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Analysis and Comparison of Position-based Routing Protocols for 3D MANETs

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Abstract

Recent evolutions of Mobile Ad-hoc Networks (MANETs) have considered microaerial vehicles (drones), generalizing the topology from a 2D model to a 3D one, thus generating a 3D MANET or Drone Ad-hoc Network (DANET). Indeed, the capability of drones to fly generates a scenario where nodes are not just distributed on a plain surface. This is a very interesting and technically challenging scenario, when considering routing of messages between endpoints.

The wireless nature of the connection, node mobility and the lack of a communication infrastructure further complicates the problem of routing messages between endpoints. This problem is clearly exacerbated in a 3D scenario; yet, the presence of alternative routes that pass through non-planar multi-hop routes provides new possibilities that are not well exploited by current state-of-the-art algorithms. It is hence very interesting for the scientific community to study how routing protocols, designed for 2D scenarios, have been adapted to deal with 3D MANETs and whether there is a winner approach among existing ones.

In this context, this thesis focuses on the difficulties and the state-of-the-art of protocols on 3D routing, drawing analysis strengths and weaknesses of all the related routing protocols proposed so far (to the best of our knowledge). Moreover, a comparison of these protocols through a common scenario is performed.

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Chapter 1

Introduction

Mobile ad-hoc networks (MANETs) are networks in which mobile and autonomous terminals - in this context simply referred to as *"nodes"* - are connected by wireless links, even through multi-hop communications, capable of operating without a fixed infrastructure or centralized administration. Their high flexibility have made MANETs applicable to a wide set of scenarios including all those cases where a fixed infrastructure is not available or effective (e.g., rescue teams, operations in remote rural areas, disaster environments, underwater networking). An ad-hoc network is capable of operating autonomously and, generally, it is completely self-organizing and self-configuring. Devices that represent wireless hosts may be notebook computers, PDAs, cell phones, drones, vehicles, etc, with different memory capacity, energy capacity and computing power. The main feature of this type of networks is the frequent change of topology, caused by the uncontrolled motion of the terminals. This makes routing discovery and maintenance a very challenging task.

Recent evolutions of these networks have considered vehicles (VANETs - Vehicular ad-hoc networks) and microaerial vehicles (drones or UAVs). While the former changes the scenario by just adding an increase speed of nodes and a schematic movement through streets, the latter generalizes the topology from a 2D topology to a 3D one with a free movement scheme. This difference generates the 3D MANETs or *Drone Ad-hoc Networks* (DANETs). Indeed, the capability of drones to fly generates a scenario where nodes are not just distributed on a plain surface. This is a very interesting and technically a challenging scenario, especially when considering the routing process. On the other hand, since the current commercial popularity of drones, this is the first time we can envision a real practical employment for such 3D MANETs. Therefore, even if very little scientific literature has been devoted so far to the issues and solutions related this kind of networks, this is a trend that is going to change very soon, attracting researchers and practitioners for many years, as well as to become increasingly present in real applications.

In a MANET, the communication between two nodes occurs if and only if the distance between them is less than the minimum between the two nodes' transmission ranges. If two nodes are not directly connected, multi-hop forwarding involving intermediates nodes can be used, running a routing process. The wireless nature of the connection, the mobility of the nodes and the lack of a communication infrastructure, make the problem of routing very complex. Mobile hosts are free to move in the space, resulting in a dynamic network with potentially rapid topological changes and without notice not known *a priori*. Hence, routing information is volatile and changes in time. Moreover, the mobile hosts often use batteries which have a limited energy supply and the continuous exchange of control messages for network updates may cause a fast discharge of energy power. These issues are clearly exacerbated in a 3D scenario. Several routing protocols for ad-hoc networks have been proposed in the recent years [1, 2].

A typical categorization divides routing protocols into topology-based protocols and position-based protocols (or geographic-based protocols) [25, 34]. Position-based routing protocols use a different mechanism for path discovery, which does not need to maintain routes to destinations. These routing protocols use the geographic position information of the nodes to perform packet forwarding. The position-based approach in routing becomes practical due to the recent availability of small, inexpensive low-power *Global Position System* (GPS) receivers, and the rapidly developing software and hardware solutions for determining absolute or relative position of nodes in ad-hoc networks. Each node determines its own geographic position using a location system, such as GPS. Therefore, the routing decision at each node can be based only on the position of node itself, the destination's position (being either a physical node or geographical position where data needs to reside), and the neighbors' position. This translates into a purely local routing protocols, in which the nodes do not have to know the status of the entire network and ever have to store routing tables nor do they need to transmit control messages to keep routing tables.

A scalable routing protocol is one that performs well in a large network. Some experiments [19, 34] confirm that classic topology-based (*AODV*, *DSDV*, or *DSR*) or simply flooding-based routing protocols are not scalable. So, when considering large networks with many nodes, for instance, hundred or thousand of nodes, geographically based routing protocols, when GPS information is available, would perform better in terms of achieved data rate, routing table size and low overhead, as demonstrated in [19]. This is clearly desirable in a 3D MANETs where nodes are drones, which are nowadays more and more frequently endowed with GPS technology.

Contribution

This thesis hence focuses on the analysis and comparison of position-based routing protocols running in 3D topology networks. After describing the properties and advantages of the positions-based protocols compared to the topology-based one, a comprehensive taxonomy of routing protocols for MANETs is proposed, based on the exploitation of available literature scientific works. Then, with the support of this taxonomy, a detailed description of all considered position-based protocols is done, with their possible extensions in 3D networks.

Many routing protocols have been proposed by various researches, using different models and assumptions. Of course, not all of them are experimented in same simulation scenario/environment. Therefore, one of the main contribution of this work is to study these protocols under common assumptions and experimental grounds so as to get an objective comparison. Performance results, lead to a critical exploration of efficacy and efficiency. Classical performance metrics have been studied by varying a set of parameters, providing a comprehensive and extensive analysis of the protocols under investigation.

The contributions of this thesis are as follows:

(i) Provide a critical analysis, also through common experimental scenario, on the-state-of-the-art protocols that use geographical position for packet forwarding.

(ii) Provide to the scientific community an implementation of these protocols on a well known simulator environment, in order to make possible a study support and future contributions.

(iii) Provide additional insights on the performance of these protocols in real settings.

Organization of thesis

Chapter 2 introduces MANETs, with emphasis of the subclass of DANETs, its applications and related issues. These concepts are needed to provide some insights, motivating our work so as to recognize the potential and problems of this context.

Chapter 3 provides a complete taxonomy of all the routing protocols, with particular reference to the position-based protocols. The second part of this chapter describes and analyzes the state-of-the-art of position-based protocols.

Chapter 4 describes the simulator used for tests and the different scenarios generates for simulations.

Chapter 5 shows and analyzes the results obtained from simulations, specifying the substantial differences that exist between the protocols under dynamic parameters.

Chapter 6 contains the conclusions and possible future works.

Chapter 2

Background

This chapter gives a background on MANET, including an overview of other subclass of this type of network, specifying their possible application in real world. Moreover we discuss the problem of routing in MANETs, with emphasis on position-based routing protocols and their advantages compared to classical routing protocols. In this context, a taxonomy of this class of protocols is provided. Finally we discuss the benefits of using position-based protocols, their potential and how they can improve the routing compared to topology-based protocols.

2.1 Mobile Ad-Hoc Networks

A MANET consists of a set of mobile nodes that communicate with each other over wireless links, capable of operating without centralized control or established infrastructure. In these settings, nodes can self-organize dynamically and may themselves act as routers as well. If a node needs to send a packet to another node, the latter may not be in the transmission range of the first and then intermediate nodes may be required to collaborate in forwarding the packet from source node to destination node via *multi-hop* routing. Since mobile ad-hoc networks may change their topology frequently, routing in such networks is difficult. There are a number of situations in which ad-hoc networks are desirable, e.g., in scenarios where infrastructure is not feasible or cost-effective. They have many potential applications, ranging from environmental monitoring, disaster relief, tactical scenarios etc. Given their popularity and commercial investment, this technology will continue to have significant attention over the years to come. In this context, *Wireless Sensor Networks* (WSNs) are a class of wireless ad-hoc networks that, characterized by a distributed architecture, are realized by a set of autonomous electronic devices able to gather data from their immediate environment and communicate with each other. Wireless networks of sensors are likely to be widely deployed in the near future because they greatly extend the ability to monitor and control the physical environment from remote locations, and improve the accuracy of information obtained via collaboration among sensor nodes and online information processing at those nodes.

2.1.1 Applications of MANET

Nowadays there are many applications that use MANET technology. Ad-hoc networking can be applied anywhere where there is little or no communication infrastructure or the existing infrastructure is expensive or inconvenient to use, e.g., in places where there are emergency situations such as an earthquake or a tsunami. Ad-hoc networking, and in particular MANET, allows the devices to maintain connections to the network as well as easily adding and removing devices to and from the network. The set of applications for MANET is varied, ranging from large-scale, mobile, highly dynamic networks, to small, static networks that are constrained by power sources. Typical applications include:

- **Military applications**: military equipment contains now some sort of embedded computer. Ad-hoc networking would allow the military to take advantages of network technology to maintain an information network between soldiers, vehicles, airplanes, ships and military information headquarters. The size of military network is usually very large, because it may have to cover an entire area. This is a typical scenario in which the use of drones is taking hold.
- **Industrial production**: industrial applications can require networks for indoor environment or outdoor environment. Possible applications refer to monitoring and control of industrial equipment, processes and personnel. Routing in such an environment can become especially difficult due to obstacles and noise which can affect the sensor nodes' line of sight communication, but most of these networks is static and medium sized, as installed manually in these cases and data can be routed on pre-determined paths.
- **Home applications**: these applications refer to indoor environments. Higher bandwidth might be necessary for gaming or enternainment purposes. The size of this type of networks is usually little due to the small number of terminals and needs less energy consumption.
- **Health and medical applications**: these applications are similar to industrial applications, but are defined here to be in hospitals and clinics, so inside buildings. For tracking personnel and patients, a minimum sensor mobility is required. The size of health network is usually small and uses in-door routing. Among routing requirements of health applications are reliability, robust routing, high fault tolerance and high delivery ratio.

- **Environmental applications**: environmental applications usually refer to network nodes distributed in certain areas (crops, forests, volcanoes, sea, air, space). These networks have to be of medium to high size due to the number of events they may have to detect and track. In physical world surveillance, sensor networks can be used to track different parameters such as motion, sound, temperature, light, humidity, atmospheric pressure, etc. In emergency situation surveillance, nodes may have to track natural catastrophes, detect hazardous chemical levels, fires, floods etc. WSN is a typical network used for this scenario.

- **Automotive applications**: a new type of network was considered in the '80, based on ad-hoc networks. Networks that involve vehicles are named *Vehicular Ad-hoc Networks*. The interest of automotive applications comes from the mobility of the nodes which are embedded on vehicles and communicate through wireless technology. The size of such a networks can reach metropolitan areas and this networks are characterized by nodes that move at different speeds and any direction.

- **Commercial applications**: commercial applications refer to small indoor networks used in conferences and meetings, or to larger outdoor mesh networks or extensions to services provided by cellular infrastructure.

Industrial applications, home applications and some health and medical applications require static routing (or reduced mobility) and small to medium networks. In this thesis, a focus on techniques that exploit geographic location are done. In a building of limited geographic area, the use of geographic coordinates doesn't make sense.

2.1.2 Drone Ad-Hoc Networks

Recently, with the advent of new technologies that make it possible to miniaturize complex electronic systems, different interesting gadget, that are able to move and fly autonomously or remotely controlled by a user, were born: these are called drones or *unmanned aircraft vehicles* (UAVs). Already many years ago, drone were build, especially for war environments. Nowadays, given the rapidly growing small unmanned aircraft industry and their cost reduction, their trade has been extended also in civilian applications. Thus, drones are also used in a growing number of civil applications, such as policing and firefighting, and nonmilitary security work, but often preferred in tactical and battlefield scenarios operated without a human persence, dirty or dangerous for manned aircraft. Interesting civil applications focuses on search and rescue missions. Small-scale UAVs can be equipped with imaging sensors for aerial photography to support rescue people [20]. The use of multiple UAVs rather than one UAV plays an important role, since the limited flight time of such UAVs and the fact that search and rescue missions are time critical. Authors in [3] propose the problem of deploying a high number of low-cost, low-complexity robots inside a known environment with the objective that at least one robotic platform reaches each of N preassigned goal locations. In [23], ab ambitious project is proposed, that tries to design and build a control system of heterogeneous multi-agents, composed of human, animals and robots, working in cooperation to solve distributed tasks that require different technical, physical and cognitive skills. Therefore, this new scenarios require that those agents could communicate with each other, to exchange relevant information. These contexts have also introduced the need for a network that extends beyond the two dimensions, since the altitude is regarded as the third dimension.

2.2 The problem of routing in MANETs

In ad-hoc networks two nodes can communicate with each other (in both directions) if and only if the distance between them is less than the minimum of their transmission range. If a node is placed outside the transmission range of a node that wants to communicate with it, multi-hop routing is used through intermediate communicating nodes, to send a message from the node to another receiver node. There are various challenges in MANET such as routing, energy consumption and bandwidth optimization, but the major challenge is the link failure due to mobility, which causes topology changes rendering routing information volatile. The utility of routing mechanism makes it an integral part of any network and there exists a multitude of routing protocols (IP routing for internet, communication protocols that connect machine, robots, drones, and protocols for ad hoc networks). Different needs and characteristics of various networks present specific challenges, requiring appropriate routing techniques.

One way of communication in such networks might seem to simply flood the entire network. However, the fact that power and bandwidth are scarce resources in such networks of low powered wireless devices necessitates more efficient routing protocols. In large networks, with many nodes, the flooding method would cause many collisions due to contemporary sending of the same packet from multiple nodes and therefore an increase of the delay time of arrival of the packet to the recipient. Moreover, flooding causes buffers to fill which translates in packets being dropped when buffers full or augmented delays due to long packet queuing times. These factors classify this method as not scalable. A scalable solution is one that performs well in a large network.

Nowadays, there are a number of routing protocols proposed for MANETs to address the multi-hop routing problem. In general these protocols can be categorized in topology-based and position-based. Topology-based routing protocols use the information about the links in the network to perform packet forwarding, position-based protocols use the position information to make routing decision. Most of position-based routing protocols are widely used in 2D MANETs, but their performance on 3D MANETs is not well studied (see 2.3.2.1).

2.3 Classification of Routing Protocols

Several routing protocols have been proposed to address the routing problem in ad-hoc mobile environments. Each protocol is based on particular concepts and strategies which can be advantageous or not based on the type of network on which the protocol is tailored (network size, number of nodes, range transmission). Mauve et al. [25] and Stojmenovic [34] divide these protocols in two main categories, topology-based routing and position-based routing.

2.3.1 Topology-based protocols

Topology-based protocols consider the network topology, and employ *routing tables* that specify the best path to route a packet from a source node to a destination node. These ad-hoc routing systems communicate either topology information or queries to all nodes in the network. Two important categories that reside in this branch of protocols are: reactive and proactive. A protocol is said *proactive* when each node keeps an up-to-date information reflecting the state of the network and this information is used when a message should be sent from one node to another to create the route. A protocol is said *reactive* when the routing path is created only when necessary.

In the literature, most of the proactive protocols have been proposed in the topology-based context, in which each node holds information relating to each other node of the network. The topology-based protocols, in fact, have been primarily designed for wired networks, or that otherwise have a static structure or that can tolerate few link disruptions. For this, the protocols based on topology information derive benefits from this static (if the topology is static, the information on the network do not change). Proactive protocols can be based on *distance-vector* strategy (e.g., *Destination-Sequenced Distance-Vector*, *DSDV*) and *link-state* strategy (e.g., *Optimized Link State Routing*, *OLSR*), and constantly discover routes and maintain them in routing tables. *Hello* packets are exchanged periodically by which nodes get informed of changes in the topology.

Instead, when the routes are calculated on a per need basis, reactive protocols are used. This method presents the main disadvantage of being very slow in forming the routes, since each node in the creation of the link requires, in on-demand mode, the connection to subsequent nodes. However, it presents the advantage of incurring less overhead (due to less control packets flowing in the network), there is less risk of congestion and the nodes can manage efficiently energy consumption. *Ad-Hoc On-Demand Distance Vector* (*AODV*) and *Dynamic Source Routing* (*DSR*) are examples of reactive protocols.

2.3.1.1 Proactive approaches

This section explains some of the state-of-the-art protocols based on proactive mechanism.

Destination Sequenced Distance Vector (DSDV)
Based on the *Bellman Ford* algorithm, *DSDV* [9] is a proactive protocol that is enhanced by the use of sequence numbers in the routing tables (*Destination Sequence Number*) to avoid loop problem. In this way, the more updated paths have a higher sequence number. Each node updates its sequence number every time that it sends an update. Each node maintains a routing table with an entry for each network node. Each entry holds a sequence number, which is updated with each change, used to avoid cycles, and distinguish old routes with the new ones. Each node transmits the updates periodically or also in case of major changes. When a node receives two paths to the same node, it chooses the one with greater sequence number, or the one with lesser hops number in case of equal sequence number. To improve the overhead of network traffic, this routing protocol uses two type of update packet:

- **Full dump**: all complete routing information are sent.
- **Incremental dump**: only updates are sent.

Topology Broadcast on Reverse-Path Forwarding (TBRPF)
TBRPF [30] is another proactive protocol. It transmits only the differences between the previous network state and the current one. With this routing protocol, each node computes a *spanning tree*, formed by all shortest path to all nodes, based on partial information stored in its topology table. To reduce overhead, each node sends only part of the spanning tree to its neighbors.

Optimized Link State Routing (OLSR)
Based on *link-state* algorithm, *OLSR* [35] is a proactive protocol that tries to reduce classic flooding and then the overhead. It uses the broadcast of link state information, to allow each node the reconstruction of the network topology. But this broadcast is optimized using a system called *MultiPoint Relaying* (MPR). MPR technique tries to avoid that each node receives the same message several times, which wastes a lot of bandwidth. This situation can be improved selecting only some neighbors, called *Multi Point Relays* (MPRs). This technique is called *partial flooding* and perform well in very dense networks. Link state information is generated only by the MPR nodes. In *OLSR*, each node chooses a subset of its neighbors, such that each two-hop away neighbor is reached through this set. Messages types are:

- HELLO: sent at regular intervals, performs the detection neighbors function, MPR nodes communication and link sensing.

- TC (topology control): used to communicate topological information from the node's point of view.
- MID: used by the nodes with multiple interfaces to declare its existence to the rest of the network.

2.3.1.2 Reactive approaches

This section explains some of the state-of-the-art protocols based on reactive mechanism.

Ad-Hoc On-Demand Distance Vector (AODV)

AODV [10] is the reactive version of *DSDV*. Routes are established *on-demand*, as they are needed. An advantage of this approach is that the routing overhead is greatly reduced, but a disadvantage is a possible large delay from the moment the route is needed until the time the route is actually acquired. In *AODV*, the network is silent until a connection is needed. At that point the network node *s* that needs a connection broadcasts a request for connection, sending a *Route Request* packet (RREQ) in broadcast on the network, when a path must be found. Other nodes that receive this RREQ packet, forward it and record the node that they heard it from, updating the routing information of *s*, that is, creates or updates the temporary route to reach the source node in its routing table. This route will serve the *Route Reply* packet (RREP) to get to the source. When a node receives such a message and already has a route to the desired node, it sends a RREP packet though a temporary route to the requesting node. The needy node then begins using the route that has the least number of hops through other nodes. Unused entries in the routing tables are recycled after a time. When a link fails, a routing error is passed back to a transmitting node sending a *Route Error* packet (RERR), and the process repeats. Much of the complexity of the protocol is to lower the number of messages to conserve the capacity of the network. For example, each request for a route has a sequence number. Nodes use this sequence number so that they do not repeat route requests that they have already passed on. Another such feature is that the route requests have a "*time to live*" number that limits how many times they can be retransmitted. Another such feature is that if a route request fails, another route request may not be sent until twice as much time has passed as the timeout of the previous route request. The advantage of *AODV* is that it creates no extra traffic for communication along existing links. Also, distance vector routing is simple, and doesn't require much memory or calculation. However *AODV* requires more time to establish a connection, and the initial communication to establish a route is heavier than some other approaches.

Dynamic Source Routing

DSR is similar to *AODV*, but it uses source routing instead of relying the routing table at each intermediate node. The source node *s* sends a RREQ packet, which contains source address, destination address, request id and path. If a host saw the packet before, discards it. Otherwise, the route looks up its route caches to look for a route to destination. If it is not find, appends its address into the packet and rebroadcast it. If a node finds a route in its route cache or is the destination, sends a RREP packet, which is sent to the source by route cache or the route discovery in RREQ packet.

2.3.2 Position-based protocols

Due to changes in topology of mobile environment, the maintenance of routing tables require an excessive overhead for update network topology information: the network information must be constantly updated, and this creates an overhead due to the exchange of control messages. Furthermore, in large networks there are more exchanges of control messages and routing tables size become very high. For this reason, topology-based routing protocols become almost useless in more dynamic and large networks.

Position-based (or *geographic*) routing protocols, use the position of the nodes in the network to make the forwarding decisions. This position-based approach is introduced to eliminate some of the limitations of the topology-based protocols in MANETs. These methods limit the bandwidth required by topology-based routing, because they do not need to establish and maintains routes, thereby eliminating routing table constructions and maintenance. The first proposed protocols that use geographic information were intended to act as a support to the topology-based protocols. For example, one of the early proposed protocol was *Location Aided Routing* (*LAR*), based on *DSR*, but limits the propagation of route request packets to a limited geographic region, as seen in Fig. 2.1, where it is most probable for the destination to be located in. In this case, location information is not used for packet forwarding decision, but it is only used to limit the propagation area. Over time, many protocols that exploit the position only for the forwarding decision, have been proposed. This thesis will refer to protocols that use position information only for the forwarding decision. An overview of position-based routing protocols and location services can be found e.g. in [25] and [34].

Position-based routing protocols are local, because a node forwards the message based only on its position, the position of the destination and the position of its neighbors to which it can communicate directly. Therefore, these protocols do not require a global knowledge of the network, but they rely on having only a piece of information (the nodes' physical location information)[1]. To use such protocols, it is necessary for nodes to obtain their coordinates either by using a *location service* such as GPS (*Global Positioning System*) or other types of position services. The position of a node associates with a neighbor is provided from several mechanism of control messages (beaconing or request messages). Positional information becomes less current as that neighbor moves and the accuracy of its position in neighbor table decreases;

[1]This is not always true. As will be seen later, some protocols use other information to make decisions, but its complexity is $O(1)$, therefore it is reasonable to also classify these protocols as local.

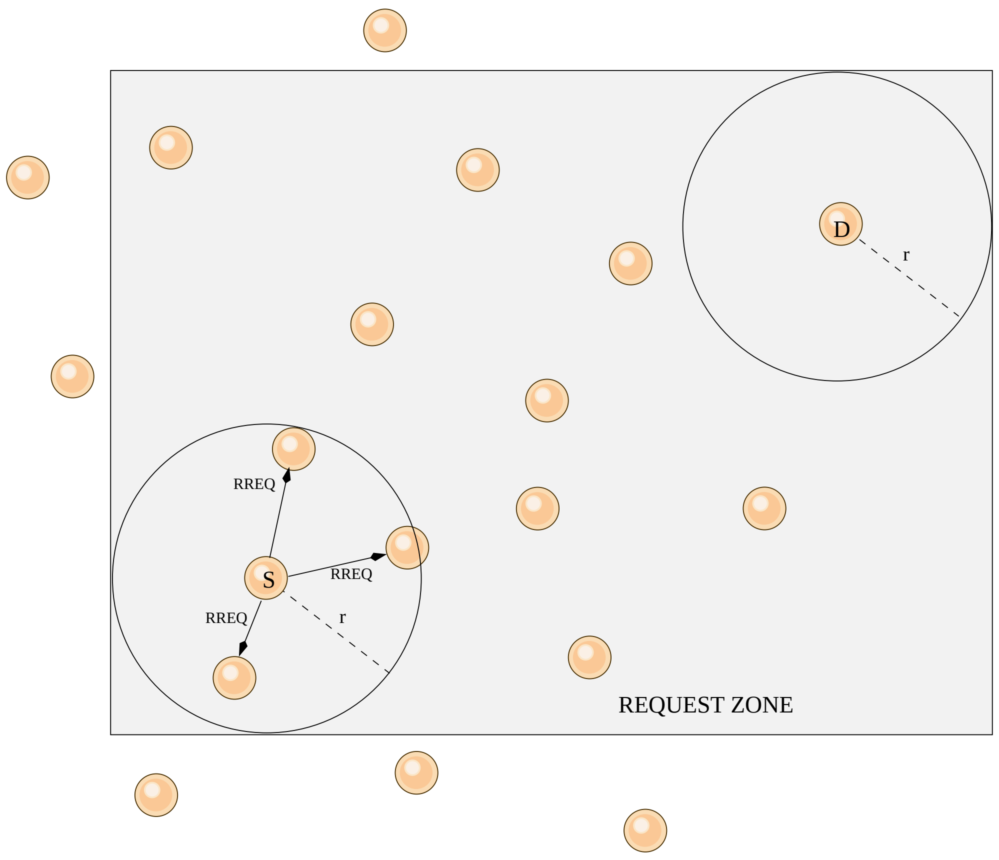


Figure 2.1: *LAR* protocol used with *AODV* or *DSR* protocols, to route a packet from S to D. Node S sends request packets to all neighbors' nodes inside the square box (called REQUEST ZONE), limiting flooding forwarding.

old neighbors may leave and new neighbors may enter radio range. In other words, neighbor tables can become inconsistent and do not reflect the current state of the network. For these reasons, the correct choice of beaconing interval to keep nodes' neighbor tables current depends on the rate of mobility in the network and range of nodes' radios. This problem, although not beyond the scope of this thesis, is treated in chapter 3, section 3.2.

In general, position-based routing protocols have the following characteristics:

- Each node can determine its position (longitude, latitude and altitude) obtained through a GPS receiver, or another such mechanism.
- Each node can determine the position of its neighbors (usually 1 hop) by using a location service (for example a set of short request position messages, or a beaconing system).
- Nodes do not need routing tables to make the forwarding decisions. Each node

only stores the information about its neighbors (position, speed, direction, etc) in a *neighbor table*.

- The routing decision at each hop can be made based on the location of the current node, its neighbors' nodes and the destination node.

There are some solutions that require nodes to memorize routes or past traffic, making these protocols not well scalable. These solutions are sensitive to node queue size, changes in node activity, and node mobility while routing is ongoing. It is better to avoid memorizing past traffic at any node if possible. However, the need to memorize past traffic is not necessarily a demand for significant new resources in the network for two reason:

- A lot of memory space is available on tiny chips.
- The store of past traffic can be deleted after a certain period of time, when the routing process is done.

So, the memory usage may be justified in order to improve the performance of some protocols. An example of routing protocol that use memory is *Depth First Search*.

2.3.2.1 Routing problem in 3D networks

Position-based routing, unlike topology-based routing, is scalable to a large number of networks nodes and is efficient when nodes move frequently, because it no need to keep routing tables up-to-date and no need to maintain a global updated view of the entire network topology. Establishment and maintenance of routes are not required, reducing packet overhead, energy and memory capacity considerably. From this feature, MANET, in particular, derive the best advantage, as these networks are composed by hosts with limited power energy and limited memory. For 2D networks, a lot of research has been done about the problem of position-based routing; however, in real scenarios, nodes may be distributed in 3D space and the extension of 2D routing protocols into 3D protocols is not trivial. Topology-based routing protocols are not sensitive to the addition of the third dimension because they rely on a link-state system knowledge. Instead, position-based protocols are based on the spatial position. In a three-dimensional space some assumptions made in 2D, such as the ability to extract planar subgraphs, break down. Durocher *et al.* [32] shows the impossibility of routing protocols that guarantee delivery in three-dimensional ad-hoc networks, when nodes are constrained to have information only about their k-hop neighborhood, in contrast to the two-dimensional case, where a protocol that uses 1-local algorithm, such as face routing (see section 3.3.3), guarantees delivery. This leads the problem of finding other solutions that can guarantee the delivery of packets, with the least use of resources. Some works have proposed several algorithms that try to achieve a higher delivery rate, with a smaller number of node involved. This thesis takes these and compares them in a fits-all simulation, to obtaining their performance.

2.3.2.2 Taxonomy

Position-based routing protocols can be divided in two main types of packet-forwarding strategies:

- **Single-path forwarding**: with single path strategy, an algorithm forwards the packet in every step to one of its neighbors. Algorithms that uses single path strategies may be even more robust and with less communication overhead.
- **Multi-path forwarding**: in this strategy the current node forwards the packet to all or part of its neighbors. Flooding can be costly in terms of wasted bandwidth, because packet become duplicated in the network. Moreover, duplicate packets may circulate forever in loop, unless certain precaution.

Single path forwarding algorithms consider another subdivision based on the type of geometric or mathematical concepts used for forwarding decision:

- **Deterministic progress-based**: with deterministic progress based routing algorithms, the current node (the node holding the packet) forwards the packet at every step to one of its neighbors that make progress to the destination.
- **Randomized progress-based**: this strategy is similar to deterministic progress-based method but in this case the next node is chosen uniformly at random or according to a probability distribution, from the set of neighbor nodes or candidate nodes.
- **Face-based** it is a strategy that allows to arrive at a delivery-rate close to 100% in some cases. In the context of a two-dimensional space, face-based algorithms allows progress between the faces defined by the nodes considering the right-hand rule, with which always guarantee reaching the destination. In the three-dimensional space, the concept of "*face*" can not be extended, but some approaches have been proposed that are based mainly on the projection of points in a plane.

2.3.2.3 Advantages of position-based routing

Position-based routing algorithms are born initially to deal with the requirement of using less resources. The reasoning behind the position-based algorithms is the following: if it is possible know the location of the destination and the neighboring

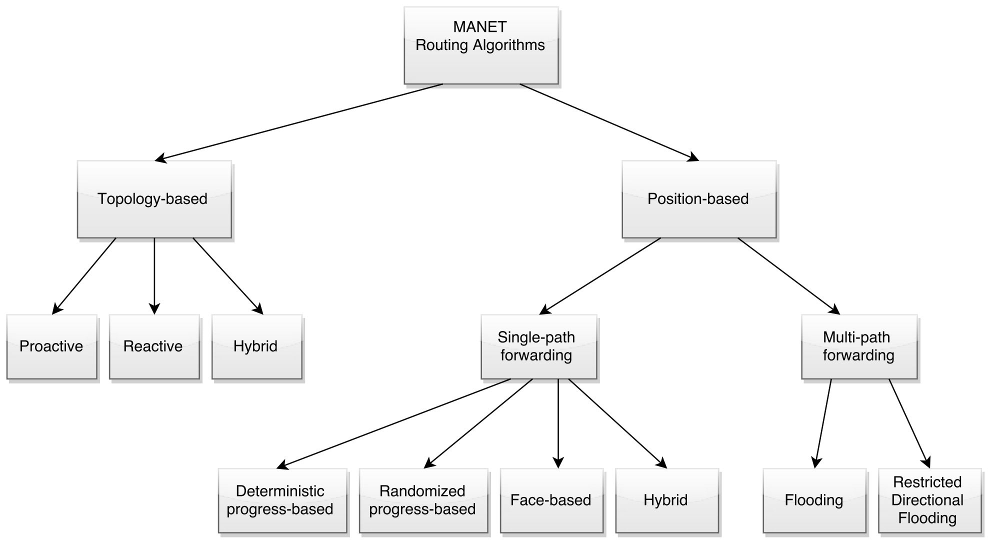


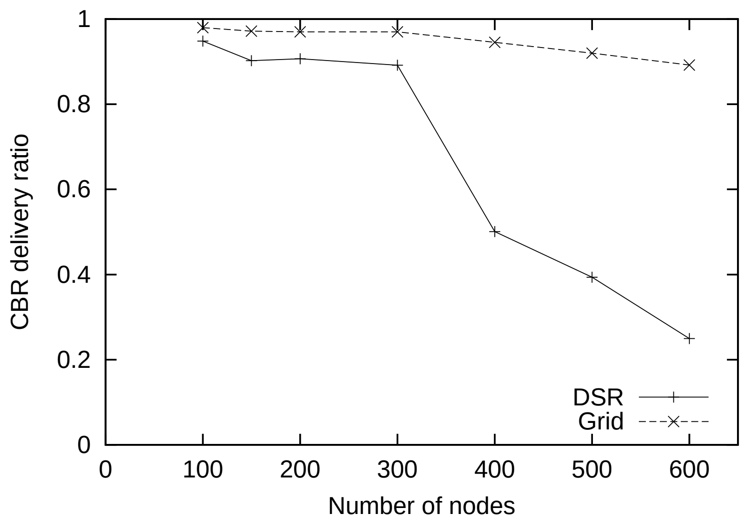
Figure 2.2: Taxonomy of routing algorithms

nodes, then we can eliminate all the work for the route search and the current node may send the packet directly to its neighbors which are located "towards" the destination node.

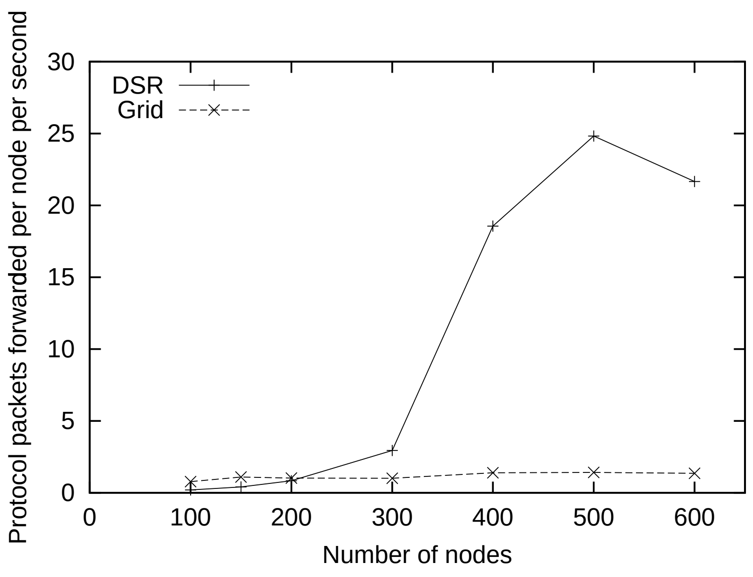
This section aims to provide an explanation of which are the metrics that provide a clear gap between the performance of the two routing strategies (positions-based and topology-based) and then the reasons why the position-based perform well in specific context. Stojmenovic [34] says that routing protocols that do not use geographic location in the routing decisions, such as *AODV*, *DSDV*, or *DSR* are not scalable. Furthermore, because of high mobility of the nodes in MANETs, the route update may be more frequent than the route requests and some of bandwidth is wasted due to most of the routing information is never uses. Reactive protocols (e.g., *AODV*) reduce number of broadcasts by establishing routes on demand basis and does not maintain the whole routing information of all nodes in the network, but need to use flooding to propagate route request packets (RREQ) in the entire network. If the number of nodes is very high and the communication requests are very frequent, the flooding mechanism becomes unsustainable. But on the other hand the use of flooding is necessary to ensure reaching the destination node. This means that topology-based protocols are not scalable, due to the effects on broadcast storm problem, while it is likely that only position-based approaches provide satisfactory performance for large networks.

In [19] an experiment compares a geographic forwarding algorithm, called *Grid* (similar to *Greedy*, described in 3.3.1) with *DSR* protocol. *Grid* uses *GLS* (*Scalable Location Service*), a distributed location service that tracks mobile node locations. Experiments, using the *ns* simulator for up to 600 mobile nodes, show that the storage and bandwidth requirements of *GLS* grow slowly with the size of the network. Comparing *Grid* with *DSR*, in a simulation with nodes that move with a maximum speed of 10 m/s, [19] obtains two pictures: Fig. 2.3a, that show the fraction data packets that are successfully delivered in simulations for increasing number of nodes, and Fig. 2.3b, that shows the number of two protocols packets forwarded per node per second as a function of the total number of nodes.

In Fig. 2.3a most of the data packets that *Grid* fails to deliver are due to *GLS* query failures; once *Grid* finds the location of a destination, data losses are unlikely, since geographic forwarding adapts well to the motion of intermediate nodes. Below 400 nodes, most of the *DSR* losses are due to broken source routes, but at 400 nodes and above, losses are mainly due to flooding-induces congestion. So, *Grid* does a better job than *DSR*, especially in large networks. Fig. 2.3b counts only protocol packets (route request, route reply, hello, etc.). *DSR* produces less control overhead for small networks, but at 400 nodes and above, suffers from network congestion and almost half of the route reply and cache reply messages are dropped due to congestion which causes new insertions of even more route requests into the network. Also, the source route is vulnerable to failure. *Grid* produces less overhead for large networks, because only local exchange of position information, through small packets, occurs.



(a)



(b)

Figure 2.3: Performance comparison of *DSR* and *Grid* routing protocols. Pictures taken from [19]

Chapter 3

Routing in 3D Networks

This chapter describes the current state-of-the-art of position-based protocols and their *modus-operandi*. The overview starts by discussing single-path forwarding strategy algorithms, introducing the necessary terminology and concepts needed to better comprehend multi-path approaches. These two strategies perform differently, in terms of delivery rate and path dilation.

3.1 Notation and Preliminaries

3.1.1 General Model

In the following we will use this conventions and notations:

- A model of MANET is represented, in R^2 and R^3 spaces, by a geometric graph $G = (V, E)$, consisting of a finite set $V = v_1, v_2, ..., v_{\mathrm{N}}$ of nodes and a subset E of cartesian product $V \times V$, the elements called edges (links from a node to another). Fig. 3.1 shows two model of graphs, that represent two examples of networks.

- All nodes have the same communication range r, which is represented as a disc in 2D space and as a sphere in 3D space. The graphs thus obtained is called *Unit Disk Graph*, $UDG(V, r)$ and *Unit Ball Graph*, $UBG(V, r)$ respectively. An example of *Unit Disk Graph* is represented in Fig. 3.2

- We define $dist(u, v)$ as the distance between two nodes u and v, given by the formula of the Euclidean distance:

$$dist(u, v) = \sqrt{(u_x - v_x)^2 + (u_y - v_y)^2 + (u_z - v_z)^2}$$

- Two nodes are said to be neighboring and connected by a link if the Euclidean distance is at most r:

$$u \text{ is neighboring of } v \text{ if } dist(u, v) \leq r$$

- For a node u, we define the set of its neighbors as $N(c)$
- A path from a node s to a node d is a sequence of nodes $s = v_1, v_2, ..., v_\mathrm{k} = d$, such that v_i and $v_{\mathrm{i}+1}$, $1 \leq k - 1$, are neighbors.

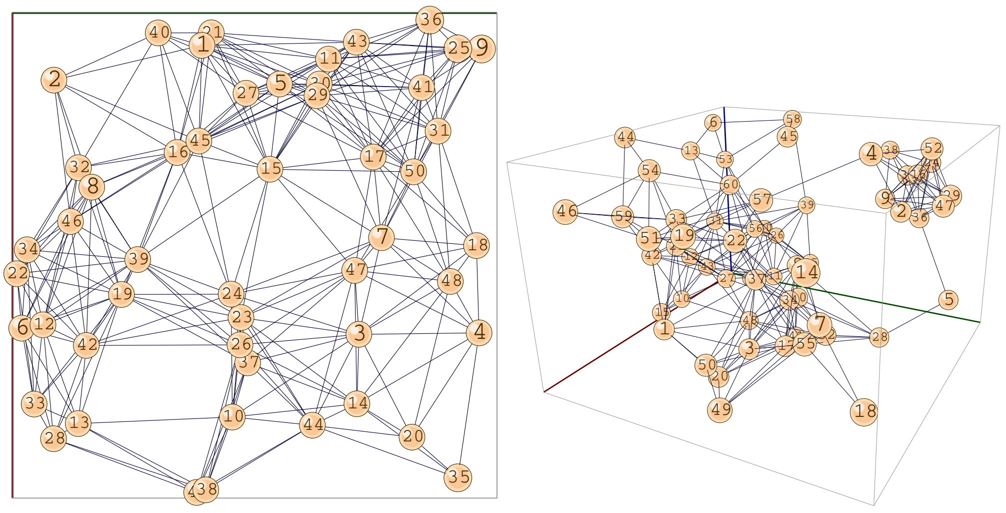

(a) **(b)**

Figure 3.1: Two graphs of nodes that represent two wireless networks. Lines are wireless links that connect each pair of nodes. Figure (a) is a 2D network, figure (b) is a 3D network.

3.1.2 Terminology

In order to provide a uniform and fair treatment of all algorithms, a common terminology to define uniform concepts is introduced.

- The *source node* is the node that sends the packet, and *destination node* is the node that receives the packet. They are called respectively s and d.
- The *current node* is the node that applies the algorithm at a given time and that has in its memory the package to be forwarded, and is called c.
- The *previous node* is the node that sent the packet to c in the previous step, and is called $prev$.

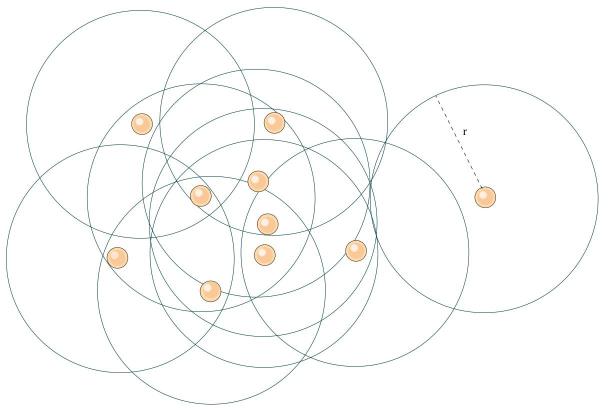


Figure 3.2: Every node has a disk around itself, which represents the coverage area of its transmission range. Every node that is located inside this disk, can communicate directly to the done to which the disk belongs

- The *neighborhood* of the current node c is the set of all nodes connected directly to c, called $N(c)$. The size of $N(c)$ is indicated with n.
- The disk centered at node c with radius r is called $disk(u, r)$ and covers the transmission area of c in two-dimensional space.
- The sphere centered at node c with radius r is called $ball(u, r)$ and covers the transmission area of c in three-dimensional space.

3.1.3 Metrics

In this thesis we are interested in the following performance metrics for routing protocols.

- **Delivery Rate**: delivery rate is the ratio of the number of packets received by the destination (or destinations) to the number of packets sent by the source (or sources). The first goal that a routing algorithm must achieve is get a guaranteed delivery rate. Unfortunately many algorithms based on heuristic techniques fail to reach a delivery rate of 100%.

$$DeliveryRate\% = \frac{NumberDataPacketReceived}{NumberDataPacketSent} * 100$$

- **Path Dilation**: path dilation is the ratio of the number of hops traversed by the package during execution of the algorithm to the length of shortest path. The secondary goal, but not the least important, is to get a path dilation close as possible to 1, that is, the routing algorithm must travel a path of length as close as possible to the length of the shortest path.

$$PathDilation = \frac{HopsRoutedByAlgorithm}{MinimumPathLength}$$

- **Delivery Time**: in this work, the delivery time is defined as the time spent from when the package arrives from the MAC layer of the source node to the delivery of the same packet at the recipient node. This metric can be traced back to the number of hops paths, but, as in this thesis we evaluate real-world scenarios, we need an index of time. Sometimes, the delivery time is proportional to the path dilation.

$$DeliveryTime = time(PacketDelivered) - time(GetPacketFromMAC)$$

The above metrics are analyzed by dynamic parameters such as the number of nodes in the network, the value of threshold, and others, to evaluate the behavior of the algorithms.

3.2 Neighborhood Discovery

In position-based routing protocols, each node must know the location of all its neighbors. There are several techniques for acquiring this information, based on a periodic beacon exchange (proactive approach) or location request messages (reactive approach). This chapter aims to provide an overview of the techniques of the neighborhood discovery. One of these techniques is in fact incorporated in the implemented routing protocols of this thesis, in order to bring simulations to a more real context, that is without the ideal situation that the nodes know a priori their neighbors.

With a periodic beacon exchange, *beaconing* method, each node sends in broadcast a small packet, called "*beacon*" that contains its identity, position and other information (e.g., its speed and direction). Neighbor nodes receiving this beacon and store location information in their *neighbor-table.* This is a proactive approach and is totally independent of the data traffic. With the location request message the node that holds a packet and has to forward it, sends in broadcast a *request message* that contains its identify. The neighbor nodes that receive the request message from a node, reply with an hello packet that contains location information and its identify, and send it to the requester node. This is a reactive approach and depends of the data traffic.

3.2.1 Beaconing

The problem of neighborhood discovery can be identified when the network nodes move. If a periodic beacon between nodes is started, the speed of nodes can affect the correctness of position information. Inaccurate or out-dated neighborhood information may severely affect position-based routing protocols. If a periodic beaconing is used, there are three different situations that can occur when nodes moves:

1. Nodes are listed in the neighbor table with an inaccurate position, but are still accessible.
2. A node moves within the transmission range of another node, but was not visible before (because it had not received the beacon). So, routing makes a not great decision, since it does not know that there is a new node maybe as good.
3. A node moves out of transmission range of another node. So, the routing has still that node in its neighbor table and may send a message to it, but the MAC layer is unable to reach the node. After some retransmission, the MAC layer drops the message or notify that it was not able to send and send back the packet. Then, the routing protocol selects a different next hop and sends back the packet to the MAC layer. This re-routing has three consequences:
   - Delay grows.
   - Effective bandwidth decreases.
   - Battery discharges.

In addition to the incorrect position information, the beaconing system has other problems, as the unnecessary use of network resources and the interference with data traffic. In [24], authors analyze the impact of inaccurate and out-dated neighbor information on the performance of the network for position-based routing, and propose some solutions that can solve these problems. They explain that no research has investigated this problem, which could become important for the effectiveness and efficiency of position-based routing.

3.2.1.1 Beaconing Strategies

To improve the accuracy of the beaconing, several strategies are proposed:

- Time-based beacon: each node sends a beacon periodically (every t seconds).
- Distance-based beacon: each node sends a beacon only when it is moved of d meters from its original last sending position.
- Speed-based: the frequency of the beacons is proportional to the speed of the nodes.

In [24] simulations are carried to see the effectiveness of these beaconing strategies varying the beacon period B, depending on the time, on the distance and on the speed of nodes. Clearly, the use of beaconing is closer to a more realistic scenario, where nodes do not know a priori their neighbors. This assumption leads to the conclusion that the delivery rate can be reduced, compared to the ideal case. This fact is then confirmed by conducted tests.

3.2.2 Location Request Message

Location Request Message technique is a reactive approach for neighborhood knowledge. In [24] this method is cited only as *fully reactive* and it is not explored in detail. Only when a node receives a data packet and must send it, before sends a request packet in broadcast, that reaches all its neighbors. These last node, receiving the request message, forward to the requester an hello packet providing their id, their position data and other information (e.g., speed). The requester node, on receiving these hello packets from all its neighbors, can choose the next node to forward the data packet. Note that the requester node is not able to know when it has received the hello message from all the neighbors (it does not know the size of its neighborhood). For this reason a timer, called $timerSend$, that the applicant must wait before sending the data packet. This timer allows hello messages to arrive in time to the requester node before forwarding.

If there is a consistent flow of packets in the network, this method may result in an exponential increase of control messages (request messages and hello messages) since, for every single packet, a location request message is sent. Moreover, if more data packets arrive immediately after the first data packet in the same node, a repeated position request is redundant, as the neighborhood has not changed and the position, most likely, are slightly different. The solution to this problems uses another timer and a boolean variable, and is described in the following:

- Each node owns a boolean variable $haveToRequest$ initialized to $true$.
- Each node owns a timer $timerRequest$ that, when expires, performs $haveToRequest = true$.
- Before transmitting a data packet, a node checks the $haveToRequest$ variable: if $haveToRequest$ is $true$, the node sends a broadcast beacon request, starts the $timerToRequest$ and perform $haveToRequest = false$; then, attends the $timerSend$ before sending the data packet. If $haveToRequest$ is $false$ sends immediately the data packet.

This method avoids sending too many requests for location when many data packets arrive at a node in a very small time, causing too much traffic control. If other packets arrive at the node while a packet is already waiting to send, these are put in a queue; when $timerSend$ expires, all of the packets in the queue are sent in the order to arrival. Duration of all the timers in this technique can be chosen depending on various factors, as the speed of nodes. The method described above is implemented in the work of this thesis, to simulate a complete real position-based routing protocol, and obtaining a more real performance results.

3.3 Single-path Forwarding Algorithms

Single path algorithms forward the packet in each step to only one of node's neighbors. This class of algorithms has the property that only a single copy of a packet is present in the entire network at all time. This strategy reduces the chance of collision of packets, compared to flooding strategy. This group can be divided into three types of algorithms:

- Deterministic Progress-based algorithms
- Randomized Progress-based algorithms
- Face-based algorithms

3.3.1 Deterministic Progress-based Algorithms

The notion of *progress* is the key concept of several GPS based methods proposed in 1984-86. Originally, given a transmitting node c, the progress of a node u was defined as the projection onto the line connecting c and the destination d of the distance between c and the receiving node u. This first definition is now considered as *Most Forward Routing* (discussed in the following).

Deterministic progress-based algorithms are defined here as follows. The current node c (the node holding the packet) forwards the packet at every step to one of its neighbors that makes progress to the destination. The progress depends on the forwarding strategy chosen (e.g., the node nearest to the destination) and almost all the strategies described later try to send the package in the general direction of the destination node. A neighbor is in *forward direction* if the progress is positive; otherwise it is said to be in *backward direction*. Examples of those strategies are *Greedy* [13], *Compass* [12] and *MFR* [16].

Greedy

With greedy forwarding strategy, the current node c forwards the packet to the neighbor node u that minimizes the distance to the destination node d, $min\{dist(u_1, d), ..., dist(u_n, d)\}$. Note that, in greedy method, c's distance does not compare against the distances of its neighbors. There are two forwarding algorithms that use greedy strategy, and differ on which neighbors consider on the choice.

- *Greedy* [13]: the current node c forwards a packet to one of its neighbors that is closer to d than c and any other neighbors of c.
- *GEDIR* [18]: the current node c forwards a packet to one of its neighbors that is closer to d than any other neighbors of c, not necessarily closer to d than node c itself.

This routing method is a *loop-free* algorithms, and [18] proof the following theorem:

Theorem 1. *Routing algorithms in wireless networks in which nodes forward the message to several neighbors closest to the destination or with the most forward progress (i.e., the MFR and GEDIR algorithms and their enhancements, e.g., flooding and 2-hop routing) are inherently loop-free.*

In *GEDIR*, all neighbors are considered. So, also the nodes that are in backward direction can be chosen and the only kind of loop that may be formed using this algorithm is the local loop between c and the node $prev$ that sent the message to c in the previous step [18], but this case is avoided by the assumption mentioned follow. If the next node for forwarding is the node that sent message to c, it means that the packet has reached a local minimum c and then the algorithm fails. An example of pseudo code of *GEDIR* algorithm is written in Algorithm 1. Instead, in *Greedy*, only the neighbors that are closer to the destination than c are considered. If no one is closer to d, algorithm fails. An example of pseudo code of *Greedy* algorithm is written in Algorithm 2. Fig. 3.3 shows an example of choosing of next node using *Greedy*. The current node c has five nodes that are in the direction of destination node d, but the node that is closer to the destination is 2 (see the dotted line). With *GEDIR*, in some cases, the node on which the algorithm fails can not be the true local minimum: for example, in the same figure, if node 3 is removed, node 2 selects node 7 as the next (farther from destination, but this is allowed by the *GEDIR* definition). Node 7 finds that its next node to be closer to the destination is still the node 2, but here the algorithm fails. Node 7 become the local minimum, but node 2 is the node closest to the destination. In this thesis we refer to *Greedy* algorithm and specify when we consider *GEDIR*.

Algorithm 1 One step of *GEDIR* algorithm

```
1: procedure GEDIR($c, d, prev, N(c)$)
2:     $next \leftarrow u_i : min\{dist(u_i, d), 0 \leq i < n\}$
3:     if $next = prev$ then
4:         return $fail$
5:     end if
6:     return $next$
7: end procedure
```

Algorithm 2 One step of *Greedy* algorithm

```
1: procedure GREEDY($c, d, N(c)$)
2:     $next \leftarrow u_i : min\{dist(u_i, d) : dist(u_i, d) < dist(c, d), 0 \leq i < n\}$
3:     if $next = NULL$ then
4:         return $fail$
5:     end if
6:     return $next$
7: end procedure
```

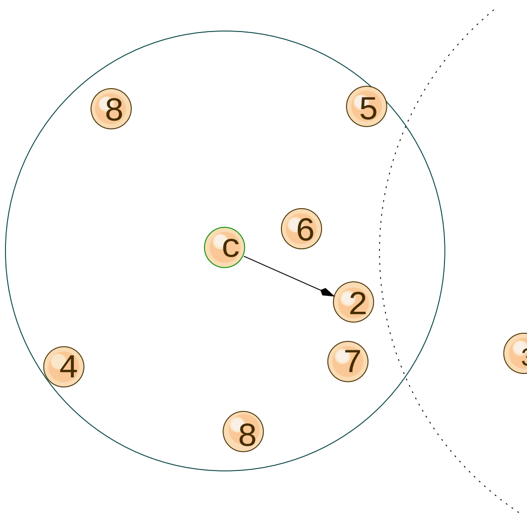


Figure 3.3: A step of *Greedy* algorithm, based on distance between neighbor nodes and destination node.

Compass

With *Compass* forwarding algorithm [12] (or *Directional algorithm, DIR*), the current node c uses the location information of d to calculate its direction. Then, forwards the packet to the neighbor node u such that the direction cu is closest to the direction cd, that is the neighbor node u that minimizes the angle between u, c and the destination node d, $min\{\angle u_1cd, ..., \angle u_ncd\}$. In Fig. 3.4 node c chooses node 6 as the next node, since the angle $\angle 6cd$ is the smallest among all. *Compass* is a not a loop-free algorithm and [18] proof the following theorem:

Theorem 2. *Any memoryless routing algorithms in ad-hoc wireless networks in which a node currently holding the message forwards it to its neighbors with the closest direction toward the destination (and to some other nodes) is a not loop-free algorithm.*

This theorem is proven by an example of a loop that consists of four nodes, show in Fig. 3.5. There are four nodes, 1, 2, 3, 4, and nodes 3 and 4 are not connected (because they are outside their own transmission range). Node 1 receives a packet from node c and selects node 3 to forward the message because the direction of 3 is closer to destination d than the direction of its other neighbor 2. Similarly, node 3 selects 2 (source node 1 is not considered), node 2 selects 4, and node 4 selects 1. The travel continues with this loop. If a loop occurred, the nodes on the loop are not able to recognize the loop unless packet id is memorized (for each forwarded packet). So, with a memoryless *Compass* routing algorithm, a local minimum can not be recognized. Algorithm 3 shows the pseudo code of *Compass*.

Algorithm 3 One step of *Compass* algorithm

```
1: procedure COMPASS($c, d, N(c)$)
2:     $next \leftarrow u_i : min\{angle(u_icd), 0 \leq i < n\}$
3:     return $next$
4: end procedure
```

Most Forward

Most Forward, a.k.a *MFR* forwarding algorithm [16] is very similar to *Greedy*, but, in this case, the current node c forwards the packet to the neighbor node whose projection on the line between the current node c and the destination d is closer to d, $min\{d(u'_1, d), ..., dist(u'_n, d)\}$. If the packet reaches a local minimum, the algorithm fails. In most cases *MFR* choose the same path of *Greedy*. In Fig. 3.6 an example of this strategy is shows. Node c selects node 5 as next node, since the latter has the smallest projected distance to d, on the line sd. *Most Forward* is a *loop-free* algorithm, and Theorem 1 refers also to this. A pseudo code of *Most Forward* is shown in Algorithm 4.

Ellipsoid

In *Ellipsoid* forwarding algorithm [22], the current node c forwards the packet to the

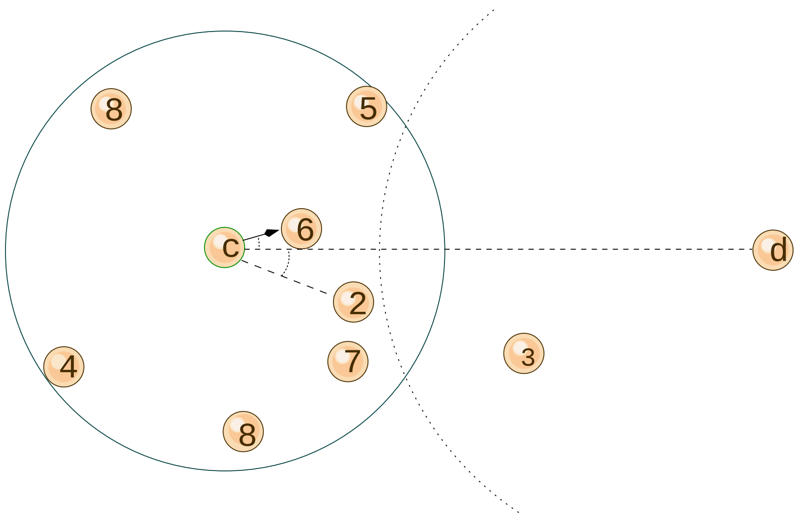


Figure 3.4: A step of *Compass* strategy, based on angle formed by current node, neighbor nodes and destination node.

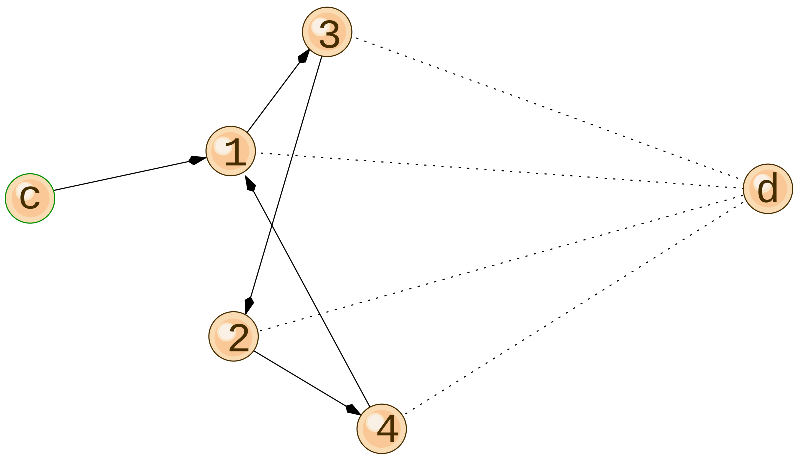


Figure 3.5: A loop with *Compass*.

neighbor node u that minimizes the sum of the distance from node c to u and the distance from node u and the destination node d, $min\{dist(u_1, c)+dist(u_1, d), ..., dist(u_n, c)+d(u_n, d)\}$. If the packet reaches a local minimum, the algorithm fails. In Fig. 3.7 there is an example. A pseudo code example of *Ellipsoid* is shown in Algorithm 5.

3.3.1.1 3D extension for deterministic progress-based algorithms

The extension of these algorithms in 3D networks, proposed in [15], is relatively simple, as we need only the definition of the Euclidean distance between two points u and v in three dimensions and the definition of the sphere with center c and radius r.

Algorithm 4 One step of *Most Forward* algorithm

```
1: procedure MFR($c, d, N(c)$)
2:     $next \leftarrow u_i : min\{dist(u_i^{CD}, d), 0 \leq i < n\}$
3:     return $next$
4: end procedure
```

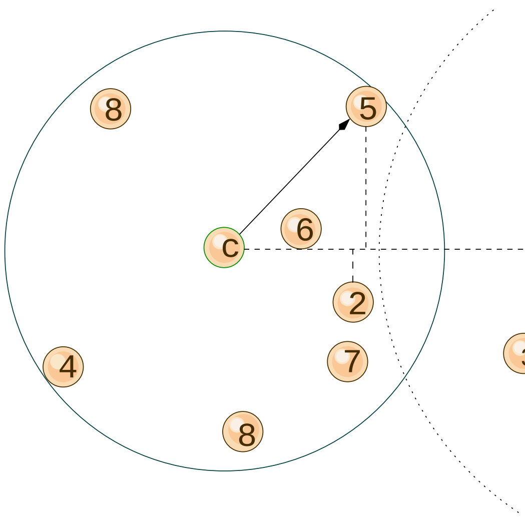


Figure 3.6: A step of *Most Forward* strategy, based on projected distance between neighbor nodes and destination node.

Algorithm 5 One step of *Ellipsoid* algorithm

```
1: procedure ELLIPSOID($c, d, N(c)$)
2:     $next \leftarrow u_i : min\{dist(u_i, c) + dist(u_i, d), 0 \leq i < n\}$
3:     return $next$
4: end procedure
```

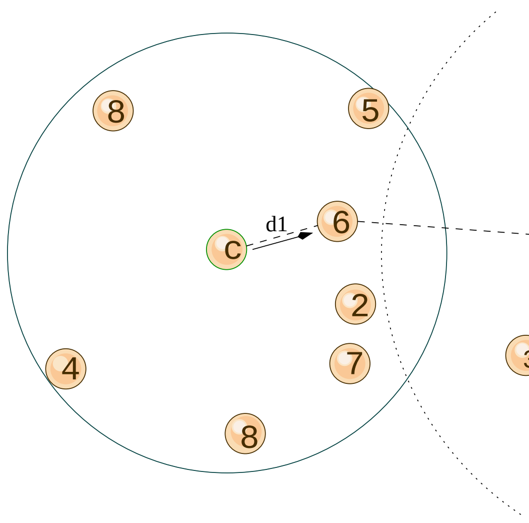


Figure 3.7: A step of *Ellipsoid* strategy, based on sum of distance between each neighbor node and destination node and distance between the same neighbor node and current node.

3.3.1.2 The local minimum problem

Progress-based routing strategy is subject to the problem called *local minimum*, in which a packet may fail to reach the recipient because it is stuck in a node, called local minimum, that has no neighbor that make progress to the destination, even if the source and destination are connected in the network. If a local minimum node is reached, the algorithm fails and the packet can not be delivered to the destination node. If network is sparse, all algorithms that uses progress-based strategy have a low delivery rate, due to the local minimum phenomenon. These characteristic are seen in Chapter 5, where the delivery rate test results are show. For this reason, these algorithms are only used in very dense graphs, because there are low probability to found local minima, and as stages in other more sophisticated algorithms. Fig. 3.8 describe an example of a failure state with *Greedy* and *GEDIR*. In this example, node 6 sends the packet to node 1 using greedy forwarding. If *Greedy* is used, node 1 does not have any neighbor that is closer to destination *d* than itself, and *Greedy* fails. From node 1, *GEDIR* selects node 6 as next node, but node 1 has received the packet from node 6 and, for the above assumption, *GEDIR* fails. However, the figure shows that a valid path (blue path) from node 1 and node *d* exists.

Depth First Search

In [17], authors propose to use *depth first search* (DFS) method for routing decision. *DFS* algorithm performs DFS search in a given graph in distributed way, using a progress-based forwarding strategy. The property of DFS is that it creates a path in the graph without making any jumps from a node to another node that is not it's

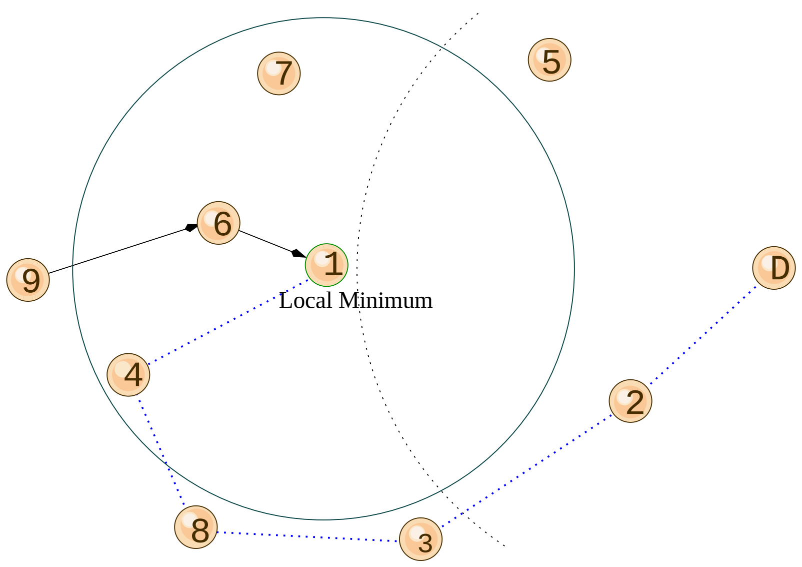


Figure 3.8: A local minima example executing *Greedy* and *GEDIR* algorithms

neighbor. This property allows DFS to be used in a local routing protocol.

The basic mechanism of DFS search is described in the following. Initially, all nodes are "colored" as white. A node is colored as white when it is not yet visited by DFS search. The sender node s colors itself as gray and starts visiting its first neighbor node. Gray nodes are nodes that are visited. Each white node visited for the first time changes its color to gray, and visit its first white neighbor node. If DFS returns in a gray node, this node selects another white neighbor. If there is no choice (all neighbor nodes are gray), DFS returns in the node which came the first visit, and here another white node is selected. The process stops when it returns to the sender node s or find a target node d.

The *DFS* forwarding algorithm defined in [17] follows this mechanism. Each node has a list in its local memory that contains id of packets received. If a packet arrives in a node, its id is stored in this list. If a packet id is not found in local memory of a node, for this packet, white color of this node is assumed; otherwise, if the packet id is present, the node is gray (that is it received packet at least once). The process of visiting nodes coincides with sending packets between nodes. If a node receives a packet for the first time, it memorizes also the node that forwarded that packet. So, each node store a list of tuple $id, from$, where id is the packet id, $from$ is the node from which the packet arrived.

The source node s starts *DFS* coloring itself as gray and storing id packet in its list (the $from$ field is empty). Each DFS packet has one bit that indicates whether the message is forwarded or returned. When a node c receives a packet for the first time, add a tuple $(id, from)$ into its memory, and orders its neighbors according to distance

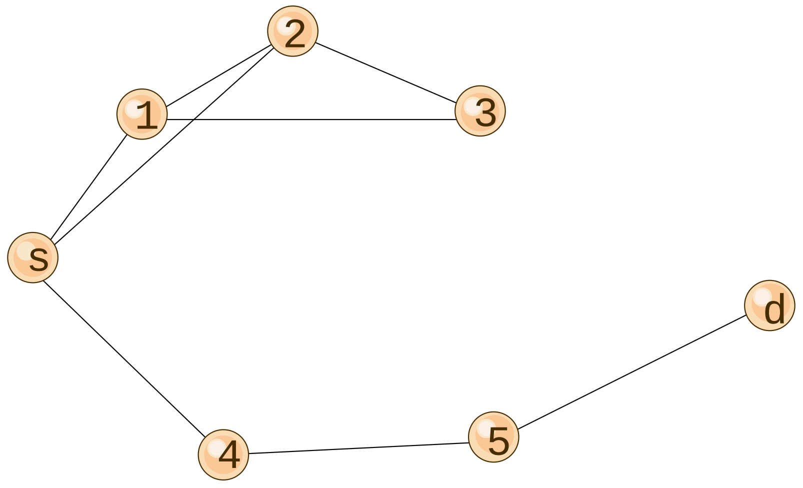


Figure 3.9: Path performed by *DFS*. The node sequence is $s - 2 - 3 - 1 - 2 - 1 - s - 1 - 3 - 2 - 1 - 2 - s - 1 - s - 4 - 5 - d$.

from destination d (this is the greedy method). The only node not to be taken into account in the ordered list is node $from$ that sent the packet to c. The packet is then forwarded to the first choice u among neighbors (the first node chosen is the node that is closest to the destination). If there is no choice, the packet is returned to $from$.

A gray node c, upon receiving forwarded packet from any node b, will reject the packet immediately, returning it to b (returned message). A gray node b, upon receiving a returned message from node c, will forward the message to the next choice e in its sorted list of neighbors, if such a neighbor exists. If b has no more neighbors in its list, the packet will be returned to the node $from$ which sent the message for the first time to b (memorized in packets list). To know which is the next node in the ordered list to send the packet, an index L is used. L is the index, in the list, of the last neighbor u selected for packet forwarding. When a new node has to be chosen, L is increased. The pseudo code of *DFS* can be given in Algorithm 6.

DFS has one drawback: there are some situations in which the algorithm visit few nodes many times, forming a sort of limited loop. Fig. 3.9 shows an example of this case. The path performed by *DFS* is shown in the following (the arrows with f and r represents respectively a forwarded packet sending and a returned packet sending).

$$s \xrightarrow{f} 2 \xrightarrow{f} 3 \xrightarrow{f} 1 \xrightarrow{f} 2 \xrightarrow{r} 1 \xrightarrow{f} s \xrightarrow{r} 1 \xrightarrow{r} 3 \xrightarrow{r} 2 \xrightarrow{f} 1 \xrightarrow{r} 2 \xrightarrow{r} s \xrightarrow{f} 1 \xrightarrow{r} s \xrightarrow{f} 4 \xrightarrow{f} 5 \xrightarrow{f} d$$

This basic *DFS* method can be improved in several ways. For example, an improvement could be to memorize all the neighbor that sent a forwarded packet which was then reject, in order to not choose them for next forwarding. However, this addition increases the memory requirements.

Algorithm 6 One step of DFS algorithm

```
1: procedure DFS($c, d, from, N(c)$)
2:     if $c$ is source node then
3:         $L \leftarrow 0$
4:         add in packet list entry $< id, -, L >$
5:     else
6:         if forwarded packet then
7:             if $id$ packet is present in packet list then
8:                 set a returned packet
9:                 $next \leftarrow from$
10:                return $next$
11:            else                                        ▷ packet arrived for the first time
12:                $L \leftarrow 0$
13:                add in packet list entry $< id, from, L >$
14:                sort $N(c)$ (expcept $from$) according to distance from $d$ as
     $u_0, u_1, ..., u_k - 1$
15:                if $L < k$ then
16:                    set a forward packet
17:                    $next \leftarrow u_L$
18:                    $L++$
19:                    return $next$
20:                else
21:                    set a returned packet
22:                    $next \leftarrow from$
23:                    return $next$
24:                end if
25:            end if
26:        else                                            ▷ returned packet
27:            sort $N(c)$ (expcept $from$) according to distance from $d$ as $u_0, u_1, ..., u_k - 1$
28:            if $L < k$ then
29:                set a forward packet
30:                $next \leftarrow u_L$
31:                $L++$
32:                return $next$
33:            else if $c$ is source node then
34:                return$fail$                          ▷ source node is not connected to $d$
35:            else
36:                set a returned packet
37:                $next \leftarrow from$
38:                return $next$
39:            end if
40:        end if
41:    end if
42: end procedure
```

3.3.2 Randomized Progress-based Algorithms

Randomized-based forwarding algorithm, also called *Random Walk* algorithms, try to solve the local minimum problem described in previous section, by choosing the next node randomly from a subset of the current node's neighbors that makes progress to the destination. Already since 1984, some authors have tried to put the concepts of randomization algorithms in order to avoid the emergence of loops: authors of [29] study the case where a packet destined towards a destination node d in the network are routed with equal probability towards one immediate neighboring node that lies in the general direction of d; in [27] authors present examples of several situations where *Greedy* and *Compass* algorithms fail, and then propose the *Randomized Compass Routing*; in [36] authors propose several variations of greedy and compass heuristics with using randomization, combining them in various way. Routing algorithms that use randomization are usually considered to fail when the number of hops in the path computed so far exceeds a *threshold* value. The choice of this value is important because determines the probability of reaching the destination and length of the path traveled by algorithm: if *threshold* valued is little, the chances of reaching the destination are few, if is great, the chances are many, but with a very large number of hops. A typical value for the *threshold* is the number of nodes in the network graph, or multiple of them. Performance of randomized algorithms, in terms of delivery rate, are much better than deterministic algorithms in general, but they are worse in terms of path dilation.

Random Compass

Random Compass is a first randomized algorithm proposed in [27]. In this method the current node c choose a neighboring node, called $ccw(c)$, that minimizes the angle $\angle dc\{ccw(c)\}$, and a neighboring node, called $cw(c)$, that minimizes the angle $\angle\{cw(c)cd\}$. ccw and cw refer respectively to *counterclockwise* and *clockwise*, that are the respective directions of searching from line cd.

In [37] authors propose a set of randomized routing algorithms that uses various methods. In this context, the most significant algorithms are considered in the following.

RCompass

In *RCompass* algorithm, d selects one neighbor u_1 of c above the line cd such that $\angle dcu_1$ is the smallest angle among all such neighbors, and one neighbor u_2 of c below the line cd such that $\angle u_2cd$ is the smallest angle among all such neighbors. Then it choose the next node u uniformly at random from u_1 and u_2.

WeightedRCompass

WeightedRCompass algorithm selects u_1 and u_2 in the same way described in *RCompass*, but the next node u is chosen from u_1 and u_2 with probability $\theta_2(\theta_1+\theta_2)$ and $\theta_1(\theta_1+\theta_2)$, respectively.

Best2Compass

With *Best2Compass* algorithm u_1 and u_2 are selected in such a way that $\angle dcu_1$ (or $\angle u_1cd$) and $\angle dcu_2$ (or $\angle u_2cd$) are the two smallest such angles among all neighbors of c. This method is different from *RCompass* in that the directions of the smallest angles are not considered.

Best2Greedy

Best2Greedy algorithm selects u_1 and u_2 in such a way that they are the closest and the second closest neighbors of c to the destination d.

3.3.2.1 3D extension of randomized algorithms

Extension of randomized algorithm is not trivial, because it is not obvious to choose the best way to determine candidate neighbors. The reason is that in a three-dimensional graph there is no concept of above and below a line passing from source to destination. So, directly using of some algorithms, as *RCompass* or *WeightedRCompass*, that use a line sd for reference, is not possible. Therefore, in [4] authors propose an extension for the algorithms seen above, called by them *AB algorithms* (Above/Below), from 2D to 3D, that uses the concept of 3D planes. This new algorithm is called *AB3D*.

AB3D

AB3D is a randomized routing algorithms that uses three parameters for make forwarding decisions. The first parameter is m, that indicates the number of possible candidates, and can be 3 or 5. The second is R that is one of CM (as *Compass*), GR (as *Greedy*) or MF (as *Most Forward*) and represent the strategy for choosing candidate nodes. Similarly, the symbol S represents the probability weighting when randomly choosing between more than one candidate neighbors and it is one of U, A or D.

If the symbol S is U, then the next node is chosen uniformly at random from n_i, that is with probability:

$$P_U(n_i) = \frac{1}{m}.$$

If the symbol S is D then the next node is chosen from n_i with probability:

$$P_D(n_i) = \frac{1 - p_i}{p_0 + ... + p_{\text{m-1}}}, \text{ where } p_i = dist_i = dist(n_i, d).$$

If the symbol S is A then the next node is chosen from n_i with probability:

$$P_A(n_i) = \frac{1 - p_i}{p_0 + ... + p_{\text{m-1}}}, \text{ where } p_i = \theta_i = \angle n_i cd.$$

The steps of the algorithm are the following. The current node c selects a node n_1 from its neighbors, chosen according to the method defined in R (CM, GR or MF). Define the plane PL_1 identified by the three nodes s, d and n_1. If m is 5, define also

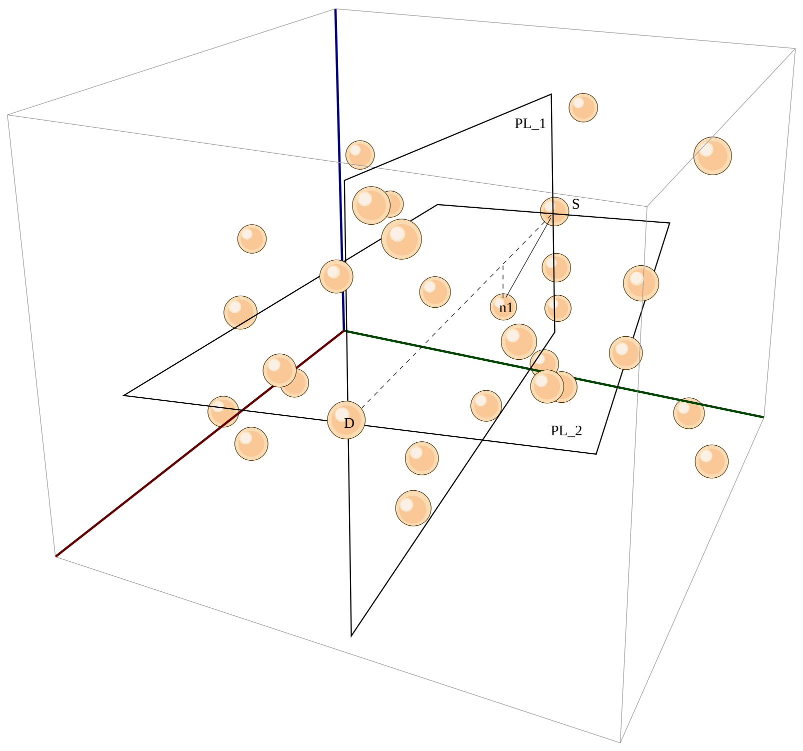


Figure 3.10: In AB3D, plane PL_1 passes through s, d and n_1, plane PL_2 is orthogonal to PL_1. Both planes contain the line sd.

the plane PL_2 that is perpendicular to PL_1 and passes through c and d, such that the intersection line between the two planes is the line cd. Fig. 3.10 shows an example of network graph and its subdivision with the two planes. Then, if the parameter m is 3, *AB3D* select another two nodes, in addition to n_1. One neighbor n_2 is chosen from the above of the plane PL_1 according to R and one neighbor n_3 is chosen from the below of the plane PL_1 according to R. If m is 5, in addition to n_1, the algorithm choose from $N(c)$ four neighbors n_2, n_3, n_4, n_5 each one in one side of the four regions that result from the intersection between PL_1 and PL_2. Once these candidates are determined, node c selects one of these nodes randomly, according to the probability weighting determined by S, and forwards the packet to the chosen node.

3.3.2.2 Unification of randomized algorithm - Random Walk

The algorithms seen above have a common mechanism: they choose m neighboring nodes that satisfy a certain requirement and then one node is chosen among these according to a certain probability (uniform or weighted). In this work, all these algorithms are generalized in a single algorithm, called *Random Walk* (*RW*) and that accepts some parameters. Abdallah et al. in [4] and [5] calls this generic algorithm

AB, but does not include all the variants described in [37] (e.g. *Best2Compass* and *Best2Greedy* can't be defined by *AB3D* algorithm), then here a more general algorithm that encompasses all and adds other variants is defined. Note that in *RW*, and obviously in previous randomized algorithms, the greedy method does not maintain the status of its failure condition, because it must be able to allow to go back, selecting also nodes that have backward progress (*GEDIR* algorithm is used to choose the candidate nodes in *RW*). If the deterministic termination condition would be present, randomization would not make sense. The pseudo code of *RW* can be given in Algorithm 7.

Random Walk
Random Walk (*RW*) algorithm has four attributes, that are:

- m: are possible candidate neighbors to choose from $N(c)$.
- R: is the name of progress-base algorithm used to choose the m candidates, and it is one of R (Random), CM (Compass), GR (Greedy) or MF (most Forward), as in *AB3D*.
- S: is used to represent the probability weighting when randomly choosing, and it is one of U (Uniform), D (Distance) , A (Angle), PD (Projection Distance). Probability weightings are defined as in *AB3D*.
- ab (above-below): is a boolean flag indicating whether to define the candidates over and below the Plane PL_1 (or even over and below the plane PL_2, if $m = 5$), or select candidates without considering the planes.

In the papers that propose randomized-based algorithms there is no explicit indication of whether the previous node *prev*, the node that sent the packet at the previous step, is chosen again by the current node c in the next step. Some tests show that the performance of *RW* improve when the previous node is not included in the candidates list. So, our implementation of *RW* assumes that the previous node *prev* is not considered (of course it is considered as the only neighbor of c).

In the simulations of this thesis, only this algorithm with different parameters is performed. In table 3.1, *RW* is associated with most of the algorithms defined in [4, 5, 27, 37].

3.3.3 Face-based algorithms

Face, a.k.a, *Perimeter* forwarding method has been proposed first time in [12] and optimized in [26]. This method is a typical planar graph technique which involves walking adjacent faces using the *right-hand rule* and it is the first geographic routing algorithm that guarantee a delivery rate of 100% in 2D network graphs. Position information can be used to extract a *planar subgraph* that is a graph that contains

Algorithm 7 One step of *Random Walk* algorithm

```
procedure RW($c, d, p, N(c), m, R, S, ab$)
    if $ab = YES$ then
        $sum_p \leftarrow 0$
        for $i \leftarrow 0$ to $n$ do
            $n_i \leftarrow R(c, d, N(c))$
            $N(c) \leftarrow N(c) \setminus n_i$
            $p_i \leftarrow S(n_i, c, d)$
            $sum_p \leftarrow sum_p + p_i$
            if $N(c)$ is empty then
                break
            end if
        end for
        $next$ ←choose one of $n_i$ with probability equal $(1 - p_i)/sum_p$
    else                                                        ▷ ab = NO
        if $m = 3$ then
            $n_1 \leftarrow R(c, d, N(c))$
            $c$ computes the plane $Pln_1$
            $above$ ← all the nodes above $Pln_1$ from $N(c)$
            $below$ ← all the nodes below $Pln_1$ from $N(c)$
            $n_2 \leftarrow R(c, d, above)$
            $n_3 \leftarrow R(c, d, below)$
            $sum_p \leftarrow 0$
            for $i \leftarrow 1$ to 3 do
                $p_i \leftarrow S(n_i, c, d)$
                $sum_p \leftarrow sum_p + p_i$
            end for
        else if $m = 5$ then
            $c$ computes the plane $Pln_2$ ortogonal to plane $Pln_1$
            $above_o$ ← all the nodes above $Pln_1$ and above $Pln_2$ from $N(c)$
            $above_e$ ← all the nodes above $Pln_1$ and below $Pln_2$ from $N(c)$
            $below_o$ ← all the nodes below $Pln_1$ and above $Pln_2$ from $N(c)$
            $below_e$ ← all the nodes below $Pln_1$ and below $Pln_2$ from $N(c)$
            $n_2 \leftarrow R(c, d, above_o)$
            $n_3 \leftarrow R(c, d, above_e)$
            $n_4 \leftarrow R(c, d, below_o)$
            $n_5 \leftarrow R(c, d, below_e)$
            $sum_p \leftarrow 0$
            for $i \leftarrow 1$ to 5 do
                $p_i \leftarrow S(n_i, c, d)$
                $sum_p \leftarrow sum_p + p_i$
            end for
        end if
        $next$ ←choose one of $n_i$ with probability equal $(1 - p_i)/sum_p$
    end if
    return $next$
end procedure
```

Table 3.1: List of randomized algorithm and their attribute values in *RW*.

Name	**Attribute values in RW**
RCompass (2D)	RW(3, CM, U, ab = YES)
WeightedRCompass (2D)	RW(3, CM, A, = YES)
Best2Compass (2D)	RW(3, CM, U, ab = NO)
Best2Greedy (2D)	RW(3, GR, U, ab = NO)
AB3D(R, S)	RW(3, R, S, ab = YES)
AB3D(m, R, S)	RW(m, R, S, ab = YES)

faces whose corners are the terminal node. So that routing can be performed on the faces of this subgraph. This type of algorithms suffers from the problem of a high traffic. Some alternatives that seek to hybridize this algorithm with the first progress-based algorithms seen so far, such as *Greedy*, have been proposed. These hybrids sacrifice a bit of the delivery rate for the reduction of traffic. For example *GFG (Greedy-Face-Greedy)*, also called *Greedy Perimeter Stateless Routing (GPSR)* (in [7], with little enhancements), is an hybrid algorithm that start from greedy approach until the packet find a local minimum, then it change and switch to *Face* algorithm, until to find a node closer to that in which one was blocked, and then return to greedy. *GFG* is described in 3.3.4.

3.3.3.1 Connected Planar Sub-graph

Face algorithm work by finding a connected planar sub-graph of *UDG* and then applying routing algorithm for planar graph on this sub-graph. In this section we describe a distributed algorithm for extracting a connected planar sub-graph from *UDG*, called *Gabriel Graph* (*GG*)[1]. Each node can run this algorithm and the only information needed is the position of each of its neighbors. Let $disk(u, v)$ be the disk with diameter $dist(u, v)$. Then, the *Gabriel graph GG* of a graph G, denoted by $GG(G)$ is a geometric graph in which the edge (u, v) is present if and only if $disk(u, v)$ contains no other points of G. Then a *Gabriel Graph* does not contains two edge that crosses, and [21] demonstrates that if we apply this algorithm to each vertex of G then the resulting graph is connected. Fig. 3.11 show an example of graph planarization.

Face

In [26], two algorithm that make routing are proposed, *Face1* and *Face2*. In this work, only *Face2* algorithm is considered, that is more optimized than *Face1*. *Face2* algorithm starts by extracting the *GG* sub-graph from *UDG*. Then the packet are routed over the faces of *GG*, which are intersected by the line between the source

[1] Another sub-graph of G is *Relative Neighbourhood Graph* ($RNG(G)$), in which each node u keeps its outgoing edge uv if circles with centers u and v and radii $|uv|$ contains no other node than v. In this thesis the *RNG* will not be considered

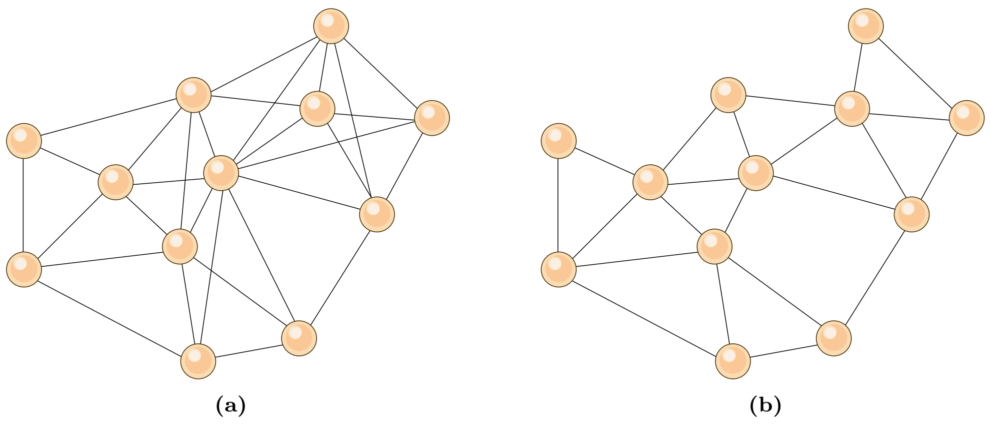


Figure 3.11: Planarization of a graph (a) to extract the *GG* sub-graph (b).

and the destination, sd, using the right-hand rule. The boundary of current face f is traversed in the counterclockwise direction, unless the current edge crosses sd at an intersection point p. At this point, the algorithm switches to the next face sharing the edge (that contains the previously intersection point) and continues with the right-hand rule. This process is repeated until the packet arrives to the destination. In Fig. 3.12), an example of *Face2* behavior are shown. Node x uses right hand rule to forward packet to node 5, then to node 9. At this point, for right hand rule, the next node should be 2, but link between 9 and 2 crosses the line xd, and the same happens with nodes 8 and 3. So, the next node is 4. In Algorithm 8 the pseudo code of *Face2* is reported.

Algorithm 8 *Face2* algorithm

```
1: $p \leftarrow s$
2: while $p \neq d$ do
3:     let $f$ be the face of $G$ with $p$ on its boundary that intersects $(p, t)$
4:     traverse $f$ until reaching an edge $(u, v)$ that intersects $(p, t)$ at some point $p' \neq p$
5:     $p \leftarrow p'$
6: end while
```

3.3.3.2 3D extension of Face routing algorithms

In 3D graphs, extracting a straight line planar graph is impossible because the line sd does not determine the faces in this 3D graph. So, the notion of planarization and traversing faces do not exist. Thus, *Face* algorithm cannot directly applicable on a 3D graphs. Kao et al. in [15] propose a heuristic that adapt the face strategy using the projected graph to deal the problem. This approach presents two problems: first, this method doesn't guaranteed the delivery rate, because in many cases the projection of

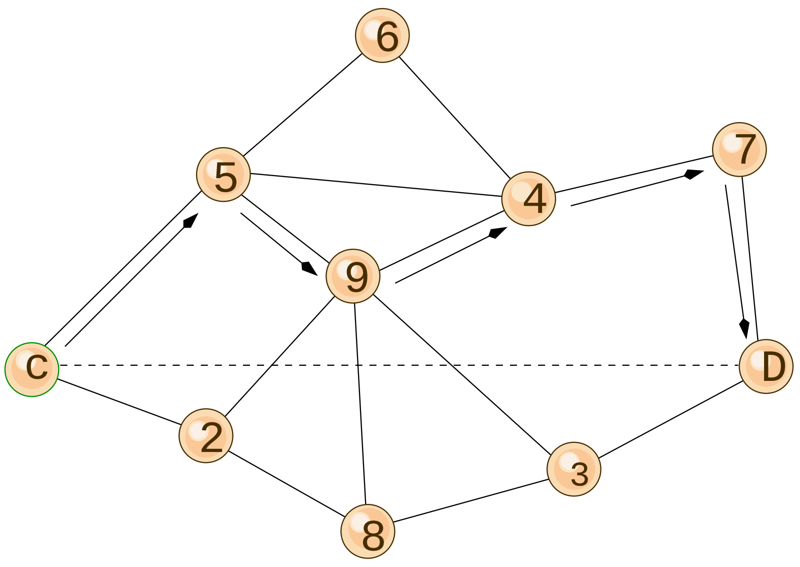


Figure 3.12: Forwarding steps of *Face2* algorithm.

the nodes in a plan may generate cycles from which *Face* algorithm can not get out, and second, the planar graph cannot be extracted from the projected graph using only its local information before projection.

However, the experiments show that the delivery rate is significantly better than the other progress-based routing algorithms. Moreover, in [12] it is shown that if the 2D network of nodes forms a layer of a thickness of not larger than $1/sqrt(2)$ times the range of a node, then there exists a particular algorithm based on face strategy which can guarantee a *delivery rate* to 100%. The following is a treatment of main 3D face routing algorithms proposed in recent years.

Projective face

The first extension of *Face* algorithm in 3D space provides using two orthogonal planes intersected to the line connecting source and destination. In [15] authors propose *Projected Face*, that proceed as follows. The points of the networks are firstly projected onto one plane that contains the line sd, with third point chosen randomly. *Face* algorithm is performed on this projected graph. If the routing fails, the points are then projected onto the second plane, that is orthogonal to the first plane and also contains the line sd. *Face* algorithm is again performed. Fig. 3.15 shows an example of planes configuration in *Projective Face*. Note that, in this case (and in all the following algorithms), since the delivery rate is not guaranteed, the algorithm needs a *local threshold* value, $TTLF$ (*Time To Live Face*), in order to terminate the algorithm in case it not reached the destination. This is necessary because the algorithm can get stuck in a loop. More precisely, in this version of algorithm, $TTLF$ counter is started twice, once for the first plane and one for the orthogonal plane, obtaining a *global*

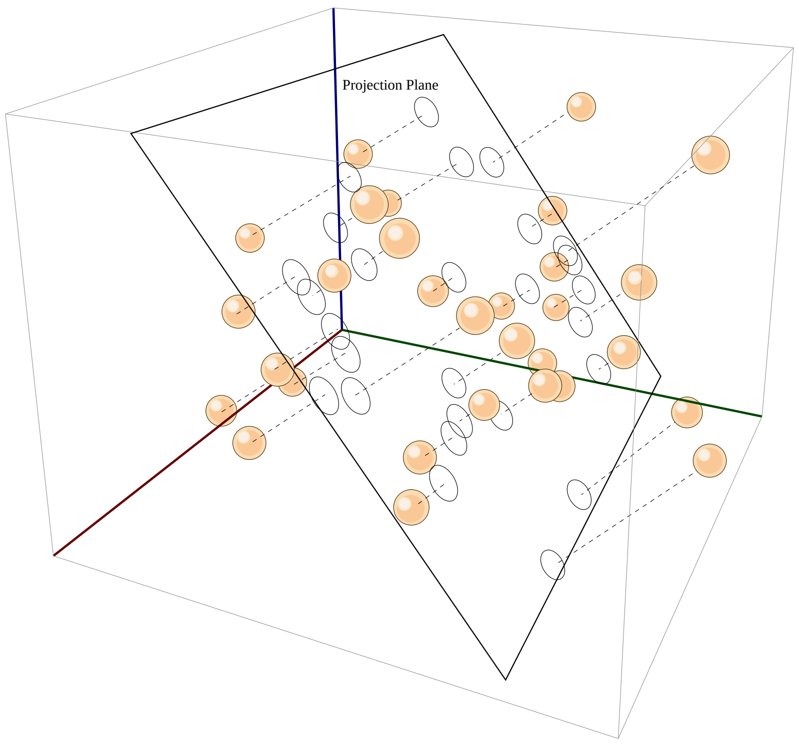


Figure 3.13: Nodes projected on a plane

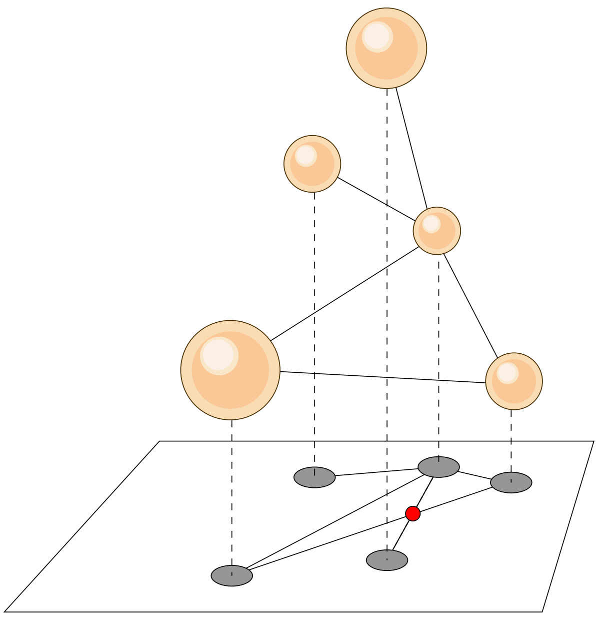


Figure 3.14: Cross link in red circle

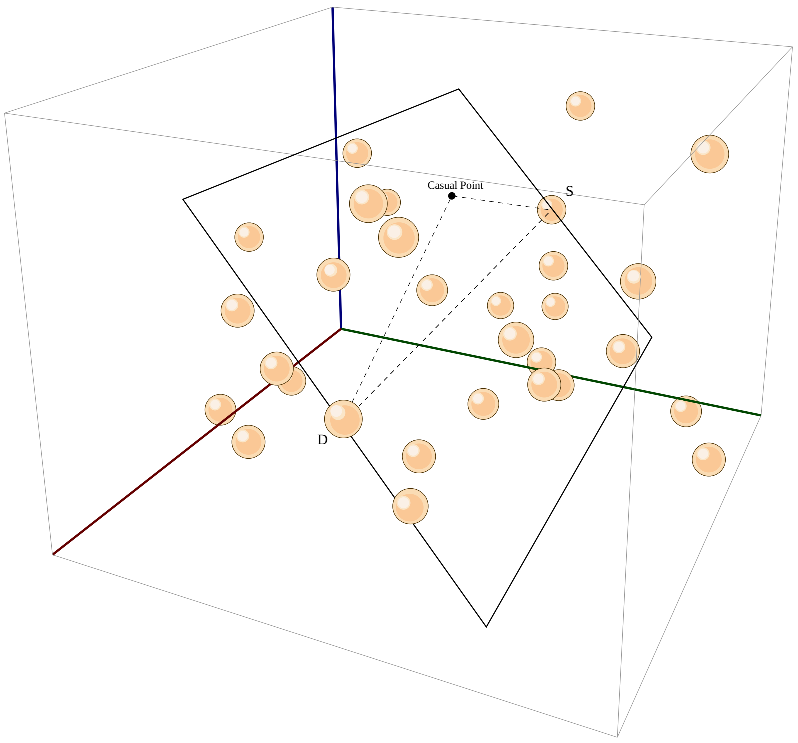


Figure 3.15: Computing of a plane with *Projective face* algorithm

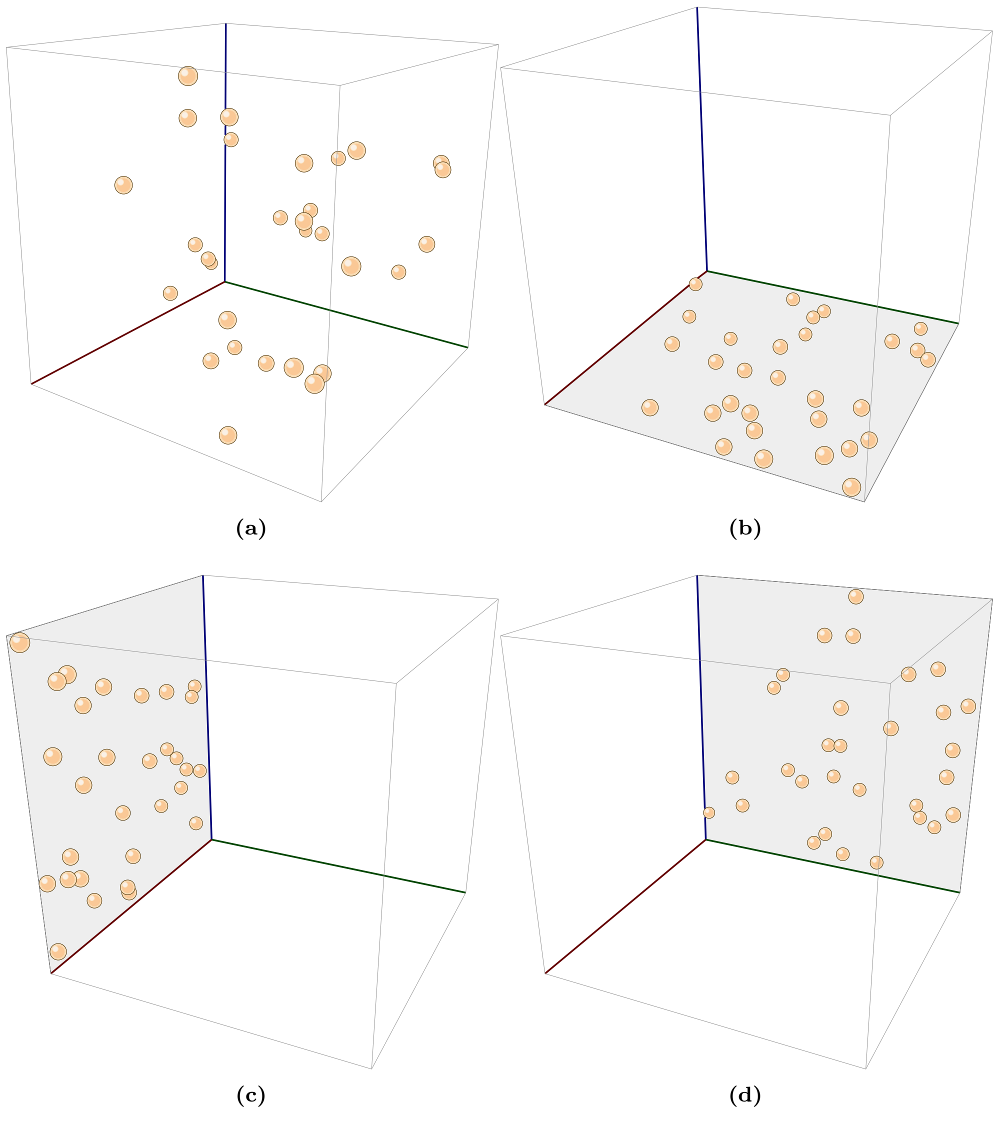
threshold value ,TTL, at most $2 * TTLF$. As discussed in the next chapter, this first extension, in some cases, provides a delivery rate greater than 90%, though suffering a very high path dilation.

CoordinateFace(3)

CoordinateFace(3) (*CFace(3)*), proposed in [4], uses another set of projection planes, that is the planes xy, xz and yz for the projection of the nodes. *CFace(3)* works as follow. All nodes are projected on the first xy plane ($node.z = 0$) and then the face routing is started on the projected graph. If the packet does not arrive at the destination ($TTLF$ has expired) , original coordinate of all nodes are projected in xz plane ($node.y = 0$) and face routing is again performed. If again the packet does not arrive to the destination, original coordinate of all nodes are projected on yz plane ($node.x = 0$) and face routing is again performed. If the packet does not arrive with this last plane, algorithm fails. Fig. 3.16 shows all the three projections on the coordinate planes. Note that, in this algorithm, TTL is at most $3 * TTLF$. As we will see, the delivery rate is typically greater greater than that of the *Projective face*, but with a greater path dilation. A pseudo code of *CFace(3)* is shown in Algorithm 9.

Adaptive Least-Squares Projective Face

Authors of [14] proposes three heuristics to modify and improve *Projective Face* algorithm. The new algorithm is called *Adaptive Least-Squares Projective Face*, (*ALSP*



(a) **(b)** **(c)** **(d)**

Figure 3.16: Projection of graph nodes (a) on the three planes xy (b), xz (c) and yz (d) in *CFace(3)* algorithm.

Algorithm 9 *CFace(3)* algorithm

```
$c \leftarrow s$
Compute the projected graph on the $xy$ plane ($z = 0$)
while pre-set TTLF is not reached do
    Perform $Face$ algorithm step
    if $d$ is reached then
        return $true$
    end if
end while
Compute the projected graph on the $xz$ plane ($y = 0$)
while pre-set TTLF is not reached do
    Perform $Face$ algorithm step
    if $d$ is reached then
        return $true$
    end if
end while
Compute the projected graph on the $yz$ plane ($x = 0$)
while pre-set TTLF is not reached do
    Perform $Face$ algorithm step
    if $d$ is reached then
        return $true$
    end if
end while
return $fail$
```

Face). The three heuristics are:

- Least-Squares Projection (LSP) Plane;
- Adaptive Behavior Scale (ABS);
- Multi-Projection-Plane Strategy.

In the *Projective Face*, a third point is chosen randomly, together with the source and the destination points, to compute the first projection plane. Instead, *ALSP Face* choose the third point adopting a mathematical optimization technique (first heuristic) for finding the best fitting plane to the set of neighbor nodes: using the current node, its neighbors up to two hops away, and the destination node, the initial projection plane is determined by using *least-squares error minimization* of the distance of the nodes to the plane, minimizing the sum

$$\sum_{i=1}^{m}(r_i)^2$$

where r_i is the Euclidean distance from a point i to its perpendicularly projected point in the least-squares projection plane (*LSP* plane), as seen in Fig. 3.17. To maintain the local characteristic of the routing algorithm, authors propose that only the source, destination and the neighboring nodes within the 2-hops scope of the current node be selected as the set of points for computing the least projection plane [2] Then, nodes are projected to this plane and *Face* routing is performed. This *LSP* plane aim to have a less distorted projected graph so that the number of crossing edges can potentially be reduces. The second heuristic defines a parameter called *Adaptive Behavior Scale* (*ABS*) that is used to determine when recalculate the *LSP* plane, in order to ensure that the plan is always appropriate for the current node. Third heuristic uses a set of N_s projection planes arranged in a fixed order about an axis. The algorithm switches between these planes, following the order, to disrupt any looping that may occur during routing. In Algorithm 10 *ALSP Face* is written in pseudo code.

In [14] it is said that by performing the face routing on the additional projection plane, there is a significant increase in the delivery rate. Therefore, third heuristic tries to increase the number of projection planes. But this reasoning is true only up to a certain point: if it is true that the delivery rate is slightly increased, it is also true that the path followed by the packet becomes enormously long, because, for each projection plane, the threshold value (here, $TTLF$) is reset to the its pre-set value. Such a high traffic for only one packet might not be acceptable in real world. Then it is not clear So, this thesis consider the third heuristic using only two additional planes, chosen as in *Projective Face*.

[2]for simplicity of implementation, in this work the 1-hop scope of current node was used for *LSP* plane computing

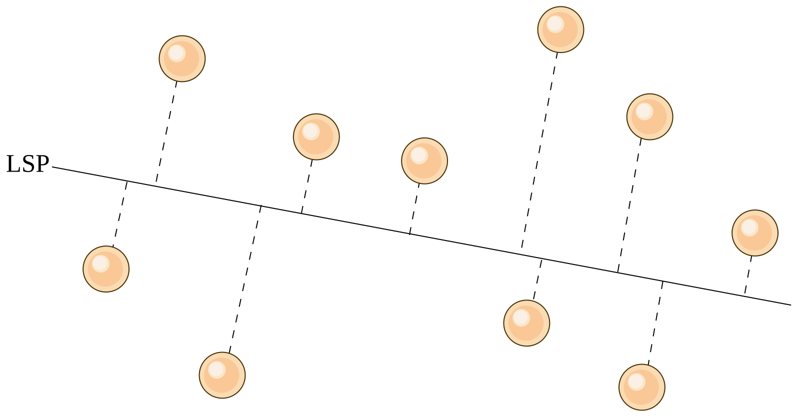


Figure 3.17: 2D graphic representation of computing *Least-Squares Projection* (LSP) plane, as the first projection plane.

Algorithm 10 *Adaptive Least-Squares Projective Face* algorithm, refering to [14] adapted to this thesis.

```
1: Input The source node ($s$), the destination node ($d$) and a 3D geometric graph.
2: Output return $true$ if the delivery is successful else return $false$.
3: $c \leftarrow s$
4: while pre-set TTLF is not reached do
5:     Compute LSP plane using position of $c$, $t$ and the 1-hop neighbors of $c$.
6:     Compute the projected graph on the LSP plane.
7:     while pre-set ABS is not reached do
8:         Perform a 2D Face routing step.
9:         if $t$ is reached then
10:            return $true$
11:        end if
12:    end while
13: end while
14: while pre-set number of projection planes $N_s$ is reached do
15:    Compute the next projection plane.
16:    Compute the projected graph on the plane.
17:    while pre-set TTLF is not reached do
18:        Perform a 2D Face routing step.
19:        if $t$ is reached then
20:            return $true$
21:        end if
22:    end while
23: end while
24: return $false$
```

3.3.4 3D Hybrid Algorithms

In this section we will discuss a set of 3D hybrid algorithms that have been proposed to solve some disadvantages of the algorithms previously seen. These algorithms work at different times using one of two algorithmic methods in alternate way (for example greedy phase and face phase, as in *GFG*). Initially the algorithm begins with a method, then, if a certain condition is satisfied (or not), the algorithm switches to the other method. The three classic combinations that we'll see, will be the combination of two algorithms that are part of the three categories seen above: *progress-based/randomize-based*, *progress-based/face-based*, *randomized-based/face-based.* Typically the primary stage is a progress-based strategy, while the second, also called *recovery phase*, a is random-based or face-based strategy. All the algorithms treated follows set the packet with two modalities, which represent the two used methods.

Greedy-Random-Greedy

Greedy-Random-Greedy (*GRG*) algorithm belongs to *progress-based/randomized-based* class, and uses *Greedy* as the primary stage and a randomized algorithm, such as *Random Walk*, as a recovery strategy. Unlike the recovery strategy based on face routing, randomization strategy is able to obtain a delivery rate similar but with a much lower path dilation. The general idea of this algorithm is the following: the algorithm starts with proceeding the greedy phase until it find a local minimum c. At this point, it will switch to random phase, as recovery strategy, where the node c randomly selects one of its neighboring nodes, using probability distributions defined in $RandomWalk$. In this case, it is very likely that the next node chosen u is not a local minimum, then resumes the greedy forwarding. If the node u is another local minimum, is again the recovery phase.

Greedy-Face-Greedy

Greedy-Face-Greedy algorithm (*GFG*), also defined as *Greedy Perimeter Stateless Routing* algorithm (*GPSR*) for 2D networks, uses a combination of greedy method with face method. With *GFG*, a flag is stored in data packet. This flag can be set into greedy-mode and face-mode (or perimeter-mode), indicating whether the packet is forwarded with *Greedy* or *Face* algorithm. The algorithm starts from s with *Greedy*, setting the packet into greedy-mode and forwarding it. A node that receives a greedy-mode packet, searches from its neighbors the node that is closest to the destination. If this neighbor exists, the current node forwards the packet to this, otherwise marks the packet into perimeter-mode. *GFG* algorithm forwards the perimeter-mode packets performing the same planar graph as the *Face2* algorithm. Moreover, when a packet enters in perimeter-mode at node x, *GFG* set the line xd as a reference line to the crossing with the faces and records in the packet the location of x as the node when greedy forwarding mode failed. This information is used at next hops to determine whether and when the packet can be returned to greedy-mode: upon receiving a perimeter-mode packet, the current node c first compare the location of x stored in

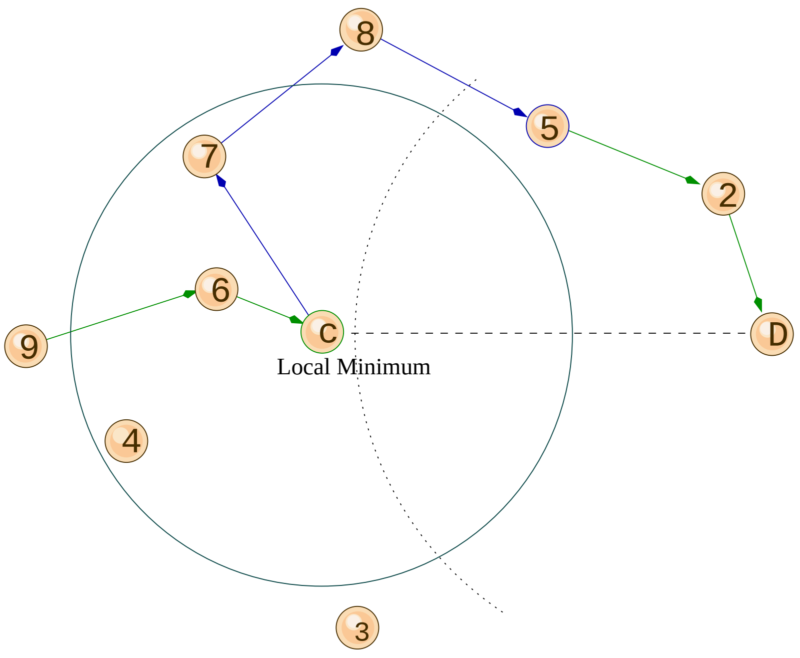


Figure 3.18: Example of *GFG* algorithm. Green arrows represents packet forwarding in greedy-mode, blue arrows are represents packet forwarding in face-mode.

the packet with the forwarding node's location. *GFG* returns in greedy-mode if the distance from the forwarding node to d is less than the distance from x to d. In this case the packet is set into greedy-mode and algorithm continue greedy progress towards the destination. Fig. 3.18 shows an example, where the packet travels nodes 9, 6 and c in greedy-mode (the green path), stopping at node c, that is the local minimum. Then, from node c the face-mode is started, and forwards the packet on progressively closer faces of the planar graph, each of which is crossed by the line cd. The packet reaches nodes 7, 8 and 5 (the blue path). Node 5 is closest to the destination d than c, so the packet can be returned to greedy-mode and reaches destination d (the second green path). *GFG* has the same guaranteed delivery rate (100%), but reduces the number of hops traveled compared to pure face routing strategy. A pseudo code of *GFG* algorithm is given in Algorithm 11.

RW-CFace(1)-RW

This algorithm, initially conceived in [4] as *AB3D-CFace(1)-AB3D*, starts with *RW* algorithm. Once the local threshold $TTLR$ is passed and the algorithm reaches a local minimum, it switches to *CFace(1)*. *CFace(1)* traverses one projective plane, which is chosen randomly from the xy, yz, or xz planes, starting from the node in which the algorithm is switched. At this point, $TTLF$ is initialized to 0 and *CFace(1)* restarts. If the destination is not reached during this phase and $TTLF$ is passed (a looping occurs), the algorithm goes back to *RW* and $TTLR$ restarts at 0.

Algorithm 11 *Greedy-Face-Greedy* algorithm

```
1: $c \leftarrow s$
2: while pre-set TTL is not reached do
3:     while $c$ is not a local minimum do
4:         Perform Greedy algorithm step
5:         if $d$ is reached then
6:             return $true$
7:         end if
8:     end while
9:     let $p$ be the closest node to $d$ before turn on face phase
10:    $p \leftarrow c$
11:    while $dist(p, d) <= dist(c, d)$ do
12:        Perform $Face$ algorithm step
13:        if $d$ is reached then
14:            return $true$
15:        end if
16:        if pre-set TTLF is reached then
17:            return $fail$
18:        end if
19:    end while
20: end while
```

RW-CFace(3)

This algorithm starts as *RW-CFace(1)-RW*, but instead of going back to *RW* if the phase in a projective plane fails, *RW-CFace(3)* tries the other two projective planes, define as in *CFace(3)*. This algorithm starts with *RW* stage and if the destination is not reached and $TTLR$ is passed, the algorithm switches to *CFace(3)* using the first xy plane. Again if a loop occurred ($TTLF$ is reached), it switch to yz plane, and finally the same process is make for xz plane.

3.4 Multi-path Forwarding Algorithms

Flooding is a routing protocol used by routers to forward an incoming packet on all lines except the one it came from. *Multi-path* strategy uses a partial flooding mechanism to deliver the packet to the destination. With partial flooding each node may forward the packet to more than one of the neighbors. Flooding-based algorithms present the problem of packet redundancy: a node can receive a packet for the second time, or even several times, resulting in a very high traffic if it does not have a mechanism to recognize and eliminate these duplicate packets. Moreover, this situation, can lead to an infinite sending of packets. To avoid infinite sending of duplicate packets there are two shrewdness:

- **Jump count**: the package has a counter to be decremented when a new router is crossed. Ideally, the value of this counter should be the same as the shortest path between source and destination, but not knowing the topology of the network, it can be assigned a value equal to the diameter of the network, or the number of nodes in the network.
- **Store sequence number**: this strategy need a sort of memory mechanism, that store in a *sequence number table* the sequence number of the packets arriving from all the neighbors, for some time. If any packet reach a node, the node check in the *sequence number table* if the sequence number of the packet is present. If so, it just ignores it and does not forward it, otherwise insert the sequence number within the table and forwards the packet.

In this thesis a partial flooding strategy (also called restricted directional flooding) is considered. A partial flooding try to send packet to more than one of the neighbors that are located closer to the destination, than the forwarding node itself. Examples of routing algorithms that use this strategy are *Distance Routing Effect Algorithm for Mobility* (*DREAM*) and *Location-Aided Routing* (*LAR*). We consider only *LAR* algorithm for its 3D extension, comparison and hybridizing it with *RW* algorithm.

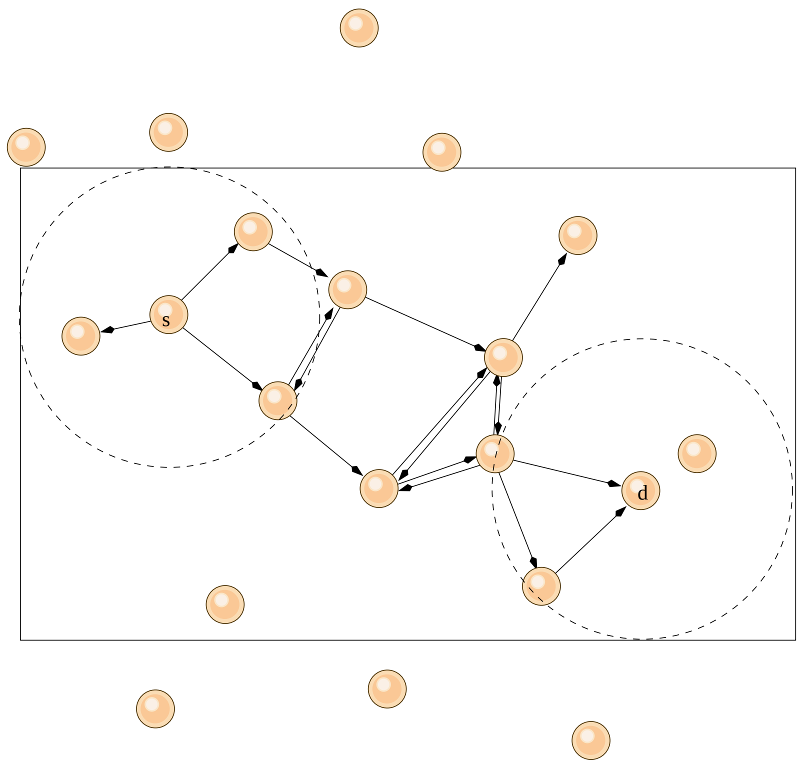


Figure 3.19: Performing of *LAR* algorithm. Packets are forwarded only to nodes that are located within the defined area.

LAR

This algorithm uses the position information of nodes to restrict the flooding process. LAR strategy was created first time in reactive topology-based algorithm, to reduce the sending area of Request Message (RREQ) during the route discovery phase. With the available information of source node and destination node positions, the flooding area is (in 2D) a minimum size rectangle with $disk(s, r)$ in one corner and the expected zone in the other corner. Expected zone, in the original definition [38], is a circle around d of radius equal to $v_max * (t_1 - t_0)$ where t_1 is the current time, t_0 is the time stamp of the position information that c has about d, and v_max is the maximum speed of the node in the network. In our case, since we analyze static scenarios ($v_max = 0$), the expected zone is $disk(d, r)$. Figure 3.19 shows an example of packet forwarding in LAR area, depending on position of source and destination.

3.4.0.1 3D extension of partial flooding algorithms

3D extension of this class of algorithms does not require considerable changes. It is sufficient extend in three dimensional space the flooding areas in which packets can be forwarded.

LAR 3D

In the extension of LAR algorithm in 3D space, with three-dimensional coordinates of source and destination positions, the source node computes the expected zone for d, which is a sphere around d of radius equal to $v_max * (t_1 - t_0)$ where t_1 is the current time, t_0 is the time stamp of the position information that c has about d, and v_max is the maximum speed of the node in the network. This zone is used to define the 3D flooding area, which is the minimum size rectangular box with $ball(s, r)$ in one corner and the expected zone in the opposite corner. In our case, since we analyze static scenarios ($v_max = 0$), the expected zone is $ball(d, r)$.

RW-LAR

RW-LAR was proposed in [5] and hybridize *Random Walk* with *LAR*. This algorithm try to reduce the high path dilation of *LAR* algorithm. All the combinations in *RW-LAR* use the same partitions as in *Random Walk* algorithm. The difference is that, while *RW* select only one of the m candidates chosen from the neighborhood, *RW-LAR* sends the packet to all those selected candidates which are within the rectangular box defined as in *LAR*.

Chapter 4

Simulation Environment

This chapter provides some insights on the simulation environment used for the experimentation. In addition, we provide some common settings related to the simulations such as the orchestration of the simulation scenario.

4.1 Network Simulator 2 (NS-2)

Network Simulator 2, widely known as *NS-2*, is an object-oriented, discrete event-driven simulator tool that is useful in studying the dynamic networks. This simulator can simulate wired as well as wireless network and communication protocols (e.g., routing algorithms, TCP, UDP). In general, NS-2 provides users with a way of specifying such network protocols and simulating their corresponding behaviour. Since it was born, in 1989, NS-2 has gradually gained great popularity and, ever since, several revolutions and revision have marked the growing maturity of the tool, with the contribution of many users in the field and, since 1995, with support of DARPA (Defence Advanced Research Project Agency). In NS-2, many network protocols are implemented, located in the different logical network layers:

- Phy/MAC layer (links, CSMA/CD, etc).
- Network layer (AODV, DSR, etc).
- Transport layer (TCP, UDP, etc).
- Application layer (web, telnet, ftp, etc).

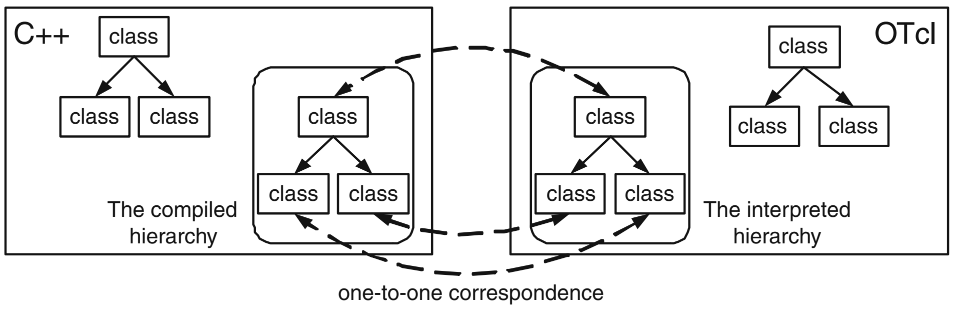


Figure 4.1: Two language structure of NS-2. Class hierarchies in both the languages (C++ and OTcl) may be standalone or linked together. OTcl class hierarchy is the *interpreted hierarchy* and C++ class hiearchy is the *compiled hierarchy*

4.1.1 Why use NS-2?

NS-2 is a free open source common simulator with support for simulations of a large number of protocols and also provides opportunity to study large-scale protocol interaction in a controlled environment. Moreover, NS-2 allows users to extend the code by implementing their own protocols. In fact, in the work of this thesis, a new routing agent module has been implement to add new georouting functionalities. However, NS-2 has certain disadvantages, such as NS's dual language implementation is proving to be a barrier to some developers. But increasing awareness among the researchers along with the other tools like tutorials, manuals and mailing lists have improved the situation.

4.1.2 Basic architecture

NS-2 is written in C++ and Object-oriented Tool Command Language (OTcl), that split the programming model. So, the implementation of this model is distributed between two languages, in order to provide adequate flexibility without losing performance. While the C++ defines the internal mechanism of the simulation and all the objects of network communication (nodes, packets, links), the OTcl sets up simulation by assembling and configuring the objects as well as scheduling discrete events. These two languages are linked using TclCL, mapping variables (instvars) and functions (instprocs), in the OTcl domains, into C++ objects. In this way it is possible to run simulations without the need to recompile at every change, being able to act directly in the script, which is then translated from OTcl in C++ (see Fig. 4.1). The choice of using two languages instead of one comes from the fact that C++ is faster in execution, but less convenient to change; to the contrary, OTcl has lower performance, but it can be changed very quickly, which is ideal for touch-ups configurations.

NS-2 can be invoked by executing *NS* command from the shell environment, followed

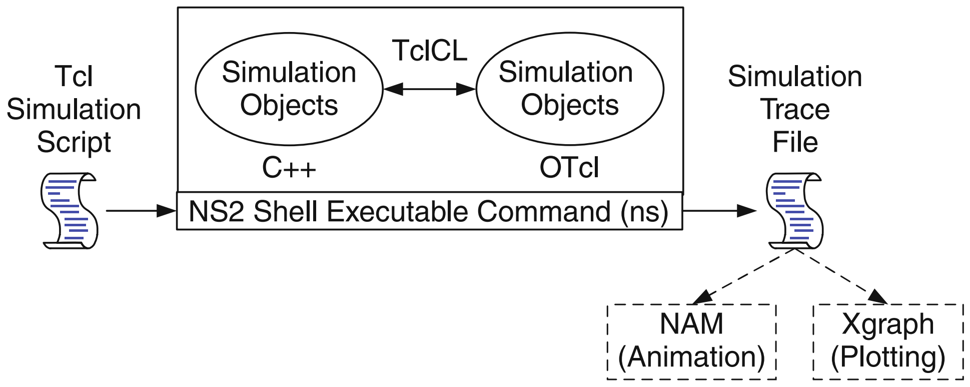


Figure 4.2: Basic architecture of *NS-2*

by a Tcl script, that represents the simulation scenario. A scenario script, typically, includes the definition of the network topology, the type of terminals, the active flows, the type of connection between nodes (wired or wireless), the movement of the nodes, and more. After simulation, NS-2 outputs either text-based simulation results. To interpreter these results graphically and interactively, tool such as NAM (Network AniMator) and XGraph are used. Fig. 4.2 shows the basic architecture of *NS-2* and all its steps.

In Network Simulator 2 physical activities are translated to events, that are queued and processed in the order of their scheduled occurrences. The scheduler maintains the chain of events and simulation (virtual) time. At runtime, it moves along the chain, and dispaches one event after another. Since there is only one chain of events in a simulation, there is exactly one Scheduler object in a simulation. NS-2 supports four types of schedulers: List Scheduler, Heap Scheduler, Calendar Scheduler (default) and Real-time Scheduler.

4.2 Experimental Scenario

A 3D MANET consists of n hosts located at different positions, at different altitudes and connected between them through wireless links. Many of the works considered in this thesis, have simulated their proposal on a scenario that is not very realistic. For example, a typical scenario reproduced is a networks of 75 nodes inside a cube with sides of length 100 units, and each node has a transmission range of 25 units. Possible real networks contain a higher number of terminals, in a much larger structure than a cube of side 100. In fact, many real-world applications are based on longer distances, e.g, tactical or environmental disaster scenarios which need to cover a vast territory. The basic feature of the simulation scenario involves the random placement of n nodes in a three-dimensional space, especially inside a cube of 500 units of side length. In this work one unit is associated to a one meter in real world. This area size is closer to the real typical area sizes.

Another common choice that many researchers have adopted in their work is to start with the calculation of all connected components in the graph (LCC), then select the largest connected component to perform the routing algorithms. This method can creates considerable results as, declaring to position n nodes and then taking the LCC, each different simulation is started with a different number of nodes involved, more precisely $n_LCC \leq n$. This approach is not flexible when we are interested in studying the impact of node density in the performance metrics of interest.

In this work each graph is generated with a set of nodes placed in the space, constituting a connected ad-hoc network wherein between each pair of nodes exists a least one path and all the nodes are connected. To do this, the Dijkstra shortest path algorithm is used. In this regard, each graph is generated in the following steps:

1. All the n nodes are inserted in a list Q.
2. Every node in the list Q si randomly placed in a position (x_i, y_i, z_i) within a cube of side length N.
3. Starting from a defined node u (e.g., node 1) a Dijkstra algorithm is launched for evaluate which nodes are connected to u. Each node that the algorithm meets is removed, if any, from the list Q.
4. If Q is not empty, return to step 2.

In this way, each graph has always all n connected nodes, without leaving any node, or group of nodes, stayed to itself, which would have not reason to exist in the graph.

For simplify the simulation, it is assumed that the nodes are not moving in space, getting an ad-hoc static network. This choice depends on the necessity of having to consider some initial essential parameters for the comparison (as the minimum path) calculated in generation of graphs, that they would change with the addition of mobility, not allowing a more precise analysis of the results. This slightly sacrifices the faithful reproduction of reality, but it is easy to imagine many scenarios of application in which sensor, drones, etc., are arranged in a space area to form an ad-hoc network, finally settled (or at most moving for a few meters). For a more comprehensive comparison, it is chosen to perform all the algorithms in networks with a variable number n of nodes, in particular $n = \{50, 100, 150, 200\}$, in order to evaluate the behavior of those algorithms varying the size of network. A different number of nodes within a cube of equal size causes a change in the density of nodes themselves, therefore causing a variation in the number of the average neighbors for each node. This feature has highlighted some aspects, first including the different results that algorithms have

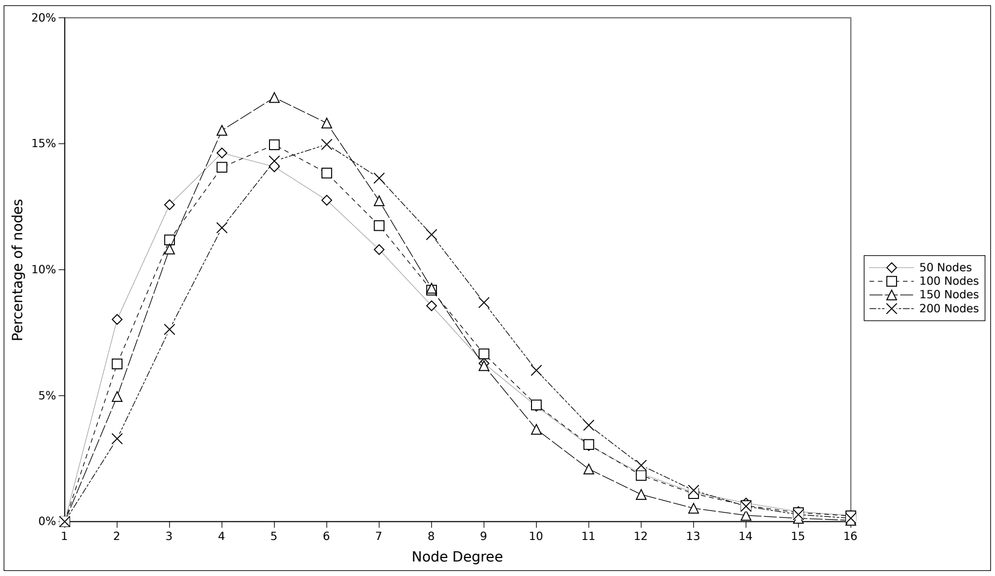


Figure 4.3: Node degrees in 10,000 generated graphs with n = 50, 100, 150 and 200

produced in each size class of network. In fig. 4.3 the histogram shows the node degrees (average size of neighborhood) in the graph, with changing the chosen values for n. It can be noticed how, as the number of nodes grows, a good percentage of them has a greater degree, which indicates a strongly connected graph. Instead, as the number of nodes decreases, many nodes have a lesser degree, obtaining a tree-like graph. These two extreme values affect the performance of the proposed routing algorithms, in particular progress-based algorithms, such as *Greedy*. Indeed, these algorithms have a greater chance of successfully deliver the packet, since, in the two extreme cases, it is less likely to encounter a "void" between source and destination. The next chapter will deal this aspect.

Each node reproduces an 802.11 wireless devices to the MAC layer, with a FreeSpace propagation model . The transmission range for simulations is fixedly set to 100 units (in real space, 100 meters).

For the general comparison, the base values of time-to-live (TTL) are defined in terms of number of hops and are chosen according to the size of the network (number of nodes). In particular, given n the number of nodes in the graph, in the base scenario a threshold value is chosen for the randomized algorithms, called $TTLR$[1], equal to n hops, and a threshold value for face-based algorithms, called $TTLF$, equal to $2n$ hops. Since there are hybrid algorithms that use several phases, these two threshold values can be reset, and the algorithms can also continue indefinitely. So, in addition to those local thresholds, a $global threshold$ (TTL) is set to drop the packet if the total number of hops exceeds a limit value, that here is chosen equal to $6n$. This value is chosen

[1]TTL = Time-To-Live

because some algorithms use more times the local thresholds; for example, *CFace(3)* use three projection planes and so use three time the $TTLF$ threshold ($2n * 3 = 6n$).

Some results shown in the next chapter refer to different simulation scenarios, with different parameters than those presented above, for the comparison of different aspects of algorithms of the same class: will be specified when different criteria will be chosen from the base testbed.

To reproduce the data flows, a CBR (Constant Bit Rate) model is chosen, with different characteristic depending on the type of test that is going to analyze. In particular, two types of scenario are studied: the first, Single Flow scenario, analyzes the performance of the routing algorithms with the simulation of sending only one packet through the graph (from one source to one destination) during all the time testing; the second, Multi Flow scenario, uses multiple streams of packets that are sent from multiple sources to multiple destinations in the same time testing.

4.2.1 Single Flow

The Single Flow scenario provides a CBR flow generated by a single source node in the entire network graph. The CBR agent sends one packet during the entire simulation time, to analyze the inherent performance of each routing algorithm without the presence of external impact factors (noise traffic, interferences, etc.). Source and destination nodes are respectively always 0 and 1 for each network graph. This deterministic choice of the two nodes may seems wrong, but it originates anyway a randomized situation: the nodes, in each different graph, are completely placed in random positions, making a further random choice of source node and destination node unnecessary. To calculate the average delivery rate, the delivery rate is determined 20 times on as much different graphs and an average is calculated. This process is repeated further 100 times - getting a total of 2000 different simulations for each instance (algorithm, nodes) - and the average delivery rate and its variance are determined. Additionally, out of the same 2000 runs used, the average path dilation and its variance are computed. The path dilation is not considered in case the algorithm fails.

With flooding-based algorithms, the measurement of the two metrics is carried out in a different way, to avoid errors and ambiguities. In the case where the same packet travels in multiple copies within a network, the destination may receive the packet several times. In this case, the delivery and path length are counted only for he first copy of the packet arrived at its destination. Subsequent copies are not consider. Table 4.1 summarizes simulation characteristics.

Table 4.1: Settings of simulated topology in Single Flow experiment.

Parameter	**Value**
Wireless MAC	802.11, FreeSpace model
Cube size	500 units of side length
Network size (n)	$\{50, 100, 150, 200\}$ nodes
Transmission range (r)	100 units
Face threshold ($TTLF$)	$2n$
Random threshold ($TTLR$)	n
Time-to-live (TTL)	$6n$
Flows	Single Flow (one packet)

4.2.1.1 Single Flow with dynamic thresholds

Another two experiments aim to show the effect of varying threshold values on the average delivery rate and path dilation of specific algorithms. In particular, for randomized-based algorithms (RW and GRG) an environment with 150 nodes is created and every test is run with $TTLR$ value that assumes the values $n/2$, n, $1.5n$ and $2n$ (the TTL threshold is set to $2 * TTLR$ for GRG). For face-based algorithms (*Projective Face*, *CFace(3)*, *ALSP Face* and *GFG*) an environment with 150 nodes is created and every test is run with $TTLF$ value that assumes the values n, $2n$, $3n$ and $4n$ (the TTL threshold is set to $3 * TTLR$ for *GFG*)

4.2.2 Multiple Flow

To consider a more real scenario, in which multiple streams coexist with each other (for example, a scenario in which the sensors continuously transmit environmental data or video streams), the Multiple Flows scenario provides more CBR streams of data packets (that can simulate video or audio streams) generated by different source nodes, towards different destinations. Any data flow may be subject to a cross-flow with other data flows, disturbing the normal working to it and involving other network entities, such as the nodes' buffer or the links' capacity. This test aims to verify the robustness of the position-based routing algorithms in presence of multiple data streams. Few research works have studied the behavior of these algorithms with different scenarios from the single-packet mode, undoubtedly unrealistic.

Three types of scenario are tested with a three numbers of flows that act simultaneously: the first with 5 flows, the second with 20 flows and the third with 40 flows. Each stream is delivered from a different source node and is directed to a different destination, getting that each network node has almost one incoming flow and almost one outgoing flow, but can has two streams, one incoming and one outgoing, in the same time. Packet size value is 256 bytes and the interval between packets is 50

Table 4.2: Settings of simulated topology in Multi Flow experiment.

Parameter	**Value**
Wireless MAC	802.11, FreeSpace model
Cube size	500 units of side length
Network size (n)	150 nodes
Transmission range (r)	100 units
Buffer size	100 packets
Packet size	256 bytes
Packet interval/rate	50 ms / 40 Kbps
Face threshold ($TTLF$)	$2n$
Random threshold ($TTLR$)	n
Time-to-live (TTL)	$6n$
Flows	{5, 20, 40} flows (multiple packets)

milliseconds. Duration of every test is 5 seconds. Also in this case 2000 simulations are run as described above. As there are multiple streams and multiple packets in each single simulations, the average values of delivery rate and path dilation are taken. Table 4.2 summarizes simulation characteristics.

Chapter 5

Performance Evaluation

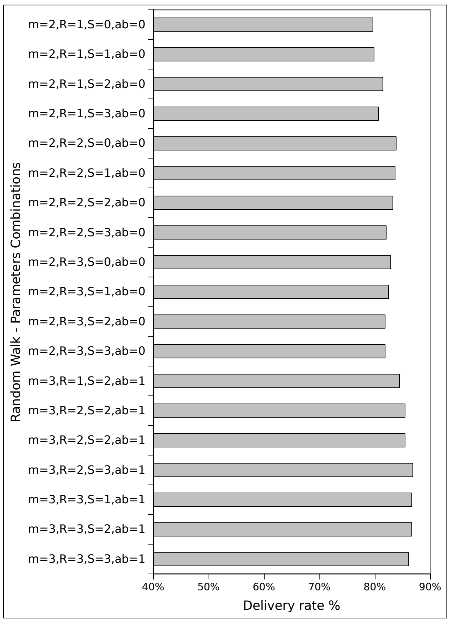
In this chapter we discuss the outcome of the experimentation and contrast the different protocols on different performance metrics. General comparison tests are conducted on the scenario described in chapter 4.

5.1 Comparison of different parameters in randomized-based algorithms

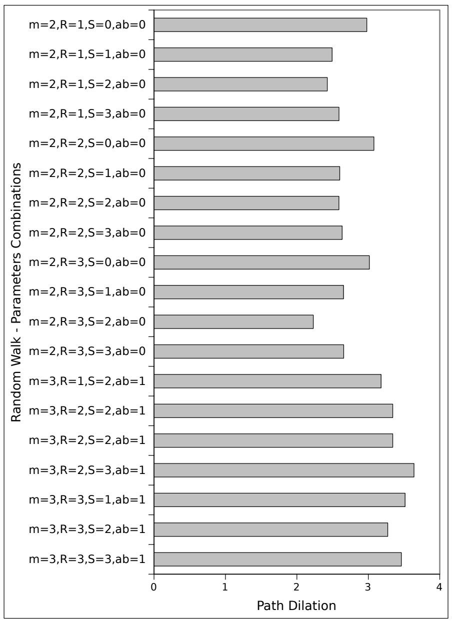
Since we have more and more different combinations of parameters in randomized-based algorithms (96), it is difficult shows all of these combinations in the general comparison. After testing all possible parameter combinations of the randomized strategy, two best combinations are selected to be used. The test is done with *Random Walk* algorithm in a scenario with 150 nodes and $TTLR = n = 150$. One best combination provides the subdivision planes (Above/Below, ab), other best combination not. Also in the dynamic threshold ($TTLR$) comparison, both the combinations are used. The motivation of this choice is to study the behavior of RW with and without the use of subdivision plans. Comparing the two combinations in the same scenario, it is possible to conclude whether the choice of the next node, according to a subdivision of the space operated by plans, can effectively perform well, or not.

For reason of space, in Fig. 5.1 there are shows only the results of the most efficient and most interesting parameter combinations. Note that all these combinations of parameters enable RW to achieve a delivery rate greater than 80% and that almost all of them reach the destination with a path length relatively short. Two of the best results are obtained by the following combinations (however, in following subsequent tests, best results were obtained by other combinations. Therefore, the choice of these two combinations was made on a one test instance, given that in any case the differences in performance were minimal).

- $m = 3, R = Greedy, S = Angle, ab = YES$
- $m = 2, R = Compass, S = Angle, ab = NO$



(a)



(b)

Figure 5.1: Performance of best parameters combinations in *Random Walk*, considering the simulation scenario described in 4.1 with 150 nodes. m is the number of candidate nodes, R indicates which strategy is used to choose candidate nodes (random, greedy, compass, most forward), S indicates how the chances of choosing the next node are made (uniform, distance, angle, projected distance) and ab indicates if consider planes subdivision or not.

In Single Flow scenario, both combinations are used in RW and only the combination with plane subdivision ($ab = YES$) is used in other random algorithms (*GRG*, *RW-CFace(1)-RW*, *RW-CFace(3)*). In Multi Flows scenario only the combination with plane subdivision is used in all the algorithms.

5.2 Standard comparison results

Results of general comparison of all the algorithms of this thesis is shown in Figs. 5.2, 5.3, 5.4 and 5.5, respectively related to 50, 100, 150 and 200 nodes in the graphs. It it immediately evident, from the result given in those graphics, that deterministic progress-based algorithms (*Greedy*, *Compass*, *Most Forward* and *Ellipsoid*, in first 4 columns) have the lowest delivery rate, less than 60% in the case of 150 nodes (Fig. 5.4a). This makes clear that cubic networks with side length of 500 units and 150 hosts, are a critical scenario for deterministic progress-based algorithms, because there is more chance of finding local minima. Instead, as seen in other cases (Figs. 5.2a, 5.3a and 5.5a) delivery rate of the same algorithms tends to increase. About path dilation, deterministic progress-based can nearly always find the minimum path, thus obtaining a path dilation value close to 1, as seen in all path dilation histograms. For this reason this type of algorithms are used in combination with algorithms that offer a high delivery rate, but a too high traffic.

RW algorithm, obtains better results in delivery rate, but slightly worse results in path dilation (between 2 and 3). This decline is not very bad, whereas the delivery rate can exceed a value of 90% in case of 50 nodes, as seen in Fig. 5.2a. As seen, in all four scenarios the performance of two combinations of parameters in *RW* are the same, with a slight increase by the combination $m = 3, R = Greedy, S = Angle, ab = YES$ for $n = 200$ (Fig. 5.5a). This means that with this scenario configuration the forwarding strategy with plane subdivision perform well not significantly.

Maintaining a delivery rate almost equal, also *GRG* offers a shorter path in all four network sizes, since a *Greedy* scheme is integrated in this. This can be noticed, for example, in Fig. 5.4 where RW and GRG delivery rate's columns are almost at the same height (Fig. 5.4a), while GRG path dilation's column is lowest than the column of $RW(m = 3, R = Greedy, S = Angle, ab = YES)$ (Fig. 5.4b), and also the delivery time is reduced (Fig. 5.4c).

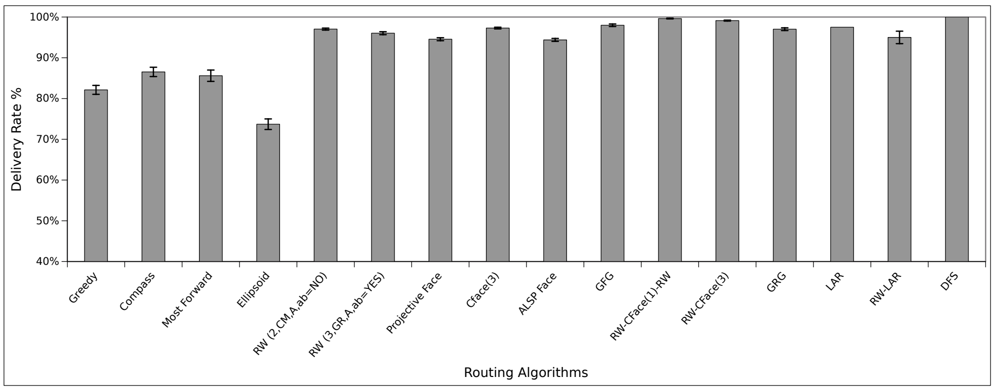
Face-based routing algorithms (*Projective Face*, *CFace(3)* and *ALSP Face*) can generally achieve better results than the previous ones. As can be seen in Fig. 5.2a, these have better performance than randomized-based algorithms (about 97% of delivery in some cases), but when the size network grows, in Figs. 5.3a, 5.4a and 5.5a, a little overcoming of delivery rate can be noted. *CFace(3)* can be defined as *Projective Face*, only choosing two plans that are xy plane and xz plane, and with the addition of the xz plane. So, since the algorithm have three chances to find the destination instead of two as *Projective Face*, the delivery rate is a little higher, with a little higher path dilation ($TTLF$ is counted 3 times). However, the results of all these three algorithms, regarding the number of traveled hops, are very bad, with a path dilation that reaches peaks of 35 times the minimum path length (see Fig. 5.5b). It means that many instances of tests use almost all the set global threshold, TTL, before the packet reaches the destination. In particular, for *CFace(3)* and *ALSP Face*, when the graph size increase, there is an increase in the number of crossing edges, which means greater chance for entering into loops, therefore increasing the probability of having to project to the second and third plane. Face-based strategy is born to give a guaranteed delivery in two-dimensional graphs, and forcing of these in three-dimensional environments causes a series of long and unnecessary forwards of packets, since no planarization of graphs is applied.

Greedy-Face-Greedy algorithm is particularly able to find a short routing path and it is used to reduce the bad effects caused by the above three seen algorithms. Comparing the difference in performance of *ALSP* and *GFG* (that uses *ALSP* strategy) algorithms, as can be seen in the results of the path dilation in Figs. 5.2b, 5.3b, 5.4b and 5.5b (ALSP and GFG histograms), the values of the latter are reduced considerably, reaching a maximum of 15 times the minimum path length. Moreover, *GFG* offers better results compared to *ALSP*, also with regard to the delivery of the packet.

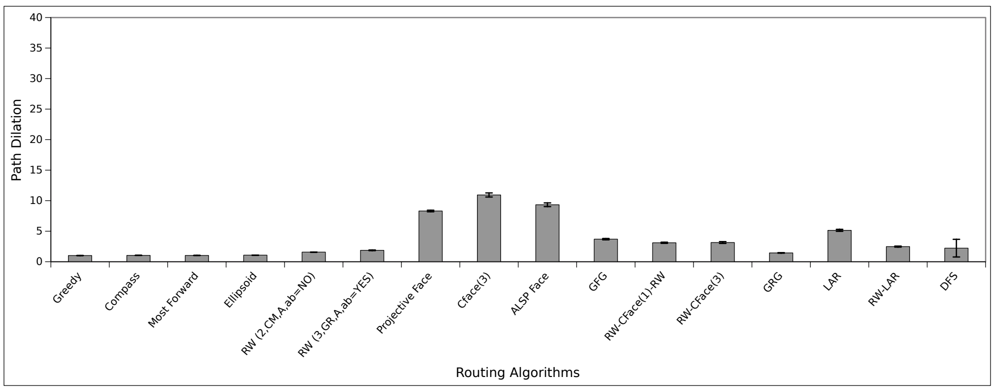
In comparison of *CFace(3)* with the two *RW-CFace(1)-RW* and *RW-CFace(3)*, it is seen that *RW-CFace(1)-RW* performs better than *CFace(3)* in terms of delivery, and decreases the path dilation. *RW-CFace(3)* reaches an higher delivery rate (about 98%), always maintaining a low path dilation, compared to *CFace(3)* (the small increase in the path length of *RW-CFace(3)* is due to the fact that the algorithm does not return to *RW* phase, but continues with *CFace(3)* until the threshold expires).

LAR and *RW-LAR* algorithms are partial flooding-based. *LAR* has a relevant traffic with a nearly guaranteed delivery in case of fewer and closer nodes. In more large networks, because increasing the number of nodes implies increasing of density, the path dilation of *LAR* increases, because the restriction area includes many more nodes, and the delivery rate decreases. The descent of the delivery rate is due to the increase of nodes covering around the 3D cube simulation. This increases the probability that the path from source to destination lies outside the *LAR* area.

DFS algorithm maintains a guaranteed delivery in a static network. Then, only its path dilation is analyzed. Since increasing the number of nodes implies increasing the possibility for long detours being discovered during depth search, the path dilation is increased; however, to 200 nodes (Fig. 5.5b the value does not exceed 4, reaching a less traffic than *GFG* and *RW-LAR*. Whereas it achieves a delivery rate of 100%, it is one of the best algorithms, except that it is not a memoryless algorithm (this question is discussed in the conclusions).



(a)



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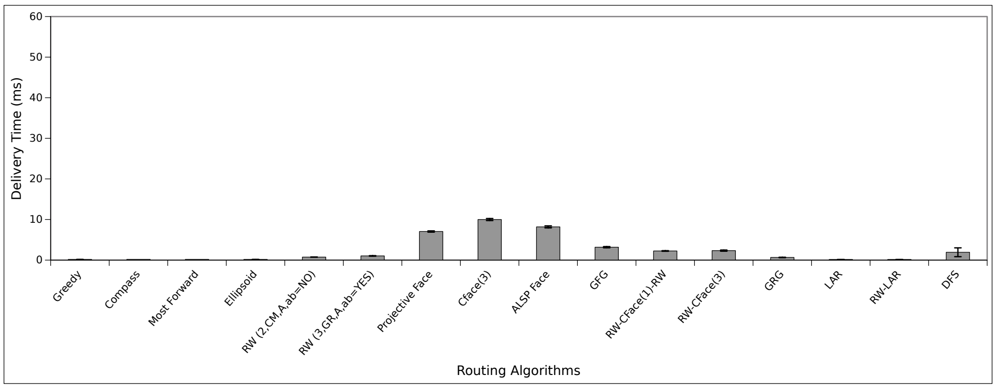
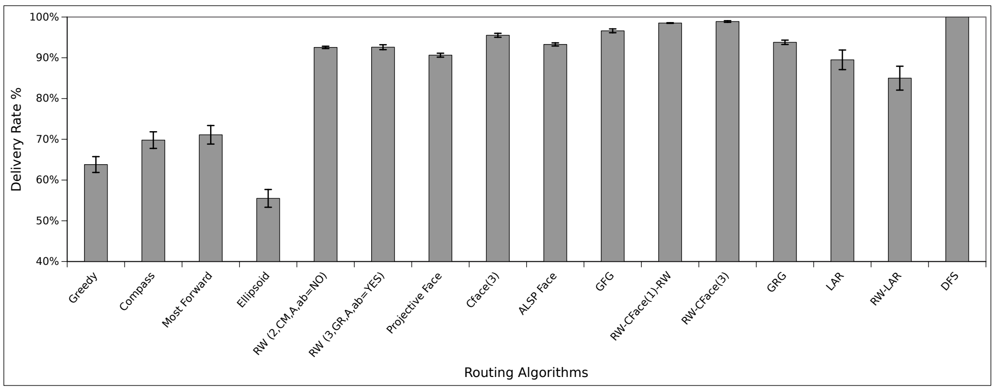


(c)

Figure 5.2: Delivery rate (a), path dilation (b), and delivery time (c) of all algorithms, in a graph of 50 nodes, with TTLF = 2N (100), TTLR = N (50) and TTL = 6N (300)



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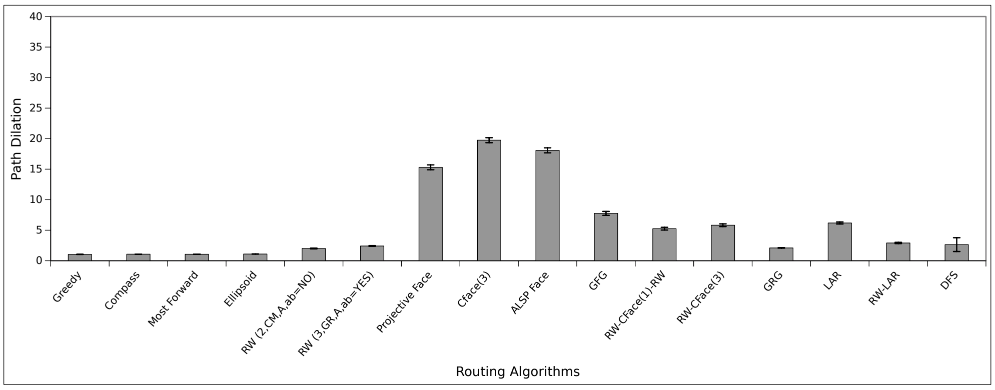

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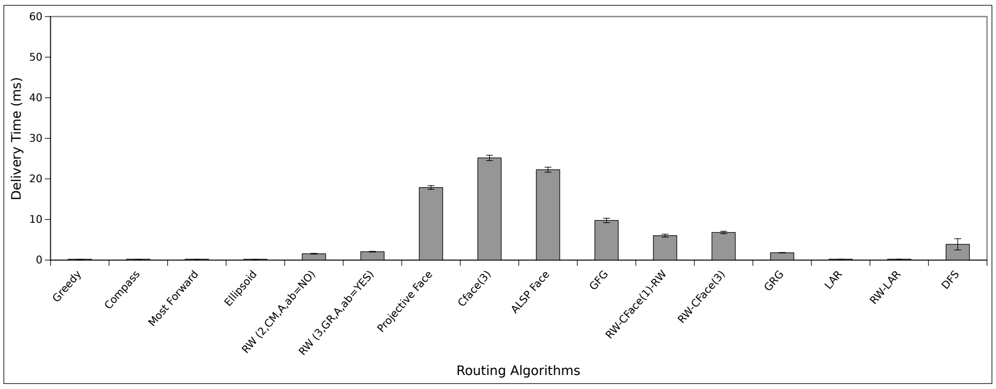
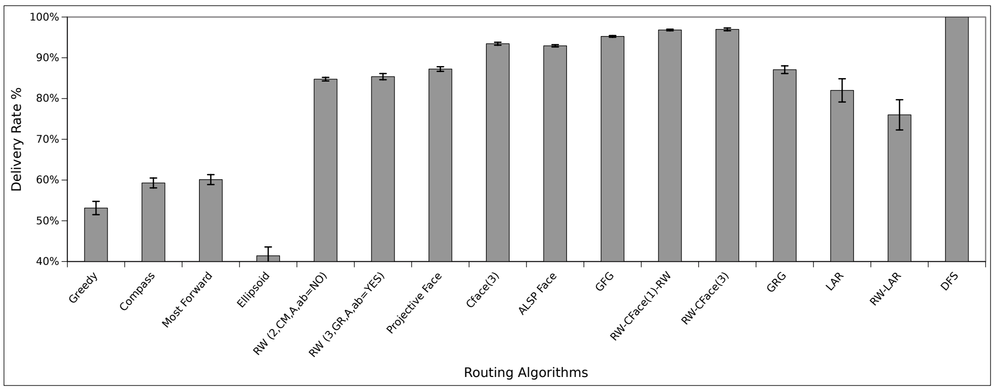
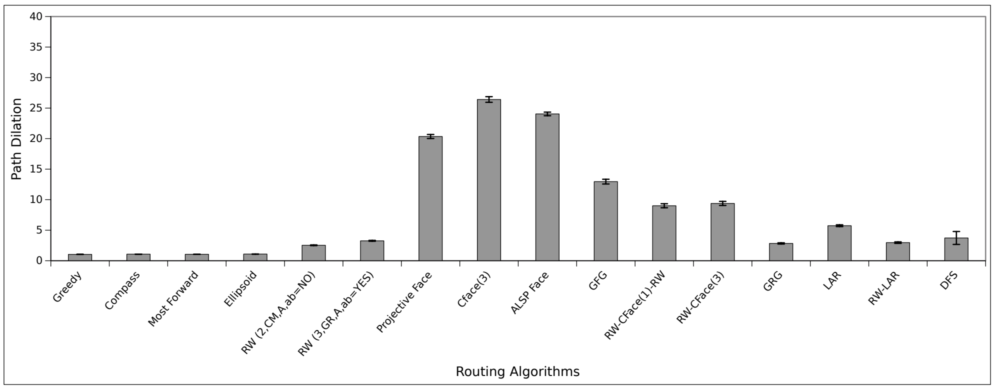


(c)

Figure 5.3: Delivery rate (a), path dilation (b) and delivery time (c) of all algorithms, in a graph of 100 nodes, with TTLF = 2N (200), TTLR = N (100) and TTL = 6N (600)



(a)



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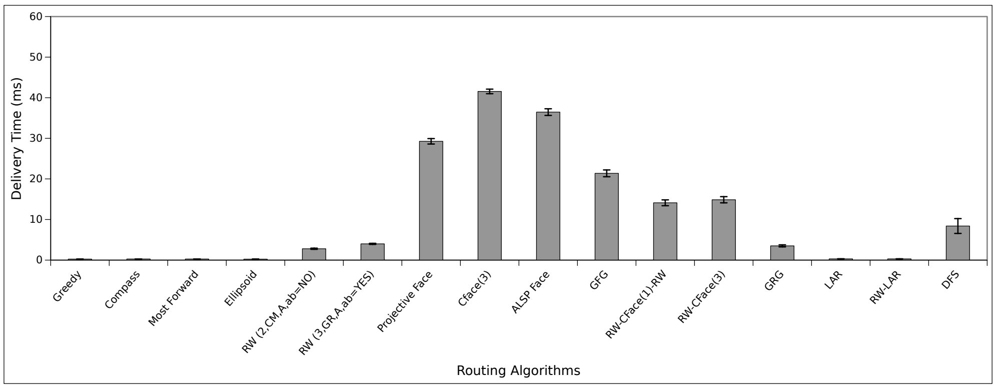
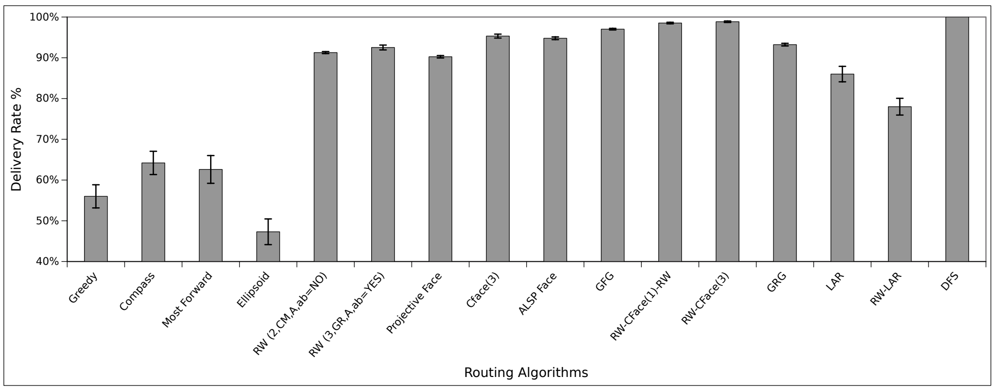
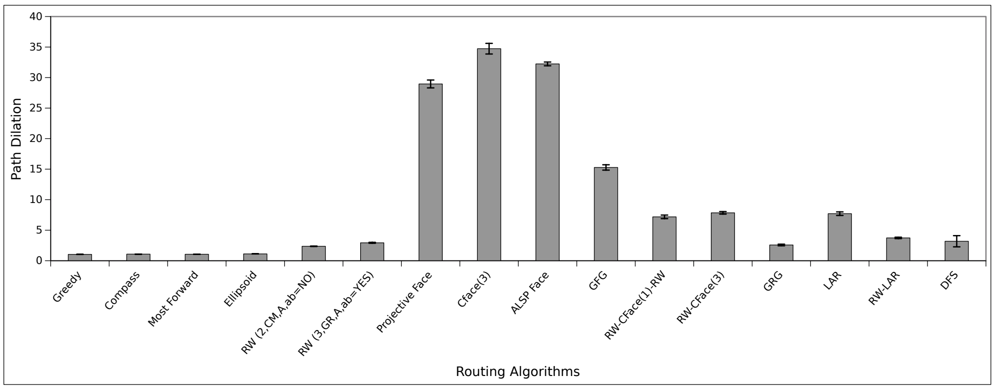


(c)

Figure 5.4: Delivery rate (a), path dilation (b) and delivery time (c) of all algorithms, in a graph of 150 nodes, with TTLF = 2N (300), TTLR = N (150) and TTL = 6N (900)



(a)



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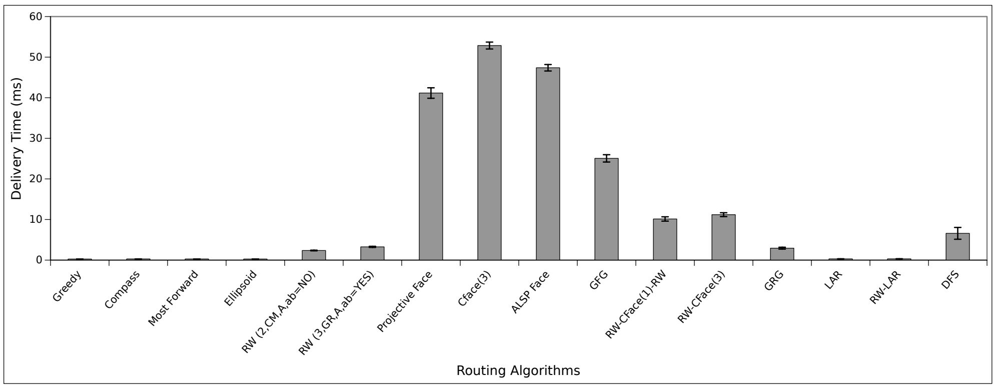


(c)

Figure 5.5: Delivery rate (a), path dilation (b) and delivery time (c) of all algorithms, in a graph of 200 nodes, with TTLF = 2N (400), TTLR = N (200) and TTL = 6N (1200)

5.3 Comparison results with dynamic threshold values

The aim of this test is to see the effect of the threshold respectively for randomized-based and face-based algorithms. That is, to see how effective is to increase their threshold values ($TTLR$ and $TTLF$) to increase performance. To get a fair treatment of the various instances of tests, the TTL value is calculated equal to $2 * TTLR$ for random comparison and to $3 * TTLF$ for face comparison, as in this test are the $TTLR$ and $TTLF$ thresholds to be dynamic in this test, and not the number of nodes n.

5.3.1 Dynamic TTLR threshold

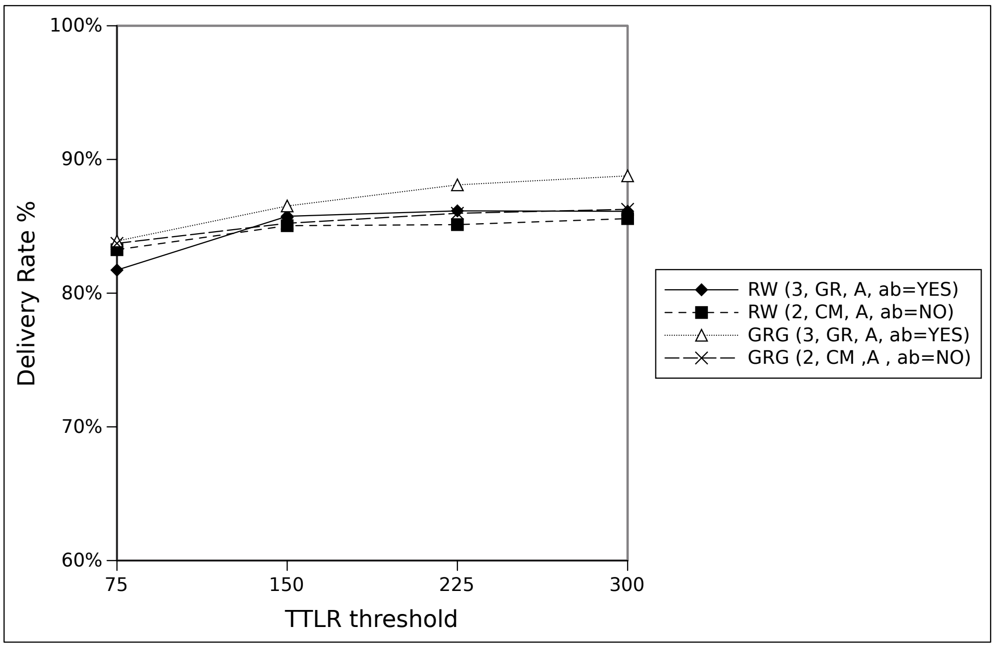
Figs. 5.6 show the effect of varying the $TTLR$ threshold value on the average delivery and average path dilation of the two algorithms that use pure randomized strategy, *Random Walk* and *GRG*, with two parameters combinations. Remember that the two best parameters combination chosen and used on both the algorithms in this test are:

- $m = 3, R = Greedy, S = Angle, ab = YES$
- $m = 2, R = Compass, S = Angle, ab = NO$

As seen in Fig. 5.6a, the delivery rate is generally stable from a $TTLR$ value of 150. It means that, in this scenario and this configuration of the network, it is useless to increase the threshold value up to n, to increase the chance to reach the destination. Since the little increasing of the delivery rate means more success delivered packets added to the average path dilation, then there is an increase of the path dilation. The simulation results also confirm this expectation, with an increase in the path dilation, as seen in Fig. 5.6b, corresponding to an increase in TTL threshold.

5.3.2 Dynamic TTLF threshold

Figs. 5.7 shows the effect of varying the $TTLF$ threshold value on the average delivery and average path dilation of the four algorithms that use pure face strategy, *Projective Face*, *CFace(3)*, *ALSP Face* and *GFG*. Remember that *GFG* uses *ALSP Face* algorithm as recovery phase. The increase in the delivery rate, in Fig. 5.7a, is very significant for all the algorithms until the threshold value of 300 ($2n$). Fig. 5.7b shows the corresponding path dilation, that continues to increase even though the delivery rate stop increasing noticeably. This indicates that a lot of looping occurs during the routing process. *ALSP Face*, *CFace(3)* and *GFG* algorithms perform well together in terms of delivery rate, than other algorithms, but *CFace(3)* has a path dilation that grows more compared to the other. *GFG* algorithm perform well in delivery rate, as



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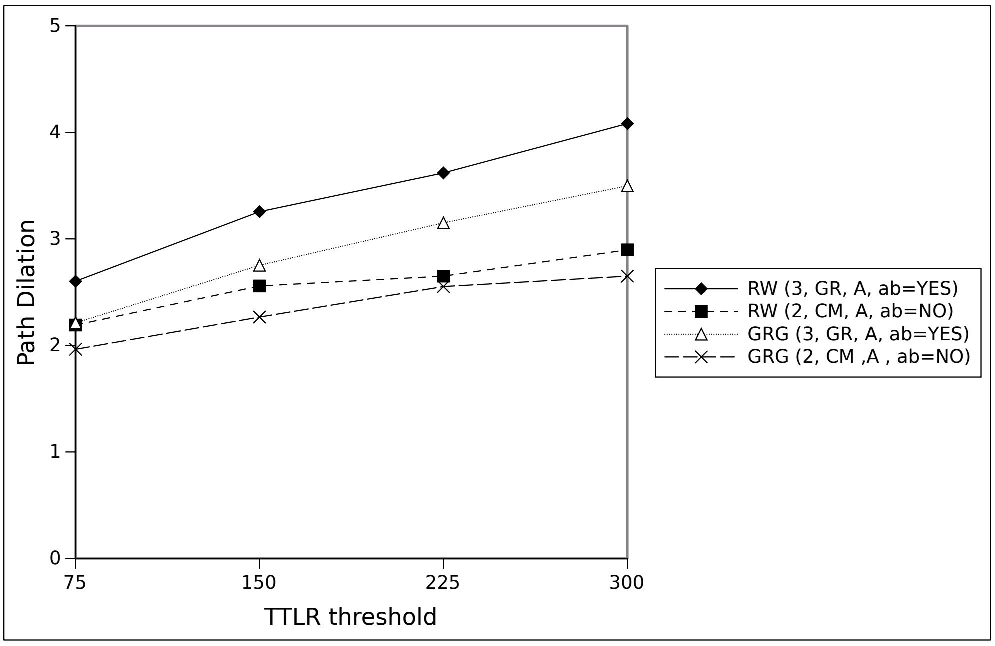
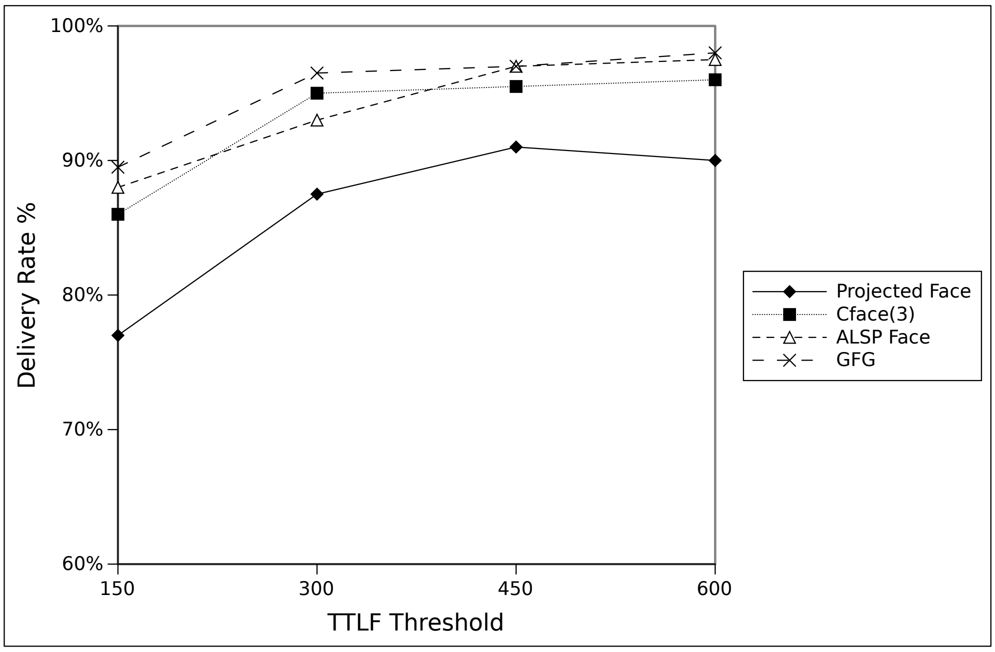


(b)

Figure 5.6: Delivery rate (a) and path dilation (b) of *Random Walk* and *Greedy-Random-Greedy* algorithms, in a graph of 150 nodes, with $TTLR = 75$, 150, 225, 300, and a global threshold TTL of $2 * TTLR$.



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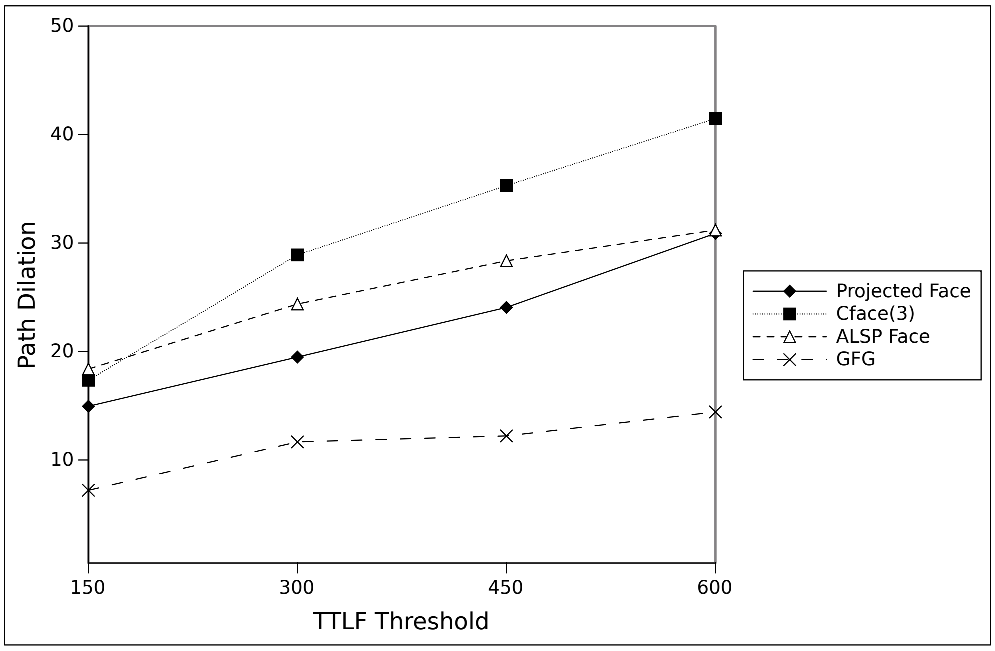


(b)

Figure 5.7: Delivery rate (a) and path dilation (b) of *Projected Face*, *CFace(3)*, *ALSP Face* and *GFG* algorithms, in a graph of 150 nodes, with $TTLF$ = 150, 300, 450, 600, a global threshold TTL of $3 * TTLF$ and an ABS value of 100.

ALSP Face, and has the least path dilation than other algorithms (the value remains permanently below 10). Moreover, *GFG* has a path length that increases much more slowly than the others one; this means that even for very long threshold values, it can reach the destination with short path.

5.4 Comparison results with noise traffic

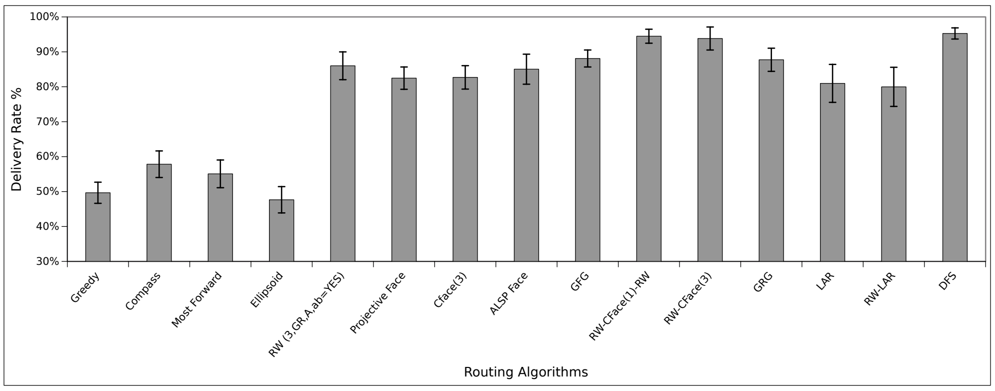
Figs. 5.8, 5.9, 5.10 show the results from Multi Flow simulations. From the test, the noise traffic has not affected little the performance of almost all algorithms (path dilation is not shown in this test, since results would be the same as those in Single Flow simulations). The only decrease in performance can be seen in face-based algorithms, where the delivery rate decreases much. Following a longer path and being in competition with multiple streams, with face routing some packets may drop. *CFace(3)* has the greatest descent in the case of 40 flows, as seen in Fig. 5.10a. Moreover, always the face-based algorithms have an high delay to delivering the packet (more than 1 second), caused by the many queues due to traffic. It is clearly that face-based algorithms are not suitable to a scenario with multi data streams. Progress-based, randomized-based and *DFS* algorithms have not noticeable performance degradation. The slight decrease in the delivery rate in *DFS* is due to lack of the neighborhood information: in tests there have been cases of *empty neighbor table*, caused by the fact that the hello messages, in response to the position request messages came later than the expiry of *timerSend* (caused by queues), resulting in a packet forwarding with an empty neighborhood, and then a subsequent failure.

5.5 Comparison results with dynamic min path length

This section shows the results relating to the application of all the routing algorithms considered in classes of graphs in which the length of the shortest path source-destination is respectively 1-3, 4-6, 7-9, and >10 hops. These results can be seen in Figs. 5.11, 5.12, 5.13, 5.14. Note that for the first class (1-3 hops), all the algorithms have a high delivery rate and a small path dilation. This happens because there is very little chance that in a so few hop distance there are holes (local minima).

When it start to move to longer paths, deterministic progress-based strategies are the first to degenerate, because, as the destination is more distant, there is a greater probability to finding holes (localm minima). As seen in Fig. 5.14a, progress-based algorithms reach about 10% of delivery rate.

RW and *GRG* algorithms perform well up to 4-6 length of minimum path, but from this point the delivery rate decreases. This is because the increasing of number of link to choose from source to destination reduce the probability of choosing the right



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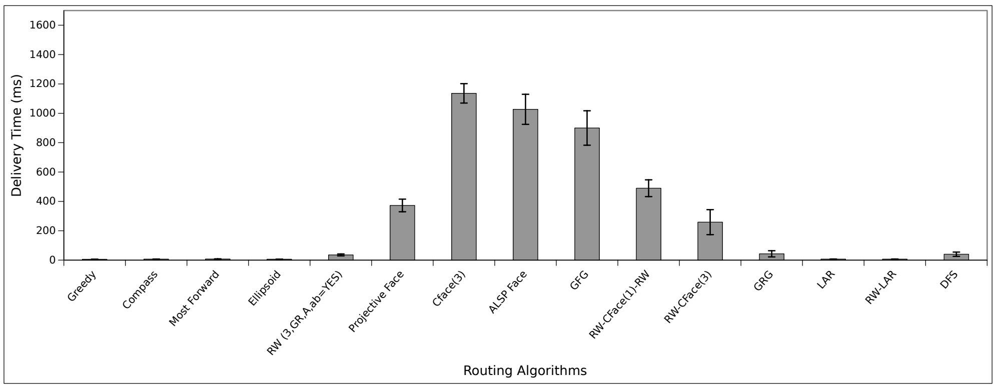


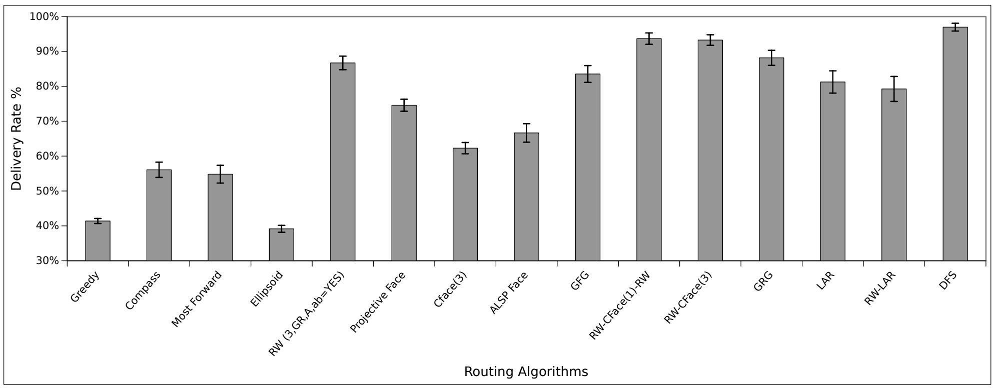
(b)

Figure 5.8: Delivery rate (a) and delivery time (b) of all algorithms, in a graph of 150 nodes with 5 concurrent data streams.

path. However, the path length of the delivered packet remain short (see Fig. 5.14b, RW and GRG histogram).

Performance of face-based and hybridized algorithms are also good for high lengths, due to the fact that they succeed in reach the destination within the $TTLF$ or TTL, despite the increasing of the distance from source to destination. However, the length of path performed and delivery time are too high, due to an increase in the number of crossing links during the travel.

DFS remains delivery time guaranteed. For path lengths >10, path dilation is slightly greater than 5, which means that also work well for very long distances.



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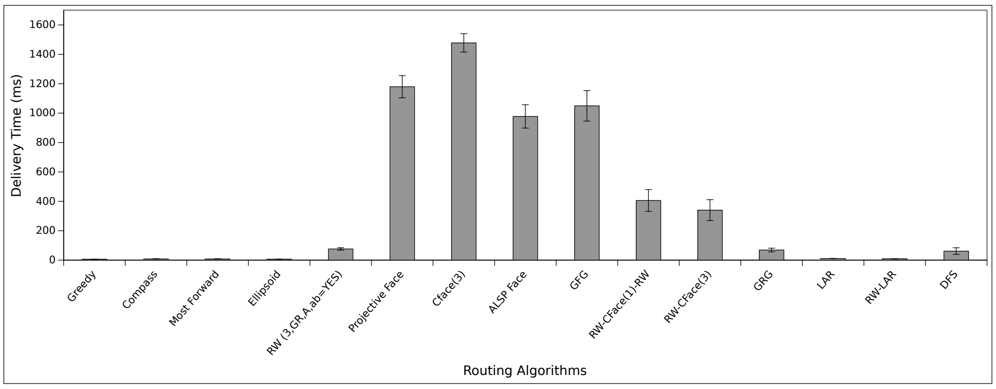
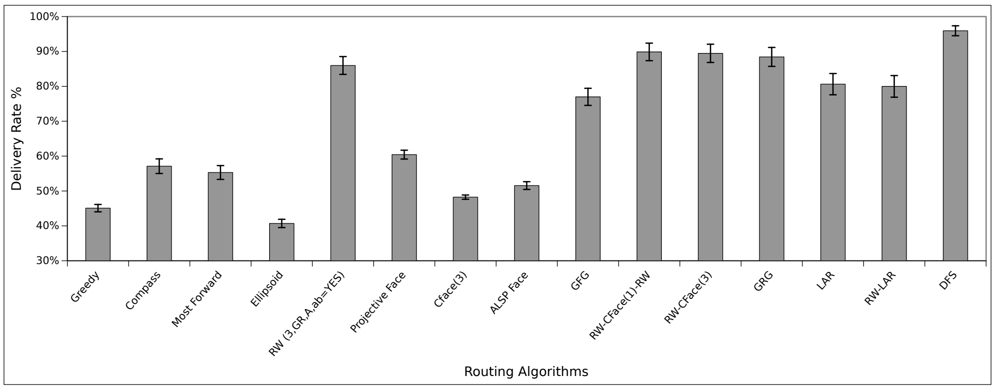


(b)

Figure 5.9: Delivery rate (a) and delivery time (b) of all algorithms, in a graph of 150 nodes with 20 concurrent data streams.



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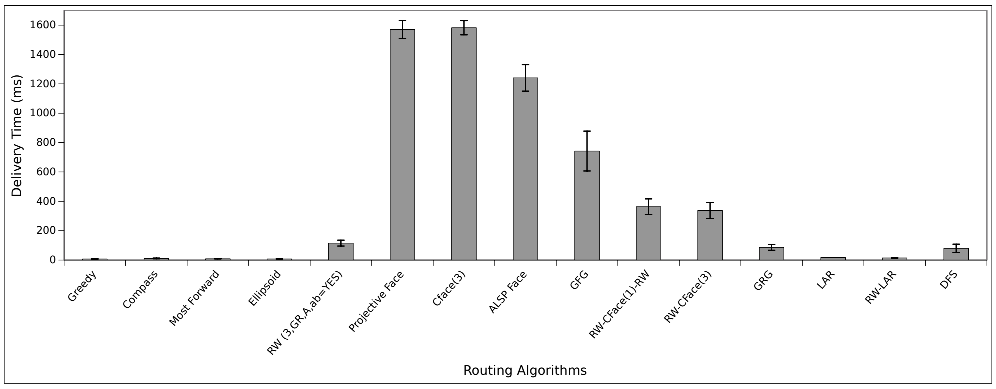

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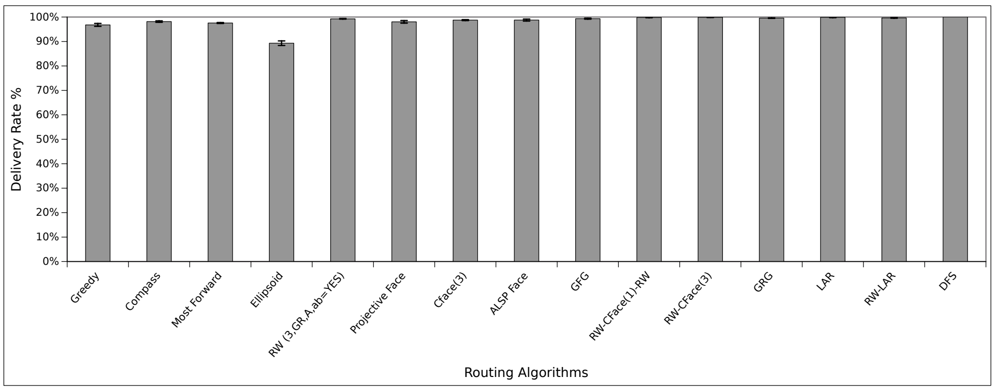
Figure 5.10: Delivery rate (a) and delivery time (b) of all algorithms, in a graph of 150 nodes with 40 concurrent data streams.



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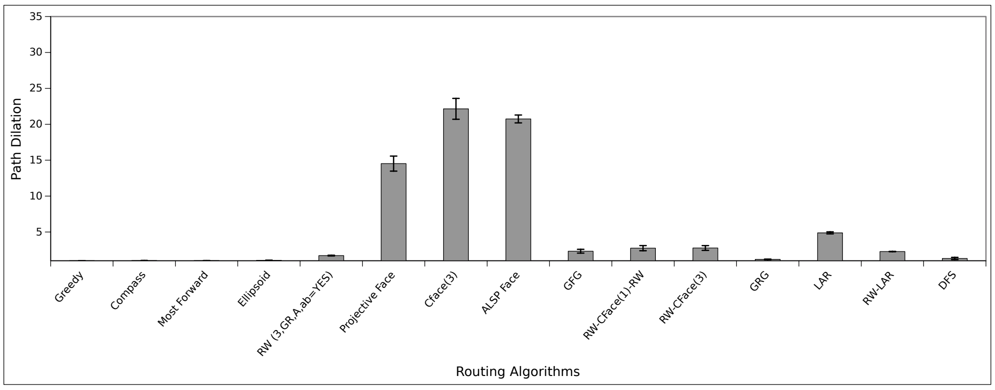

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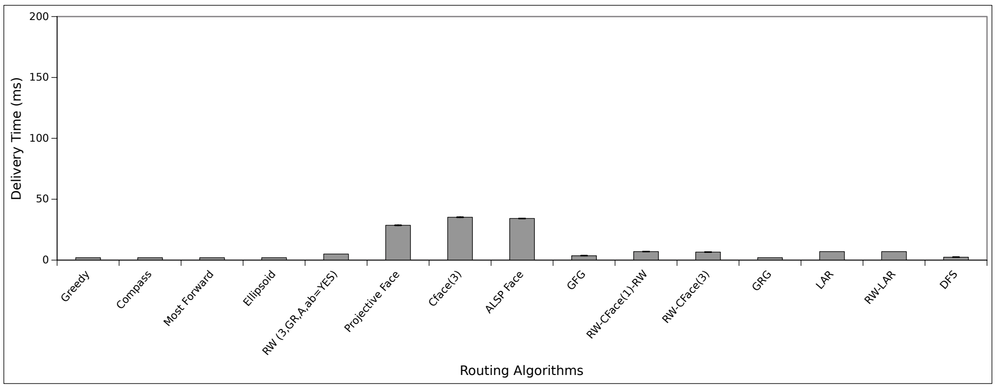
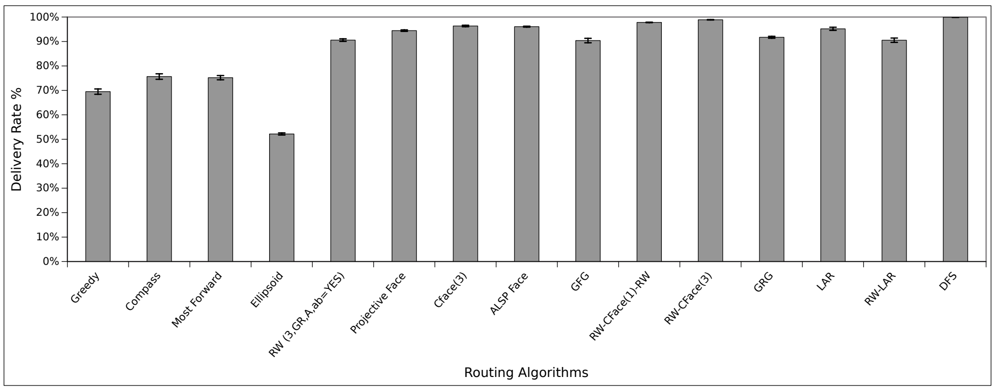
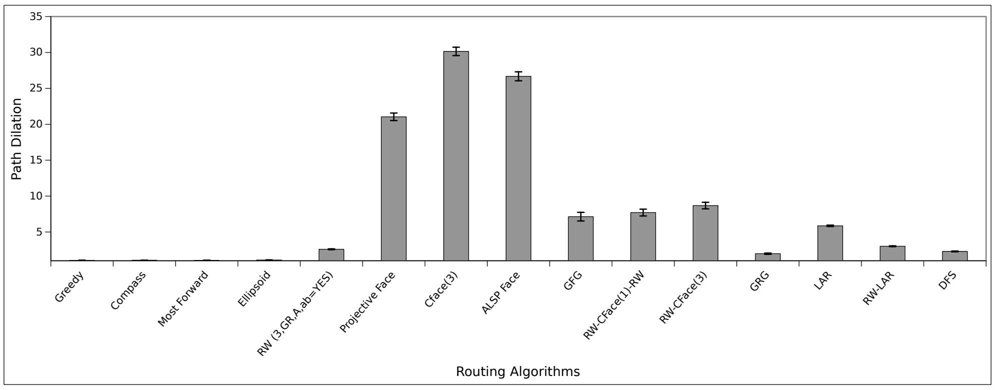


(c)

Figure 5.11: Delivery rate (a), path dilation (b), and delivery time (c) of all algorithms, in a graph of 150 nodes with minimum path length of each pair source-destination of 1, 2 or 3 hops.



(a)



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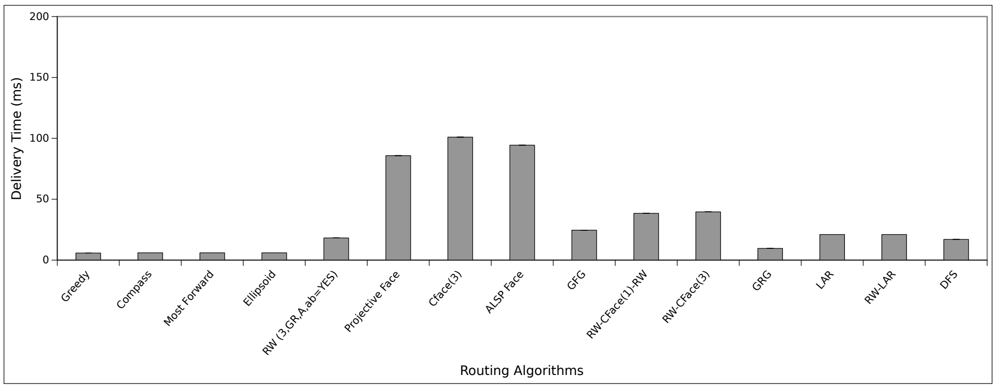
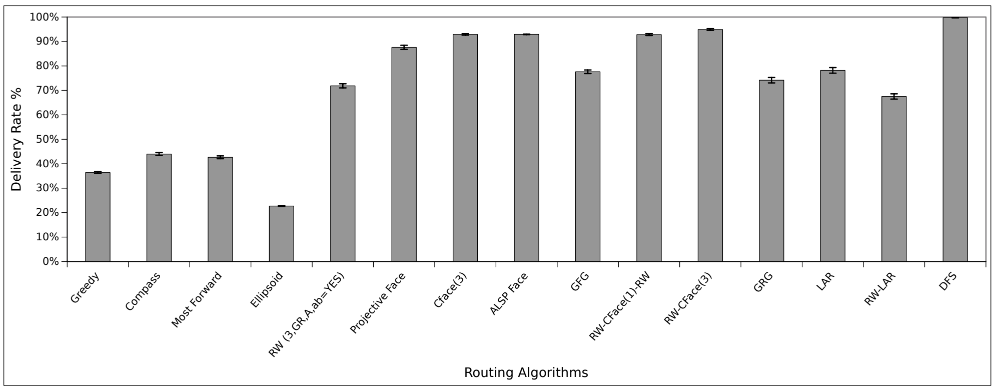


(c)

Figure 5.12: Delivery rate (a), path dilation (b), and delivery time (c) of all algorithms, in a graph of 150 nodes with minimum path length of each pair source-destination of 4, 5 or 6 hops.



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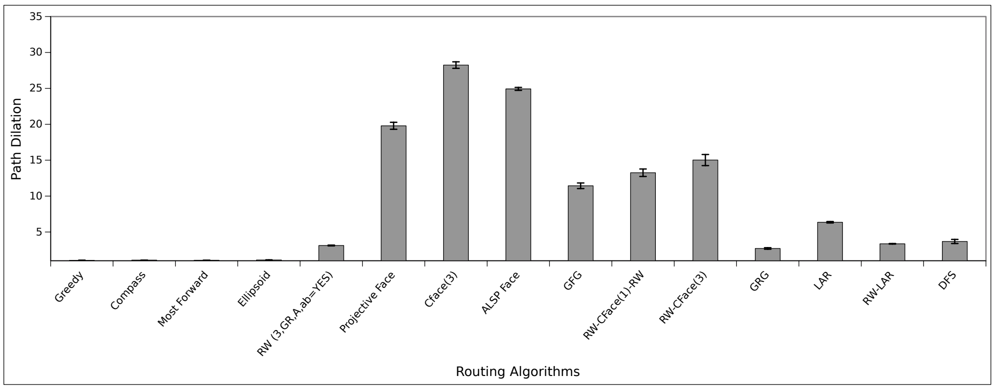

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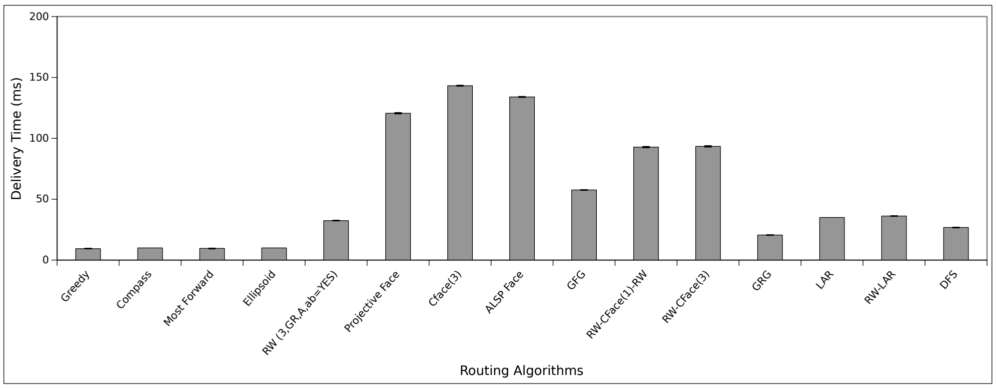

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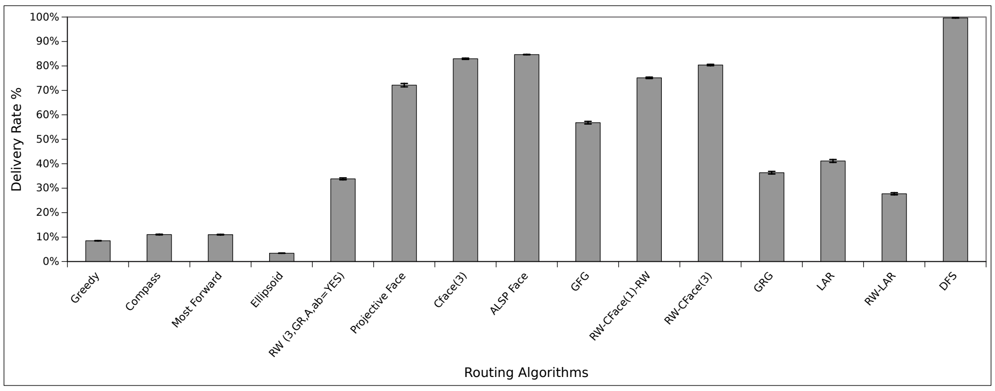
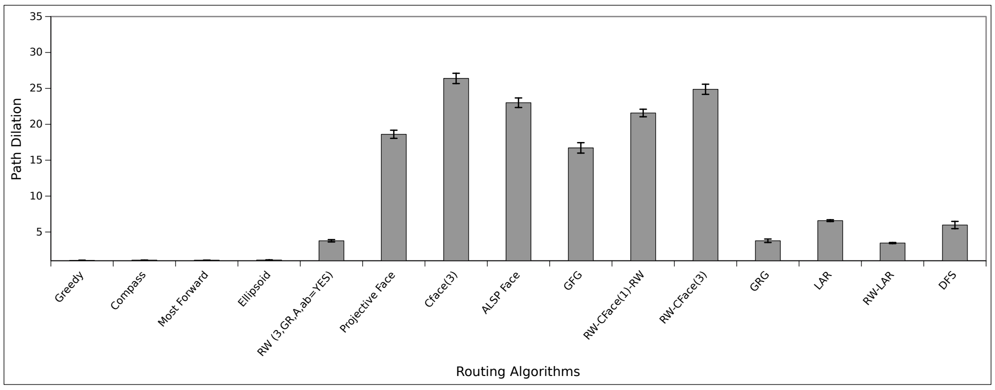
Figure 5.13: Delivery rate (a), path dilation (b), and delivery time (c) of all algorithms, in a graph of 150 nodes with minimum path length of each pair source-destination of 7, 8 or 9 hops.



(a)



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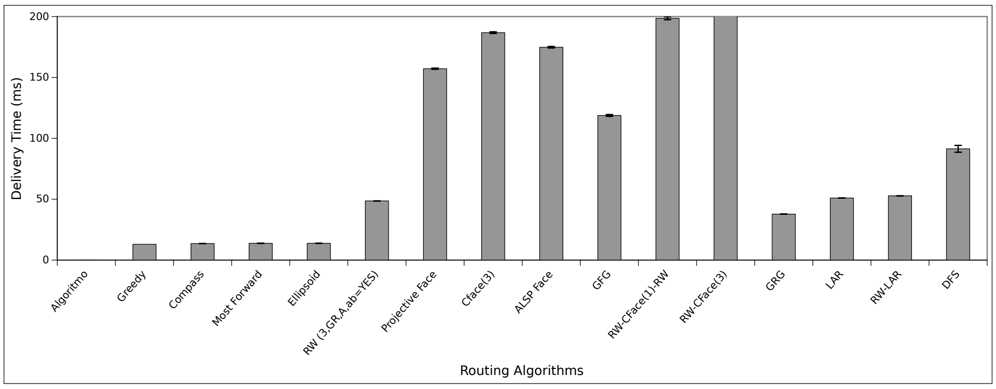

(c)

Figure 5.14: Delivery rate (a), path dilation (b), and delivery time (c) of all algorithms, in a graph of 150 nodes with minimum path length of each pair source-destination greater than 10 hops.

5.6 Summarized Results

A taxonomy of described and tested position-based algorithms is given in table 5.1. It summarizes the main characteristics of these techniques, reporting the results in terms of performance quality. These characteristics are described as follows (delivery and path dilation are already defined in 3.1.3).

- **Loop Freedom**: a data packet can be resent into the network to nodes that have previously received the same packet. Thus, the packet can circulate around the network on the same path. In this context, a loop occurs when a path is repeated several times and an expiration of a threshold is necessary to terminate the process.
- **Path Strategy**: algorithms can use either the single path strategy which requires only a single packet is present in the network at any time, or the multi path strategy which requires many copies of the same packet are present in the network.
- **Forwarding Method**: it indicates the forwarding strategy to send packets. There are four main forwarding strategies: progress-based, randomized-based, face-based and hybrid-based, that uses combinations of the first three strategies.
- **Memory**: there are routing protocols which require nodes to maintain information about the status of the other nodes. So, these protocols (e.g., *DFS*) can be categorized according to the memory requirements of the nodes. If nodes need more than the position information of themselves, their neighbors and the destination (and other information with complexity O(1)), they are considered to have a memory requirement.
- **Scalability**: ad hoc networks have varying size. A routing protocol that perform well also in large size networks is considered scalable. Scalability is not measured in a particular way and it depends on the outcome of a certain protocol simulation. In this thesis, scalability is valued based on the path dilation and memory requirement.

From the table we can see some considerations. Progress-based forwarding algorithms are highly scalable, but have a low delivery rate. These algorithms are suitable for dense and uniform networks, where there are not voids (local minima). Furthermore, these can be used in combination with other algorithms to reduce the path to reach the destination. Randomized-based forwarding strategy have one of the best performances in terms of scalability and delivery. It can outperform the progress-based strategy in sparse networks. Face-based forwarding algorithms have a significant path dilation; thus, they are not appropriate for dense networks, because there are many crossed links, and for flow data scenarios. But they perform well in sparse networks, where there are few nodes and so few crossed links. Partial flooding-based algorithms can be used in small/medium networks, where multi path strategy does not greatly reduces the performances. Hybrid-based algorithms can perform well in a large range of network types, since they combine some advantages from base algorithms: delivery rate is high, path dilation is not high and scalability is high; this depends on the progress/randomized strategy combined with face-based methods. The only delivery guaranteed algorithm is *DFS*, with a low path dilation. It uses memory requirement. Several improvements can be make to reduce the amount of data memorized in nodes. Scalability of this forwarding algorithm can be discussed (see conclusion in Cap. 6), considering the currently available technologies and methodologies to improver the memory requirement. If a small/medium network is considered, *DFS* algorithm is one of the best choices.

Table 5.1: All the algorithms considered in this thesis, with their characteristic and performance results.

3D Algorithm	Loop Freedom	Path Strategy	Forw. Method	Memory	Delivery Rate	Path Dil.	Scalability
Greedy	Yes	Single path	Prog-based	No	Low	Very Low	High
Compass	No	Single path	Prog-based	No	Low	Very Low	High
Most Forward	Yes	Single path	Prog-based	No	Low	Very Low	High
Ellipsoid	Yes	Single path	Prog-based	No	Low	Very Low	High
Random Walk	Yes*	Single path	Rand-based	No	Medium	Low	High
Projective Face	No	Single path	Face-based	No	Medium	High	Medium
CFace(3)	No	Single path	Face-based	No	High	High	Medium
ALSP face	No	Single path	Face-based	No	High	High	Medium
GFG	No	Single path	Hybrid-based	No	High	Medium	High
RW-CFace(1)-RW	No	Single path	Hybrid-based	No	High	Medium	High
RW-CFace(3)	No	Single path	Hybrid-based	No	High	Medium	High
GRG	Yes	Single path	Hybrid-based	No	Medium	Medium	High
LAR	Yes/No**	Multiple path	Prog-based	Yes/No**	Medium	High	Medium
RW-LAR	Yes/No**	Multiple path	Prog-based***	Yes/No**	Medium	Medium	Medium
DFS	Yes	Single path	Prog-based	Yes	Guaranteed	Low	Medium****

* Since randomized, there are no repeated cycles.

** *LAR* and *RW-LAR* are loop free if the nodes store received packets in its memory to not retransmit the same, otherwise, a loop occurs and a time-to-live is necessary to drop the packets.

*** Even if *RW* is used for the selection of the nodes, it does not make a random choice, since the packet is sent to all chosen nodes.

**** *DFS* uses memory to store the past traffic.

Chapter 6

Conclusions and Future Works

This thesis has deepened, in many ways, the problem of position-based routing applied on three-dimensional networks. Firstly, the reasons of using an approach based on the position are discussed, and then the problems and limitations of the algorithms that use these techniques. Through experimental evaluation we have shown that almost all the algorithms do not guarantee the delivery of packets, not even using the planarization models, which guarantee the delivery of networks to two-dimensional networks. The reason is that, in 2D networks, searching the border of a face is a trivial one-dimensional search; in 3D networks the search space is two-dimensional, and for this reason a local (stateless) routing protocol can not ensure to reach the recipient node.

Deterministic memoryless progress-based strategies can perform well in very dense networks, with a path length closed to the minimum path one, but not in sparse networks, due to the problem of local minima. These algorithms, in particular *Greedy*, that is loop-free, may be used in combination with other algorithms, as seen, in order to reduce effectively the number of nodes traveled.

The random component in a forwarding decision offers a better chance to reach the destination. In this thesis, recovering all algorithms based on randomization, a unification of all of these into a single algorithm (*Random-Walk*), with different input parameters, is be made. With the best combinations of possible parameters, *Random Walk* reaches a delivery rate of 80%, with a path length of at most three times the minimum path length in the considered scenarios. Hybridizing this with *Greedy*, getting *GRG*, can reduce the path length, up to 1.5 times, reaching a slight improvement of packets delivery.

Algorithms based on planarization (face-based algorithms) are able to reach very high values of performance in delivery of packets, whit the cost of a very high path length. The choice of one of these algorithms hybridized with a progress-based one (getting *GFG*) has, in part, raised from the heavy traffic. However, the application of two-dimensional geometric concepts, as the planarization of a graph, does not seem to be a very efficient idea applied in three-dimensional environments, as the number of crosses links is noticeable when the graph is projected, and the followed path is not always *towards* the target node as the two-dimensional case, producing unnecessary several hops and traffic, that generate, in case of multiple streams, many packets dropping and an high delivery time.

DFS seems to be one of the best algorithms, with the drawback that requires memory by the nodes. If the network becomes large, the amount of memory may be prohibitive, but some considerations about it can be made. For example, information about a packet in nodes' memory can be deleted after packet's time-to-live has expired. So, since the *time-to-live* and the bandwidth are small, the amount of routing information stored in each node is small. Furthermore, nowadays many devices are able to acquire a large amount of memory consuming very little power energy. The memory requirement is now no longer a problem and this feature can make scalable also not memoryless algorithms.

This thesis suggests which protocols are most suitable for certain applications and helps to understand which of them can be enhanced and which ones are not suitable for the 3D context. Position-based protocols in 3D networks leaves room for further research and progress, but its advantages for future network design look very promising.

As future works we deem worth pursuing an approach similar in spirit to [8]. In [8], an efficient geometric routing algorithms is proposed. Authors consider the routing on hull, that is a 3D analogue to face routing. The proposal of this methodology is mainly based on the concept of PUTD (*Partial Unit Delaunay Triangulation*) to define a "*hull*", in which the algorithm is limited to explore. The basic idea foresees that the packet, as soon as found in a local minimum, covers only the nodes that are in this hull, i.e., those nodes that have the greatest likelihood and quickness of reaching the destination node. This context introduces the notion of subspace, where the packet can travel through its hull. Such a hull is formed by triangles (group of 3 nodes connected to each other) and edges (two nodes connected to each other), which can be obtained through methods similar to planarization, using only the neighborhood to 1 hop away. Once PUDT, on the local minimum m in which *Greedy* algorithm has locked, is calculated, *Depth First Search* algorithm is started, to travel the relative subspace's hull. If *DFS* found a node closer to the destination than m, *Greedy* restarts. Since *DFS* is used for routing, this method is delivery guaranteed, and also *DFS* requires less memory and power energy, because not all the nodes are considered, but only those belonging to the relative hull. This may be an interesting starting point, being one of the possible true extensions of face routing in 3D networks. Further studies can verify its efficiency and costs in various scenario types (multicast, virtual coordinates, energy efficient scenario, etc.), with an improvement of the technique.

Some improvements of *GRG* algorithm are proposed in [28]. The proposed technique is a memoryless greedy-random-greedy strategy with four improvements that try to increase the performance of *Random Walk* method.

- **Region Limited Random Walk**: when the algorithm switch from *Greedy* to *Random Walk* phase in a node c, a sphere of dimension k-hops with center c is defined. The algorithm operates within this sphere, that is, *Random Walk* travels the nodes that are located at most k hop away from c. The k value increases when a certain threshold of number of traveled hops is exceeded.
- **RW on the hull**: the search can be limited on the surface (hull) that delimits the hole in which *Greedy* stopped. It uses, as above, the concept of PUTD.
- **Sparse subgraph**: the concept of *connected dominating set* is used to applying the algorithm in a restricted set of few *major* nodes in the network. This improvement aims to reduce the number of nodes (and hence reduce number of edges) in dense regions.
- **Power of choice for *RW***: *Random Walk* does not send the packet to the node from which the packet came (this improvement is already implemented in this thesis).

Random Walk, unlike that above, is memoryless and thus it is highly suitable for MANETs. This line of research can be further analyzed and deepened, since the randomization is considered a powerful scheme for routing, applicable for real network.

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