip throughout the topology. The number of free roaming nodes starts from 50 and increases to 200 free roaming nodes by increments of 25. The metric used to evaluate the effect in this scenario is only the end-to-end delay time because the main focus of this chapter is to minimise the delay time and thus improve the performance of FA-GPSR.



(a) Delay time in the case of using multiple ferries and one source

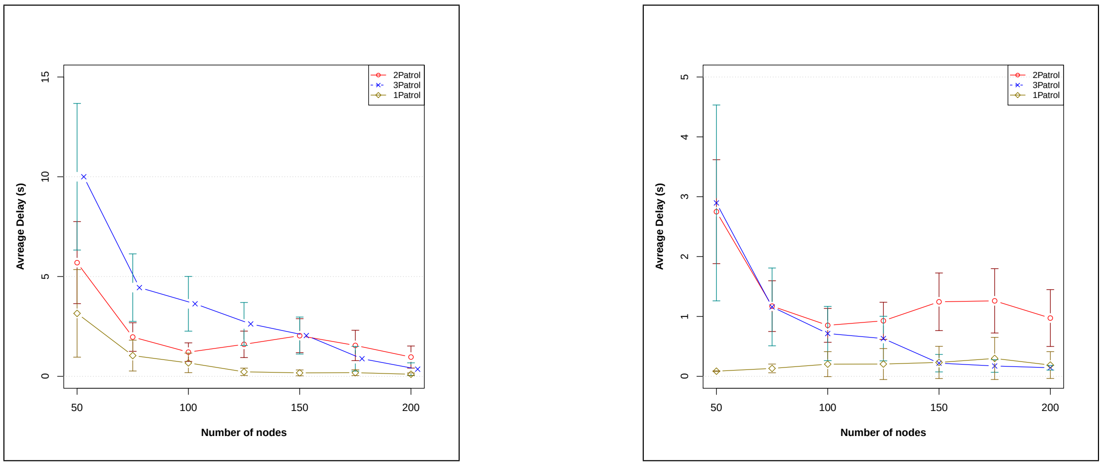


(b) A zoomed graph of using one patrol and three patrols in the case of single source node

Figure 5.7: Average end-to-end time using a randomised one-source node

Figure 5.7 shows the average delay time in the case of a randomised one-source node. The choice of the source and destination nodes in this case is based on the following conditions: They should be from the officers group, command a unit in the battlefield and the distance between them should be the farthest distance between any two nodes in the topology.

Using one and three patrol nodes the delay times are very close to each other and nearly stable, as shown in Figure 5.7b. When 50 free roaming nodes are used, the delay times for one or three patrol nodes is 0.03 seconds, while it is 9 seconds with two patrol nodes. The difference between these times is due to the distance between the the two nodes, which consumes more time.



(a) Delay time in the case of using multiple ferries and three source nodes

(b) Delay time in the case of using multiple ferries and five source nodes

Figure 5.8: Average end-to-end time using single and multiple ferries and multiple randomised source and destination nodes

Figure 5.8 shows the average delay time in the case of multiple randomised ferries and multiple destination nodes. Using three source nodes as shown in Figure 5.8a resulted in long delays of 7 and 10 seconds when using 50 free roaming and two or three patrol nodes respectively. This is due to the use of two recovery methods in FA-GPSR to transmit the packets to a patrol node. The use of one patrol node resulted in a delay time of 4 seconds. As the number of free roaming nodes increased delay time decreased for all cases because of the presence of more nodes to support transmitting of packets.

Increasing the number of source nodes to 5, as shown in Figure 5.8b, resulted in less time compared to three source nodes in all cases. Using two or three patrol nodes and 50 free roaming nodes resulted in a delay time of 3 seconds for the two cases. As the number of free roaming nodes increased, the delay time decreased. The use of one patrol node resulted in a delay of less than one second , which remained stable as the number of free roaming nodes increased.

5.4 The impact of changing the distance on packet retransmission

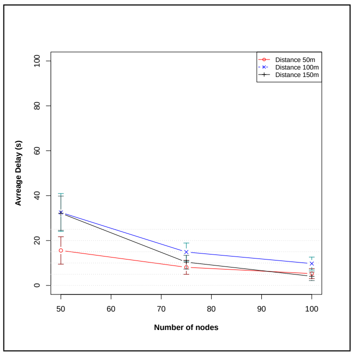
As explained in the previous sections, due the use of two recovery methods, the increase of ferries has negative affects on the performance of FA-GPSR. In this section, the distance for retransmission will change, so that the patrol node will retransmit the packets when the distance remains at the value explained in algorithm 4.4.1. The scenario for the experiments in this section is similar to the scenario explained in section 5.3.1.1; it features the use of three patrol nodes and is the worst-case scenario.

Note that the patrol node is not a special node that connects the disconnected areas, but is a normal unit doing its normal duty. In addition, it cooperates with other nodes in the battlefield to deliver messages to their final destinations. The waiting scheme does not apply in this algorithm because the main role of the patrol node is its duty so; it will not wait to receive the messages from the forwarding nodes. Yet, it will support the forwarding nodes to carry packets if there is a connection with the patrol node; if not, the packets will be discarded.

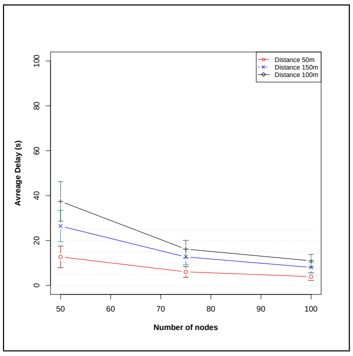
5.4.1 End-to-End Delay

Figure 5.9 shows the average end-to-end delay time for three distances, i.e.50, 100, and 150 metres. As the distance increased, the delay time increased because the probability of requiring more nodes for forward the packets to the final destination also increases as distance increases. Furthermore, as the distance decreased, the chance to communicate with the destination node, or the need for a lower number of forwarding nodes increased.

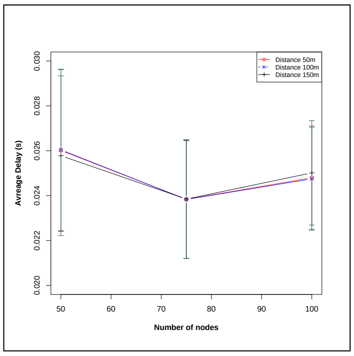
A comparison of Figure 5.9 with the similar scenario shown in Figures 5.2, 5.3 and 5.4 reveals when the distance is 50 meters the end-to-end delay is quite similar because the default distance was 60 meters in the case of similar scenario. Increasing the distance to 100 and 150 meters and using 50 free roaming nodes, doubled the delay time as shown in Figures 5.2, 5.3 and 5.4. As the number of



(a) Source node is node 0 and the destination node is node 3



(b) Source node is node 0 and the destination node is node 4

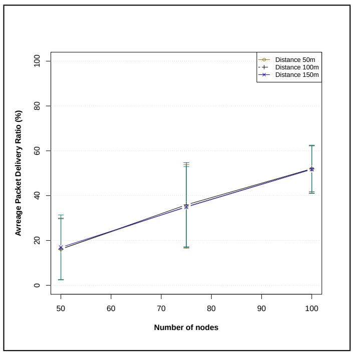


(c) Source node is node 0 and the destination node is node 5

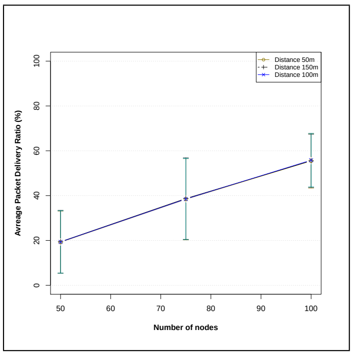
Figure 5.9: Average end-to-end delay time for different distances

free roaming nodes increased, the delay time decreased. In the case where the destination is in the right corner as shown in Figure 5.9a, increasing the distance to 150 meters and increasing the number of free roaming nodes resulted in decrease in the delay time to less than 5 seconds.

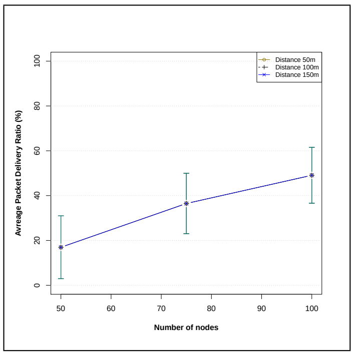
5.4.2 Packet Delivery Ratio



(a) Source node is node 0 and the destination node is node 3



(b) Source node is node 0 and the destination node is node 4



(c) Source node is node 0 and the destination node is node 5

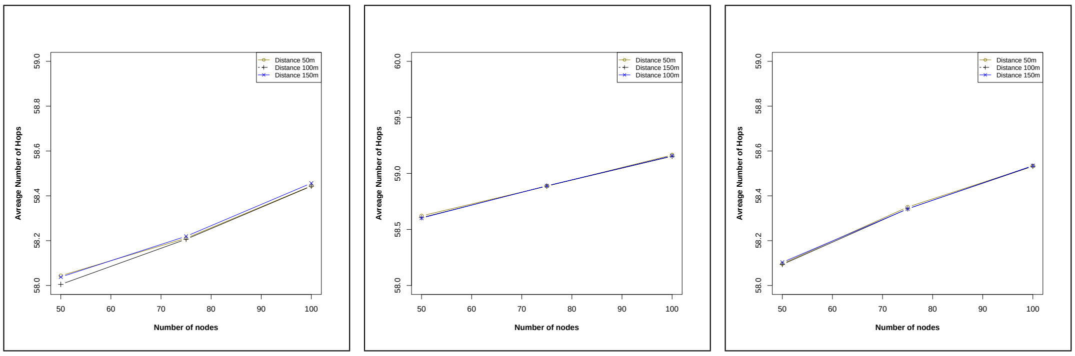
Figure 5.10: Average packet delivery ratio for different distances

Figure 5.10 shows the average packet delivery ratio using three patrol nodes with different distances when patrol nodes are supposed to retransmit the packets.

Increasing the distance did not affect FA-GPSR performance, and there is stability in the ratios for all scenarios, as shown in Figures 5.10a, 5.10b and 5.10c. As the number of free roaming nodes increased, the average packet ratios also increased, with a linear relation for all scenarios.

Comparing Figures 5.10a, 5.10b and 5.10c to Figures 5.5a, 5.10b and 5.5c, it can be seen that changes in the distance resulted in a slight increase in the best cases, which is highlighted by plotting the confidence interval value if there is communication between the nodes in the topology. In addition, crossing between the lines in the graphs, which represents the performance at 100 and 150 meters indicates that this change slightly increased the ratios by nearly 1% in all cases.

5.4.3 Number of Hops



(a) Source node is node 0 and the destination node is node 3 (b) Source node is node 0 and the destination node is node 4 (c) Source node is node 0 and the destination node is node 5

Figure 5.11: Average number of hops using a variety of distances

Figure 5.11 shows the average number of hops for all scenarios using three patrol nodes and a variety of distances to the retransmission location. The number of hops appears to be similar and there is no significant difference among the scenarios. When 50 free roaming nodes are used, the number of hops is nearly 50, and as the number of free roaming nodes increased the number of hops also increased. This is due to the use of two recovery methods in FA-GPSR, as explained in the previous chapter.

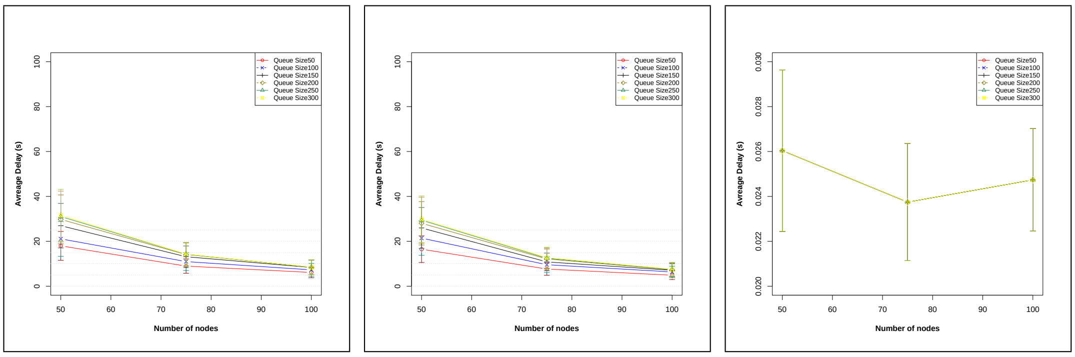
Comparing Figure 5.11 to Figure 5.6, which displays the results from using the default distance, there is no difference in terms of number of hops. This indicates the changes the distance do not affect the number of hops in FA-GPSR and that the algorithm efficiency remains coherent.

5.5 The impact of changing buffer size

Once the patrol node receives the packets, it will buffers them for retransmission. The buffering is limited to the size of the buffer in a node [134]. During a communication, the patrol node can buffer packets for retransmission in accordance with its available capacity.

This section investigates the effect of changing the queue buffer size on the performance of FA-GPSR in terms of end-to-end delay, average packet ratio and number of hops. The scenarios used in this section are similar to the ones explained in section 5.4. The number of packets used in this section begins at 50 and increases to 300 packets in increments of 50 for each patrol node.

5.5.1 End-to-End Delay



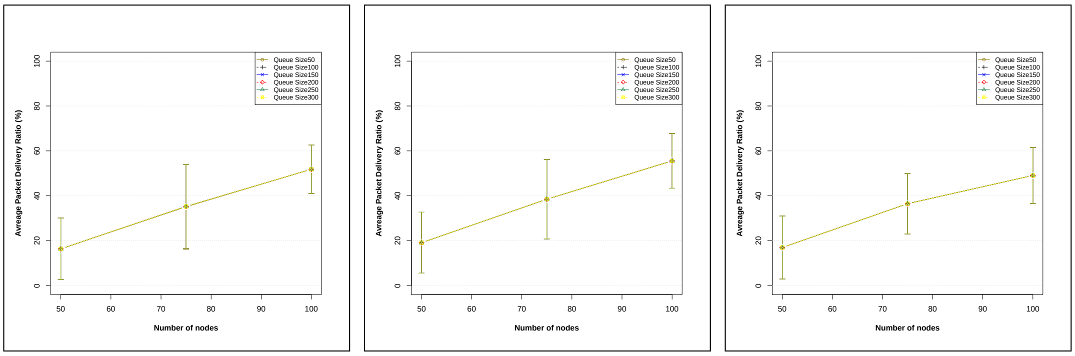
(a) Source node is node 0 and the destination node is node 3 (b) Source node is node 0 and the destination node is node 4 (c) Source node is node 0 and the destination node is node 5

Figure 5.12: Average end-to-end delay time with the use of different queue buffer sizes

Figure 5.12 shows the average end-to-end delay for different sizes of the queue buffer for the different scenarios. In the experiments represented in Figures 5.12a and 5.12b, the average delay time is similar to the delay time in the sections 5.4 and 5.3.2, where the destination node is NODE 3 and NODE 4, respectively, and three patrol nodes are used as shown in Figures 5.2, 5.3 and 5.9. As the queue size increases, the mean delay time also increases because the total number of packets increases while the throughput remains stable due to the unchanged number of nodes. In addition, the use of two recovery methods in FA-GPSR also increases the delay time as explained in previous chapter.

As the number of nodes increases, however, the delay time decreases because of the increased probability of a connection between the nodes.

5.5.2 Packet Delivery Ratio



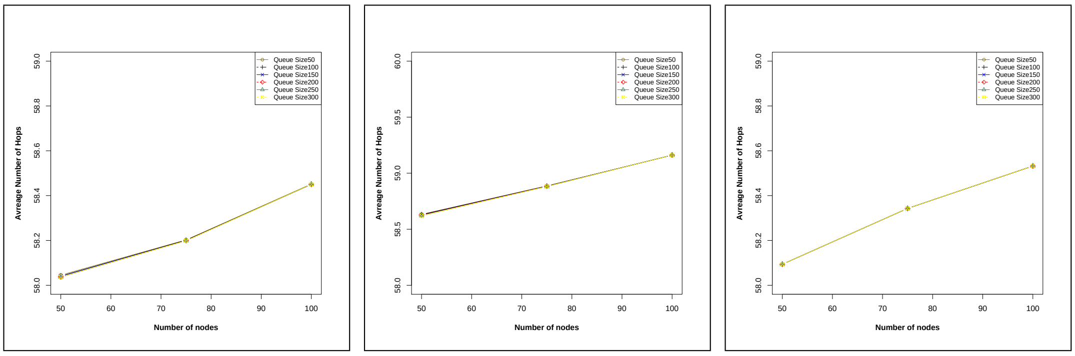
(a) Source node is node 0 and the destination node is node 3 (b) Source node is node 0 and the destination node is node 4 (c) Source node is node 0 and the destination node is node 5

Figure 5.13: Average packet delivery ratio with the use of different queue buffer sizes

Figure 5.13 show the average packet delivery ratio in different scenarios when three patrol nodes are used in each scenario. As the number of nodes increased, the delivered packet ratio also increased due to the availability of communication between nodes. The patrol node is not observing any waiting time procedure in FA-GPSR. Therefore, the number of packets buffered depended on the communication between the forwarding node and the patrol.

The change in the queue buffer size does not affect FA-GPSR performance in terms of packet ratio compared to the case explained in section 5.3.2. Each packet has a Time To Live (TTL), which means that when TTL has expired the packet will be discarded. So, as the buffer size increased, the probability of expired TTL also increased.

5.5.3 Number of Hops



(a) Source node is node 0 and the destination node is node 3 (b) Source node is node 0 and the destination node is node 4 (c) Source node is node 0 and the destination node is node 5

Figure 5.14: Average number of hops with the use of different queue buffer sizes

Figure 5.14 shows the average number of hops the packet needs to traverse for reaching the final destination. As the number of nodes increased, the number of hops also increased slightly. The change in buffer size did not affect the number of hops compared to the results discussed in section 5.3.2. This is because when the patrol node reaches the location of the destination node, and communicates with the destination node either directly or via an intermediate node it will send all buffered packets at the same time.

The average number of hops in Figures 5.14a, 5.14b and 5.14c is similar because of the way that the patrol nodes work in this scenario. Each patrol node covers one-third of the area, so the number of free roaming nodes is similar in the different scenarios as the number of hops is nearly equivalent.

5.6 Summary

This chapter discussed the effect of increasing the number of ferries to FA-GPSR, especially on the delay time, to see the possibility of decreasing the delay to a reasonable time. The chapter also discussed the effect of changing the retransmission distance from the ferry to the destination node, and changing the number of messages that can be buffered.

The first part of the chapter discussed using one ferry node or more in three different scenarios, with the location of the destination nodes changing in each scenario. The results showed that the use of a single ferry covering the whole area worked best comparing to the use of more than one ferry due to the large one patrol coverage and divided the region to small sectors when using more than patrol. Moreover, the destination location has an impact on the end-to-end delay time because when the destination nodes were where the ferry passes at the beginning of journey, the delay is shorter.

The second and third part of the chapter examined the worst case from the first part. That was the use of three patrol nodes and modify the distance of which, the ferry start retransmit, as well as the number of messages that are buffered in the patrol nodes. The results showed that the increased distance increased positive impact, especially if there were an increased number of nodes in the topology.

Furthermore, as the number of messages buffered increased, the time required to deliver messages also increased. This is because the calculation of the delay time is based on the mean of all times in each case. The change in buffer size did not affect the protocol performance in term of the packet delivery ratio or number of hops, because FA-GPSR does not support the waiting function. The main task of the patrol node in the topology is to monitor and support the cooperation between nodes and to connect a part of the topology that is outside the coverage, during its completion of the main task. The use the one ferry to cover the entire area in each trip is better than the use of two or three ferries, because each ferry in this case will cover only a part of the topology and not the entire region. In addition, FA-GPSR does not allow message exchange between ferries, which leads to the need of more nodes to participate in the forwarding process.

Chapter 6

Conclusions and Future Works

Overall, this research aimed to propose and evaluate a new routing algorithm for loosely coupled nodes problem caused by the deployment in a large area, based on the use of real-life scenarios such as the characteristics of military applications that can influence network performance. The new routing algorithm was designed, implemented and tested by applying advanced simulation techniques. Every single objective and sub-objective as listed in Section 1.3 was investigated; the viability of the objectives of designing real-life scenarios, designing a new routing algorithm called Ferry Assisted- Greedy Perimeter Stateless Routing (FA-GPSR), and the performance assessment of a FA-GPSR enabled network was proved via theoretical analysis and experimental evaluation. The experimental results showed that the FA-GPSR algorithm supports efficient and reliable message delivery. The simulation runs showed that the new routing algorithm (FA-GPSR) delivers more packets than other similar algorithms.

6.1 Summary of the Results

Using a scenario that reflects reality is the best method for evaluating routing protocols in MANET. The lack of real-life scenarios for network simulators has been a motivation for this study to implement such scenarios as the tools for evaluating existing geographical routing protocols in the literature.

Each application with MANET, as the preferred architecture for communication, has its own characteristics that could have positive or negative effects on the routing process. Accordingly, the application characteristics could be used in a suitable manner to support communication between the nodes.

In this project, a military unit deployment plan was implemented using the NS-3 simulator to determine the impact of the behaviour of the plan and the movement restrictions of the unit members on communication between the nodes. The following sections summarise the inferences drawn from the experimental results reported in the previous chapters.

6.1.1 Benefit of using a real-life scenario to design FA-GPSR

In this research, it was assumed that every application has characteristics that distinguish it from others, and it is important to consider these characteristics for enhancing the network performance. A real-life scenario of a battalion unit implemented using the NS-3 simulator served as the platform for evaluation. The use of a military application in this thesis led to the selection of geographic routing protocols because a military unit is equipped with global positioning system (GPS) devices. In addition, military unit members are well trained to use paper maps to determine their location in case their GPS devices fail. Three geographic routing protocols, Greedy Perimeter Stateless Routing algorithm(GPSR), Divisional Perimeter (GPSR-DP) and Buffering Zone Greedy Forwarding Strategy (GPSR-BZGFS), were adopted in the implemented scenario to evaluate the network performance. The results showed that the nodes were able to communicate but the performance was poor based on the number of packets successively received by the destination node. The average packet ratio in the case of low density was extremely low. The node movement restrictions resulted in regular disconnection between the nodes, thereby decreasing the packet delivery ratio. The message retention mechanism in FA-GPSR implemented by forwarding packets to the patrol node and buffering; this feature improved network performance. The route repair process followed by FA-GPSR is based on deciding the time at which the forwarding node needs to change the forward mode to send packets to the patrol node. These features are based on the investigation of the characteristics of the application and selection of characteristics that support the transmission process. The tested protocols did not benefit from the node behaviour in the topology in terms of supporting communication. Using a real-life scenario helps to determine the factors in a particular application that can affect communication and proves that the nodes are able to communicate; however, the network performance is extremely poor. Based on these factors, a novel algorithm (FA-GPSR) was implemented in this thesis. The proposed algorithm uses the characteristics of the application to support routing and improves the network performance as explained in the previous chapters, particularly in Chapter 3.

6.1.2 FA-GPSR message delivery efficiency

In this thesis, packet delivery ratio, end-to-end delay, and number of hops were employed as the metrics of protocol efficiency. Packet delivery ratio is an important metric because the objective of this research is to increases the number of packets successfully received by the final destination node. In the proposed scenario, FA-GPSR works more efficiently than other protocols, especially in terms of the number of packets successfully received by the final destination node. The packet delivery ratio of the tested protocols, Greedy Perimeter Stateless Routing algorithm(GPSR), Divisional Perimeter (GPSR-DP) and Buffering Zone Greedy Forwarding Strategy (GPSR-BZGFS), did not exceed 2% when the number of nodes distributed in the area was low, whereas that of FA-GPSR was nearly 15% under the same conditions. The packet delivery ratio increased with the number of distributed nodes for all protocols. However, when there were 200 nodes in the topology, the packet delivery ratio of FA-GPSR was more than 50%, whereas that of the other protocols was 30%. Increasing the load on the network by increasing the number of packets generated by the source nodes influences the network performance. Whenever the number of messages created increases, it will adversely affect the routing effectiveness of the protocols. This decreases the packet delivery ratio owing to regular disconnection in the network because a larger area is used for the network topology. In addition, FA-GPSR suffers from patrol movement; thus, the patrol node may fall outside the transmission range of the forwarding nodes. Nevertheless, FA-GPSR outperforms the other protocols under heavy network load.

6.1.3 Better late than never

FA-GPSR suffers from delay because it needs more time than the other protocols to deliver packets; this is because the patrol node needs more time to complete its mission. An attempt was made to reduce this delay by changing the number of patrols. Using a single patrol in the topology means that this patrol will cover the entire topology over a certain period. However, using more than one patrol means that the topology will be divided into a number of sectors, and each patrol will cover one sector. Changing the number of patrols is not the only factor affecting the delay; the results showed that the locations of both the source node and the destination node affect the delay. In all the experiments, the source node was located at the centre of the rear area, and the location of the destination node varied among the upper-right, upper-middle, and upper-left corners. When the destination node was located in the upper-right corner, the ideal number of patrols for reducing the delay was one or two. When the destination node was located in the upper-middle or upper-left corner, the ideal number of patrols for reducing the delay was one or three. The location of the destination node influences the delay, and the common number of patrols in all cases was one because one patrol could cover the entire area, whereas only small sectors could be covered by more than one patrol. In addition, all the protocols studied in this thesis, including the proposed protocol, used a recovery method in the case of failure to forward the packets, i.e. the greedy method. The recovery method follows a longer path in order to avoid empty areas; thus, it requires more time. The topology is a large area, resulting in regular disconnection between nodes; consequently, the routing protocols use the recovery method more frequently.

However, the increase in the packet delivery ratio from 2% (tested protocols) to 15% (FA-GPSR), in spite of the delay in the case of low-density nodes, shows that FA-GPSR is more efficient than the other protocols.

6.1.4 Increases in parameters is not always better

In this thesis, the number of ferries was increased to minimise the end-to-end delay and enhance FA-GPSR performance. In addition, the distance to the destination node and buffer size was calibrated to investigate their impact on FA-GPSR performance. It was found that changing (increasing or decreasing) these parameters had no effect on the efficiency of the protocol in terms of the number of messages received.

The nature of patrol node's duty and its motion are the main factors affecting routing performance; one patrol covers the entire area, resulting in better performance as compared to the use of two or three patrols in terms of minimising end-to-end delay. The end-to-end delay was minimised by using one patrol node to cover the entire area for a reasonable time. To use more than one patrol node, the topology should be divided into small and parallel sectors in order to allow each patrol to cover one sector. The reason for imposing the restriction explained above, i.e. not allowing messages to be exchanged between patrols, could be that the use of more than one patrol does not minimise the delay. FA-GPSR does not use a waiting scheme for the patrol node; thus, changes in the distance to the destination node for retransmission and changes in the buffer size do not influence routing performance. A waiting scheme could increase the number of packets that can be buffered by the patrol node, resulting in an increase in the packet delivery ratio. However, the main goal of FA-GPSR is to use a node to support cooperation with other nodes without affecting their major duty.

6.2 Significant outcomes from the scientific contributions

The major contributions and findings of this thesis are summarised below.

6.2.1 Utilising information derived from application characteristics to increase path stability for loosely coupled nodes in MANET

It was identified that for developing a new protocol in MANET, it is important to know and describe the impact of the communication characteristics on the application itself. The knowledge arisen from these characteristics can support the design and validation of any new protocol. In addition, it can help to choose a suitable protocol for an application. To determine these properties, it is necessary to conduct a realistic study on network simulators. Most of the protocols in the literature have been proposed for general use; hence, they should be evaluated in different systems to show that they perform well. It is difficult to develop a general platform reflecting different systems in order to evaluate routing algorithms in MANET. Therefore, it is necessary to evaluate current protocols in real-life scenarios for a certain application that prefers to use MANET as a means of communication.

In this project, a real-life scenario of a military unit deployment was implemented using the NS-3 simulator in order to evaluate three geographic routing algorithms: GPSR, GPSR-DP, and GPSR-BZGFS. The results showed that for a given network set up with a given network density and node mobility, communication between nodes can be established for successful delivery of packets. The area of the topology and node movement adversely affect the overall network performance based on the number of packets successfully delivered to the final destination(s). The main reason for this is the regular disconnection caused by the military restriction on node movements. The application characteristics are not considered in these protocols, resulting in poor network performance. The military unit plan has information that can support communication between the nodes to improve network performance by increasing the number of delivered packets.

Moreover, it is necessary to have a message retention mechanism that improves message delivery performance of the network in a military scenario. Thus, the use of node duty to support communication as an essential part of the new algorithm (as is the local routing repair functionality) has been taken into account. All these important features were considered in designing FA-GPSR to improve the network performance.

6.2.2 Designing Ferry-Assisted Greedy Perimeter Stateless Routing protocol (FA-GPSR)

The FA-GPSR algorithm provided the network with the following features:

FA-GPSR utilises nodes' duties to support communication

The cooperative work between nodes in a topology was identified as an important issue. However, this does not need to have any impact on the main duty of each participant. Most of the protocols using the message ferrying (MF) scheme prioritise the duty over the cooperative work to support communication in MANET, which is a drawback of these algorithms. FA-GPSR avoids the prioritising mechanism by allowing the forwarding node to add the patrol node address to the packet header in the case of the dead-end problem. The forwarding node(s) changes the forward mode to the patrol-seeking mode. This new mode consists of two modes: patrol-seeking greedy (PSG) and patrol-seeking recovery (PSR). Therefore, the forwarding node(s) does not need to move to be in the transmission range of the patrol node, nor does the patrol node need to change its route to be in the transmission range of the forwarding node. These two methods add important features to FA-GPSR as compared to the existing routing algorithms assisted by the MF scheme. When the messages arrive at the patrol node, FA-GPSR restores the original destination node address and determines the location in the patrol path for retransmission. At this location, the patrol node adopts two methods to communicate with the destination node(s): direct communication if the destination node is in its transmission range and indirect communication if the patrol node is the nearest node to the destination node and out of its transmission range. Using the patrol node duty to support communication in the battlefield, without affecting the patrol node duty, is the main advantage of FA-GPSR. The main objective of FA-GPSR is to use the node duties without affecting them. This feature supports the cooperative work between nodes in a topology to deliver services to any requester without affecting the main job of the nodes in the topology.

FA-GPSR enhances network performance

The presence of few number of nodes in the topology can result in a poor performance for the MANET networks, i.e. when the MANET becomes a sparse network. FA-GPSR improves the network performance based on the average packet delivery ratio metric. The packet delivery ratio of GPSR, GPSR-DP, and GPSR-BZGFS was very low, whereas that of FA-GPSR was better when evaluating the impact of communication between station nodes. As the network load increases, FA-GPSR outperforms GPSR and GPSR-DP. GPSR-BZGFS has the lowest packet delivery ratio because it uses the buffer strategy. Evaluating the impact of communication among mobile nodes, which increase the complexity of the network, FA-GPSR continues outperforming the other routing algorithms. The packet delivery ratio of GPSR and its variants remains lower than FA-GPSR.

However, increasing the network load affected the network performance owing to the dynamic mobility of the nodes. Despite this mobility, FA-GPSR outperformed the other protocols in this situation. The source node(s) and the destination node(s) were retained as mobile nodes to evaluate the impact of such a scenario on the routing performance. The results were expected to be similar to the above-mentioned results. FA-GPSR outperformed the other protocols; its packet delivery ratio measured higher than the others.

FA-GPSR uses the application characteristics to enhance network performance. It employs these characteristics and node behaviour to support communication in the topology and improve network performance. This is the core functionality of FA-GPSR to increase the packet delivery ratio. It is based on the use of a special node, whose main role is to travel around the topology, fill gaps in the topology caused by empty areas, and prevent node mobility that results in regular disconnection.

At low network density, FA-GPSR suffers from long delays because it needs more time than the other protocols to deliver messages, due to the nature of the patrol node duty. The patrol node needs more time to cover its area. An attempt to reduce this delay by changing the number of patrols has been described in Chapter 5.

The results showed that the use of the patrol node is not the only reason for the delay; the locations of the destination nodes also influence the delivery time. If the destination is at a location that the patrol visits first, the delay will be minimised. A good example is when the destination node is located in the upper-middle part of the topology: the use of three patrols is better than the use of one or two. This is because three patrols will cover smaller sectors, and the middle sector covers the destination node.

However, in general, using one patrol to cover the entire topology is better than using two or three patrols. The use of one patrol node reduces the delay when the destination node is located in the upper-right corner, whereas delivering packets to a destination located in the upper-left corner required less time. This is because the patrol node visits the upper-left corner before other locations.

FA-GPSR does not allow packet exchange between the patrol nodes to avoid the loop problem, caused by changes in the destination location. In addition, FA-GPSR does not use any waiting feature, which is one of the features that can increase the packet delivery ratio, because the main purpose of FA-GPSR is to increase cooperation between nodes without affecting the nodes duties; a waiting scheme will influence the node duties.

The distance for retransmission is changed so that the patrol node will retransmit the packets when the distance remains at the value defined by FA-GPSR. In addition, the buffer size is changed to store more packets for delivery to the final destination. These parameters do not affect FA-GPSR performance because they need to be supported by the waiting feature, which is not employed in FA-GPSR. The delay decreases with the distance to the destination node.

In conclusion, FA-GPSR is a novel hybrid geographic routing protocol developed on the basis of real-life scenarios to enhance the packet delivery ratio in MANET. The objective of this protocol is to solve the problem of loosely coupled nodes caused by deployment in a large area, on the basis of the application characteristics, which influence the node behaviour in the topology. This protocol works according to clear logic and is not affected by any assumptions that are not logical.

6.2.3 Designing simulation model for the evaluation of FA-GPSR

This thesis addressed the lack of geographic routing protocols which are necessary for simulating recently developed routing algorithms in NS-3 simulator and also for evaluating FA-GPSR against these routing algorithms. Accordingly, by using the idea of geographic routing algorithms, two recent variants of GPSR were implemented and reported in this thesis. The GPSR variant introduced by Wei et al. [4], employs a strategy known as the buffering zone greedy forwarding strategy (BZGFS), and the GPSR variant introduced by Guoming et al. [5], is a divisional perimeter (DP) forwarding algorithm. These variants are not available for public use; hence, in this thesis, they were implemented from scratch in the NS-3 simulator for comparison purposes. These algorithms were applied as new techniques to enhance the default GPSR.

6.3 Directions for Future Work

The work conducted in this thesis has shown that using application characteristics makes FA-GPSR relatively efficient and reliable. Using FA-GPSR has produced interesting results which are reported in this thesis; yet, there are a number of issues which require further investigations.

- This thesis showed that FA-GPSR works well in a simulated environment, but its efficiency in a real environment remains unknown. The drawback of an experiment is that it is difficult to repeat it with the same conditions, and to ensure that the experimental conditions remain the same all the time. To overcome these problems, we need a practical experiment in a real environment which is expected to provide more valuable insights for the efficiency of the designed routing algorithms.

- Security issues related to routing have not been addressed in this thesis. This thesis assumed that all nodes in the topology are not selfish and are able to cooperate with others to deliver packets. This assumption is logical for military applications. In a military application, the packets need to be secure, and enemies should not be able to intercept the transmitted messages. Nevertheless, potential security issues caused by selfish nodes in other applications still remain open to further investigations.

- As the results have shown, there is a large delay in FA-GPSR which is due to the use of more than one recovery method. This means that optimisation is needed to merge these two techniques together to minimise the caused delay; this is also a potential area for future research.

- The real-life scenario used in this thesis is the deployment of a certain type of military unit. Each military unit has its own characteristics; thus, investigating other types of military units could lead to generalising these characteristics and standardising a routing algorithm for military applications to be used in different scenarios.

- FA-GPSR does not allow packet exchange between patrol nodes to avoid the loop problem. The investigation of this problem can provide some solution that allows packet exchange between patrol nodes and enhance the performance by minimising delay and increasing packet delivery ratio.

- FA-GPSR does not employ the waiting feature, which can increase the packet delivery ratio. It could be useful to study ways to employ this feature without affecting the main objective of FA-GPSR, i.e. to enhance cooperation between nodes without influencing the main duties of the nodes in the battlefield.

- FA-GPSR should be investigated in civil environments to identify the characteristics shared between different applications. As mentioned previously, each application has its own characteristics that distinguish it from others; however, there may be some shared characteristics that could support communication and enhance routing performance.

- FA-GPSR uses location services derived from the NS-3 simulator to update nodes according to the recent locations of their neighbours. Future works could examine the use of location services routing to investigate the impact of these algorithms on FA-GPSR. In addition, it is possible to optimise FA-GPSR by integrating it with novel location services routing developed on the basis of the same objectives.

- FA-GPSR has examined the communication between stationary source and destination nodes, mobile source and destination nodes, and stationary source and mobile destination nodes. Future investigation should include FA-GPSR being examined in the situation when the source node is mobile and destination is fixed and evaluate its performance when the military unit Commander is mobile.

References

[1] Abdoul-Kader Harouna Souley and Soumaya Cherkaoui, "Realistic urban scenarios simulation for ad hoc networks", in *2nd International Conference on Innovations in Information Technology*, 2005. vi, 5

[2] Parth H Pathak and Rudra Dutta, "A survey of network design problems and joint design approaches in wireless mesh networks", *Communications Surveys & Tutorials, IEEE*, vol. 13, no. 3, pp. 396–428, 2011. xiii, 15, 16

[3] Eiman Alotaibi and Biswanath Mukherjee, "A survey on routing algorithms for wireless ad-hoc and mesh networks", *Computer Networks*, vol. 56, no. 2, pp. 940–965, 2012. xiii, 3, 15, 20, 24, 25, 26, 30, 31, 46, 77

[4] Wen Wei and Zhang Heng Yang, "Increasing packet delivery ratio in gpsr using buffer zone based greedy forwarding strategy", in *Data Storage and Data Engineering (DSDE), 2010 International Conference on*. 2010, pp. 178–182, IEEE. xiii, 8, 12, 31, 34, 35, 109, 138

[5] Tang Guoming, Xie Yi, Tang Daquan, and Tang Jiuyang, "Divisional perimeter routing for gpsr based on left and right hand rules", in *Computer Science and Network Technology (ICCSNT), 2011 International Conference on*. 2011, vol. 2, pp. 726–729, IEEE. xiii, 8, 12, 31, 37, 38, 109, 138

[6] Yueyue Li, Stylianos Papanastasiou, Javad Akhlaghinia, and Evtim Peytchev, "Tmda: A broadcast-based message delivery algorithm for vanets", *International Journal On Advances in Telecommunications*, vol. 6, no. 1 and 2, pp. 34–44, 2013. 1

[7] Pratibha Sahu, Navdeep Kaur Saluja, and Ragini Sen, "A survey–performance based routing protocols in wireless ad-hoc networks environment", *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)*, vol. 2, no. 3, pp. PP–1270, 2013. 2

[8] Elizabeth M Royer, P Michael Melliar-Smith, and Louise E Moser, "An analysis of the optimum node density for ad hoc mobile networks", in *Communications, 2001. ICC 2001. IEEE International Conference on*. IEEE, 2001, vol. 3, pp. 857–861. 2

[9] Victoria Manfredi, Mark Crovella, and Jim Kurose, "Understanding stateful vs stateless communication strategies for ad hoc networks", in *Proceedings of the 17th annual international conference on Mobile computing and networking*. ACM, 2011, pp. 313–324. 4, 42

[10] Priyanka Goyal, Vinti Parmar, and Rahul Rishi, "Manet: Vulnerabilities, challenges, attacks, application", *IJCEM International Journal of Computational Engineering & Management*, vol. 11, no. 2011, pp. 32–37, 2011. 4

[11] Victoria Manfredi, Robert Hancock, and Jim Kurose, "Robust routing in dynamic manets", in *Annual Conference of the International Technology Alliance*, 2008. 4

[12] Khaled Alekeish and Paul Ezhilchelvan, "Consensus in sparse, mobile ad hoc networks", *Parallel and Distributed Systems, IEEE Transactions on*, vol. 23, no. 3, pp. 467–474, 2012. 4

[13] Thierry Plesse, Cedric Adjih, Pascale Minet, Anis Laouiti, Adokoé Plakoo, Marc Badel, Paul Muhlethaler, Philippe Jacquet, and Jérôme Lecomte, "Olsr performance measurement in a military mobile ad hoc network", *Ad Hoc Networks*, vol. 3, no. 5, pp. 575–588, 2005. 6, 54, 55

[14] P Holliday, "Self organisational properties of military ad hoc wireless networks", in *Land Warfare Conference*, 2002. 6

[15] Brad Karp and Hsiang-Tsung Kung, "Gpsr: Greedy perimeter stateless routing for wireless networks", in *Proceedings of the 6th annual international conference on Mobile computing and networking*. 2000, pp. 243–254, ACM. 7, 8, 31, 32, 33, 37, 38, 47, 67, 97, 104, 108, 109, 111, 118

[16] Anshuman Tiwari, *proxy-AODV: Extension of AODV for partially connected ad hoc networks*, PhD thesis, Indian Institute of Technology Bombay, 2006. 9

[17] Hirokazu Miura, Daisuke Nishi, Noriyuki Matsuda, and Hirokazu Taki, "Message ferry route design based on clustering for sparse ad hoc networks", in *Knowledge-Based and Intelligent Information and Engineering Systems*, pp. 637–644. Springer, 2010. 9

[18] Bahadir K Polat, Pushkar Sachdeva, Mostafa H Ammar, and Ellen W Zegura, "Message ferries as generalized dominating sets in intermittently connected mobile networks", *Pervasive and Mobile Computing*, vol. 7, no. 2, pp. 189–205, 2011. 9

[19] Ranju Pant, Apinun Tunpan, Preechai Mekbungwan, Rujipol Virochpoka, and Kanchana Kanchanasut, "Dtn overlay on olsr network", in *Proceedings of the Sixth Asian Internet Engineering Conference*. ACM, 2010, pp. 56–63. 9

[20] Brendan Burns, Oliver Brock, and Brian Neil Levine, "Mora routing and capacity building in disruption-tolerant networks", *Ad hoc networks*, vol. 6, no. 4, pp. 600–620, 2008. 9

[21] Chrisy Samara, Eirini Karapistoli, and Anastasios A Economides, "Performance comparison of manet routing protocols based on real-life scenarios", in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2012 4th International Congress on*. IEEE, 2012, pp. 870–877. 10, 53

[22] Mario Gerla, "From battlefields to urban grids: New research challenges in ad hoc wireless networks", *Pervasive and mobile computing*, vol. 1, no. 1, pp. 77–93, 2005. 10

[23] Wenrui Zhao, Mostafa Ammar, and Ellen Zegura, "A message ferrying approach for data delivery in sparse mobile ad hoc networks", in *Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing*. ACM, 2004, pp. 187–198. 12, 75, 76, 85

[24] Charles E Perkins and Elizabeth M Royer, "Ad-hoc on-demand distance vector routing", in *Mobile Computing Systems and Applications, 1999. Proceedings. WMCSA'99. Second IEEE Workshop on*. IEEE, 1999, pp. 90–100. 14, 28

[25] Ashish Raniwala and Tzi-cker Chiueh, "Architecture and algorithms for an ieee 802.11-based multi-channel wireless mesh network", in *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*. IEEE, 2005, vol. 3, pp. 2223–2234. 15

[26] Jie Wu, *Handbook on theoretical and algorithmic aspects of sensor, ad hoc wireless, and peer-to-peer networks*, CRC Press, 2004. 16, 17, 24

[27] Chai-Keong Toh, "Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks", *Communications Magazine, IEEE*, vol. 39, no. 6, pp. 138–147, 2001. 17

[28] Imrich Chlamtac, Marco Conti, and Jennifer J-N Liu, "Mobile ad hoc networking: imperatives and challenges", *Ad Hoc Networks*, vol. 1, no. 1, pp. 13–64, 2003. 17, 18, 20

[29] James A DeBardelaben, "Multimedia sensor networks for isr applications", in *Signals, Systems and Computers, 2004. Conference Record of the Thirty-Seventh Asilomar Conference on*. IEEE, 2003, vol. 2, pp. 2009–2012. 17

[30] Hao Yang, Haiyun Luo, Fan Ye, Songwu Lu, and Lixia Zhang, "Security in mobile ad hoc networks: challenges and solutions", *Wireless Communications, IEEE*, vol. 11, no. 1, pp. 38–47, 2004. 18

[31] R Periasamy, C Ranjithkumar, and P Panimalar, "A study on multicast routing protocols for manets: Mrmp, eramobile, tsmp, lam, puma.", *Inter-*

national Journal of Computer Science & Network Security, vol. 13, no. 9, 2013. 18

[32] Marcelo M Sobral and Leandro B Becker, "Evaluating the benefits and feasibility of coordinated medium access in manets", *ACM SIGBED Review*, vol. 8, no. 4, pp. 22–29, 2011. 19

[33] Marco Conti and Silvia Giordano, "Mobile ad hoc networking: milestones, challenges, and new research directions", *Communications Magazine, IEEE*, vol. 52, no. 1, pp. 85–96, 2014. 19

[34] Sanjeev Kumar, Santosh Kr Paul, and Shyam Singh Rajput, "Applying qos in manet using stigmergy of ants.", *International Journal of Computer Applications*, vol. 85, 2014. 19

[35] Srdjan Capkun, Levente Buttyán, and J-P Hubaux, "Self-organized public-key management for mobile ad hoc networks", *Mobile Computing, IEEE Transactions on*, vol. 2, no. 1, pp. 52–64, 2003. 19

[36] Dmitri D Perkins, Herman D Hughes, and Charles B Owen, "Factors affecting the performance of ad hoc networks", in *Communications, 2002. ICC 2002. IEEE International Conference on*. IEEE, 2002, vol. 4, pp. 2048–2052. 19

[37] Karthikeyan Sundaresan, Seung-Jong Park, and Raghupathy Sivakumar, "Transport layer protocols in ad hoc networks", in *Ad Hoc Networks*, pp. 123–152. Springer, 2005. 19

[38] Ian D Chakeres and Joseph P Macker, "Mobile ad hoc networking and the ietf", *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 10, no. 1, pp. 58–60, 2006. 19

[39] Ossama Younis, Latha Kant, Kenneth Young, David Shallcross, Kyriakos Manousakis, Kaustubh Sinkar, Miriam Tauil, Sunil Samtani, Charles Graff, and Mitesh Patel, "Automated design algorithms for tactical wireless networks", *Ad Hoc Networks*, vol. 11, no. 8, pp. 2461–2469, 2013. 20

[40] Prasant Mohapatra and Srikanth Krishnamurthy, *AD HOC NETWORKS: technologies and protocols*, Springer, 2005. 20

[41] Romeu Monteiro, Susana Sargento, Wantanee Viriyasitavat, and Ozan K Tonguz, "Improving vanet protocols via network science", *arXiv preprint arXiv:1301.0965*, 2013. 20

[42] William Stallings and William Stallings, *Data and computer communications*, vol. 6, Prentice hall New Jersey, 1997. 21

[43] A Behrouz Forouzan, *Data Communications & Networking (sie)*, Tata McGraw-Hill Education, 2006. 21

[44] Fred Halsall and Data Links, "Computer networks and open systems", *Addison-Wesley Publishers*, pp. 112–125, 1995. 21

[45] Stefano Basagni, Marco Conti, Silvia Giordano, and Ivan Stojmenovic, *Mobile ad hoc networking*, John Wiley & Sons, 2004. 22

[46] Jack L Burbank, Philip F Chimento, Brian K Haberman, and W Kasch, "Key challenges of military tactical networking and the elusive promise of manet technology", *Communications Magazine, IEEE*, vol. 44, no. 11, pp. 39–45, 2006. 23, 54

[47] Fanfan Yao, Renjie Xu, Qiang Liang, and Lanjuan Tong, "Some key issues on modeling and simulation of military communication network", in *Computer Science and Electronics Engineering (ICCSEE), 2012 International Conference on*, March 2012, vol. 1, pp. 532–535. 23

[48] Holger Füßler, Martin Mauve, Hannes Hartenstein, Michael Käsemann, and Dieter Vollmer, "Mobicom poster: location-based routing for vehicular ad-hoc networks", *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 7, no. 1, pp. 47–49, 2003. 25, 31

[49] Charles E Perkins and Pravin Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (dsdv) for mobile computers", in *ACM SIGCOMM Computer Communication Review*. ACM, 1994, vol. 24, pp. 234–244. 27, 44, 45

[50] Philippe Jacquet, Paul Muhlethaler, Thomas Clausen, Anis Laouiti, Amir Qayyum, and Laurent Viennot, "Optimized link state routing protocol for ad hoc networks", in *Multi Topic Conference, 2001. IEEE INMIC 2001. Technology for the 21st Century. Proceedings. IEEE International.* IEEE, 2001, pp. 62–68. 27, 28, 44

[51] Charles E Perkins, *Ad hoc networking*, Addison-Wesley Professional, 2008. 28, 29

[52] David B Johnson, David A Maltz, Josh Broch, et al., "Dsr: The dynamic source routing protocol for multi-hop wireless ad hoc networks", *Ad hoc networking*, vol. 5, pp. 139–172, 2001. 28, 29

[53] Xiaoyan Hong, Kaixin Xu, and Mario Gerla, "Scalable routing protocols for mobile ad hoc networks", *Network, IEEE*, vol. 16, no. 4, pp. 11–21, 2002. 30

[54] Stefano Basagni, Imrich Chlamtac, Violet R Syrotiuk, and Barry A Woodward, "A distance routing effect algorithm for mobility (dream)", in *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking.* ACM, 1998, pp. 76–84. 30

[55] Asad Amir Pirzada and Chris McDonald, "Trusted greedy perimeter stateless routing", in *Networks, 2007. ICON 2007. 15th IEEE International Conference on.* 2007, pp. 206–211, IEEE. 31

[56] Godfried T Toussaint, "The relative neighbourhood graph of a finite planar set", *Pattern recognition*, vol. 12, no. 4, pp. 261–268, 1980. 32

[57] M Shanudin, M Ismail, and R Saqour, "Impact of mobility metrics on greedy ad hoc network routing protocol and improvement using angular prediction model", in *Networks, 2005. Jointly held with the 2005 IEEE 7th Malaysia International Conference on Communication., 2005 13th IEEE International Conference on.* IEEE, 2005, vol. 1, pp. 6–pp. 34

[58] Sunder Aditya Rao, M Pai, Mounir Boussedjra, and Joseph Mouzna, "Gpsr-l: Greedy perimeter stateless routing with lifetime for vanets", in *ITS*

Telecommunications, 2008. ITST 2008. 8th International Conference on. IEEE, 2008, pp. 299–304. 35

[59] Christian Lochert, Martin Mauve, Holger Füßler, and Hannes Hartenstein, "Geographic routing in city scenarios", *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 9, no. 1, pp. 69–72, 2005. 35, 36, 37

[60] Bijan Paul, Md Ibrahim, Md Bikas, and Abu Naser, "Vanet routing protocols: Pros and cons.", *International Journal of Computer Applications*, vol. 20, 2011. 36, 48

[61] Kevin C Lee, Jerome Haerri, Uichin Lee, and Mario Gerla, "Enhanced perimeter routing for geographic forwarding protocols in urban vehicular scenarios", in *Globecom Workshops, 2007 IEEE*. IEEE, 2007, pp. 1–10. 36, 37

[62] Fabrizio Granelli, Giulia Boato, Dzmitry Kliazovich, and Gianni Vernazza, "Enhanced gpsr routing in multi-hop vehicular communications through movement awareness", *Communications Letters, IEEE*, vol. 11, no. 10, pp. 781–783, 2007. 38

[63] Yan-Bo Wang, Tin-Yu Wu, Wei-Tsong Lee, and Chih-Heng Ke, "A novel geographic routing strategy over vanet", in *Advanced Information Networking and Applications Workshops (WAINA), 2010 IEEE 24th International Conference on*. IEEE, 2010, pp. 873–879. 38

[64] Jian Chen, Yong Guan, and Udo Pooch, "Customizing gpsr for wireless sensor networks", in *Mobile Ad-hoc and Sensor Systems, 2004 IEEE International Conference on*. IEEE, 2004, pp. 549–551. 38

[65] Wenjie Shu, Ping Wang, Aihuang Guo, Xinhong Wang, and Fuqiang Liu, "Enhanced gpsr using neighbor-awareness position update and beacon-assist geographic forwarding in vehicular ad hoc networks", in *Intelligent Vehicles Symposium, 2009 IEEE*. IEEE, 2009, pp. 1143–1147. 39

[66] Kevin Fall, "A delay-tolerant network architecture for challenged internets", in *Proceedings of the 2003 conference on Applications, technologies, archi-*

tectures, and protocols for computer communications. ACM, 2003, pp. 27–34. 39, 40

[67] Artemios Voyiatzis, "A survey of delay-and disruption-tolerant networking applications", *Journal of Internet engineering*, vol. 5, no. 1, 2012. 40

[68] Vincent Borrel, Mostafa H Ammar, and Ellen W Zegura, "Understanding the wireless and mobile network space: a routing-centered classification", in *Proceedings of the second ACM workshop on Challenged networks*. ACM, 2007, pp. 11–18. 40

[69] Muhammad Mukarram Bin Tariq, Mostafa Ammar, and Ellen Zegura, "Message ferry route design for sparse ad hoc networks with mobile nodes", in *Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing*. ACM, 2006, pp. 37–48. 41, 75

[70] Padma Mundur and Matthew Seligman, "Delay tolerant network routing: Beyond epidemic routing", in *Wireless Pervasive Computing, 2008. ISWPC 2008. 3rd International Symposium on*. IEEE, 2008, pp. 550–553. 41, 42

[71] Amin Vahdat, David Becker, et al., "Epidemic routing for partially connected ad hoc networks", Tech. Rep., Technical Report CS-200006, Duke University, 2000. 41

[72] Anders Lindgren, Avri Doria, and Olov Schelén, "Probabilistic routing in intermittently connected networks", *ACM SIGMOBILE mobile computing and communications review*, vol. 7, no. 3, pp. 19–20, 2003. 41

[73] Thrasyvoulos Spyropoulos, Konstantinos Psounis, and Cauligi S Raghavendra, "Spray and wait: an efficient routing scheme for intermittently connected mobile networks", in *Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking*. ACM, 2005, pp. 252–259. 41, 45

[74] Tara Small and Zygmunt J Haas, "Resource and performance tradeoffs in delay-tolerant wireless networks", in *Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking*. ACM, 2005, pp. 260–267. 41

[75] Philo Juang, Hidekazu Oki, Yong Wang, Margaret Martonosi, Li Shiuan Peh, and Daniel Rubenstein, “Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with zebranet”, in *ACM Sigplan Notices*. ACM, 2002, vol. 37, pp. 96–107. 41

[76] Yu-Chee Tseng, Sze-Yao Ni, Yuh-Shyan Chen, and Jang-Ping Sheu, “The broadcast storm problem in a mobile ad hoc network”, *Wireless networks*, vol. 8, no. 2-3, pp. 153–167, 2002. 41

[77] Yue Cao and Zhili Sun, “Routing in delay/disruption tolerant networks: A taxonomy, survey and challenges”, *Communications Surveys & Tutorials, IEEE*, vol. 15, no. 2, pp. 654–677, 2013. 42

[78] Zhensheng Zhang, “Routing in intermittently connected mobile ad hoc networks and delay tolerant networks: overview and challenges”, *Communications Surveys Tutorials, IEEE*, vol. 8, no. 1, pp. 24–37, First 2006. 42

[79] Athanasios V Vasilakos, Yan Zhang, and Thrasyvoulos Spyropoulos, *Delay tolerant networks: Protocols and applications*, CRC Press, 2012. 43, 44

[80] Jörg Ott, Dirk Kutscher, and Christoph Dwertmann, “Integrating dtn and manet routing”, in *Proceedings of the 2006 SIGCOMM workshop on Challenged networks*. ACM, 2006, pp. 221–228. 43

[81] Jani Lakkakorpi, Mikko Pitkänen, and Jörg Ott, “Adaptive routing in mobile opportunistic networks”, in *Proceedings of the 13th ACM international conference on Modeling, analysis, and simulation of wireless and mobile systems*. ACM, 2010, pp. 101–109. 43

[82] Laurent Delosieres and Simin Nadjm-Tehrani, “Batman store-and-forward: The best of the two worlds”, in *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2012 IEEE International Conference on*. IEEE, 2012, pp. 721–727. 43

[83] David Johnson, Ntsibane Ntlatlapa, and Corinna Aichele, “Simple pragmatic approach to mesh routing using batman”, *2nd IFIP International Symposium*

on Wireless Communications and Information Technology in Developing Countries, CSIR, Pretoria, South Africa, 2008. 43

[84] Ranjana Pathak, Peizhao Hu, Jadwiga Indulska, and Marius Portmann, "Protocol for efficient opportunistic communication", in *Local Computer Networks (LCN), 2013 IEEE 38th Conference on*. IEEE, 2013, pp. 244–247. 44

[85] Christian Raffelsberger and Hermann Hellwagner, "A hybrid manet-dtn routing scheme for emergency response scenarios", in *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2013 IEEE International Conference on*. IEEE, 2013, pp. 505–510. 44

[86] Ranju Pant, Apinun Tunpan, Preechai Mekbungwan, Rujipol Virochpoka, and Kanchana Kanchanasut, "Dtn overlay on olsr network", in *Proceedings of the Sixth Asian Internet Engineering Conference*. ACM, 2010, pp. 56–63. 44

[87] Shweta Jain, Snehapreethi Gopinath, and Dipankar Raychaudhuri, "Star: Storage aware routing protocol for generalized delay tolerant networks", in *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2011 IEEE International Symposium on a*. IEEE, 2011, pp. 1–4. 44

[88] Yang Chen, Wenrui Zhao, Mostafa Ammar, and Ellen Zegura, "Hybrid routing in clustered dtns with message ferrying", in *Proceedings of the 1st international MobiSys workshop on Mobile opportunistic networking*. ACM, 2007, pp. 75–82. 44

[89] Mirco Musolesi and Cecilia Mascolo, "Car: context-aware adaptive routing for delay-tolerant mobile networks", *Mobile Computing, IEEE Transactions on*, vol. 8, no. 2, pp. 246–260, 2009. 45

[90] Christian Kretschmer, Stefan Ruhrup, and Christian Schindelhauer, "Dt-dymo: delay-tolerant dynamic manet on-demand routing", in *Distributed Computing Systems Workshops, 2009. ICDCS Workshops' 09. 29th IEEE International Conference on*. IEEE, 2009, pp. 493–498. 45

[91] Ian Chakeres and Charles Perkins, “Dynamic manet on-demand (dymo) routing”, *draft-ietf-manet-dymo-14 (work in progress)*, 2008. 45

[92] Cong Liu and Jie Wu, “Efficient adaptive routing in delay tolerant networks”, in *Communications, 2009. ICC’09. IEEE International Conference on*. IEEE, 2009, pp. 1–5. 45

[93] John Whitbeck and Vania Conan, “Hymad: Hybrid dtn-manet routing for dense and highly dynamic wireless networks”, *Computer Communications*, vol. 33, no. 13, pp. 1483–1492, 2010. 45

[94] Vasco NGJ Soares, Joel JPC Rodrigues, and Farid Farahmand, “Geospray: A geographic routing protocol for vehicular delay-tolerant networks”, *Information Fusion*, vol. 15, pp. 102–113, 2014. 46, 48

[95] L Franck and F Gil-Castineira, “Using delay tolerant networks for car2car communications”, in *Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium on*. IEEE, 2007, pp. 2573–2578. 46

[96] Yueyue Li and Evtim Peytchev, “New traffic message delivery algorithm for a novel vanet architecture”, in *ICWMC 2012, The Eighth International Conference on Wireless and Mobile Communications*, 2012, pp. 395–401. 46

[97] Jason LeBrun, Chen-Nee Chuah, Dipak Ghosal, and Michael Zhang, “Knowledge-based opportunistic forwarding in vehicular wireless ad hoc networks”, in *Vehicular technology conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*. IEEE, 2005, vol. 4, pp. 2289–2293. 46

[98] Ilias Leontiadis and Cecilia Mascolo, “Geopps: Geographical opportunistic routing for vehicular networks”, in *World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007. IEEE International Symposium on a*. IEEE, 2007, pp. 1–6. 46

[99] Jó Agila Bitsch Link, Daniel Schmitz, and Klaus Wehrle, “Geodtn: Geographic routing in disruption tolerant networks”, in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*. IEEE, 2011, pp. 1–5. 47

[100] Pei-Chun Cheng, Jui-Ting Weng, Lung-Chih Tung, Kevin C Lee, Mario Gerla, and Jerome Haerri, "Geodtn+ nav: A hybrid geographic and dtn routing with navigation assistance in urban vehicular networks", *MobiQuitous/ISVCS*, 2008. 47

[101] Jani Kurhinen and Jukka Janatuinen, "Geographical routing for delay tolerant encounter networks", in *Computers and Communications, 2007. ISCC 2007. 12th IEEE Symposium on*. IEEE, 2007, pp. 463–467. 48

[102] Erik Kuiper and Simin Nadjm-Tehrani, "Geographical routing in intermittently connected ad hoc networks", in *Advanced Information Networking and Applications-Workshops, 2008. AINAW 2008. 22nd International Conference on*. IEEE, 2008, pp. 1690–1695. 48

[103] Muhammad Azizur Rahman, Algirdas Pakštas, and Frank Zhigang Wang, "Network modelling and simulation tools", *Simulation Modelling Practice and Theory*, vol. 17, no. 6, pp. 1011–1031, 2009. 48

[104] Vern Paxson and Sally Floyd, "Why we don't know how to simulate the internet", in *Proceedings of the 29th conference on Winter simulation*. IEEE Computer Society, 1997, pp. 1037–1044. 48

[105] George S Fishman, "Principles of discrete event simulation", 1978. 48

[106] E. Weingartner, H. vom Lehn, and K. Wehrle, "A performance comparison of recent network simulators", in *Communications, 2009. ICC '09. IEEE International Conference on*, June 2009, pp. 1–5. 48, 49, 50

[107] Luc Hogie, Pascal Bouvry, and Frédéric Guinand, "An overview of manets simulation", *Electronic notes in theoretical computer science*, vol. 150, no. 1, pp. 81–101, 2006. 48

[108] Kevin Fall and Kannan Varadhan, "The network simulator (ns-2)", *URL: http://www. isi. edu/nsnam/ns*, 2007. 49

[109] Thomas R Henderson, Sumit Roy, Sally Floyd, and George F Riley, "ns-3 project goals", in *Proceeding from the 2006 workshop on ns-2: the IP network simulator*. ACM, 2006, p. 13. 49

[110] Juan Luis Font, Pablo Iñigo, Manuel Domínguez, José Luis Sevillano, and Claudio Amaya, "Analysis of source code metrics from ns-2 and ns-3 network simulators", *Simulation Modelling Practice and Theory*, vol. 19, no. 5, pp. 1330–1346, 2011. 49

[111] Vinita Mishra and Smita Jangale, "Analysis and comparison of different wireless network simulators", in *VESIT, International Technological Conference-2014 (I-TechCON), Jan. 03*, 2014, vol. 4. 49

[112] Jianli Pan and Raj Jain, "A survey of network simulation tools: Current status and future developments", *Email: jp10@ cse. wustl. edu*, 2008. 49, 50

[113] Namrata Marium Chacko, John Major, et al., "A comprehensive overview on different network simulators.", *International Journal of Engineering Science & Technology*, vol. 5, no. 2, 2013. 49

[114] András Varga et al., "The omnet++ discrete event simulation system", in *Proceedings of the European Simulation Multiconference (ESM2001)*. sn, 2001, vol. 9, p. 185. 49

[115] OPNET Modeler, "Opnet technologies inc", 2009. 49

[116] Srinivasan Keshav, *REAL: A network simulator*, University of California, 1988. 49

[117] Gilberto Flores Lucio, Marcos Paredes-Farrera, Emmanuel Jammeh, Martin Fleury, and Martin J Reed, "Opnet modeler and ns-2: Comparing the accuracy of network simulators for packet-level analysis using a network testbed", *WSEAS Transactions on Computers*, vol. 2, no. 3, pp. 700–707, 2003. 50

[118] Amit Jardosh, Elizabeth M Belding-Royer, Kevin C Almeroth, and Subhash Suri, "Towards realistic mobility models for mobile ad hoc networks", in *Proceedings of the 9th annual international conference on Mobile computing and networking*. ACM, 2003, pp. 217–229. 50

[119] Injong Rhee, Minsu Shin, Seongik Hong, Kyunghan Lee, Seong Joon Kim, and Song Chong, "On the levy-walk nature of human mobility", *IEEE/ACM Transactions on Networking (TON)*, vol. 19, no. 3, pp. 630–643, 2011. 50, 51

[120] Erik Kuiper and Simin Nadjm-Tehrani, "Geographical routing with location service in intermittently connected manets", *Vehicular Technology, IEEE Transactions on*, vol. 60, no. 2, pp. 592–604, 2011. 50, 51

[121] Tracy Camp, Jeff Boleng, and Vanessa Davies, "A survey of mobility models for ad hoc network research", *Wireless communications and mobile computing*, vol. 2, no. 5, pp. 483–502, 2002. 50

[122] Radhika Ranjan Roy, *Handbook of mobile ad hoc networks for mobility models*, Springer, 2010. 51

[123] M. Nakamura, "Analysis of alternatives for tactical digital battlefield operation over low-bandwidth legacy radios", in *Military Communications Conference, 2008. MILCOM 2008. IEEE*, Nov., pp. 1–7. 56

[124] Command and Staff College Saudi Arabia, *Joint Planing and Operation*, vol. 2, Command and Staff College Saudi Arabia, 2010. 56, 57

[125] Command and Staff College Saudi Arabia, *Planning and preparing orders for land forces*, vol. 3, Command and Staff College Saudi Arabia, 2011. 56, 71

[126] Command and Staff College Saudi Arabia, *Joint intelligence preparation of the operational environment*, vol. 3, Command and Staff College Saudi Arabia, 2011. 57

[127] Command and Staff College Saudi Arabia, *Military Movmeents*, vol. 4, Command and Staff College Saudi Arabia, 2011. 57

[128] Gunnar G Løvås, "On performance measures for evacuation systems", *European Journal of Operational Research*, vol. 85, no. 2, pp. 352–367, 1995. 71

[129] Wenrui Zhao and Mostafa H Ammar, "Message ferrying: Proactive routing in highly-partitioned wireless ad hoc networks", in *Distributed Computing Systems, 2003. FTDCS 2003. Proceedings. The Ninth IEEE Workshop on Future Trends of*. IEEE, 2003, pp. 308–314. 75

[130] Kuo-Feng Ssu, Chih-Hsun Chou, Wei-Tong Wang, and Shin-Hung Chung, "Improving data transmission with helping nodes for geographical ad hoc routing", *Computer Networks*, vol. 51, no. 18, pp. 4997–5010, 2007. 75

[131] Chia-Ho Ou, Kuo-Feng Ssu, and Hewijin Christine Jiau, "Connecting network partitions with location-assisted forwarding nodes in mobile ad hoc environments", in *Dependable Computing, 2004. Proceedings. 10th IEEE Pacific Rim International Symposium on*. IEEE, 2004, pp. 239–247. 75

[132] Wenrui Zhao, Mostafa Ammar, and Ellen Zegura, "Controlling the mobility of multiple data transport ferries in a delay-tolerant network", in *INFOCOM 2005. 24th annual joint conference of the IEEE computer and communications societies. Proceedings IEEE*. IEEE, 2005, vol. 2, pp. 1407–1418. 110

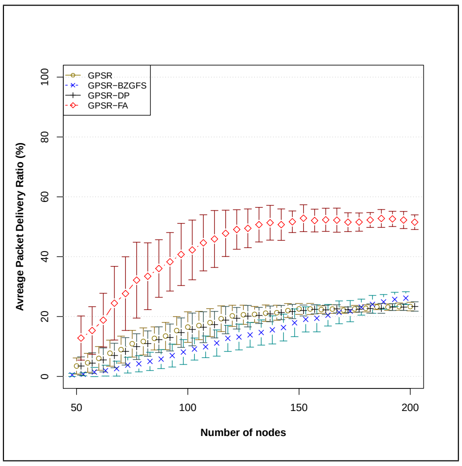
[133] Dongjin Son, Ahmed Helmy, and Bhaskar Krishnamachari, "The effect of mobility-induced location errors on geographic routing in mobile ad hoc sensor networks: analysis and improvement using mobility prediction", *Mobile Computing, IEEE Transactions on*, vol. 3, no. 3, pp. 233–245, 2004. 111

[134] Meenakshi Bansal, Rachna Rajput, and Gaurav Gupta, "Mobile ad hoc networking (manet): Routing protocol performance issues and evaluation considerations", *The Internet Society*, 1999. 124

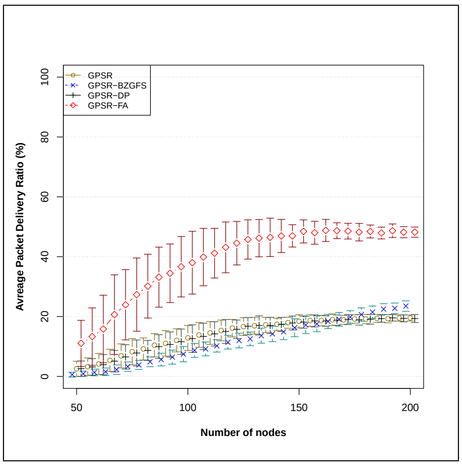
Appendices

A Low load packets

A.1 Packets delivary ratio (Figuer 4.6 and 4.14)

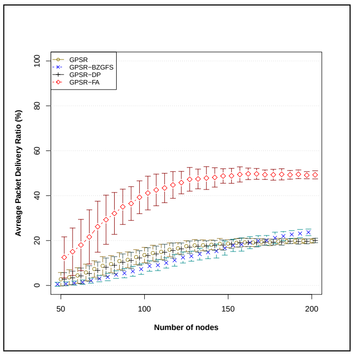


(a) Two source nodes

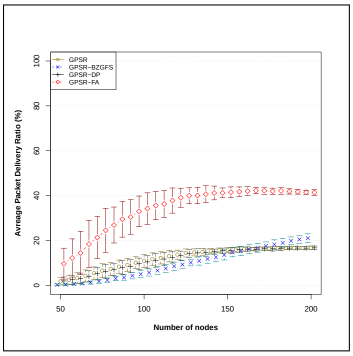


(b) Three source nodes

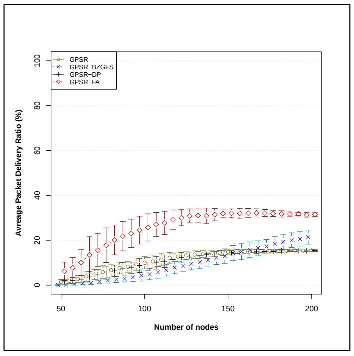
Figure A.1.1: Average packet delivery ratio using different number of source and destination nodes and low load packets/ group 1



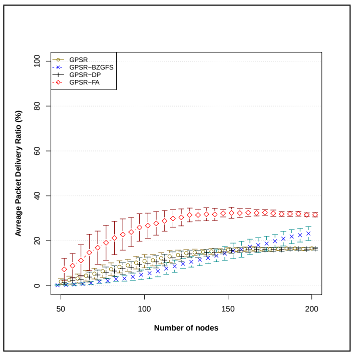
(a) Foure sources nodes



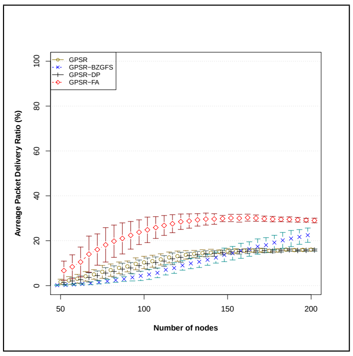
(b) six source nodes



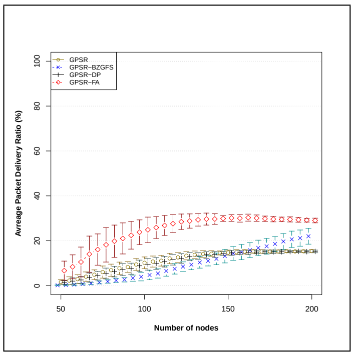
(c) 10 source nodes nodes



(d) 12 source nodes



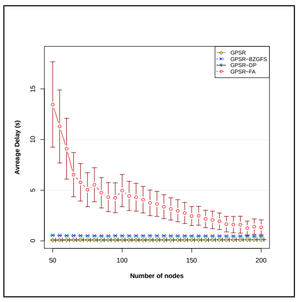
(e) 13 source nodes



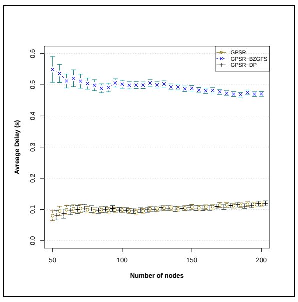
(f) 14 source nodes

Figure A.1.2: Average packet delivery ratio using different number of source and destination nodes and low load packets/ group 2

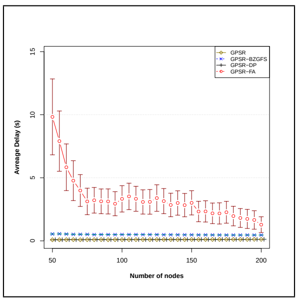
A.2 End to end delay (Figuer 4.17)



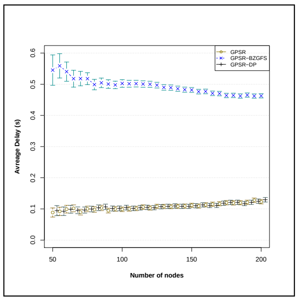
(a) Using three source nodes



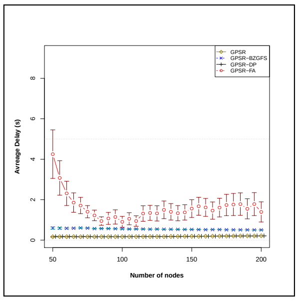
(b) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS



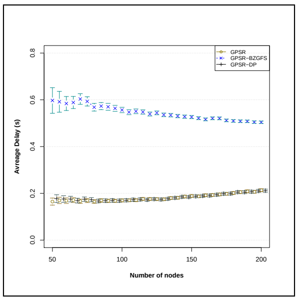
(c) Using four source nodes



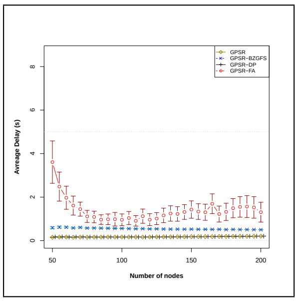
(a) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS



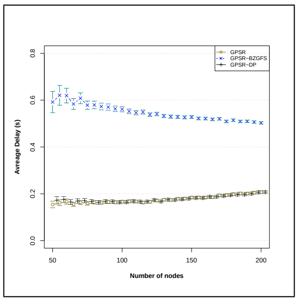
(b) Using 10 source nodes



(c) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS



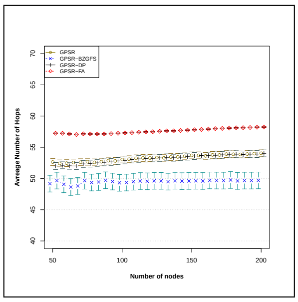
(d) Using 11 source nodes



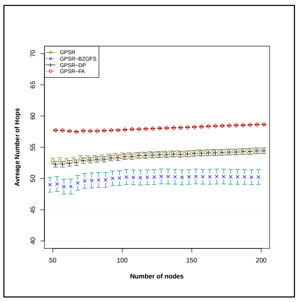
(e) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS

Figure A.2.1: Average low load packet end-to-end delay using multiple number of source and destination nodes to examine the impact of communication between station nodes

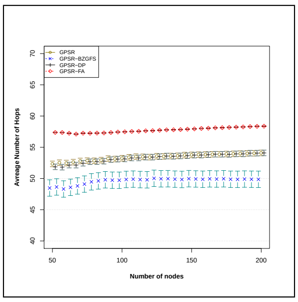
A.3 Number of hops (Figuers 4.13 and 4.20)



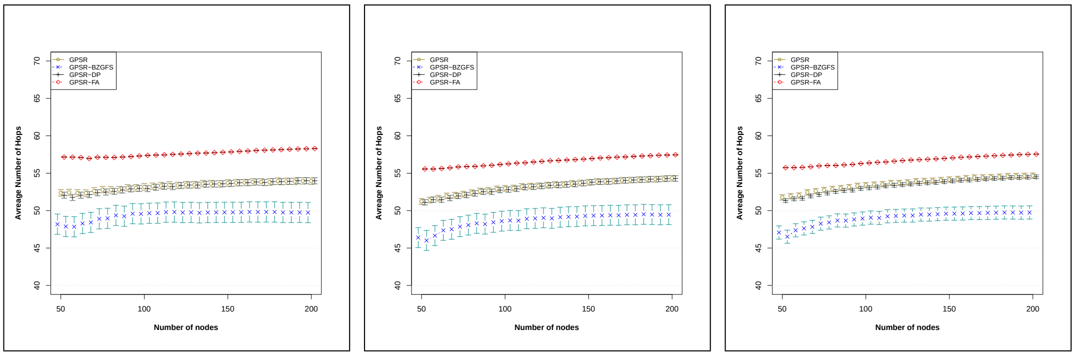
(a) Using three source nodes and one packt/s



(b) Using four source nodes and one packt/s



(c) Using five source nodes and one packt/s

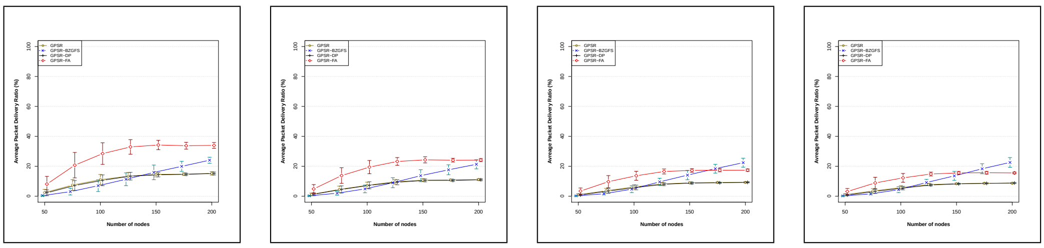


(a) Using six source nodes and one packt/s (b) Using ten source nodes and one packt/s (c) Using 11 source nodes and one packt/s

Figure A.3.1: Average number of hops using low load packets and multiple source and destination nodes

B Medium load packets

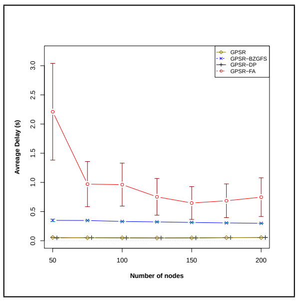
B.1 Packets delivery ratio (Figuer 4.7)



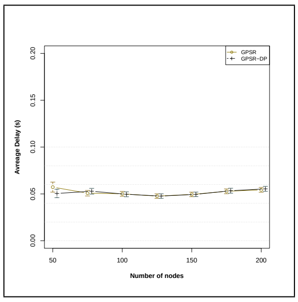
(a) Three source nodes (b) 7 sources nodes (c) 11 source nodes (d) 13 source nodes

Figure B.1.1: Average medium load packet delivery ratio using different number of source and destination

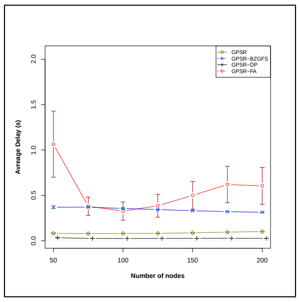
B.2 End to end delay (Figuer 4.18)



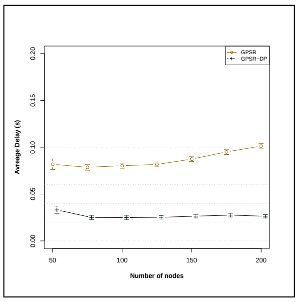
(a) Using three source node



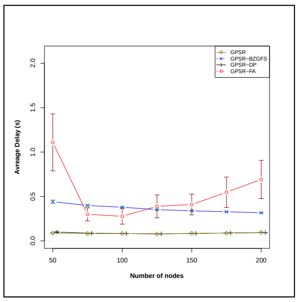
(b) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS



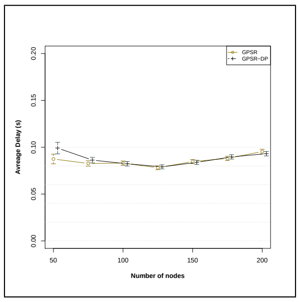
(c) Using seven source node



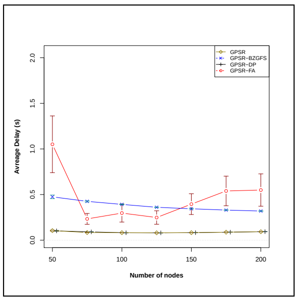
(d) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS



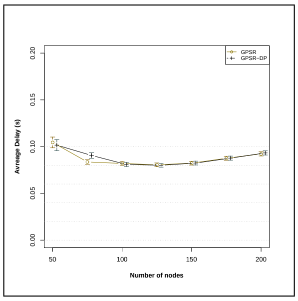
(e) Using 11 source node



(f) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS



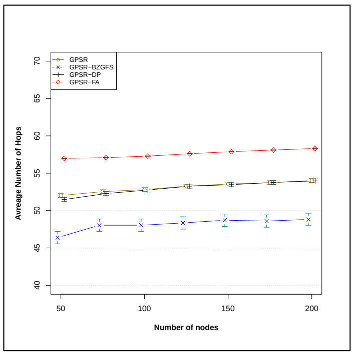
(g) Using 13 source node



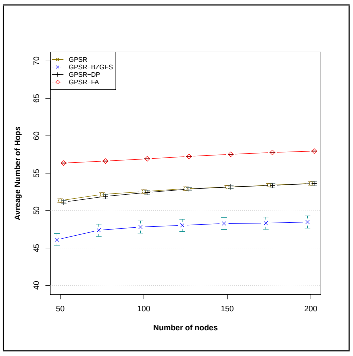
(h) A zoomed graph of GPSR,GPSR-DP and GPSR-BZGFS

Figure B.2.1: Average medium load packet end-to-end delay using multiple number of source and destination nodes

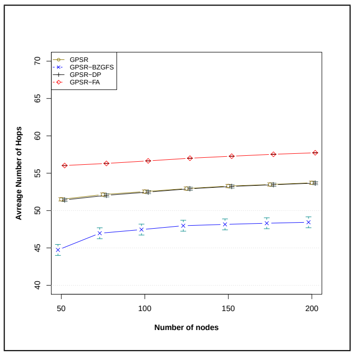
B.3 Number of hops (Figuers 4.13 and 4.20)



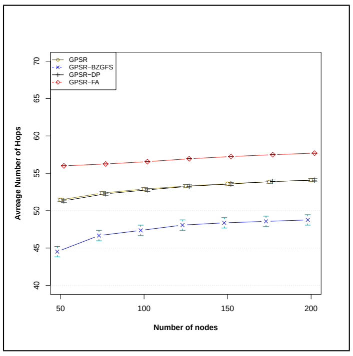
(a) Using three source nodes and one packt/s



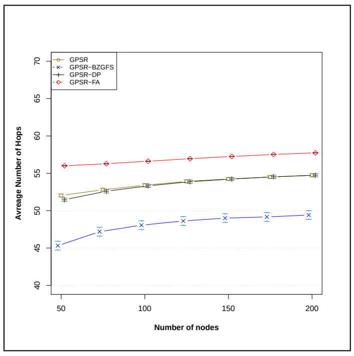
(b) Using five source nodes and one packt/s



(c) Using seven source nodes and one packt/s



(d) Using nine source nodes and one packt/s

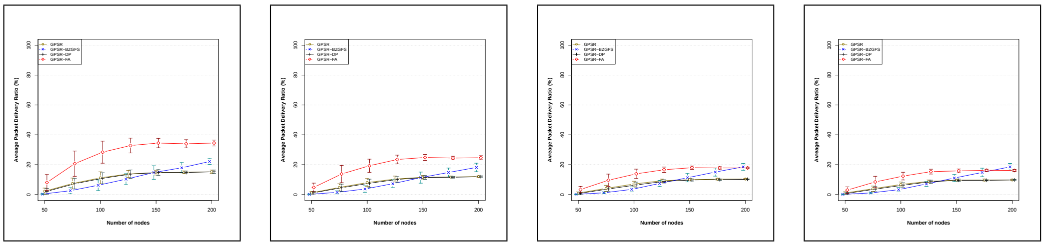


(e) Using 11 source nodes and one packt/s

Figure B.3.1: Average medium load packet number of hops using single number of source and destination nodes

C High load packets

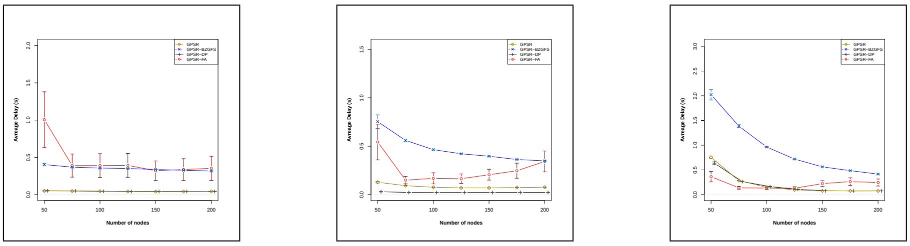
C.1 Packets delivery ratio (Figuer 4.8)



(a) 3 source node (b) 7 sources nodes (c) 11 source nodes (d) 13 source nodes

Figure C.1.1: Average high load packet delivery ratio using different number of source and destination nodes

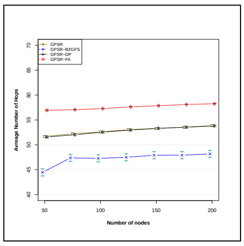
C.2 End to end delay (Figuer 4.12)



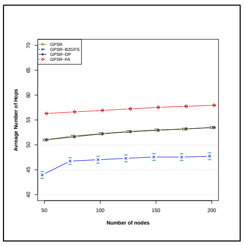
(a) three source node (b) seven sources nodes (c) 13 sources nodes

Figure C.2.1: Average delay time using different number of source and destination nodes and high load packets

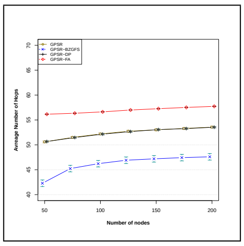
C.3 Number of hops (Figuers 4.13 and 4.20)



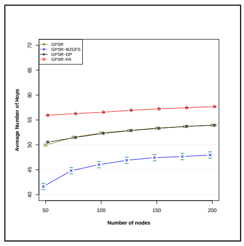
(a) Using three source node and 10 packets/s



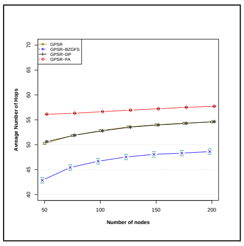
(b) Using five source node and 10 packets/s



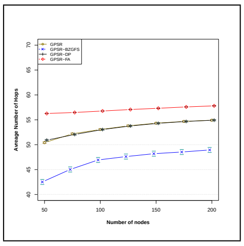
(c) Using seven source node and 10 packets/s



(d) Using nine source node and 10 packets/s



(e) Using 11 source node and 10 packets/s



(f) Using 13 source node and 10 packets/s

Figure C.3.1: Average number of hops using different number of source and destination nodes and high load packets