Scalable Routing Mechanisms for Mobile Ad Hoc Networks

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Abstract. Nowadays an increasing number of portable devices with wireless communication capabilities start to play an important role in our daily lives. People rely on being connected to computer networks where they can access services that empower both their professional and personal life experience, interconnecting computers, cell-phones, sensors and other common objects that start to offer these type of services. However, existing network infrastructures have not been designed for supporting such a large number of heterogeneous devices and seamless mobility is considered a great challenge. An existing alternative that departs from traditional network infrastructures focuses on the devices' ability to inter-connect themselves, creating wireless multi-hop networks. In fact, the Internet Engineering Task Force (IETF) Mobile Ad-hoc NETwork (MANET) working group, has defined two different routing protocols that explore the capabilities of wireless multi-hop networks by creating an ad-hoc network. In particular, the working group has defined a proactive routing protocol for dense and less dynamic networks with high load of traffic, as well as a reactive routing protocol aiming at tackling sparser networks with higher mobility. However, many other routing protocols and approaches have been proposed in the literature and, bearing in mind the main guidelines from the IETF working group and the challenges posed by mobility and the increasing number of devices, a thorough analysis of important routing protocols for Mobile Ad Hoc Networks will be presented. This analysis will consider the study of works relevant to the development of scalable routing approaches, capable of providing a solution for the current dissemination of wireless-capable devices and need to interconnect them. A complexity comparison of these protocols will also be presented, as well as performance evaluation of the main existing solutions for large-scale MANETs.

1 Introduction

Computer networking has long evolved since the first packet switching that existed in the early 60's. Not only has the number of connections between users and devices increased, but these connections have also diversified from copper cables, through optical fibre into the wireless medium. In particular, wireless technologies have registered a remarkable evolution in order to cope with the increasing portability of computers and other gadgets such as personal-digital-assistants, media players, cell-phones among others.

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Recent technological advances have promoted a massive dissemination of wireless capable devices with greater processing power, higher memory and autonomy, increasing the connectivity between users and different services and applications. As a result, in a near future, users are expected to own several hundreds of gadgets requiring wireless connections [1] amongst themselves and other users, motivating the development of networks capable of connecting them whilst supporting several applications' requirements, demanding a considerable amount of physical resources from the available infrastructures. Such demand of intra and inter networking capabilities will compel researchers and network providers to create alternative communication paradigms to the existing ones and deploy suitable infrastructures.

Despite the flexibility provided by new long-range wireless technologies, such as Worldwide Interoperability for Microwave Access (WiMAX) [2] and Long Term Evolution (LTE) [3], these networks are still expensive and do not scale with ease. For instance, in events where thousands of people are gathered, such as a football game or a concert, these networks are known to fail in delivering a good quality of experience when users try to share their emotions by sending emails, photos and other content. Moreover, in rural areas or disaster scenarios, the coverage provided by these approaches is usually limited or unavailable either by option from the operators or as result of existing damage on the infrastructures.

Another typical characteristic of the spreading wireless gadgets is their portability, creating new challenges related with mobility. This aspect is crucial for users who expect seamless connectivity regardless of their movement and action. However, different trajectories may reduce connectivity coverage or, on the other hand, increase the number of connections and consequently the number of packet collisions, resulting in the disruption of paths established by routing protocols.

Bearing in mind the necessity to handle the restrains of existing infrastructures, and the urge to provide alternatives where they are not available, the concept of Ad-hoc networks has been suggested. This has enabled the impromptu creation of wireless multi-hop networks, where each wireless node behaves as router. By using this approach, users are capable of maintaining their own network, being able to locally share their contents without requiring additional infrastructures. User mobility is of course an important requirement and thus Mobile Ad-hoc Networks (MANETs) must be able to handle the creation and destruction of new links between different users, a task usually delivered to a routing protocol.

While MANETs give users the freedom to create networks in the spur of the moment, without any particular restrictions, these networks may also suffer from scalability problems. In fact, the role of routing protocols may become extremely challenging when the number of connected nodes increases. This difficulty results from the non-existence of a well defined organisation and from interference phenomena intrinsic to wireless technologies.

Conventional routing used in wired and in infrastructure-based wireless networks could not be applied to these spontaneously created wireless networks, due to their dynamics. Distance-vector and link-state routing approaches have been used to establish routes in these networks, using techniques such as Multipoint Relay nodes, in order to optimize the forwarding of topology-related routing packets. However, these proactive routing schemes were not always suitable for networks where high mobility patterns were registered, motivating the creation of reactive on-demand routing alternatives. These protocols strive for typically having a reduced amount of control traffic, finding paths solely when required. Since on-demand routing suffered from an initial delay when retrieving paths and is prone to increased overhead in networks with high number of traffic flows, hybrid routing approaches were developed, trying to join the best of both proactive and reactive routing approaches. Other routing schemes take advantage of knowledge about nodes' positions. This class of routing protocols, geographical routing protocols [4], are characterized for having low overhead and memory requirements, however positioning information may not be available or it may be inaccurate in several scenarios, such as indoor scenarios or large and dense urban areas [5].

Wireless multi-hop networks have increasingly stood out for being available anywhere, without requiring any existing infra-structures, and for being self-organised, self-administrated and self-maintained. For this purpose, as previously mentioned, several works already exist on this topic. However, maintaining routing performance for large-scale networks is a critical issue [6]. Taking this problem into account, different works propose schemes involving techniques such as dynamic addressing, keeping network nodes organised in a well defined topology; geographic partitioning, in order to easily create stable clusters; and also typical clustering solutions, to simply reduce the total amount of routing traffic.

While some approaches aim at scalable routing using different approaches, they lack a thorough evaluation of the impact of different mobility models. In fact, regarding this aspect, most routing solutions disregard the dynamics of different mobility models, focusing only on one mobility pattern. Nevertheless, in order to appropriately evaluate the efficiency of an Ad-hoc network and the performance of routing protocols, these aspects have to be taken into account. Moreover, other works that study the impact of mobility fail to provide an extensive evaluation with existing mobility models [7].

A different perspective on wireless multi-hop routing has been provided with the definition of Delay-Tolerant Networks (DTNs). In these networks, routing protocols are designed to deliver traffic that is not delay sensitive, despite the sparse intermittently connected properties of such network. Conventional routing in wireless multi-hop networks is not suitable for highly dynamic scenarios, as it needs to establish an end-to-end path before starting the routing of data packets, which may not be possible at a given moment.

Even though most wireless networks are in fact intermittently connected due to interferences in the wireless medium, the mobility of nodes has also an important role in this aspect. Typical DTN solutions such as PRoPHET [8] are capable of operating with delay tolerant traffic when wireless connections are not reliable, but fails to perform well with completely unknown node mobility. Other approaches focus on more stable parameters, such as social interactions between nodes. For instance, the Friendship-based Routing (FBR) protocol [9] or the Social Aware Networking (SANE) scheme [10] take into account social interactions, both physical and virtual, in order to make a packet forward decision.

In this work, routing in multi-hop wireless networks is presented in Section 2, being also analysed existing proactive, reactive and hybrid routing approaches in Sections 3, 4 and 5 respectively. In these sections scalability issues of the protocols are considered and their complexity will be addressed in Section 6. A performance analysis methodology, which considers several routing parameters and compares them in two different scenarios, is presented in Section 7, followed by a through evaluation of three main routing protocols in Section 8. Finally, the conclusions and final thoughts on the current state of scalable routing in Mobile Ad-hoc Networks are presented in Section 9.

2 Presentation of Wireless Multi-hop Routing

In multi-hop wireless ad-hoc networks each wireless-capable device will behave as network router, creating the opportunity for other devices to use its resources in order to reach a distant node by issuing another hop. These networks, commonly referred as self-X networks, are expected to be spontaneously created, administrated and organised, relying on a routing protocol to maintain and acquire the paths between each node in the network.

Regarding the analysis of existing routing protocols for wireless multi-hop ad-hoc networks to be presented in this work, it will not consist on an exhaustive listing of existing routing protocols, but instead on a thorough analysis of works relevant to the development of insights towards scalable routing in MANETs. Other works provide a more generalized and broad list of routing protocols including position-based, multicast, multipath or even power-aware approaches [11,12,13]. However, these works do not focus specifically on the scalability of the routing concept and present protocols which provide only minor changes to other existing approaches with little added value. Some of these works are solely concerned with network awareness and dynamic routing, presenting extensions and new metrics to known routing protocols [14].

Currently there are several routing protocols that had a paramount importance in the development of ad-hoc networks which will be described and analysed. Nonetheless, this work focuses mainly in analysis of the protocols' ability to scale in large networks. A taxonomy of these routing protocols is depicted in Figure 1, showing the relationships between the different approaches to routing.

Despite all the provided mechanisms by each routing protocol, which will be presented, they are all subject to certain limitations and may fail in their purpose of scaling in large networks. Regarding the scalability of existing routing protocols their communication and storage complexity play an important role. Even though hierarchical solutions aim at being more scalable, this is not always true, since the complexity of these protocols is not necessarily better than flat solutions. Therefore, this work will also consider, for each class of routing protocols, a unique comparison table that highlights the techniques used by each routing scheme as well as their communication and storage complexities, in order to better understand their characteristics.

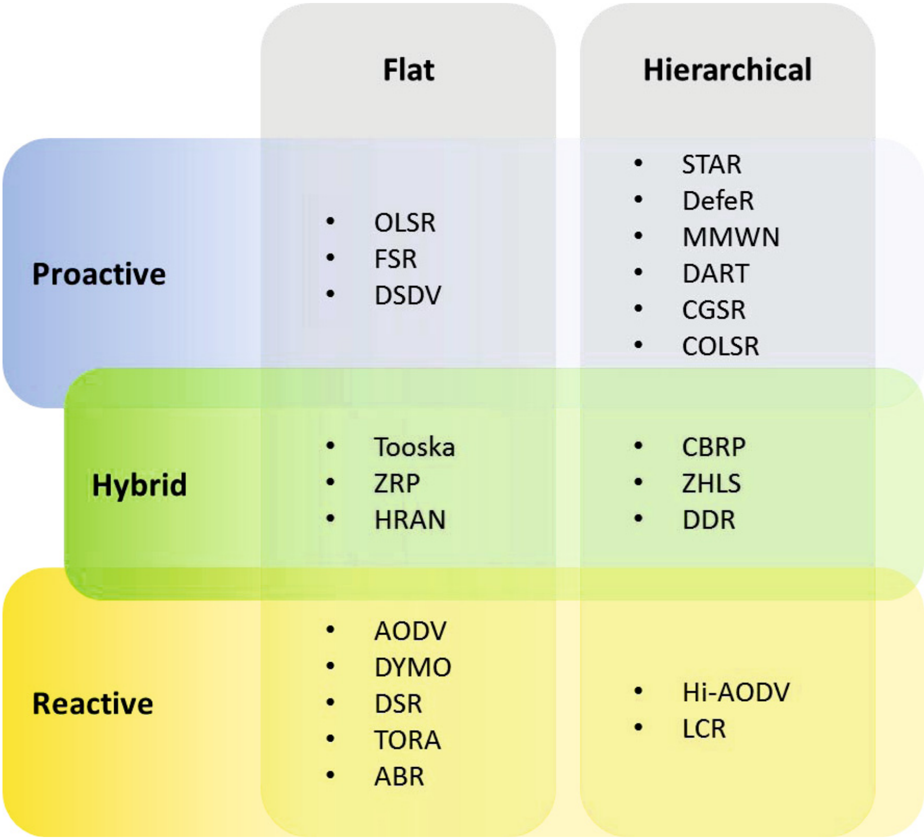


Fig. 1. Taxonomy of Wireless Multi-hop Routing Protocols

3 Proactive Routing Protocols

Following the inspiration provided by typical routing protocols used in wired networks, proactive routing protocols are based on the periodic exchange of routing messages in order to maintain updated routing tables. This paradigm allows a prompt retrieval of the next-hop to where data should be forwarded. However, this periodic update always occurs, even when there is no data to be transmitted, wasting resources without need.

3.1 Flat Proactive Routing Protocols

Flat Routing Protocols are characterized for not having any particular hierarchy to help in the organisation of the network. These are most the commonly found protocols and represent the foundation of MANET routing.

3.1.1 Highly Dynamic Destination-Sequenced Distance-Vector Routing Protocol

A routing protocol that results from a modification to the well known Distributed Bellman Ford algorithm [15], the Destination-Sequenced Distance-Vector (DSDV) protocol [16] is a routing solution where looping related issues are efficiently solved. It is a multi-hop pro-active protocol where each node stores a routing table with one entry to all possible destinations and the number of hops to each node [17]. In addition to this, not being dependent of any intermodal coordination mechanism allows the DSDV protocol to be robust solution for routing in MANETs. The protocol is also designed taking into account Medium Access Control (MAC) Layer details and sleeping nodes which should not be disturbed unless necessary, thus improving the total network lifetime.

The DSDV protocol periodically broadcasts update packets or whenever relevant information is available. These packets contain a new sequence number and information about the destination's address, the number of hops required to reach the destination and the sequence number of the previously received information regarding that destination. Routes containing the most recent sequence numbers are preferred when a path calculation is to be made.

A drawback from the standard DSDV implementation is observed when an existing path becomes invalid due to one or more broken links. When this occurs, the DSDV protocol assigns infinity to the path's metric and an odd sequence number (greater than the older one), which will be propagated through the network. However, while the link failure information is being propagated, some nodes will still drop several packets due to inaccurate information. This phenomenon is referred in literature as a stale route, requiring additional mechanisms to improve the response to a link failure. The Improved DSDV protocol [18] tackles this problem by maintaining a secondary routing table, which contains alternative routes to all the available destinations.

3.1.2 Optimized Link-State Routing Protocol

The Optimized Link-State Routing Protocol [19] is a variant of the typical link-state routing protocols which inherits the advantage of having routes immediately available while, at the same time, providing adequate optimisations for Ad-hoc Networks. The main mechanisms used by Optimized Link State Routing (OLSR) to improve its performance are the exchange of a reduced and non-synchronized amount of control packets used for link sensing and neighbourhood detection. This improvement consists of an efficient flooding technique based on the selection of Multipoint Relays (MPRs), minimizing the required bandwidth for protocol operations and avoiding the reception of redundant control messages [20]. An additional mechanism ensures that the required topology information is efficiently selected and diffused throughout the network.

Link Sensing

By periodically sending *HELLO* messages through the available wireless interfaces in which connectivity is confirmed (1-hop exchange between neighbour nodes), the OLSR protocol performs a link sensing operation. From this operation results a link set which contains the available information on "local" (1-hop) interfaces and on "remote" (2-hop) interfaces. This procedure may be replaced by link-layer information, if such feature is both available and sufficient to populate the link set, thus avoiding the exchange of *HELLO* messages.

Each link contained in the link set is described by a pair of interfaces, the local and the remote interfaces, and it has associated to itself the status of being either symmetric or asymmetric, depending on whether it can respectively send and receive data packets.

Neighbourhood Detection

The neighbourhood detection process consists in maintaining a set of neighbourhood tuples directly connected with the nodes' main address. The relationship between the OLSR main address and additional addresses is defined through the exchange of Multiple Interface Declaration (MID) messages.

There is a clear relationship between the neighbourhood set and the link set earlier described. In fact a node may only be considered "neighbour" of another iif there is a link between each other.

In addition to the neighbour set, there is a 2-hop neighbour set consisting of a set of nodes which have a symmetric link to a symmetric neighbour, being all this information gathered from the exchanged *HELLO* messages.

Still contained within the neighbourhood detection process, the population of both Multipoint Relay and Multipoint Relay Selector Sets is performed. MPRs are responsible for the existing flooding optimisation in OLSR as only them forward routing messages, avoiding a pure flooding approach where all nodes forward the protocol messages. Additionally they also avoid the transmission of duplicate messages by maintaining a Duplicate Set which records recently received messages as a "duplicate tuple" containing information about the originator address, message sequence number and a boolean indicating whether the message has been transmitted or not.

The selection of the MPR set is performed individually by each node which is responsible for selecting the most suitable nodes in its symmetric 1-hop set. This selection is performed in such a way that the node populating the set is able to reach all its strict 2-hop symmetric neighbours through the neighbours contained in the MPR set. Whenever changes occur in the 1-hop or strict 2-hop symmetric neighbours set, a complete recalculation of the MPR set is performed. Even though the MPR set does not have to be minimal, all strict 2-hop neighbours have to be reached through the selected MPR nodes and, in the worst case scenario, the MPR set may consist of the entire neighbourhood set, resulting in a typical link-state routing full flooding strategy.

The calculated MPR set may vary depending on the existing neighbourhood and on the nodes' willingness to act as MPR. This parameter is defined by the node depending on the available resources and other characteristics, being the values between WILL_NEVER and WILL_ALWAYS.

Finally, the MPR Selector set of a node n consists of all the addresses of nodes which have selected n as MPR.

Topology Discovery

By performing the already mentioned link sensing and neighbour detection procedures, each node is able to communicate with the directly connected neighbour nodes and it can participate in an optimised flooding mechanism. However, this information has to be disseminated through the entire network in order to allow the construction of routes to every node. This is done by MPR nodes which periodically send a Topology Control (*TC*) message with a set of links, known as Advertised Link Set, which contains the links to all the nodes in the MPR Selector set.

MPRs broadcast *TC* messages, flooding them to all the nodes in the network using other MPRs to efficiently improve the distribution of topology information, enabling greater scalability.

The generation of Topology Control messages is periodically performed by all MPR nodes in a time interval defined by the constant TC_INTERVAL, which can have several values such that, for a lower interval, a higher capacity of reaction to link failures is achieved. Related with failures, whenever a change to the MPR Selector set is detected, possibly due to a link failure, a new *TC* message should be sent earlier than the next interval generated message.

A common problem inherent to proactive protocols is the synchronization of control messages such as *HELLO* and *TC* messages. This increases the network overhead and may lead to losses due to collisions. In order to avoid this phenomenon, which typically arises with periodically sent messages, the OLSR protocol randomly defines a value named *jitter* which should be between 0 and MAXJITTER. This value is used in the actual message interval by subtracting the *jitter* value to it, thus varying the period in which messages are sent, and avoiding equal message transmission times which may synchronize.

OLSR v2

Currently still under development by the Internet Engineering Task Force (IETF) MANET working group, a new version of the OLSR protocol, the Optimized Link State Routing version 2 (OLSRv2) [21], proposes an update to the mechanisms of its predecessor. Even though the main algorithms are maintained, this new version offers a more modular and therefore flexible architecture, allowing, for instance, the addition of security extensions without compromising backwards and forwards compatibility [22]. Moreover, it also uses the Neighborhood Discovery Protocol (NHDP) [23] for the discovery of 1-hop and 2-hop neighbours, as well as discovering whether links are bidirectional, by sending *HELLO* messages similarly to the standard version of OLSR. The OLSRv2 protocol also implements the MPR Flooding process so that the link state information advertised by the protocol is efficiently propagated.

3.1.3 Fisheye State Routing Protocol

The proactive Fisheye State Routing (FSR) protocol [24] is inspired and takes its name from a well known technique proposed by Kleinrock et al. named Fisheye [25], originally used to reduce the size of samples required to represent graphical data. Similarly to a fish's eye, where the images are more detailed closer to the eye's focal point, a node using the FSR protocol has a better perception of its closer neighbourhood, updating information about more distant nodes with a lower periodicity.

As a link-state routing protocol, the FSR protocol maintains a topology map of the network at each node. However, instead of flooding a network change when it is detected, it proposes a different scheme for information dissemination [26].

In order to reduce routing control overhead, instead of sending routing updates at a fixed period, the FSR protocol uses different time intervals to exchange its routing information with nodes at different distances. Each node receives routing updates from further away nodes less frequently, maintaining a less accurate view of distant routes. However, whenever data is forwarded through the network, the precision of the used routes gradually improves as it gets closer to the desired destination.

3.2 Hierarchical Proactive Routing Protocols

The definition of specific hierarchies by different routing protocols has commonly been used, aiming at keeping the protocols more scalable. In contrast with typical flat routing protocols, hierarchical protocols usually exchange their routing information in different ways, according to a cluster or node hierarchy level.

The usage of hierarchies in conjunction with proactive routing approaches can be observed as a hierarchy of clusters, as an organised tree of addresses, or even as trees of paths forming a topology. Several schemes exist and all attempt to efficiently handle routing with the least overhead possible, as presented next.

3.2.1 Source-Tree Adaptive Routing Protocol

The Source-Tree Adaptive Routing (STAR) protocol [27,28] is a link-state protocol which has on average less overhead than on-demand routing protocols. Its bandwidth efficiency is accomplished by restraining the dissemination of link-state information only to the routers in the data path towards the desired destinations. STAR also creates paths that may not be optimal while avoiding loops, such that the total available bandwidth is increased. Moreover, STAR has specific mechanisms to know when update messages must be transmitted to detect new destinations, unreachable destinations, and loops.

Despite being able to scale, as each node only maintains a partial topology graph of the network, the STAR may suffer from large memory and processing overheads in scenarios where constant mobility may report different source trees, and routing paths are too big due to the network size.

3.2.2 Multimedia Support in Mobile Wireless Networks

The work entitled Multimedia support in Mobile Wireless Networks (MMWN) [29], the authors propose an architecture consisting of two main elements, corresponding to different node types, which can either be switches or endpoints. Both of these can be mobile, however only switch nodes can route packets and only endpoints can be sources or destinations for packets. This protocol also keeps a cluster hierarchy as a location management scheme, capable of obtaining the address of an endpoint. This information is kept as a dynamic distributed database, such that in each node there is a location manager node.

The proposed hierarchy allows the necessary amount of routing messages to be reduced, as only location managers are required to update their information and only then perform the location finding process [30]. However, this aspect is also negative on the overall performance of the protocol, as routing is strongly related with the hierarchy of the network, making the routing process complex and more vulnerable to disruptions when location managers change.

3.2.3 Cluster-Head Gateway Switch Routing

Using the mechanisms introduced by DSDV, another proactive hierarchical routing protocol is the Cluster-head Gateway Switch Routing (CGSR) protocol [31], which uses a routing approach where clusters are formed by electing a cluster head node, aiming to reduce the communication overhead, and thus making routing scalable and efficient. After the election of a cluster head, all nodes within its range will be considered as belonging to that cluster and all route updates should be done within its scope. All route discovery packets are forwarded through the cluster-head node.

One important task of this protocol is, essentially, the clusterhead election process. Authors argue that, when using distributed clustering algorithms, two possible choices are the lowest-Identifier (ID) algorithm and the highest-connectivity (degree) algorithm. The most important aspect to be taken into consideration when picking a clustering algorithm is stability. In order to avoid constant cluster head changes, which can harmfully impact the performance of other underlying protocols being used (such as DSDV), the algorithm chosen by the CGSR protocol is the Least Cluster Change (LCC) clustering algorithm [32]. This clustering algorithm is proposed as an improvement to existing algorithms, achieving enhanced stability.

Even though the proposed two-level cluster hierarchy may reduce the amount of flooding for dissemination of routing information, as only the cluster-heads are responsible for this task, the process of maintaining these clusters involves additional overheads, in particular the election of an appropriate cluster-head node. Moreover, this special node will always represent a bottleneck on each cluster, overloading it and possibly leading to a faster energy depletion and consequent cluster-head re-election.

3.2.4 Cluster-Based OLSR Extensions to Reduce Control Overhead in Mobile Ad Hoc Networks

The work entitled "Cluster-based OLSR (C-OLSR) extensions to reduce control overhead in mobile ad hoc networks" [33], proposes an extension to the OLSR protocol by introducing a cluster organised network. The authors propose a scheme where the existing clusters are considered as nodes themselves, using the MPR concept created by OLSR applied to clusters. This structure, in conjunction with the definition of Cluster *HELLO* (C-*HELLO*) and Cluster Topology Control (C-*TC*) messages, allows the maintenance of paths among the existing clusters while reducing the required amount of routing information, as only MPR Clusters generate C-*TC* messages.

Even though this paper uses the OLSR protocol for intra-cluster routing, proposing the mentioned C-*HELLO* and C-*TC* extensions to support a clustered network, the propagation of these new messages across clusters may have a negative impact. Moreover, the proposed mechanisms may suffer from mobility phenomena which, as in other approaches, require an additional overhead of updating the entire network structure.

3.2.5 Dynamic Address Routing for Scalable Ad-Hoc and Mesh Networks

Inspired on a previously work on a Dynamic Addressing paradigm, the authors propose Dynamic Address Routing (DART) for Scalable Ad-hoc and Mesh Networks [34], a proactive hierarchical approach that efficiently manages the organisation of nodes into zones for large scale networks. Address allocation and lookup are the main drawbacks of this proposal. However, the published work presents schemes to tackle these problems, showing how addresses can be allocated taking into account node positioning, by building a tree with l levels where l is the number of bits used in the routing address. A clear distinction is made between routing address and the identity of a node (a unique identification tag) since the routing address is dynamic and changes with node movement, contrasting with the node identifier which is always the same.

The three most important functionalities in DART are, first, the address allocation responsible for maintaining one routing address per network interface according to the movement and current position of a node; second, the routing which determines how to deliver packets from source to destination and, finally, the node lookup which consists in a distributed lookup table in charge of mapping identifiers to network addresses.

The DART proposal reveals to be an efficient solution for routing in large scale Adhoc networks. However, for small networks the Dynamic Address Heuristic has a strong overhead impact and in general it is difficult to implement, as the distributed lookup table is hard to manage.

Tree-Like Distance Vector

Inspired by the work presented in DART, the Tree-like Distance Vector (TLDV) routing protocol [35] uses a $2^b - ary$ tree locator and Distributed Hash Table (DHT), as opposed to DART's binary tree. The protocol also maintains at each node a routing and a neighbourhood table, being the routing table organised into $\lceil \log_{2^b} N \rceil$ rows with $(2^b - 1)$ entries each, in a network with N nodes. A major contribution from the TLDV protocol is not being restricted to the binary tree used by DART, exploiting a different space structure. However, the choice of parameter b needs careful consideration and strongly depends on the network's intrinsic properties. A trade-off between lower and higher values of b must be achieved between the size of the routing table, the amount of available locators and also route efficiency.

3.2.6 Deferred Routing Protocol

The Deferred Routing (DefeR) [36] approach consists on efficiently handling routing in clustered networks by defining a multiple view network hierarchy, achieved by aggregating clusters into different levels and by postponing routing decisions throughout traversed clusters until the final destination is reached [37]. Moreover, this routing protocol considers an enhanced mechanism that selects the most appropriate gateways by resorting to a link quality estimator [38].

This network organisation resembles the cartographic division of the world into continents, countries and cities, assigning identifiers with different granularities to each region. Another work with a similar approach, inspired by computational geometry techniques, is the Greedy Distributed Spanning Tree Routing protocol [39], which defines convex hull trees using nodes' absolute position information, which may not always be available, in order to optimize the routing process by sending packets to hulls which contain the desired destination's position.

In DefeR, a tree organisation of clusters is considered and, instead of traversing the entire tree looking for the desired cluster destination, the search can be optimized to a complexity of $O(\lfloor \log_2(n+1) \rfloor)$, for n clusters, without using any geographical position information [40]. Therefore, routes are established according to the cluster hierarchy, exploiting the different granularity levels of clusters within clusters. Moreover, the reliability of the links between clusters is taken into account, rather than minimizing the total hop count from source to destination.

One key advantage of using Deferred Routing is that, by keeping its optimised network hierarchy, it is able to limit not only the effects of micro but also macro-mobility, as clusters not involved in the mobility process of nodes are oblivious to changes in other clusters. Moreover, DefeR does not require additional routing messages for inter-cluster routing, being adaptable to any available link-state routing protocol with small changes to their own routing messages. The hierarchy employed by DefeR is based on a binary tree structure, motivated by the bisection that occurs in growing clusters and also by the base-2 logarithmic complexity of balanced binary-search-trees.

4 Reactive Routing Protocols

Proposed as an alternative to the expensive periodic update of proactive routing schemes, reactive protocols were introduced, performing route discoveries on-demand to avoid the waste of resources experienced with proactive solutions. This approach seems more suitable for mobile Ad-hoc networks where topology changes occur constantly. However, on-demand solutions suffer from an initial delay on retrieving a routing path which may not be acceptable, while at the same time the flooding of Route Request (RREQ) for route retrieval also adds an increased network overhead. In fact, several works aim solely at reducing the Broadcast Storm Problem (BSP), which was named after the broadcasting process typically involved in the dissemination of routing information of on-demand routing protocols [41].

4.1 Flat Reactive Routing Protocols

Similarly to proactive routing protocols, reactive approaches for wireless multi-hop routing can also be divided in two different categories where either flat or hierarchical network organisations are considered.

4.1.1 Ad Hoc On-Demand Distance Vector Routing Protocol

Designed for mobile wireless Ad-hoc networks, the Ad hoc On-demand Distance Vector (AODV) [42] routing protocol requires low memory and processing, while providing quick adaptation to dynamic link conditions. In addition to this, AODV has a low communication overhead and provides loop-free unicast routes in a reactive way, without having to maintain routes to destinations that are not currently in use.

Upon a request of a route to a destination, RREQ Packets are broadcasted throughout the network nodes until they reach their final destination or, alternatively, until an intermediate forwarding node, already containing an active/updated path to the destination, responds with a Route Reply (RREP) packet. Since each forwarding node keeps a reference of the source node triggering a RREQ, as well as the neighbour node likely to be used as next hop towards that destination, when processing a response message (a RREP), a node will route it back along the expected hops until it reaches the source node, making the new path available [43].

For efficiently managing the above described process, AODV uses sequence numbers to avoid loops and keep awareness of updated routes. Additionally, an assumption of bidirectional links is also present when a RREP is sent to its originating node. However, if unidirectional links exist, an alternative procedure needs to be used, in order to allow these packets to be correctly replied.

One important practice to be considered in AODV is the usage of an expanding ring search technique. This measure aims at preventing unnecessary network-wide dissemination of RREQ messages by controlling the extent to which these packets are broadcasted. This optimisation can be achieved by effectively setting some AODV specific parameters to the most appropriate level.

In order to keep accurate information about the active routes and avoid disruptive failures, each node monitors the link status of their next hops in these paths. The monitoring process is typically achieved by exchanging *HELLO* messages through the links, even though other mechanisms may be used. Upon the detection of a link break, a Route Error (RERR) message is used to notify the other nodes present in the path that a link loss occurred. Then, after receiving this message, the source node may decide to re-trigger a new RREQ, setting up a new route. Some extensions to AODV have already been proposed to address this specific point, for instance the Ad hoc On-demand Distance Vector Backup Routing (AODV-BR) Protocol [44].

The authors propose a modified version of the AODV protocol which not only uses the Expanded Ring Search (ERS) mechanism, but also a new approach named Hop Prediction, which improves the route search used by AODV. History records are maintained to each discovered route in order to optimise the ERS and reduce the overall routing overhead.

4.1.2 Dynamic Source Routing Protocol

An example of a completely reactive protocol with support of unidirectional links is the Dynamic Source Routing (DSR) [45] protocol proposed in the IETF MANET working group [46]. Aiming at scalability, in a network of at most two hundred nodes, the DSR protocol provides a soft-state approach where the two basic operations are Route Discovery and Route Maintenance, supporting asymmetric routes and assuming a typically small network diameter.

Designed for Internet Protocol version 4 (IPv4) addresses, provided by any mechanism such as Dynamic Host Configuration Protocol (DHCP) for dynamic assignment or static configurations, the DSR protocol is a loop-free protocol capable of quickly adapting to network topology changes. These adjustments of the topology only have an impact on the protocol when they affect paths currently active, being ignored by any other nodes. However, in order to avoid routing based only on flooding, topology changes related with mobility or other circumstances are not expected to happen so fast that the DSR protocol cannot adapt.

DSR uses explicit source routing, where an ordered list of nodes through which the discovery packet will pass, from source to destination, is used to allow multiple paths that enable the usage of load balancing mechanisms [47]. It also enhances the protocol robustness by tolerating path failures, choosing alternative ones immediately. Route caching is also an interesting feature that results from the forwarding and overhearing nodes' action of gathering information that can be used in the future, avoiding the Route Discovery process. When queried about a path, by performing a search in its local cache, a node can immediately retrieve the desired route and avoid further overheads of a Route Discovery process.

In the worst case scenario, when a complete Route Discovery has to be performed, the first node, the initiator, transmits a RREQ that will be broadcasted to all of the nodes until it reaches the destination node, the target. When this node is finally reached, it checks for a previous path cached to the initiator and sends a RREP. Otherwise it will start a new RREQ for the initiator, piggybacking the list retrieved by the first Route Discovery. Optionally, the target could simply reverse the path contained in the list given by the received RREQ, avoiding additional overhead but losing the asymmetric path support property.

Route maintenance in DSR states that each node is responsible for managing the flow over the link from that node to the next hop. This can be done either by using software or hardware acknowledgements, and a limited number of retransmissions. After the maximum number of retransmissions, a link is said broken and so the link is removed from Route Cache and a RERR is returned. If an alternative path exists in the initiator it shall be used, otherwise a new Route Discovery should be triggered.

4.1.3 Temporally-Ordered Routing Algorithm

Being a member of the link-reversal algorithms class, the multi-path and loop-free Temporally-Ordered Routing Algorithm (TORA) [48], is an on-demand source initiated routing protocol designed for multihop networks, which can also have destination initiated proactive routing for path optimisation and maintenance purposes.

Concerning routing, TORA routers only keep information about their one-hop neighbours and perform on-demand routing when retrieving a path to a destination. This operation performs best in networks with relatively sparse traffic patterns. At the same time, destination oriented mechanisms can also be triggered to maintain and monitor the path.

Summarizing TORA, it can be defined as four separate basic functions, namely creating routes, maintaining routes, erasing routes and optimising routes. For this, four different packet types are used: Query, Update, Clear and Optimisation [49]. TORA is an interesting protocol from the point of view that it does not use shortest paths to support its decisions and neither does it follow a link-state nor distance-vector algorithm.

4.1.4 Dynamic MANET On-Demand Routing Protocol

Much resembling with DSR and AODV, Dynamic MANET On-demand (DYMO) routing protocol [50] is a reactive loop-free routing protocol. Designed for networks with bidirectional links and capable of handling a wide range of mobility patterns, by dynamically determining routes in large scale networks, DYMO is best suited for sparse traffic scenarios. Having only to maintain minimal routing state information, it is a light-weight protocol applicable to devices with memory constraints.

The most relevant operations of the DYMO routing protocol are similar with DSR's Route Discovery and Route Maintenance. The former starts with the initiator node by sending a RREQ Packet to be broadcasted by all nodes until it reaches the desired target destination, which then replies with a RREP Packet through the best path, defined by a list that contains all the RREQ forwarding nodes. In order to reduce RREQ overhead, a forwarding node containing an active path to the destination may automatically respond with a RREP packet on behalf of the target node, avoiding further propagation of messages. An additional consideration is the usage of an adequate value for the HopLimit parameter which, to delimit the expanding ring of a RREQ, may be defined as described for the AODV protocol.

Complementing the above presented process, the Route Maintenance procedure is responsible for safeguarding the existing routes in use [51]. Route lifetime is extended by routers whenever a packet is correctly forwarded or a RERR packet is sent towards the packet source to indicate that the path contains an invalid or missing node. Additionally, by monitoring links over which traffic is flowing, any broken link detection should also immediately issue a RERR packet in order to swiftly notify DYMO nodes that certain routes are no longer available.

4.1.5 Associativity Based Routing

The Associativity Based Routing (ABR) [52] principle consists on the fact that after some migration process, where associativity ticks can be analysed, a certain stability time will exist, where a node will stay dormant within a cell before it moves again. The associativity tickets are analysed on the link layer level allowing to understand the degree of mobility of a node, where low associativity tickets are a synonym of a higher state of mobility and, on the other hand, high associativity ticks represent a stable state [53].

Route Discovery and Route Re-Construction are the two phases that compose the ABR protocol. During the Route Discovery phase a Query packet is broadcasted from source to destination, which then replies with a Reply message. The Query message is forwarded by every intermediate node that will keep the information of its upstream peer, removing it from the original packet and adding its own. If a duplicate Query is received by a node, it will be discarded. When a Reply message is sent back by the destination, nodes receiving this packet will set the path from source to destination as valid and active. Other nodes containing alternative paths will have them marked as invalid and will not relay packets to the destination, even if they hear the transmission.

Complementing the Route Discovery process, the Route Re-Construction phase handles possible failures caused by mobility or other situations by performing a partial route discovery, invalid route erasure, valid route update and, in the worst case scenario, new route discovery, which consists in the repetition of the entire processes described for the Route Discovery Phase.

4.2 Hierarchical Reactive Routing Protocols

The usage of Hierarchical Reactive Protocols is modest when compared with proactive or hybrid routing approaches. This is likely due to the fact that most well defined hierarchies require constant updates in order to be efficiently kept, going against the concept behind Reactive Routing, which only exchanges routing information when required. Nevertheless, some Hierarchical Reactive protocols do exist and are described in the following paragraphs.

4.2.1 Hierarchical AODV Routing Protocol

As the name indicates, the Hierarchical AODV (Hi-AODV) Routing Protocol [54,55] is a hierarchical version of the well known AODV routing protocol, using a tree based on cluster-heads for the creation of the concept of virtual nodes, which correspond to a typical cluster. The cluster-head is the only node responsible for handling control packets and managing the routing table of its own internal cluster. Having a tree composed of clusters seen as a virtual node allows Hi-AODV to reduce the number of control packets and avoid additional overhead.

In addition to the already mentioned challenges and overheads related to the maintenance of clusters and their cluster-heads (e.g. the cluster-head election process), again, it is clear that even though routing overheads can be reduced, the cluster-head will always have to be part of any routing path, leading to non-optimal paths, and additional interferences in the vicinities of cluster-heads.

4.2.2 Layered Cluster-Based Routing

The Layered Cluster-based Routing (LCR) protocol [56] is a hierarchical reactive protocol which exploits the main features of the Tiered Based Clustering Algorithm (TBCA) [57] also proposed by the same authors. This clustering scheme is organised into layered stages so that the number of nodes participating in the clustering process, at a given instant, is reduced. By the end of the clustering process a connected dominating set consisting of the elected Cluster-heads and Gateway nodes is formed.

Using an on-demand approach, the LCR protocol restricts its search space to the dominating set retrieved from TBCA. Whenever a new route is required to reach a destination, the initiating or source node broadcasts a RREQ and waits for a specific time interval before issuing a new request. This request is only propagated by dominating nodes, which maintain a table of previous requests (Table_request) in order to refrain a duplicate request, thus avoiding additional overhead. When the destination node receives a RREQ, similarly to the AODV protocol, it sends a RREP and initiates a route maintenance process which periodically exchanges *HELLO* messages between the nodes involved in the route, sending a RERR message if a route failure is detected.

Additional mechanisms used by LCR concern the sensing period of the source and dominating nodes. In fact, the source node's sensing wait time is set to a sensing period equal to Short InterFrame Space (SIFS), where the cluster-head's waiting time is equal to Point coordination InterFrame Space (PIFS) and the Gateway (GW)'s waiting time is equal to Distributed InterFrame Space (DIFS). These specific times are set in order to reduce the probability of collisions during the discovery phase.

Optimized Layered Cluster-Based Routing

An update to the LCR protocol was provided by its original authors [58], optimising the MAC-layer mechanisms to avoid collisions and defining a direction mechanism that reduces the number of dominating nodes involved in the routing process. This direction-based mechanism is free from any positioning techniques, such as Global Positioning System (GPS), using information included in the resulting layers from the clustering process and allowing dominating nodes to discard any RREQ when, for instance, it reaches higher layers than the layer where the destination is expected to be. In certain scenarios where this mechanism may not be available, the LCR protocol performs normally without any disadvantages.

5 Hybrid Routing Protocols

Recognising both the advantages and disadvantages of proactive and reactive routing protocols, hybrid routing protocols were proposed. The concept behind this new alternative is that the best of each approach (proactive and reactive) can be exploited together in the different tasks performed by a routing protocol.

5.1 Flat Hybrid Routing Protocols

Even though flat and hierarchical routing schemes can also be found in proactive and, even though less frequently, in reactive routing protocols, hierarchical routing approaches are usually more common in hybrid routing protocols which also consider flat network perspectives.

5.1.1 Zone Routing Protocol

Combining the advantages of the pro-active and reactive paradigms, the Zone Routing Protocol (ZRP) [59], proposes a zone based architecture where three embedded protocols, the Intra-zone Routing Protocol (IARP), the Inter-zone Routing Protocol (IERP) and the Bordercast Resolution Protocol (BRP), are responsible for maintaining the routing operation.

Assuming that a majority of the processed traffic occurs directly between neighbour nodes, the strategy of ZRP is to reduce the scope of proactive traffic into a zone centred on each node. The zones are defined as having a r radius expressed in hops, such that a zone includes nodes whose distance from a given node is at most r hops. Since zones overlap, ZRP is said to have a flat view of the network. This perspective results from the authors' statement that this approach can be used to detect optimal routes and to reduce network congestion.

The IARP is the protocol used within ZRP zones to proactively maintain routing tables up-to-date. In contrast, route discovery outside of a specific zone is made by the reactive IERP protocol. Using the information of IARP, an additional routing procedure is made by BRP, which consists in managing the packet delivery to the peripheral nodes in the border of a zone (bordercasting). The usage of this approach in conjunction with IERP allows a reactive route discovery to efficiently travel between zones [60].

The size of the zones used by ZRP can be managed by regulating the transmission power of devices (if such option is available). Additionally, mechanisms to efficiently and possibly dynamically choose r should be used, ensuring that a zone is big enough to provide a good connectivity between nodes, but not too big so that update traffic does not become excessive. However, such a dynamic process is complex and not easy to achieve [61]. Further works provide analytical models that determine the routing overhead incurred by the ZRP protocol and its variants. Some examples are the Independent Zone Routing Protocol (IZRP) [62], which proposes mechanisms for calculating the optimal zone radius of the node, being more efficient than the standard ZRP [63]. These mechanisms are known as min-searching and adaptive traffic estimation, and allow each node to have its own independent zone size. The Two-Zone Routing Protocol (TZRP) [64], that presents a zone-based architecture that decouples the (basic hybrid) protocol's ability to adapt to changing traffic patterns from the ability to adapt to different mobility models. And also the Fisheye Zone Routing Protocol (FZRP) [65], where the architecture defined by the ZRP uses Fisheye State Routing in its proactive operations.

5.1.2 Tooska Scheme and Mobility Aware Hybrid Routing

The Tooska Routing scheme [66] is a hybrid node-centric protocol which relies on AODV as its default routing protocol, switching to the Wireless Routing Protocol (WRP) [67] when appropriate. By selecting the nodes with more stable fixed neighbours, the core nodes, the protocol defines these intermediate nodes when data needs to be sent, through the analysis of the *HELLO* Message Counter (HMC) field stored by each node. Core nodes periodically update their routing tables by changing to the WRP protocol, informing all the remaining nodes of this change. In order to reduce the overhead introduced by the Tooska scheme, the number of core nodes is minimized by defining a minimum number of required stable neighbours.

Due to node mobility, the selection of core nodes can become inefficient in the Tooska scheme as it is proposed. Bearing this in mind, the Mobility Aware Hybrid Routing (MAHR) [68] defines an alternative selection method for core nodes, where the ratio of changing neighbour nodes is used. The routing process is similar to Tooska relying on the AODV protocol for route discovery, where the core nodes are responsible for the maintenance of routing tables by using the OLSR protocol.

5.1.3 Heat Routing for Ad-Hoc Networks

Parallel to the behaviour of heat trails in the physical world, wireless nodes using the Heat Routing for Ad-hoc Network (HRAN) protocol [69,70] emit a heat signal to be perceived by neighbour nodes. The amount of heat detected by each node depends on a gradient function such that nodes further away from the heat source register a lower level of heat when compared with 1-hop distant nodes.

The protocol's main mechanisms consist on the creation of a heat overlay, where each node proactively disseminates its topology information, with an amount of heat defined by a Time Aware Bloom Filter (TAB) which is a new type of Bloom Filter defined by the authors. The heat information is included in periodically sent *HELLO* messages, as the size of the used TAB never changes regardless of network size, creating a heat overlay or heat trails.

By using an on-demand approach, the second stage of the HRAN protocol consists on discovering a valid route from source to destination. This is achieved by issuing a predetermined number of Random Walk Request (RwREQ) queries, to be sent throughout the network. Upon receiving a RwREQ, a node checks if the received destination identifier is present in any of its registered heat trails. If a match is obtained, the random walk is terminated and a direct walk takes its place. This walk is started by sending a Follow Heat (FoHEAT) message which is only forwarded by nodes in the same heat trail, allowing the query to quickly reach the destination.

When a RwREQ reaches its intended destination node, it sends a Route Reply (RoREP) message to the source, using the discovered route, inverted. If after sending a RwREQ, a predefined time-out is reached and no RoREP is received by the source node, the protocol falls back to a typical reactive source routing protocol such as AODV. This mechanism is important as it allows the creation of heat tunnels which otherwise are only created after a route establishment, during the route maintenance process.

The final contribution of the HRAN protocol is the maintenance of routes which include the creation of heat tunnels, achieved by adding the destination's identifier in the proactively sent routing messages. This creates a "highway" for future route requests to this destination. Moreover, this process also ensures that failed routes are repaired by sending Route Repair (RoREPAIR) messages and it further aims at improving the found routing path. Since the first retrieved path may not be the shortest path due to the randomness of route discovery process, an additional message named as Route Improvement (RoIMP) is sent by the source within the heat tunnel, until it reaches the destination. In its turn, the destination sends back to the source a new RoREP, using an inverted more efficient path.

5.2 Hierarchical Hybrid Routing Protocols

Quite a few Hybrid Routing protocols for Ad-hoc networks can be found in the literature, however, despite the fact that many rely on clusters or well defined zones, not many implement a hierarchical routing scheme. The following protocols propose a hybrid routing scheme capable of retrieving inter-cluster information in a reactive approach, avoiding the necessity of restraining routing information in cluster-heads to reduce the overall overhead. However, on a downside, inter-cluster communication may be subject to route retrieval delay if no previous path has been maintained in cache.

5.2.1 Zone-Based Hierarchical Link-State Routing Protocol

The Zone-based Hierarchical Link-State (ZHLS) Routing Protocol [71], is characterized by dividing the network into non-overlapping zones where two different routing paradigms are used: proactive routing within the zones and reactive between different zones. This proposal alleviates single points of failure and bottlenecks by not being dependent on cluster-head nodes and, at the same time, by maintaining a scalable hierarchy based topology.

One important assumption, and a possible limitation from this protocol is that each node knows its own position (for instance, by using GPS) and consequently its zone ID which is directly mapped to the node position. With this approach, packets are forwarded by specifying in their header the zone ID and node ID of their destination.

The division of the network into a number of zones depends on factors such as node mobility, network density, transmission power and propagation characteristics. The geographic awareness is much more important in this partitioning process as it facilitates it when compared to radio propagation partitioning [72].

In addition to the limitation of requiring some positioning system, the ZHLS protocol requires that all nodes exchange inter-zone flooding information when only gateway nodes need this routing information for calculating the shortest path between different zones. Moreover, the ZHLS is susceptible to a route retrieval delay when establishing inter-zone paths, as reactive routing is used for this purpose.

In ZHLS, each node contains an intrazone and interzone routing table to manage routing between nodes from a same zone and from different zones respectively. The update of these tables is performed, by sending two types of Link State Packets (LSPs), node LSP and zone LSP for intrazone and interzone, in that order.

A proposal to enhance the routing, by ZHLS is given in [73], where the ZHLS Gateway Flooding (ZHLSGF) scheme is defined to reduce routing overheads and reduce routing tables' size. This modification is closely related with the nodes that act as a border between different zones, since they are responsible for calculating the shortest path between other gateway nodes, only sending interzone discovery packets between each other, thus avoiding unnecessary packet forwarding to other nodes within the zone.

5.2.2 Distributed Dynamic Routing

Another hierarchical hybrid routing protocol, the Distributed Dynamic Routing (DDR) algorithm [74], for mobile Ad-hoc networks, is a tree based routing protocol which consists of six different stages where an election of the preferred neighbour is made, followed by the forest construction which creates a suitable structure for the wireless network, allowing an improved resource utilisation. Afterwards intra and inter tree clustering is performed, followed by zone naming and partitioning. Zones are responsible for maintaining the protocol scalable and reducing the delay.

While DDR creates and maintains a dynamic logical structure of the wireless network, the Hybrid Ad Hoc Routing Protocol (HARP) [75] finds and maintains routing paths. The HARP protocol aims at discovering the most suitable end-to-end path from a source to a destination by using a proactive intra-zone routing approach and a reactive inter-zone scheme, by performing an on demand path discovery and by maintaining it while necessary.

Even though the DDR algorithm does not require any sort of cluster-head for cluster maintenance, the possibility of some nodes being chosen as preferred neighbours by other nodes may lead to the creation of bottlenecks, as they would be required to transmit an increased amount of both routing and data packets. It is important that the choice of preferred neighbours is balanced so that the overall performance of the protocol does not get compromised. Moreover maintaining the entire logical structure of the network may be somewhat heavy, depending on how dynamic nodes may be [76].

5.2.3 Cluster Based Routing Protocol

Aiming at a scalable, loop free routing protocol with support for asymmetric links, the Cluster Based Routing Protocol (CBRP) [77] proposes a variation of the "Min-Id" [78,79] for cluster formation, in which the purpose is to create a hierarchy consisting of overlapping 2-hop-diameter clusters where a node is elected as cluster head, responsible for maintaining cluster membership information. By exploiting the cluster architecture, flooding traffic used in the routing process is minimized.

As a 2-level hierarchy, this protocol can be scalable to a certain extent, however, the typical cluster formation and cluster-head election overhead still exists. Even though node mobility does not necessarily lead to inaccurate routing table calculations, as it would happen with a purely proactive approach, the inherent route retrieval propagation delay may lead to temporary loops.

In the Routing Process, RREQ packets are flooded from source to destination, but only cluster head nodes are used in this process. When these packets reach the target, a RREP is sent back to the initiator node [80]. Even though this process is triggered by an on-demand request, additionally, every node within a cluster zone periodically exchanges with its neighbours routing table information by using *HELLO* packets. This pro-active behaviour in conjunction with the reactive on-demand requests positions the CBRP within the hybrid family of routing protocols.

In addition to the Routing process, the CBRP also defines two other major components which are Cluster Formation and Adjacent Cluster Discovery. The Cluster Formation process consists on the usage of a variation of the "lowest ID" clustering algorithm where a set of rules for electing the cluster head are defined. Wrapping the whole protocol, the Adjacent Cluster Discovery process aims at discovering all bi-directionally linked adjacent nodes. The process is executed by broadcasting the summarised Cluster Adjacent Table of each cluster head as Cluster Adjacency Extension to the *HELLO* messages.

6 Routing Protocols' Complexity Analysis

Despite all the presented mechanisms, proposed by each routing protocol, they are all subject to certain limitations and may fail in their purpose of scaling in large networks. Regarding the scalability of existing routing protocols their communication and storage complexity play an important role. Even though hierarchical solutions aim at being more scalable, this is not always true, since the complexity of these protocols is not necessarily better than flat solutions. Therefore, for each class of routing protocols, considering the defined taxonomy, a comparison table highlighting the techniques used by each routing scheme as well as their complexity communication and storage complexity will be provided.

6.1 Flat Proactive Routing Protocols – Comparison

Proactive routing protocols stand out for always maintaining routes to all the available destinations. In flat organisations clustering is not typically used however other scalability mechanisms can be found. Table 1 shows these mechanisms for the presented routing protocols and analyses their complexity regarding storage and communication.

6.2 Hierarchical Proactive Routing Protocols – Comparison

Even though hierarchical proactive routing protocols present more scalability oriented features than flat ones, the communication and storage complexities are not necessarily better. Moreover, the mechanisms used for this purpose, presented in Table 2 can be quite complex and introduce additional overheads that are not accounted as routing overheads. Nevertheless, the analysed routing protocols require that all the presented aspects are available and therefore may not be as flexible as desired.

Table 1. Comparison of Flat Proactive Routing Protocols

Protocol	Cluster-based	Scalability Techniques	Communication	Storage
DSDV	no	n/a	$O(N^2)$	$O(N)$
FSR	no	fisheye updates	$O(N^2)$	$O(N)$
OLSR	no	MPR nodes	$O(M^2)$	$O(N)$

N : Total number of nodes
M : Total number MPR nodes

Table 2. Comparison of Hierarchical Proactive Routing Protocols

Protocol	Cluster-based	Scalability Techniques	Communication	Storage
CGSR	yes	Cluster-head	$O(C^2)$	$O(N)$
C-OLSR	yes	Cluster-MPRs	$O(C^2)$	$O(N)$
DART	yes (zones)	Dynamic Addresses	$O(\log_2 N)$	$O(N)$
DefeR	yes	Deferred Routing and Aggregated Networks Views	$O(C)$	$O(N)$
MMWN	yes	Location Managers	$O(N^2)$	$O(N)$
STAR	no	Partial Topology	$O(N)$	$O(D)$

N : Total number of nodes
D : Total number of destinations
C : Average number of nodes per cluster

6.3 Flat Reactive Routing Protocols – Comparison

Reactive routing protocols aim at being more lightweight than proactive ones by sending routing information only when necessary. However, this approach may result in expensive flooding of RREQ whenever a route is required. In addition to this limitation, which is more critical in scenarios with several traffic flows, these protocols also suffer from a route retrieval delay. The communication and storage complexity of reactive protocols is expected to be lower than a proactive routing protocol, as they only consider the necessary destinations. However, in a worst case scenario for reactive routing protocols, each node may be a source and destination node, resulting in a complexity similar to proactive protocols, as shown in Table 3.

Table 3. Comparison of Flat Reactive Routing Protocols

Protocol	Cluster-based	Scalability Techniques	Communication	Storage
ABR	no	Associativity Tickets	$O(N^2)$	$O(N)$
AODV	no	modified ERS	$O(N^2)$	$O(N)$
DSR	no	n/a	$O(N^2)$	$O(N)$
DYMO	no	HopLimit	$O(N^2)$	$O(N)$
TORA	no	Directed Acyclic Graph	$O(N^2)$	$O(N)$

N : Total number of nodes

6.4 Hierarchical Reactive Routing Protocols – Comparison

In the existing literature there are few Hierarchical Reactive Routing protocols since maintaining a hierarchy typically requires constant updates. Table 4 compares the performance of the two protocols which depend entirely on the robustness of the used clustering processes.

Table 4. Comparison of Hierarchical Reactive Routing Protocols

Protocol	Cluster-based	Scalability Techniques	Communication	Storage
Hi-AODV	yes	Cluster-heads as Virtual Nodes	$O(C^2)$	$O(N)$
LCR	yes	TBCA	$O(C^2)$	$O(N)$

N : Total number of nodes
C : Total number of dominating nodes or cluster-heads

6.5 Flat Hybrid Routing Protocols – Comparison

Table 5 presents a comparison of the main characteristics of the analysed hybrid routing protocols with a flat network organisation. As a direct consequence of employing both proactive and reactive routing protocols their complexity is similar to these protocols. However, these protocols also provide optimisations that may enhance the protocols performance in many situations. Moreover, the usage of zones by ZRP reveals an alternative to achieve a more scalable routing process.

Table 5. Comparison of Flat Hybrid Routing Protocols

Protocol	Cluster-based	Scalability Techniques	Communication	Storage
HRAN	no	Heat overlay	$O(N^2)$	$O(N)$
Tooska	no	HMC	$O(N^2)$	$O(N)$
ZRP	yes (zones)	Variable zone radius	$O(Z^2)$	$O(\frac{N}{Z})$

N : Total number of nodes
Z : Total number of zones or cluster-heads

6.6 Hierarchical Hybrid Routing Protocols – Comparison

Hierarchical Hybrid routing protocols provide most of the existing advantages in the previously analysed protocols. Their mechanisms and complexity are presented in Table 6, revealing that in a worst case scenario these protocols have similar complexities. The tree-based DSR protocol has a higher communication complexity as it constructs its own forest of connected zones, therefore being more complete than other protocols.

Table 6. Comparison of Hierarchical Hybrid Routing Protocols

Protocol	Cluster-based	Scalability Techniques	Communication	Storage
CBRP	yes	2-level Hierarchy	$O(\frac{N}{Z}^2)$	$O(N)$
DSR	yes (zones)	Preferred Neighbours	$O(N^2)$	$O(N)$
ZHLS	yes (zones)	No Cluster-heads	$O(\frac{N}{Z}^2)$	$O(N)$

N : Total number of nodes
Z : Total number of zones or cluster-heads

6.7 Summary and Considerations

In the existing literature several routing protocols have been created for Mobile Adhoc Networks. However not all of these protocols provide a significant new approach for routing, being many times small extensions of the most relevant routing schemes. Moreover, many works rely on complex or even unrealistic assumptions which are not suitable for dynamic networks such as MANETs.

The presented analysis of current routing protocols for MANETs highlighted the contributions provided by routing protocols separated into different routing classes, taking also into account improvements made to and provided by these protocols. Nevertheless, several issues still exist, motivating the creation of new routing mechanisms for increasingly larger autonomous networks.

The comparison of the analysed protocols showed that reactive routing protocols are not necessarily more scalable in worst case scenarios where many flows exist. Moreover, it also demonstrated that cluster-based alternatives are able to maintain a smaller communication complexity. Even though the most scalable approach is provided by the DART protocol, regarding the communication complexity, the mechanisms necessary for this scalability to be achieved involve themselves additional overhead which is neither accounted as communication nor storage complexity.

Moreover, in the presented taxonomy it becomes clear there are more proactive and reactive routing protocols, reflecting the IETF MANET working group decision to maintain only two main routing protocol approaches. In particular, there are several more proactive protocols rather than reactive ones, showing a trend in what is expected from Mobile Ad-hoc Networks. This shows that generally, the purpose of ad-hoc networks will be related with large-scale dense scenarios, where mobility is expected to be moderate.

7 Performance Analysis Methodology

The presented literature analysis shows that, despite the initial trend on Ad-hoc networks to follow reactive approaches due to mobility, a large number of works have moved towards proactive routing protocols, guaranteeing increased support for large-scale networks where mobility may still be present. Bearing this in mind, and for comparison purposes, the presented evaluation considers the popular OLSR protocol and two other alternatives C-OLSR and DefeR. These comprise, respectively, three different proactive routing approaches, employing flat un-clustered routing, flat clustered routing and hierarchical clustered routing. By analysing the three approaches it is easier to understand which technique is more suitable for large-scale networks. The OLSR protocol was chosen as a control subject, providing a basis for comparison due to its stability and popularity in MANETs, being a standard protocol – currently under improvement by the MANETs IETF working group in its second version [21] – and the other two for being evolutions of this protocol.

7.1 Objectives

In order to understand to what extent the existing Ad-hoc networks can scale, the presented performance evaluation will simultaneously assess, in different conditions, several routing aspects and metrics. The relevant parameters will be explained and varied, triggering different changes in performance of the already mentioned routing protocols. These changes are then analysed and conclusions about the impact of each change will be provided.

Such an analysis was not possible using a real testbed due to the involved network dimension and therefore a simulation environment was considered, allowing a significant amount of different repetitions and a proper validation of the presented analysis, as well as an accurate generalization of the scalability performance of the protocols.

7.2 Simulation Conditions

The provided results were obtained using the OPNET Modeler Wireless Simulator [81], where the considered wireless nodes follow the Institute of Electrical and Electronics Engineers (IEEE) 802.11g standard [82] at 2.4Ghz, and have a maximum range of 100 meters (Transmit Power of $3.7e^{-4}W$), which corresponds to the maximum obtainable range of common wireless cards [83,84], unless stated otherwise. Nonetheless, due to the accurate radio model implemented by default in the OPNET Simulator, asymmetric links or even unidirectional links may occur, as well as channel errors and multi-path interferences respectively. Moreover, the Consultative Committee on International Radio (CCIR) propagation model was used, configured to represent a small to medium city with a building coverage of 15.8 percent, as it is considered as an appropriate propagation model for MANETs [85]. The usage of this simulation environment strives for being more realistic when compared with other works, which use the outdated 802.11b with non-standard MAC layers and unlikely ranges (for instance, 250m). Each evaluated scenario has specific variations of several simulation parameters since they independently assess different characteristics. Simulation parameters not mentioned here or in the definition of the scenarios are defined with the values used by default in the OPNET Modeler Wireless Suite Simulator, version 16.0.A PL1.

All the different parameters varied in each of the defined scenarios were obtained after 30 runs per parameter, always using different seed values and the Linear-Congruential Random Number Generator Algorithm, for a total simulated time of 15 minutes (900 seconds per run), which allows routing protocols to be appropriately evaluated by guaranteeing enough mobility [86].

Taking into account the defined objectives of this evaluation and their statistical validity, all the presented results have a 95% confidence interval obtained from the central limit theorem, which states that regardless of a random variable's actual distribution, as the number of samples (i.e. runs) grows larger, the random variable has a distribution that approaches that of a Normal random variable of mean m, corresponding to the same mean as the random variable itself.

7.3 Evaluation Metrics

As previously mentioned, in order to provide a thorough evaluation of the chosen MANET routing protocols and their behaviour in large-scale networks, it is important to simultaneously assess the performance of different routing aspects, choosing appropriate comparison metrics. For this purpose the following items were considered in provided evaluation:

- Traffic Delivery Performance
  - Losses
  - End-to-end Delay.

- Routing Performance
  - Path Length
  - Routing Stability
  - Control Traffic Overhead.

Taking these different aspects into consideration, this performance assessment must involve the evaluation of a large scale network, measuring the stability and overhead of this concept, as well as its overall traffic delivery performance. Moreover, in order to allow a more exhaustive evaluation it is important to determine the protocol's ability to handle mobility phenomena, introducing dynamic scenarios with different mobility models.

The average percentage of losses and end-to-end delay reflect a protocol's competency to choose suitable paths and are taken into account in this evaluation in all the presented scenarios. The percentage of losses strongly influences the applicability of a routing protocol in different scenarios. However, in Mobile Ad-hoc Networks a high number of losses is expected due to its inherent nature, where nodes are intermittently connected and where interferences and collisions are frequent [87]. Moreover, the delay metric is also subject to these interferences, limiting the usage of real-time applications in some scenarios. Nonetheless, in an extreme outlook, where only MANETs may be available, the registered losses may not be significant and retransmission mechanisms can be used to successfully deliver the required data.

A different routing metric considers the path length (hop count), from source to destination, which typically is minimized by routing protocols in order to reduce the number of nodes that intervene in the data delivery process. By reducing the number of hops, protocols are expected to be more energy efficient. However, this is not always the best option, as bottlenecks may arise and collisions will not only originate more losses but also a faster energy depletion on nodes in "popular" paths. Regarding this aspect, the DefeR protocol follows a different approach from the other two, choosing paths that minimize the total number of cluster-hops, selecting the most suitable GW nodes according to their quality.

In addition to these metrics, it is also important to measure the required resources and, therefore, routing traffic overhead, as well as the stability of the existing routes. Regarding the latter aspect, mobility of nodes is responsible for most of the topology changes and it is the protocol's task to efficiently handle these changes.

The topology awareness of a routing protocol is a metric representative of a routing protocol's stability and knowledge about the network's structure, registering topology changes during the simulation. A topology change occurs whenever a new *TC* or a *TC* with a higher sequence number is received and also when a *TC* entry is deleted after expiry. Each topology change triggers a routing table recalculation, however, in order to reduce computational overhead, the routing table is only recalculated by default at most every 1 second, processing all the received topology changes between each recalculation. Such technique is compliant with the OLSR specification and used in existing implementations [88,89]. Moreover, all the analysed protocols use this improvement in order ensure a fair comparison between them.

The amount of processed topology changes in routing table calculation reflects a protocol's stability and will also be analysed, referred as Average Topology Changes per Routing Table calculation (AToCRT) and defined by equation 1.

$$ATоCRT = \frac{\text{Number of Topology Changes}}{\text{Number of Routing Table Calculations}} \quad (1)$$

The number of routing table calculations possible in a T seconds simulation is defined in equation 2, with i being the simulation instant where n Topology Changes occur. Since the number of topology changes is influenced by the mobility of nodes, the different speeds used in an evaluation will be reflected in the AToCRT metric and also on the total number of routing table calculations. In particular, with higher speeds, an increased number of Topology Changes throughout the time will trigger a higher number of routing table calculations, with a maximum of 1 per second, as defined by $f(n)$.

$$\text{Routing Table Calcs} = \sum_{i=1}^{T} f(TopologyChanges_i),\ f(n) = \begin{cases} 0 \text{ if } n = 0 \\ 1 \text{ if } n > 0 \end{cases} \quad (2)$$

Topology Changes are propagated by *TC* messages sent by MPR nodes. These messages are forwarded to all the elected MPR nodes and represent most of the routing overhead, as they are the only forwarded messages sent throughout the network. The number of forwards per *TC* messages must then be analysed, in order to correctly assess the scalability of a protocol.

The overall routing overhead must also be considered taking into account the periodically sent and received routing traffic from both *HELLO* and *TC* messages. This will also reflect the protocols' ability to handle a large number of nodes.

Regarding the creation of clusters used by both the DefeR and C-OLSR protocols, a static definition of the areas comprised by each cluster was used and a mechanism for the nodes to automatically update their Cluster Identifier (CID) was implemented. However, this approach does not guarantee a constant density of nodes within each cluster. Such limitation impacts the performance of both protocols, since, in a worst case scenario, all the nodes might move into one single cluster. Nonetheless, in a realistic scenario clustering algorithms may not be able to guarantee constant density unless they introduce limitations of their own (such a single-hop cluster coverage) [90].

8 Simulation Results

The performance of a routing protocol can be assessed through several parameters. Typically, a protocol's competency to deliver data packets successfully, paired with the end-to-end delay of the chosen path, determines whether a protocol has a good performance or not. However, in Mobile Ad-hoc Networks there are several other metrics and characteristics that must be analysed. The presented simulation results consider the already introduced evaluation metrics that are indicative of the protocols' behaviour taking into account scalability and resilience to mobility.

8.1 Scalability Assessment

In order to assess how scalable the mechanisms of a protocol are, a set of results where the total number of nodes increases should be obtained. By increasing the number of traffic flows, it is also possible to understand how the protocol handles not only the size of the network, but also how it copes with a demanding network where several routes must be established.

Following an approach where a growing size network is used, the total number of node clusters is incremented presenting a scalability evaluation of the routing protocols. This evaluation depicts the behaviour of these protocols with both small and large-scale networks. It is a straightforward assessment which somewhat disregards the nature of MANETs, as it does not take into account the natural behaviour of moving people, being entirely random regarding both mobility and traffic flows.

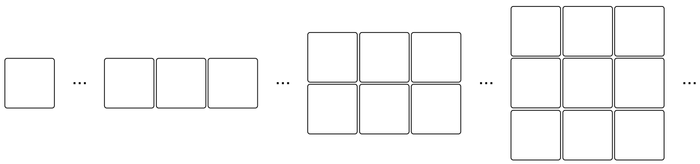


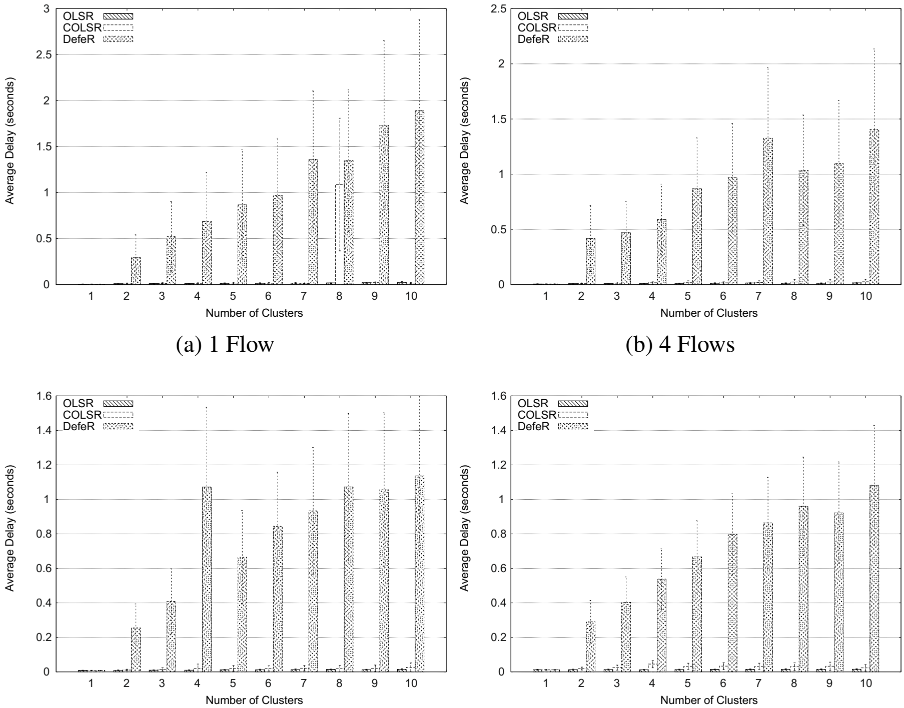
Fig. 2. Increasing Number of Clusters

A set of results from 1 cluster up to 10 clusters is provided, where each cluster has 49 nodes (which is the best number of nodes handled by OLSR [91]). The dimension of each cluster is of $500 \times 500m$, ensuring an initial constant density of the network. Figure 2 depicts the configuration of the network used in this scenario.

Regarding the smaller simulated networks with one cluster, both C-OLSR and DefeR behave exactly like OLSR, as both use it for intra-clustering and no inter-cluster operations are required. The provided results for smaller networks are important as other protocols designed for large-scale networks, such as Dynamic Address Routing, are known not to perform well in smaller networks [34].

In order to assess how the three protocols handle networks with a different number of traffic flows, the different size networks were also evaluated with 1, 4, 8 and 16 traffic flows. Each flow begins randomly after an interval between 50 and 250 seconds of simulation time, uniformly distributed, being concluded by the end of the simulation. The destination of each flow was randomly chosen, using a User Datagram Protocol (UDP) traffic type, with a constant bit rate of 8 packets of 4kbit per second, representative of typical interactive gaming, simple file transfers or information exchange [92].

In this scenario the DefeR protocol's ability to maintain a reduced overhead in scenarios where nodes are likely to move within nearby contexts is disregarded. All nodes randomly start their movement after an initial warm-up time, between 100 and 250 seconds (following an uniform distribution). The used mobility model is the Random Waypoint with a pause time of 60 seconds, without any distance or cluster restrictions, such that nodes are able to move freely across the entire network. The nodes' speed is uniform between 2 *and* $6km/h$, corresponding to pedestrians' walking speed [93].



(a) 1 Flow (b) 4 Flows

(c) 8 Flows (d) 16 Flows

Fig. 3. Average Percentage of Losses

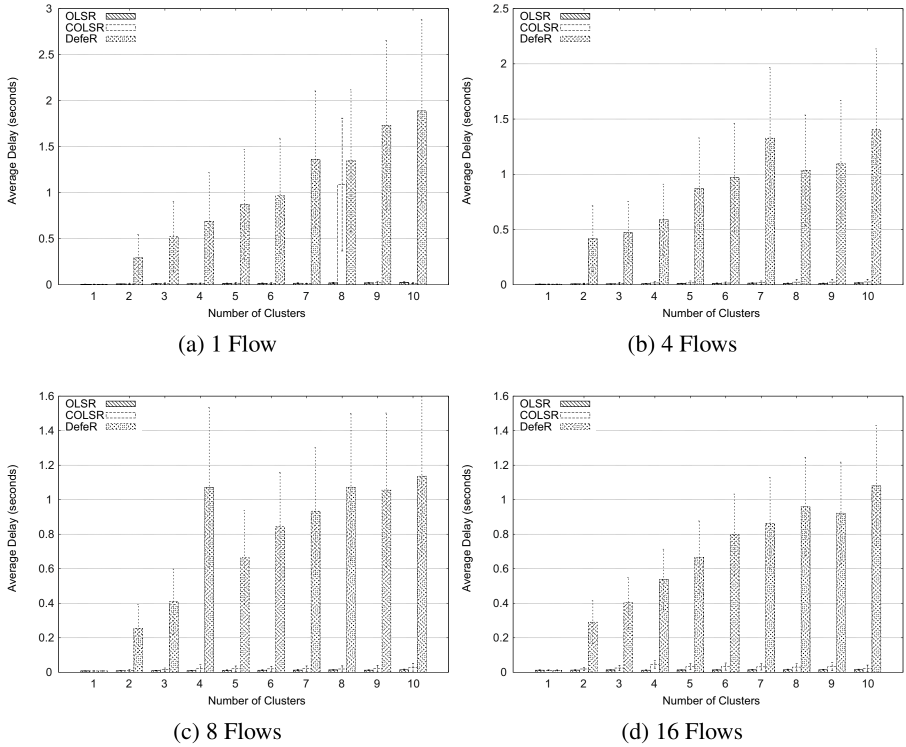
8.2 Obtained Results

Taking into account the discussed evaluation metrics, the obtained results in the defined scenario are presented next. Each metric is presented with the four different number of flows, side-by-side, in order to allow a better comparison.

8.2.1 Percentage of Losses

In any routing evaluation, the percentage of registered losses can be considered as an indicator of how a routing protocol performs. This is presented in Figure 3, where the obtained percentage of losses is clearly influenced by the number of clusters in the network. In a 1-cluster network, the three protocols have a similar performance, as all of them simply use the OLSR protocol for maintaining routing paths. While the growing number of flows varies only slightly the data traffic delivery performance, the increasing number of clusters has a higher impact, such that the C-OLSR protocol registers more than 80% of losses in networks with 4 or more clusters.

Regarding the overall percentage of losses, the DefeR protocol registers the best performance being able to constantly deliver more data packets than its competitors. However, the DefeR protocol still has a significant amount of losses in larger networks,



(a) 1 Flow (b) 4 Flows

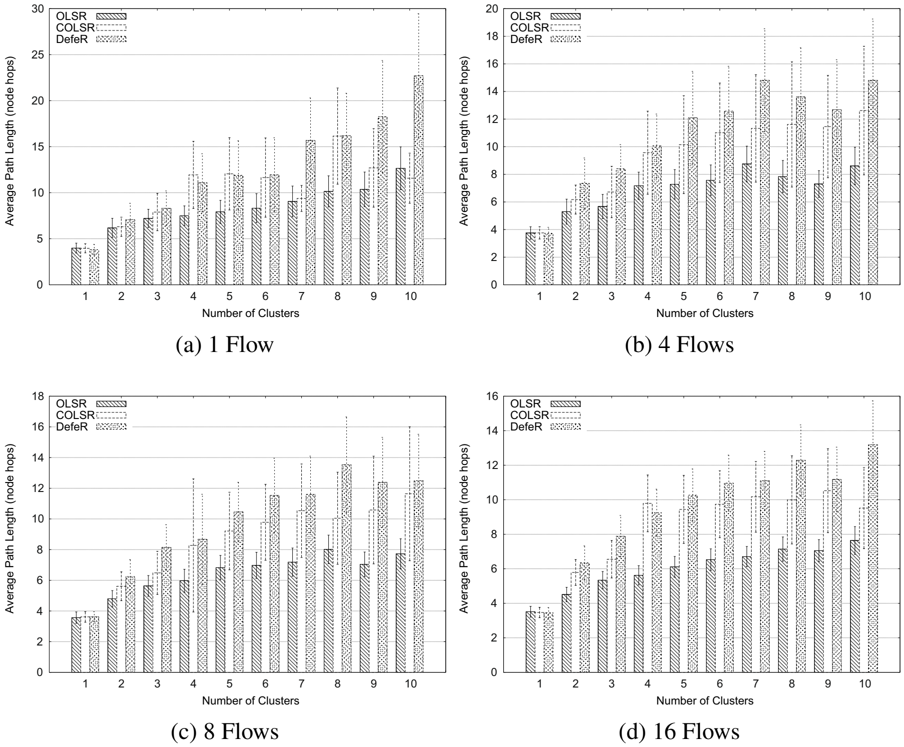
(c) 8 Flows (d) 16 Flows

Fig. 4. Average End-to-end Delay

which is consistent with the performance of other protocols such as the DSDV or the DYMO routing protocols [94]. Though many losses are not desirable, this results from the intrinsic nature of MANETs. It is important to take into account that the proposed scenario is extremely demanding, where a path from source to destination may often not exist. Despite this fact, the proposed routing approach managed to perform two times better than the C-OLSR protocol in some network configurations.

8.2.2 End-to-End Delay

In realistic multi-hop wireless networks, as previously discussed, the constraint of an existing path between any two nodes cannot be guaranteed. As a result Delay-Tolerant Networks have been proposed [94], focusing on the delivery of data packets, regardless of the time interval it might take between source and destination. While the OLSR and C-OLSR protocols simply discard packets when a route is not found, the DefeR gateways are able to re-route packets if alternative paths exist. As a result of an improved traffic delivery, the DefeR protocol has a higher end-to-end delay, as seen in Figure 4. A similar delay is found in the C-OLSR protocol for an eight cluster scenario with solely 1 traffic flow, where this protocol has an abnormal improvement in traffic delivery (see Figure 3a).



(a) 1 Flow (b) 4 Flows

(c) 8 Flows (d) 16 Flows

Fig. 5. Average Number of Hops

Considering the class of reactive routing protocols, the path discovery process is responsible for initial delays even higher than the ones registered by any of the three analysed protocols [70].

Even though the DefeR scheme is outperformed by the other two protocols, when delay is considered, its increased traffic delivery must not be disregarded as it helps to understand its origin. In fact, after a closer analysis of the obtained results, the high standard deviation reveals that the registered delay is only introduced by some flows, which are likely to be failed by the other protocols. This is the only reason for such a standard deviation, as the three protocols were equally simulated 30 times and only DefeR was this dynamic.

8.2.3 Path Length

The number of hops from source to destination is presented in Figure 5, where the OLSR protocol stands out for being able to achieve shorter routes. Regarding the cluster-based routing protocols, the DefeR protocol is able to keep up or even surpass the C-OLSR protocol's performance, while always delivering more data packets.

Once again, the increasing network size proportionally affects the metric results. However, while the average path length increases with the number of nodes, it decreases

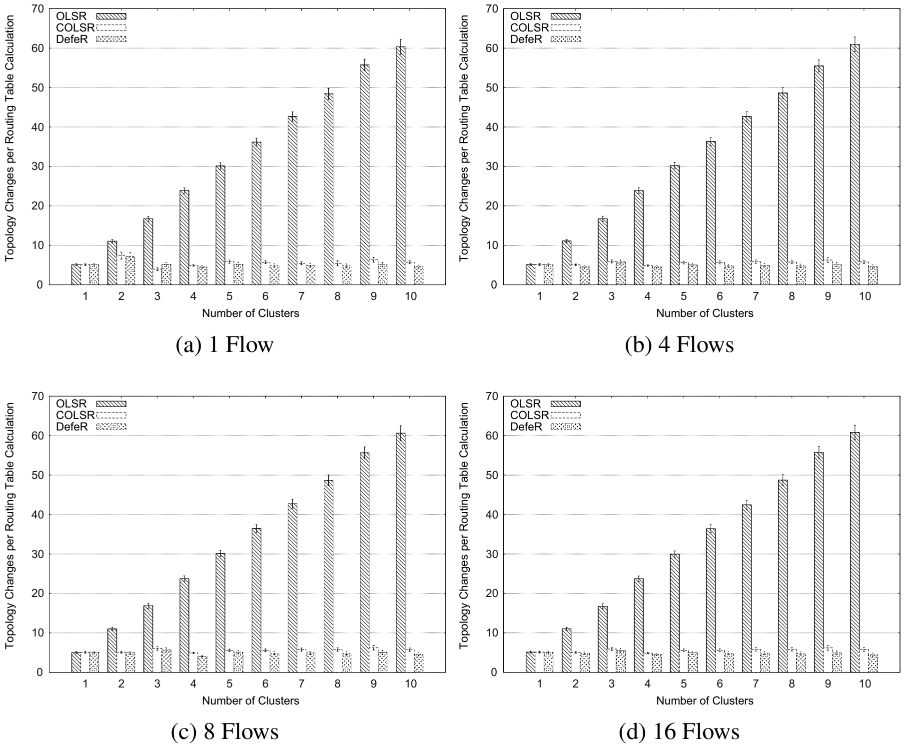


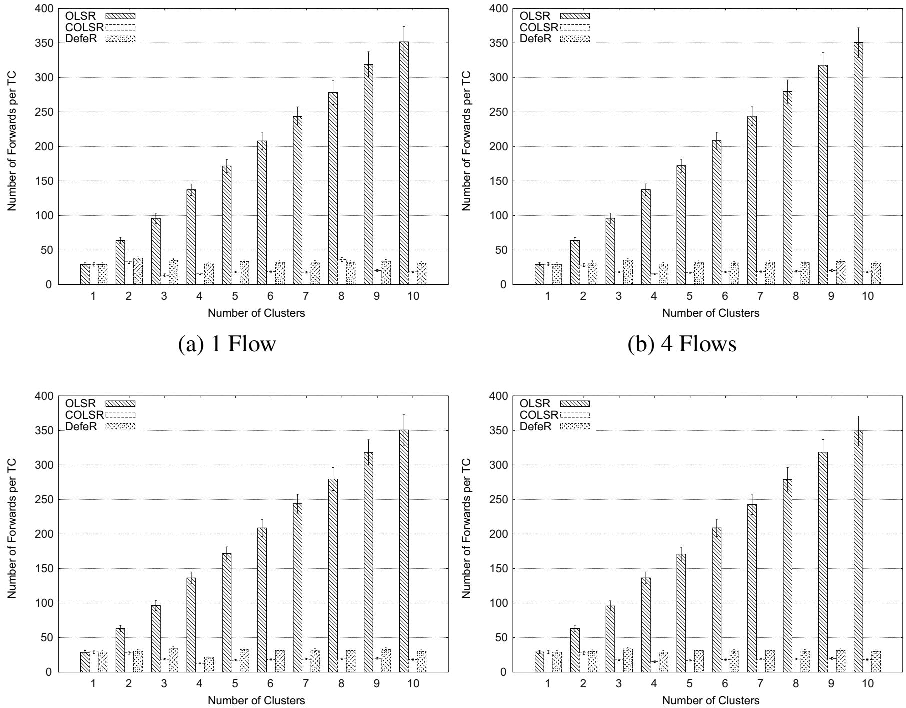
Fig. 6. Topology Changes per Routing Table Calculation (AToCRT)

with a higher number of traffic flows. A similar behaviour was found with the delay metric, as it is also influenced by the number of intervening nodes in the deliver of data packets.

8.2.4 Topology Changes Per Routing Table Calculation

In MANETs, topology changes are likely to occur very often, not only due to interferences but mainly due to the mobility of nodes. It is the routing protocol's responsibility to detect existing topology changes and reflect them when updating its routing table. However, too many topology changes have a strong impact on the overhead introduced by a routing protocol and may reveal that the protocol suffers from instability.

In Figure 6 the lack of scalability of the OLSR protocol becomes clear, resulting in a growing number of registered topology changes in networks with a higher number of nodes. On the other hand, the use of clusters by the DefeR and C-OLSR protocols allows them to achieve a more stable routing performance, keeping a fairly constant number of topology changes per routing table calculation. However, important topology changes cannot be disregarded by routing protocols. Regarding the overall routing performance of the C-OLSR protocol when compared with its unclustered version, even though it is more stable, it fails to achieve a similar traffic delivery, suggesting that its handling of topology changes does not have the same efficacy.



(a) 1 Flow (b) 4 Flows

(c) 8 Flows (d) 16 Flows

Fig. 7. Number of Forwards per *TC* message

8.2.5 Number of Forwards Per *TC* Message

Closely related with the detected number of topology changes, the ratio between sent and forwarded Topology Control messages is also a token of a protocol's ability to scale. The forwarding of *TC* messages deals with a large amount of overhead in the network and should be kept to a minimum. Due to containment of routing information within clusters, the DefeR and C-OLSR protocols require a rather small number of forwards in order to disseminate their routing information – though the C-OLSR protocol requires the smallest amount of forwards. However, once more, an excessively low number of updates may indicate that existing routes are not entirely valid.

Regarding the number of traffic flows, there is no obvious impact on this metric, as it only depends on the existing number of nodes and topology changes. The latter aspect is clearer in the OLSR protocol, as seen in Figure 7 which shows that it requires its *TC* messages to be forwarded to most of the nodes in the network.

8.2.6 Control Traffic Overhead

Since only purely proactive routing protocols are being considered in this evaluation, the number of traffic flows does not influence significantly the number of required routing messages. Figure 8 shows the total overhead of routing control traffic issued by each

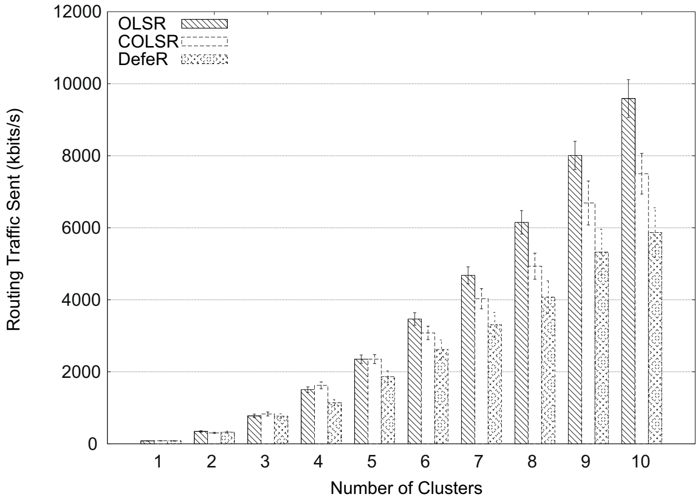


Fig. 8. Sent Routing Traffic Overhead

protocol in the scenario with 16 Flows. As the number of nodes increases, the amount of existing routing information also increases for any proactive protocol. However, the DefeR protocol increases its overhead slower than its competitors, since it requires less routing messages. Moreover, the performance of the proposed protocol can be further improved by using a clustering algorithm that provides a table with the mappings of each node to its CID, as they usually use such a table for cluster maintenance purposes.

The overhead felt by the sent routing messages is more clearly noticed by the received routing information in the entire network. While *HELLO* messages are only sent

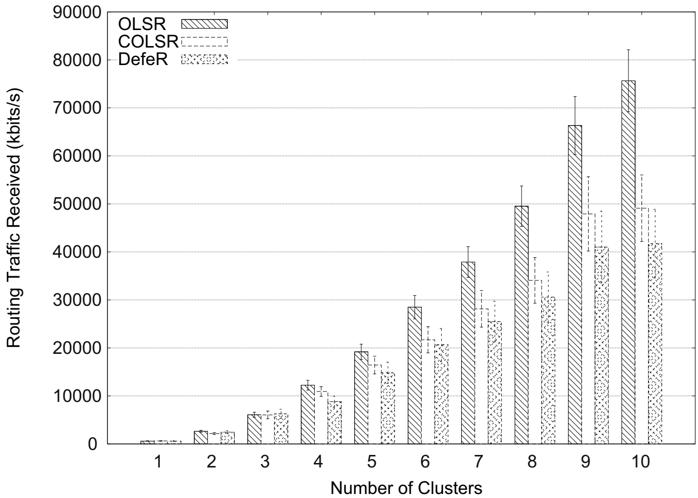


Fig. 9. Received Routing Traffic Overhead

locally, the previously analysed ratio between sent and forwarded *TC* messages determines how much more overhead is propagated through the network. Even though the C-OLSR protocol has a slightly lower ratio of forwarded *TC*s, when compared with DefeR, it has a higher received routing traffic overhead, as it sends more routing data per message. The received control traffic overhead for each protocol is presented in Figure 9.

8.3 Resilience to Mobility

The considered performance assessment must involve not only the evaluation of a large scale network, measuring the stability, overhead and overall traffic delivery performance, but also its ability to handle mobility phenomena, introducing dynamic scenarios with different mobility models.

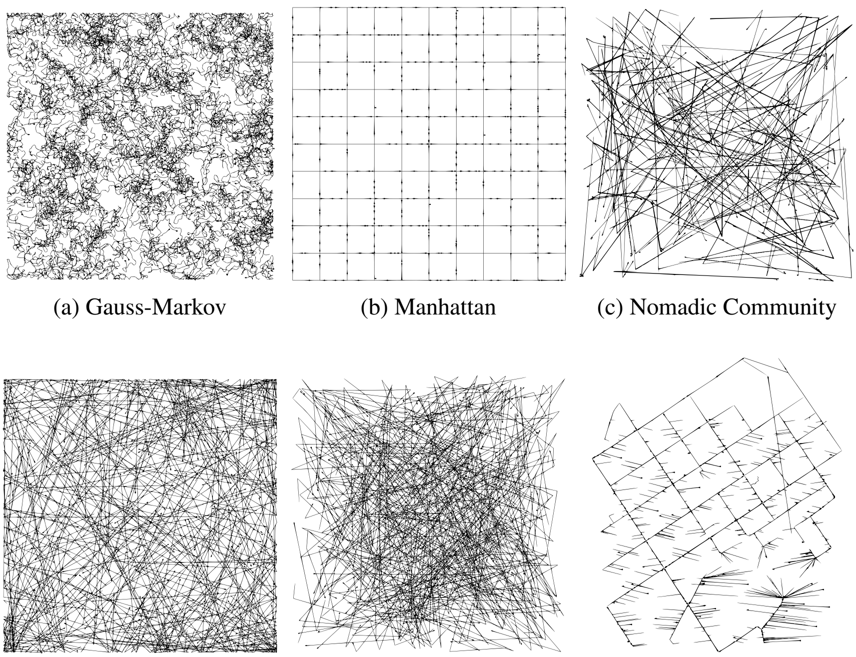
Regarding this last aspect, even though many mobility models have been proposed in previous works, each one of them has unique characteristics, therefore not replacing one other.

In this evaluation, several mobility patterns will be taken into consideration. In order to do so, the BonnMotion tool [95] has been used to generate different node trajectories, later employed in conjunction with the OPNET Modeler Wireless Simulator. These trajectories were created assuming a plausible speed for a person walking [93], between 0.5 and 1.5 m/s and a pause time of 60 seconds, when applicable. The mobility generation disregarded the first 3600 seconds, solely using the follows 900 seconds of path randomization, avoiding the initial warm-up from the random number generations, thus achieving a more stable scenario. Moreover, the area of motion was of 1500 by 1500 meters, for a total number of 541 nodes. Higher speeds were not considered, as the sense of clusters would be faded away and the realm of vehicular Ad-hoc networks would be entered. Even though new mobility models already present similarities with human mobility, the used mobility patterns were chosen for the sake of comparison with existing works on this subject.

For illustration purposes, after being imported to the simulator, the resulting trajectories were then converted to image files and are depicted in figure 10, representing the Gauss-Markov (figure 10a), Manhattan (figure 10b), Nomadic Community (figure 10c), Random Direction (figure 10d), Random Waypoint (figure 10e) and Random Street (figure 10f) Mobility Models. These different mobility models are entirely random, but each one has its own specificities. By using them the intent is to demonstrate that the DefeR paradigm is suitable in the most diverse scenarios.

In order to evaluate the performance of the chosen proactive protocols, six scenarios incorporating different mobility models and an additional one with static nodes have been used. All these scenarios have the same area and number of nodes, using the trajectories defined by the BonnMotion tool, as previously detailed.

Another important aspect that motivates and influences wireless multi-hop networks is the establishment of data flows between nodes. In the defined scenarios, 24 traffic flows with different destinations were generated in each run. From these flows, 50% were randomly chosen throughout the network, while the remaining traffic destinations were set to nodes within the cluster of the source node. By using this approach, both



(a) Gauss-Markov (b) Manhattan (c) Nomadic Community

(d) Random Direction (e) Random Waypoint (f) Random Street Map

Fig. 10. Mobile Models' Trajectories

interactions within and outside clusters were assessed, providing a complete evaluation of the protocol's performance.

Each flow was defined with a constant bit rate of 8 packets of 4kbit per second (using UDP), representative of typical interactive gaming, simple file transfers or information exchange [92], which are all well suited applications for mobile Ad-hoc networks. The start time of each flow is randomly determined following a uniform distribution between 50 and 250 seconds of simulation time, being concluded by the end of the simulation.

8.3.1 Obtained Results

The purpose of this scenario is to clearly understand the impact of different mobility models on proactive routing. The following results show their efficiency and difficulty in dealing with several distinct patterns of mobility.

8.3.2 Percentage of Losses

Figure 11 illustrates the percentage of losses registered by the routing protocols in all the defined mobility variations. In these, the DefeR protocol stands out by dint of having almost less than half of the losses than the remaining protocols. Conversely, the C-OLSR protocol registers the worst performance, having always more lost packets than the remaining protocols.

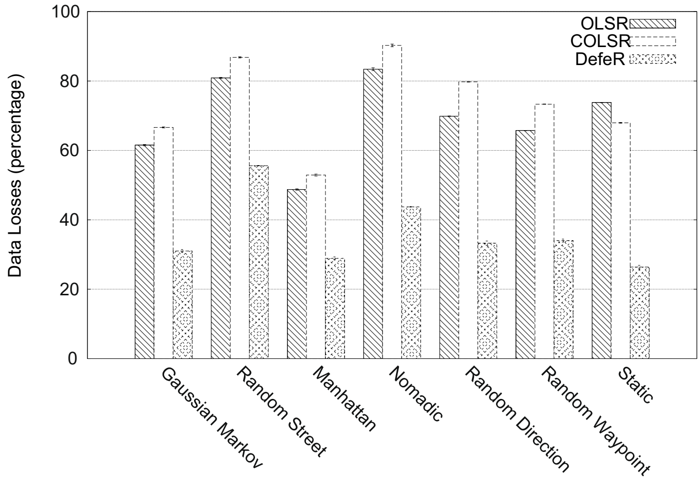


Fig. 11. Average Percentage of Losses

Regarding the Static scenario, the OLSR and C-OLSR protocols unexpectedly show worse delivery performance than in some mobile scenarios. This is a consequence of their inability to scale, as in the Static scenario more paths exist, whereas in the Manhattan scenario, for example, nodes are separated by the arrangement of the streets. However, the DefeR scheme is oblivious to the nodes' placement and has a similar performance in all the scenarios.

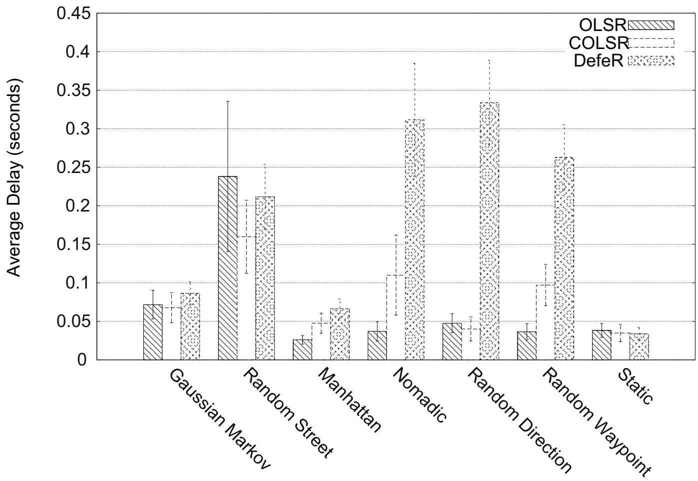


Fig. 12. Average End-to-end Delay

8.3.3 End-to-End Delay

The average end-to-end delay is presented in figure 12 for all the proposed mobility models. Being the static scenario the only exception, in the remaining scenarios the DefeR protocol presents a higher delay. This aspect may not be desirable for certain types of traffic, such as voice, which are not well suited for Ad-hoc networks. The explanation for the higher delay registered by the DefeR protocol repeats itself – as a consequence of the additional traffic delivery achieved, an increased load of traffic is forwarded instead of being dropped.

In fact, while the end-to-end delay is typically a result of a higher path length, the used metrics will show that this is not the case. Specifically, when analysing the Manhattan scenario, where the highest hop count of the all mobile scenarios is registered for DefeR (see Figure 13), it has at the same time the lowest delay of all the mobile scenarios. This confirms that the approach taken by DefeR, which sometimes uses longer but more stable paths, registers less losses and is efficient, not introducing any delay by itself. The higher delay times are not registered in the Manhattan model, as the nodes follow well defined trajectories, where the additional delay overhead in the other mobile scenarios is due only to the repairing of broken paths, allowing the increased performance in traffic delivery registered by DefeR.

The self-restoring property of the DefeR protocol may occur in demanding situations where, due to the mobility phenomena, instead of dropping packets while routing tables change, packets are held and re-forwarded to the appropriate route. Thus, as previously concluded, a higher total delay average is expectable. Moreover, when bottlenecks are avoided due to load-balancing, the re-routing process may also introduce a slight delay. However, as the DefeR scheme is able to reach more challenging destinations than its competitors, the additional delay overhead is justifiable and still suitable for many different applications.

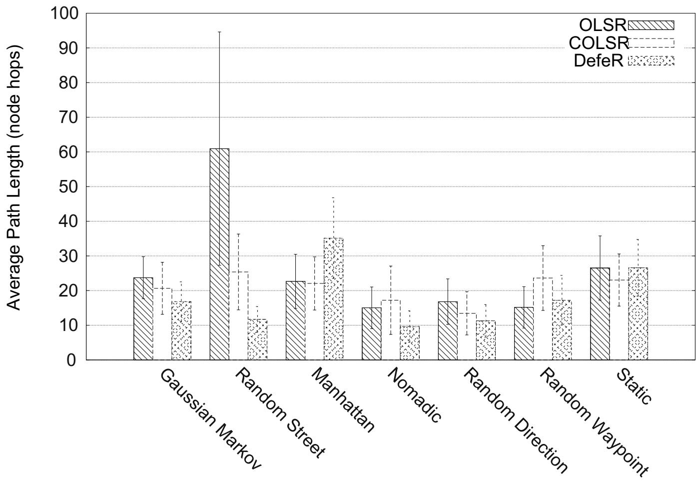


Fig. 13. Average Number of Hops

8.3.4 Path Length

Minimizing the path length is a typical target of routing protocols, with the purpose of reducing the network load and optimising packet delivery. However, due to network dynamics strongly influenced by node mobility, such a routing approach may reduce the protocols' traffic delivery as it disregards the stability of the chosen routes.

In most scenarios, the DefeR scheme is able to achieve a better path length than the remaining protocols while maintaining lower losses, as depicted in figure 13. Nevertheless, for the Manhattan, Random Waypoint and Static mobility models, the Deferred Routing Protocol has a slightly higher path length. This is a consequence of the scenarios' specificities and increased traffic performance of the DefeR, as it reaches more demanding destination nodes. The trade-off between path length and traffic efficiency, in order to achieve an increased traffic performance, should be therefore regarded as an important feature.

As a result of the randomly chosen destinations and of the wireless medium interactions, the confidence interval registered for the path length is higher than for other parameters. However, this interval is still similar to all the analysed routing protocols, validating the outcome of the parameter. The only observed exception worth of taking note occurs with the OLSR protocol in the Random Street Mobility Model. This mobility pattern is highly complex and it is clear that the OLSR protocol is not capable of dealing with the constant and close interactions between the moving nodes. In particular, the obtained standard deviation suggests that in certain occasions routing loops occur, drastically increasing the total number of hops.

8.3.5 Topology Changes Per Routing Table Calculation

When considering the scalability of a routing protocol, the stability of its routing tables is a key aspect on how it performs. The update of a routing table may be a costly procedure in terms of processing power and required energy, possibly leading to the creation and dissemination of additional routing messages, depleting the batteries of mobile devices faster than desirable.

Regarding this aspect, the OLSR protocol is clearly less scalable than the C-OLSR and DefeR protocols, which register a significantly smaller number of topology changes per routing table calculation, as shown in figure 14. In particular, the OLSR protocol has its worse performance in the static scenario. Such behaviour is a direct consequence of the wireless medium interactions of the nodes which are strongly connected in this scenario. In fact, in the mobile scenarios, where connectivity is often scarce, there is a clear reduction of the number of topology changes, suggesting once more that the OLSR protocol does not scale appropriately.

Considering the C-OLSR protocol, which benefits from the usage of clusters such as DefeR, it achieves a greater stability when compared with the standard OLSR. The number of topology changes per routing table calculation registered by this protocol is only slightly higher than the ones obtained from Deferred Routing. However, the overall performance of the C-OLSR protocol regarding traffic delivery suggests that its ability to timely register important topology changes is not appropriate, resulting in wrong or outdated routing paths. On the other hand, the DefeR awareness of the network is entirely different, detecting only the required amount of topology changes thus being more stable, leading to an increased traffic delivery performance, lower routing overhead and better energy efficiency.

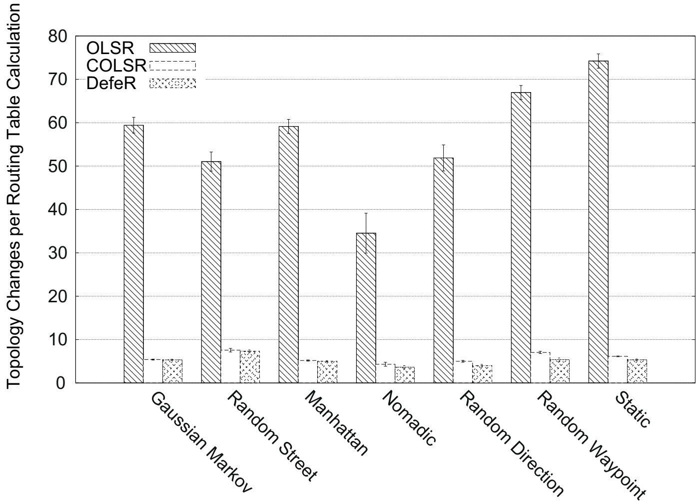


Fig. 14. Topology Changes per Routing Table Calculation (AToCRT)

8.3.6 Number of Forwards Per *TC* Message

The three considered routing protocols rely on Topology Control routing messages to propagate the required information. These messages are issued periodically and whenever a topology change is detected. Similarly to the previously analysed metric, the OLSR protocol is the worst performer, being at its lowest in the static scenario (Figure 15). The way that the OLSR routing protocol handles its routing information leads to an expensive propagation of its *TC* messages throughout the network.

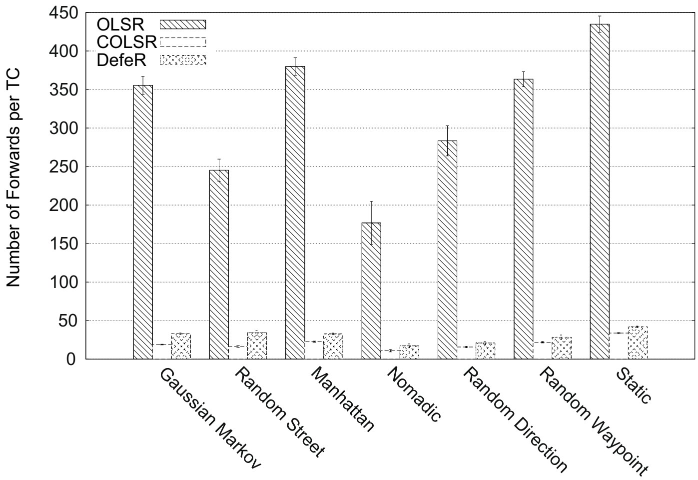


Fig. 15. Number of Forwards per *TC* message

On the other hand, the C-OLSR protocol requires less forwards per *TC* message than any of the other two protocols. Even though both C-OLSR and DefeR routing use the same clusters, it is clear that the usage of C-*HELLO* and C-*TC* messages by the C-OLSR protocol is able to reduce the ratio between forwarded and sent *TC* messages. However, the amount of information and validity contained in these messages, also needs to be considered, as the previously analysed metrics reveal.

8.3.7 Control Traffic Overhead

Figure 16 shows the total amount of routing traffic sent by each routing protocol using the different mobility models. The OLSR protocol once again stands out for having the worst performance. The lack of a well defined network structure, which can be more easily obtained by using clusters, originates an increased overhead. While in the Static scenario this protocol has a bad performance, it is in the Random Street model that more routing traffic is sent.

While the clustered version of the OLSR protocol is able to provide an improvement regarding sent routing traffic, as seen before, it is not capable of maintaining this improvement in terms of data traffic delivery. On the other hand, the proposed DefeR protocol not only outperforms the C-OLSR by having less overhead, but it also outperforms the OLSR protocol in traffic delivery, registering less losses.

Since the sent routing messages may be forwarded through several nodes, Figure 17 presents the control traffic overhead received throughout the network. These results confirm the superiority of Deferred Routing in the handling of different mobility models, being in accordance with the verified ratio between sent and forwarded *TC* messages. Moreover, these results are obtained without guaranteeing a uniform density of nodes within clusters, which would benefit the performance of the DefeR protocol even further, as presented in the following scenarios.

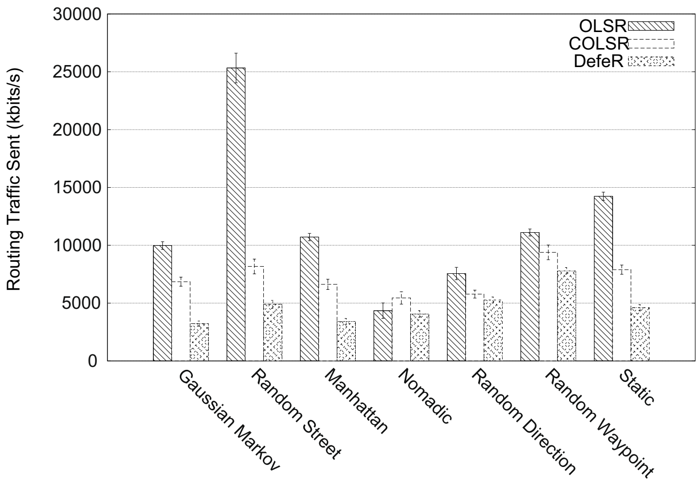


Fig. 16. Sent Routing Traffic Overhead

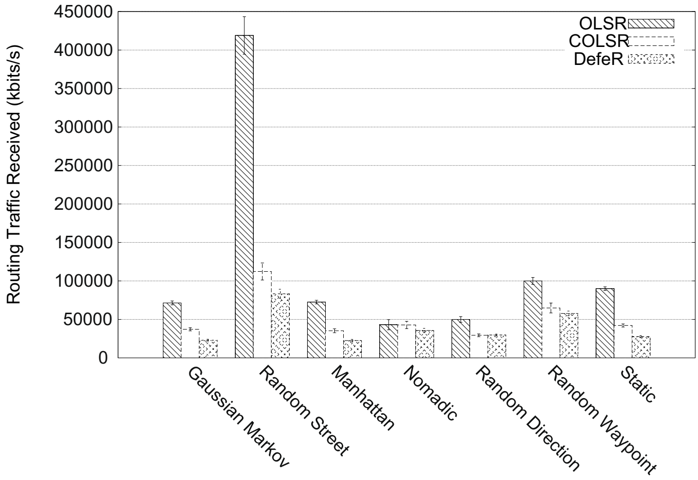


Fig. 17. Received Routing Traffic Overhead

8.4 Summary

The versatility of Mobile Ad-hoc Networks makes them suitable for a wide range of scenarios. Moreover, the dynamic nature of the wireless medium involves a large set of variables which influence the behaviour of these networks. Several parameters were considered for the assessment of three routing protocols, as well as two different scenarios with different characteristics. The protocols' scalability was tested by using a scenario with different size networks, while the effects of different mobile patterns were assessed in a scenario using seven different mobility models. The chosen routing protocols represent the proactive class of routing protocols as defined by the MANET working group, which aim at handling largely dense networks.

In the presented performance evaluation the DefeR scheme revealed that it is able to deliver more traffic than its competitors, even though it introduces some delay as a result of the path-repairing mechanism. Despite having a slightly higher delay, this protocol is still useful for many possible applications, being more stable regarding the number of required routing operations and having an overall smaller overhead, while the plain OLSR protocol showed difficulty in scaling.

The thorough evaluation obtained from all the defined scenarios and complete simulation environment, provided a good understanding of existing protocols' scalability. In particular, it revealed that existing routing protocols are already capable to handle large-scale networks, even though improvements are still desirable and questions about clustering techniques must still be addressed.

9 Conclusion

The usage of wireless multi-hop networks is undeniably important for a future world where thousands of wireless capable devices are expected to be connected. Despite the existing work on this topic, open issues such as routing scalability still exist. In this work, improved routing mechanisms as well as different scalability techniques for Mobile Ad-hoc Networks, have been described.

The IETF MANET working group presents two main routing classes of routing (proactive and reactive) however, only OLSR is aimed at dense networks and, despite using MPR nodes, there are still scalability issues. These and other approaches were analysed where the most relevant features and open issues were identified.

In order to thoroughly analyse the performance of the OLSR protocol and two other protocols aimed at scalability which consider this protocol, an extensive set of different scenarios is defined, where the protocols' performance is assessed regarding their scalability, stability and traffic delivery capabilities. The provided results were obtained from several simulations, taking into account the dynamic characteristics of the wireless link and different mobility patterns, which significantly influence MANETs.

The presented performance analysis provides a comprehensive and thorough evaluation that can be used to assess other routing protocols for MANETs. Several scenarios with different purposes are defined, scrutinising different aspects of the performance of a routing protocol, such as its scalability, regarding both the number of nodes and an increasing of flows, as well as its resilience to several distinct mobility patterns.

The importance of Mobile Ad-hoc Networks in a near future has been discussed throughout this work. From the obtained results, the performance of the routing protocols, in particular of the DefeR approach, motivate their usage in large-scale scenarios. However, the performance increase in scalability often results from the usage of clustered wireless networks, which allows routing information to be contained within limited contexts. Even though several routing protocols rely on this aspect, and considering that many clustering algorithms have already been proposed, there are still drawbacks from this approach. The modification of an existing clustering approach or even the definition of a new one should be addressed in a future work, taking advantage of the increasing availability of contextual information provided by sensors, databases, mobility and traffic patterns or even by the users themselves.

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