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Performance evaluation of ad hoc routing protocols for military communications

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SUMMARY

Mobile ad hoc networks (MANETs) are of much interest to both the research community and the military because of the potential to establish a communication network in any situation that involves emergencies. Examples are search-and-rescue operations, military deployment in hostile environments, and several types of police operations. One critical open issue is how to route messages considering the characteristics of these networks. The nodes act as routers in an environment without a fixed infrastructure, the nodes are mobile, the wireless medium has its own limitations compared to wired networks, and existing routing protocols cannot be employed, at least without modifications. Over the last few years, a number of routing protocols have been proposed and enhanced to address the issue of routing in MANETs. It is not clear how those different protocols perform under different environments. One protocol may be the best in one network configuration but the worst in another. This article provides an analysis and performance evaluation of those protocols that may be suitable for military communications. The evaluation is conducted in two phases. In the first phase, we compare the protocols based on qualitative metrics to locate those that may fit our evaluation criteria. In the second phase, we evaluate the selected protocols from the first phase based on quantitative metrics in a mobility scenario that reflects tactical military movements. The results disclose that there is no routing protocol in the current stage without modifications that can provide efficient routing to any size of network, regardless of the number of nodes and the network load and mobility. Copyright © 2011 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Over the last few years wireless computer networks have evoked much interest from the public. Universities, companies, armed forces, governmental and non-governmental organizations and agencies are now using this new technology. We can generally classify wireless networks into two categories:

- wireless networks with fixed and wired gateways; and
- wireless networks that can be set up in an 'ad hoc' fashion, without the existence of fixed access points (AP).

A mobile ad hoc network (MANET) is a wireless network in which all nodes can freely and arbitrarily move in any direction with any velocity. Routing takes place without the existence of fixed infrastructure. The network can scale from tens to thousands of nodes in an ad hoc fashion, provided the nodes are willing to take part in the route discovery and maintenance process.

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We can broadly define two main areas where MANET technology can be applied. The first area extends the current wired and wireless networks by adding new mobile nodes that use MANET technology at the edge of the network. We can list, for example, drivers in a city who can communicate with each other while obtaining traffic information, students on a university campus, company employees in a meeting room, and many other similar situations. Perhaps one day MANETs, will replace the existing wireless telephony if every user is willing to store and forward data packets with his wireless device.

The second area where MANET technology can be applied is where a communication network is needed, but there is no infrastructure available, or the pre-existing infrastructure has been destroyed by a disaster or a war. MANETs can be used in any situation that involves an emergency, such as search-and-rescue operations, military deployment in a hostile environment, police departments, disaster recovery, and many others. The lack of wired infrastructure reduces the cost of establishing such a network and makes MANETs a very attractive technology.

However, there are still many open issues concerning MANETs. They involve efficient routing due to frequent changes in the network topology over time, quality of service (QoS) issues and security, because each node in the network operates also as a router that stores and forwards data packet from other nodes. Energy consumption is another open issue as nodes in the network transmit not only its data but also data from other nodes. In addition, MANETs have lower transmission rates due to the limitation of the physical layer as compared to wired networks.

Over recent years many routing protocols for MANETs have been proposed and enhanced to efficiently route data packets between the nodes in a network. However, the performance of a routing protocol depends on many factors. A protocol may be the best for one network topology and mobility pattern, but the worst for another topology. A military mobile wireless network, for instance, has different characteristics from the same mobile wireless network designed to serve commercial needs. A simple example is the network mobility model. Commercial ad hoc networks are to some extent 'chaotic', in the sense that each node may arbitrarily choose its own velocity and direction. In a military environment, the mobility model depends on the type of operation, the size of the deployed unit and the terrain. In addition, nodes move in predefined directions with predefined velocities and operate as organized groups, again depending on the type of operation and the tactical situation.

This article differs from other works mainly in three areas. First, the evaluation process is based on both qualitative and quantitative metrics. Second, the simulated mobility and traffic scenarios reflect those in military tactical operations. Third we run extensive simulation sets in which we differentiate all the possible attributes of the network, namely the network load, the number of connections, the node density and the node mobility. Therefore, our objectives are:

- to study the routing protocols that have received close attention from the research community;
- to compare them and select those protocols based on qualitative metrics that most satisfy the IETF design considerations;
- to evaluate the selected protocols through extensive simulations under the same network parameters and mobility scenario, which reflects military tactical movements and traffic pattern;
- to make recommendations in order to increase their performance.

The rest of this paper is organized as follows. The next section provides an overview of the related work in the area of evaluation of routing protocols for wireless ad hoc networks. We discuss routing protocols in Section 3. In Section 4, we introduce the metrics under which we perform our evaluation. In Section 5, we evaluate eight routing protocols based on qualitative metrics. Results from extensive ns-2 simulations based on quantitative metrics are presented in Section 6. We conclude our paper in Section 7. Finally, we discuss recommendations and future work in Section 8.

2. RELATED WORK

Over recent years, significant work has been conducted to evaluate the performance of routing protocols in ad hoc wireless networks. Josh Broch *et al*. [1] presented one of the first and popular performance evaluation studies of multiple routing protocols (DSDV, TORA, DSR, and AODV) through

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simulations conducted with the network simulation software ns-2 [2]. They used a simple mobility scenario (random waypoint model) and a small number of network-centric metrics, such as the packet delivery ratio and the routing overhead in order to evaluate the performance of the tested protocols. In Boukerche [3] the performance evaluation of three routing protocols (AODV, CBRP, and DSR) is presented. The throughput and the average end-to-end delay are used as the evaluation metrics in simulations with a maximum number of 40 nodes. Their main finding is that source routing is much more efficient than the distance-vector-based protocols, like AODV. Boukerche [4] suggests that position-aware routing protocols, in which nodes are equipped with a GPS device, present better performance and minimize routing overhead. Another performance evaluation study for military communications is presented in Choi and Ko [5]. The authors evaluate a number of routing protocols (i.e. AODV, DSR, LAR, and OLSR) under scenarios that reflect the transmission patterns of military radios and conclude that DSR and LAR achieve better performance than the other tested protocols. In Plesse *et al*. [6] the OLSR performance is studied in military mobile ad hoc networks. Simulation results show that the OLSR presents good performance, although some internal parameters of the protocol should be tuned for optimal performance. Ahmed and Alam [7] compare three routing protocols (DSR, AODV, and TORA) through simulations conducted with a discrete-event simulator (OPNET Modeler 10.5 version). Simulation results indicate that under specific simulation parameters TORA presents a higher performance than AODV and DSR. In Divecha *et al*. [8] the effects of various mobility models on the performance of DSR and AODV are studied. For experimental purposes, four mobility scenarios are presented: Random Waypoint, Group Mobility, Freeway and Manhattan models. Performance comparison has also been conducted across varying node densities and number of hops. The experimental results illustrate that the performance of routing protocols varies across different mobility models, node densities and length of data paths. In Kumar *et al*. [9], a comparison of the performance of two prominent on-demand reactive routing protocols for MANET (DSR and AODV) is presented, along with the traditional proactive DSDV protocol. In Rahman and Zukarnain [10] the performance comparison between three routing protocols, namely AODV, DSDV and an improvement of DSDV, is presented. The authors use three network metrics, namely packet delivery ration, end-to-end delay, and routing overhead. Another performance evaluation study is presented in Qasim *et al*. [11]. The evaluation process is based on multiple network metrics in an effort to better assess the performance of the tested routing protocols. This work does not present any new optimization of the tested protocols; however, it stands as a good example in terms of the used metrics.

To the best of our knowledge this is the first work which evaluates in detail three MANET protocols (DSR, AODV and OLSR) based on five evaluation parameters (number of connections, network load, distribution of network load, network mobility, node density) with focus on the Reference Point Group Mobility (RPGM) model. The aforementioned works and other studies [12–16] are based either on fewer evaluation parameters, or they are more generic without focusing on the RPGM model.

3. CLASSIFICATION OF ROUTING PROTOCOLS

Routing protocols for MANETs can be broadly classified into three main categories.

3.1. Proactive routing protocols

In this category, every node in the network has one or more routes to any possible destination in its routing table at any given time. data received from the upper transport layer are immediately transmitted, as at least one route to the destination is already in the node's routing table. Proactive protocols present low latency but medium to high routing overhead, as the nodes periodically exchange control messages and routing table information in order to keep up-to-date routes to any active node in the network. However, a node, wasting process recourses and bandwidth, may never use some of these routes. Proactive protocols can better address security vulnerabilities, because of the periodic exchange of control messages and routing table information. Thus a loss or modification of any route update can be overcome by the next scheduled update.

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In this category, we evaluate three proactive protocols, named Optimized Link State Routing (OLSR) [17], Destination Sequenced Distance Vector (DSDV) [18] and the Cluster-Head Gateway Switch Routing Protocol (CGSR) [19].

3.2. Reactive routing protocols

Every node in the network obtains a route to a destination in a demand fashion. When the upper transport layer has data to send, the protocol initiates a route discovery process to find a path to the destination, if such a route does not already exist. Reactive protocols do not maintain up-to-date routes to any destination in the network and do not generally exchange any periodic control messages. Thus they present low routing overhead but high latency as compared to proactive protocols. Reactive protocols are more vulnerable to security attacks, as any loss or modification of route discovery and maintenance messages may have severe consequences for network performance.

In this category, we evaluate three reactive protocols, named Dynamic Source Routing (DSR) [20], Ad Hoc On-Demand Distance Vector (AODV) [21], and the Temporally Ordered Routing Protocol (TORA) [22].

3.3. Hybrid routing protocols

Under this scheme, every node acts reactively in the region close to its proximity and proactively outside of that region or zone. Hybrid protocols take advantage of both reactive and proactive protocols but may require additional hardware, such as GPS, separated or integrated into the communication device.

In this category, we evaluate two hybrid protocols named Zone Routing Protocol (ZRP) [23] and Greedy Perimeter Stateless Routing (GPSR) [24].

4. EVALUATION METRICS

The Internet Engineering Task Force MANET working group suggests two different types of metrics for evaluating the performance of routing protocols for MANETs in RFC 2501 [25]. In accordance with RFC 2501, routing protocols should be evaluated in terms of both qualitative metrics and quantitative metrics. Figure 1 depicts our evaluation process. In the first step, we locate the routing protocols that may be suitable in military communications based on qualitative metrics. In the second step, we evaluate the selected protocols from the first step based on quantitative metrics and provide recommendations to increase their performance.

4.1. Qualitative metrics

These metrics include:

- *Loop freedom*. This refers mainly, but not only, to all protocols that calculate routing information based on the Bellman–Ford algorithm. In a wireless environment with limited bandwidth, interference from neighboring nodes' transmissions and a high probability of packet collisions, it is essential to prevent a packet from 'looping' in the network and thus consuming both processing time and bandwidth.
- *On-demand routing behavior*. Owing to bandwidth limitations in the wireless network, on-demand, or reactive-based, routing minimizes the dissemination of control packets in the network, increases the available bandwidth for user data, and conserves the energy resources of the mobile nodes. Reactive routing protocols introduce a medium to high latency.
- *Proactive behavior*. Proactive behavior is preferable when low latency is the main concern and where bandwidth and energy resources permit such behavior. Mobile nodes in vehicular platforms do not face energy limitations.
- *Security*. The wireless environments, along with the nature of the routing protocols in MANETs, which require each node to participate actively in the routing process, introduce many security

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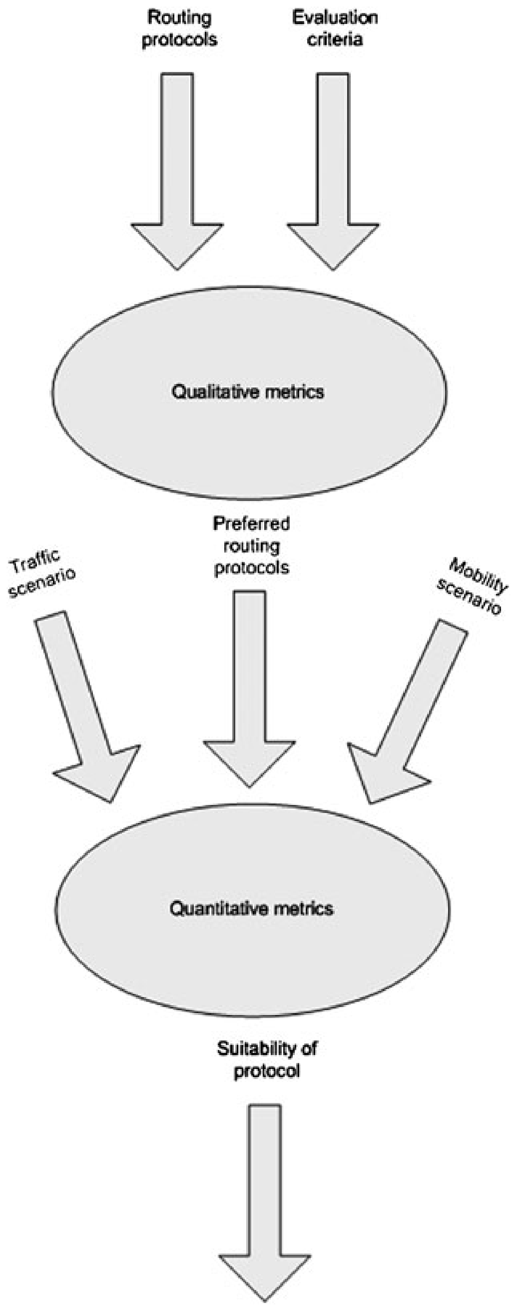

Figure 1. Evaluation process

vulnerabilities. Therefore routing protocols should efficiently support security mechanisms to address these vulnerabilities.

- *Unidirectional link support*. Nodes in the wireless environment may be able to communicate only through unidirectional links. It is preferable that routing protocols are able to support both unidirectional and bidirectional links.
- *Sleep mode*. In general, nodes in a MANET use batteries for their energy source. The protocol should be able to operate, even though some nodes are in 'sleep mode' for short periods, without any adverse consequences in the protocol's performance.
- *Multicasting*. Multicasting support is important especially for the transmission of real-time data (for example, multimedia data) in many nodes at the same time.

Therefore, a routing protocol for MANETs should keep a balance between latency and routing overhead, energy consumption, and node participation in the routing process, and should employ security mechanisms. For military communications, low latency and high packet delivery ratio are more important than low routing overhead. Energy consumption is not always a high issue in military communications, as nodes may well be suited in vehicular platforms with adequate energy resources. However, for portable man-pack radio devices, energy consumption is an important issue.

4.2. *Quantitative metrics*

Quantitative metrics broadly include:

- *End-to-end data throughput and delay*. Many metrics can be used to measure the effectiveness of the routing protocol. Design flaws that increase delay and minimize data throughput can be revealed by these metrics.
- *Route acquisition time*. How much time does a protocol need to discover a route? This is a main concern in reactive routing protocols, as the longer the time is, the higher the latency is in the network.
- *Out-of-order delivery*. The percentage of packets that are delivered out of order may affect the performance of higher-layer protocols such as TCP, which prefers in-order data delivery of packets.
- *Efficiency*. Additional metrics can be used to measure the efficiency of the protocol. One can use them to measure the portion of the available bandwidth that is used by the protocol for route discovery and maintenance. Another measurement calculates the packet delivery ratio over the total number of packets transmitted and the energy consumption of the protocol for performing its task.

All the above quantitative metrics should be based on the same network attributes, such as mobility, network density, data density, bandwidth, energy resources, transmission and receiving power, antenna types, and any other 'component' that affects the performance of a routing protocol. In our performance evaluation, we follow the general ideas described in RFC 2501, and use four quantitative metrics similar to those in Das *et al*. [26]. The packet delivery ratio and average end-to-end delay are more important for best-effort traffic. The normalized routing load will be used to evaluate the efficiency of the routing protocol. The normalized MAC load is a measure of the effective utilization of the wireless medium for data traffic. All these metrics are defined in the following paragraphs.

4.2.1. *Packet delivery ratio (PDR)*

The packet delivery ratio is defined as the fraction of all the received data packets at the destinations over the number of data packets sent by the sources (equation (1)). This is an important metric in networks. If the application uses TCP as the layer 4 protocol, high packet loss at the intermediate nodes will result in retransmissions by the sources, which may result in network congestion.

$$\text{Packet\_Delivery\_Ratio} = \frac{\text{Total\_Data\_packets\_received}}{\text{Total\_Data\_packets\_sent}} \tag{1}$$

4.2.2. *Average end-to-end delay*

End-to-end de_layincludes all possible delays in the network caused by route discovery latency, retransmission by the intermediate nodes, processing delay, queuing delay, and propagation delay. To average the end-to-end delay we add every delay for each successful data packet delivery and divide that sum by the number of successfully received data packets (equation (2)). This metric is important in delay sensitive applications such as video and voice transmission.

$$\text{Average\_End2End\_Delay} = \frac{\Sigma(\text{Time\_received} - \text{Time\_sent})}{\text{Total\_Data\_packets\_received}} \tag{2}$$

4.2.3. *Normalized routing load*

The normalized routing load is defined as the fraction of all routing control packets sent by all nodes over the number of received data packets at the destination nodes (equation (3)). This metric discloses

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how efficient the routing protocol is. Proactive protocols are expected to have a higher normalized routing load than reactive ones. The larger this fraction is, the less efficient the protocol is.

$$\text{Normalized\_Routing\_Load} = \frac{\text{Total\_Routing\_packets\_sent}}{\text{Total\_Data\_packets\_received}} \quad (3)$$

4.2.4. *Normalized MAC load*

The normalized MAC load is defined as the fraction of all control packets (routing control packets, Clear-to-Send (CTS), Request-to-Send (RTS), Address Resolution Protocol (ARP) requests and replies, and MAC ACKs) over the total number of successfully received data packets (equation (4)). This is the metric for evaluating the effective utilization of the wireless medium for data traffic.

$$\text{Normalized\_MAC\_Load} = \frac{\text{Total\_Control\_packets\_sent}}{\text{Total\_Data\_packets\_received}} \quad (4)$$

5. PERFORMANCE EVALUATION BASED ON QUALITATIVE METRICS

In this section we present the evaluation results based on qualitative metrics. The evaluation process requires studying the protocols and finding their attributes that satisfy the evaluation criteria of RFC 2501. This initial selection of protocols for further evaluation depends on their performance here.

5.1. *Proactive protocols*

All studied proactive protocols are loop-free. OSLR, as a modification of the link state algorithm, does not introduce any loops into the routing process, except for oscillations when the link costs depend on the amount of traffic carried by the link. In the MANET scheme, however, link cost depends on the number of hops from a source to a destination, thus avoiding oscillations. DSDV addresses known problems that the Distance Vector algorithm introduces, with the use of destination sequence numbers. CGSR uses DSDV as the underlying routing protocol, and thus accordingly it does not suffer from any kind of loops in the network.

The proactive behavior of these protocols is guaranteed by the periodic exchange of control messages. At any given time, every node has at least one route to any possible destination in the network. We say ‘possible destination’ because the physical existence of a node in the network does not necessarily mean that the node is active or that a route to the node exists, because the node may be out of the transmitting range of all other nodes in the network.

None of the above protocols addresses the security vulnerabilities that are obvious in wireless networks. The proper function of these protocols is based on an assumption that all the nodes exist and operate in a secure environment where link- and physical-layer security mechanisms are in place. However, CGSR seems to be the most vulnerable amongst DSDV and OLSR and an attack on nodes that act as cluster heads may have severe consequences in the network performance. DSDV is more secure than OLSR, as OLSR functionality is based on the proper behavior of the Multipoint Relay Nodes (MPRs).

DSDV and CGSR do not support unidirectional links. However, unidirectional links exist in wireless communications and they should be supported in order to take advantage of any possible paths from a source node to a destination node. In MANETs, especially, there is no such ‘luxury’ as ignoring any possible paths, as routing protocols should take advantage of any link to calculate routes in the network. OLSR designers take into account these limitations of the wireless network and support both bidirectional and unidirectional links.

As for the ‘sleep mode’ operation, only OLSR considers some extensions in its current existing design to support such an operation. In a wireless ad hoc network, in which nodes depend mainly on batteries for their energy source, the sleep mode is a serious attribute that should be supported by any routing protocol.

We have also added three additional metrics, to point out the differences in the design and implementation of the three protocols. In fact, the hierarchical routing philosophy of CGSR is better than the flat routing philosophy of DSDV and OLSR.

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Table 1. Comparison of proactive protocols

Qualitative metrics	OLSR	DSDV	CGSR
Loop-free	Yes	Yes	Yes
Security	No	No	No
Support for unidirectional links	Yes	No	No
Sleep mode	Yes	No	No
Multicasting	No	No	No
Routing scheme	Flat	Flat	Hierarchical
Nodes with special tasks	Yes	no	Yes
Routing metric	Shortest distance	Shortest distance	Shortest path

The security and robustness of the protocol are also connected to the issue, whether or not the protocol functionality depends on nodes with 'special' or 'crucial' tasks. Both OLSR and CGSR have nodes with special tasks.

The way that all the above protocols calculate their routes from a source node to a destination node follows the shortest distance approach, which computes the smallest number of hops between the source and the destination. However, as CGSR follows a cluster head-to-gateway pattern for forwarding packets, it increases the number of hops between a source and a destination node. Table 1 summarizes the performance of the above protocols, based on qualitative metrics.

By summarizing the above results, we can see that OLSR is closer to the IETF MANET working group design recommendations. Indeed, OLSR has been designed with high respect to RFC 2501. Perhaps the only visible disadvantage is the high routing overhead. However, it is mainly up to the network designer to decide what he really needs from a network. In military communications, where the main concerns are timely and reliable data delivery, OLSR may fit well as a routing protocol. If the concern is utilization of the biggest part of the available bandwidth, leaving a small part for control messages, then OLSR is not the appropriate choice. On the other hand, the CGSR clustering scheme is very reflective of an army's structure and communications and could provide a good choice with, of course, a number of extensions and modifications. Finally, given qualitative metrics and the attributes of the above protocols, we choose OLSR for further evaluation in our simulations.

5.2. *Reactive protocols*

All tested reactive protocols are loop-free. No protocol addresses security vulnerabilities that exist in a wireless ad hoc network. However, there are certain proposals for providing secure routing at Layer 3 for all tested protocols. Although security is a major concern in military communications, we find that the security mechanisms will increase processing time, power consumption, and latency. Note that reactive routing protocols already suffer from high latency in the network.

Only DSR in its current state, without any modification, can support both bidirectional and unidirectional links. However, DSR will introduce high routing overhead as routing information is stored at the data packets' header. Thus DSR will not scale well in large networks if communicating nodes are located at opposite edges of the network.

None of the three protocols supports the 'sleep mode', another important factor for power preservation, especially in battery-powered mobile nodes. TORA seems to be a more power-effective protocol, as it localizes most of its function in a small area and not in the entire network. However, the exchange of HELLO messages by the underlying Internet MANET Encapsulation Protocol (IMEP) [27] will introduce power consumption. AODV will consume more power than DSR owing to the exchange of periodic HELLO messages.

TORA does not necessarily find the shortest path between a source/destination pair, as data flows form nodes with higher height to nodes with lower height. Table 2 summarizes the performance of the above protocols based on qualitative metrics. Finally, it is important to mention that only AODV supports multicasting.

Given qualitative metrics and the attributes of the three protocols, we suggest that AODV and DSR would be good candidates for the routing protocol in military mobile ad hoc wireless networks. Therefore we choose both AODV and DSR for further evaluation in our simulations.

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Table 2. Comparison of reactive protocols

Qualitative metrics	AODV	DSR	TORA
Loop-free	Yes	Yes	Yes
Security	No	No	No
Support for unidirectional links	No	Yes	No
Sleep mode	No	No	No
Multicasting	Yes	No	No
Routing scheme	Flat	Flat	flat
Nodes with special tasks	no	No	no
Routing metric	Shortest path	Shortest path	Shortest path

5.3. *Hybrid protocols*

Both ZRP and GPSR are loop-free protocols. ZRP ensures loop-free 'behavior' by employing loop-free protocols inside inter- and intra-zones. On the other hand, GPSR's perimeter-forwarding algorithm never allows a packet to travel twice across the same link toward the same direction.

ZRP's proactive behavior is more obvious than that of GPSR, in which nodes broadcast periodic beacons to their neighbors for location update purposes. ZRP seems to present higher routing overhead depending on the zone radius. ZRP behaves like any other proactive protocol for the large value of this radius. However, one can optimize the value of the zone radius to meet the needs of the wireless network. If low latency is the main concern, reflecting lower data rates, the zone radius value should be high: at least a $zone\_radius > 1$.

None of the above protocols addresses the security vulnerabilities of wireless networks. A possible solution is again monitoring the behavior of the nodes in the network, or employing security mechanisms at the link or physical Layers. GPSR seems to be more vulnerable than ZRP, as GPRS functionality is built on accurate location advertisements by the nodes in the network. Any malfunction of the GPS devices will degrade GPSR's performance.

Only ZRP provides support for unidirectional links, hierarchical routing, and interconnection with other non-ZRP routing domains. These are important attributes for a routing protocol for MANETs as they provide the means for extending an existing network with MANET technology, or interconnecting a MANET with other mobile and fixed networks.

As for the 'sleep mode' operation, none of these protocols directly supports such operation. The ZRP 'sleep mode' depends on the routing protocols that operate in the intra- and inter-zones. If OLSR is the routing protocol for the intra-zones, then ZRP can at least partially support this mode. Table 3 summarizes the performance of the above protocols, based on qualitative metrics.

Given the above metrics and the attributes of the two protocols, we believe that ZRP would be a good candidate protocol in military mobile ad hoc networks. Although GPS devices may be supplied in the battlefield to each individual node, we do not wish to base our communications structure on a variety of devices that increase the probability of malfunctions and network failure. A promising attribute of ZRP is the optimization of the zone radius to meet communication requirements. Hierarchical routing can reduce the size of routing tables and offer better scalability in the network. However, the source code for ns-2 [28] does not employ any optimization for protocol performance, making any comparison with other protocols meaningless.

Table 3. Comparison of hybrid protocols

Qualitative metrics	ZRP	GPSR
Loop-free	Yes	Yes
Security	No	No
Support for unidirectional links	Yes	Yes
Sleep mode	Partly	No
Multicasting	Partly	No
Routing scheme	Flat and hierarchical	Flat
Nodes with special tasks	No	No
Routing metric	Shortest path	Shortest path

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6. PERFORMANCE EVALUATION BASED ON QUANTITATIVE METRICS

In this section we evaluate the three routing protocols that were chosen based on qualitative metrics. We use the Bonnmotion-1.4 software [29], developed at the University of Bonn, to create mobile node movement scenarios. As we focus on routing protocols for use in military communications, we create movements based on the Reference Point Group Mobility model (RPGM) [30]. In this model, mobile nodes move in clusters in the simulation area. This model can create movements similar to military movements as army troops move mainly by forming clusters. The movement of cluster heads is randomly chosen, and the movements of the cluster members follow the direction of the cluster head. We test the routing protocols with a number of simulations in order to evaluate their performance.

6.1. Varying the number of connections

In the first set of simulations, we increase the number of connections from 10 to 40 and keep all other parameters unchanged. The data traffic and the routing load in the network increase as we increase the number of connections. We keep a constant bit rate of 10 packets/s (40.960 kbps) for all cases. Table 4 shows the parameters of the simulations.

With this low-to-medium traffic, the routing protocols are expected to have high packet delivery ratio and low normalized routing and MAC load. We expect OLSR to have lower end-to-end delay than AODV and DSR due to its proactive behavior.

Figure 2(a) shows the packet delivery ratio of the protocols. We observe that all protocols have almost the same performance as AODV to present higher packet delivery ratio in all cases. OLSR has the worst performance, mainly because nodes within the clusters are very close and data packets are dropped at the MAC layer. The reason for the above behavior is that the network is congested at some point by the periodic transmission of OLSR HELLO and routing packets. Therefore the existence of valid routes between a source/destination pair in a node's routing table does not necessarily guarantee a better packet delivery ratio.

Figure 2(b) shows the normalized routing load of the protocols. We observe that OLSR has a normalized routing load 800% higher than AODV and DSR for 10 connections. With a higher number of connections, OLSR 'stabilizes' its routing overhead. This happens because, with a higher number of connections, the number of received packets at the destinations increases while the number of OLSR routing packets remains the same. As a result, the value of the normalized routing load fraction increases. AODV presents a higher routing load than DSR for an increased number of connections, as nodes need to transmit a higher number of routing control messages to establish and maintain those additional connections. DSR seems to be the most stable protocol regardless of the number of connections in the network due to its caching mechanism at the source and intermediate nodes.

Figure 2(c) shows the normalized MAC load of the protocols. We observe that OLSR has higher MAC load than AODV and DSR for 10 and 20 connections. However, with 30 and 40 connections, OLSR presents the lowest MAC load. The explanation is that both AODV and DSR generate a higher number of messages at the MAC layer because more control messages are needed to satisfy the establishment and maintenance of the new connections. The MAC layer generates RTS, CTS, and ACK

Table 4. Simulation parameters

Routing protocols	AODV, OLSR, DSR
Mobility model	RPGM
Simulation time	200 s
Number of nodes	50
Simulation area	$X = 2000$ m, $Y = 1000$ m
Speed	Min. = 2.0 m/s; max. = 7.0 m/s
Pause time	5.0 s
Traffic type	Constant bit rate (CBR)
Packet size	512 bytes
Rate	10 packets/s
Number of connections	10, 20, 30, 40

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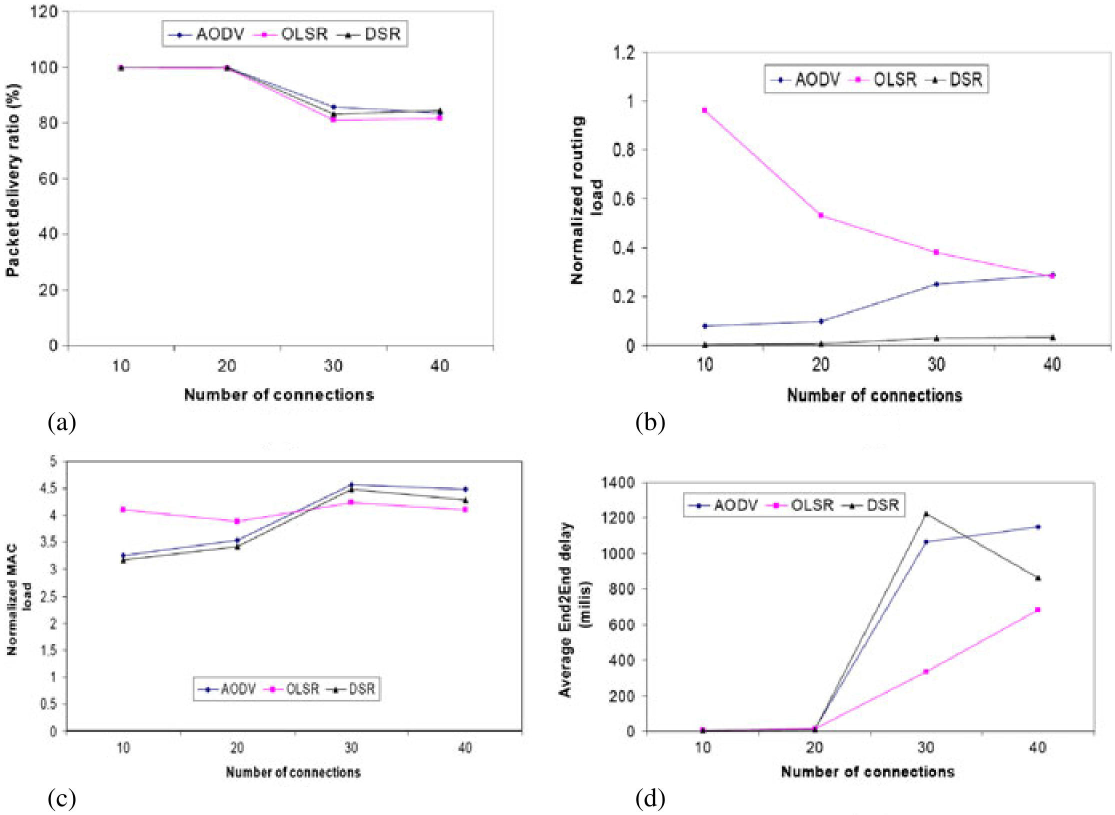

Figure 2. Varying the number of connections

messages for each transmission of RREQ, RREP, and RERR messages. Thus the higher the number of routing control messages, the higher is the normalized MAC load. On the other hand, OLSR generates those additional RTS, CTS, and ACK messages at the MAC layer only for data packet transmission, as the time interval for HELLO and other types of OLSR routing control packets remains unchanged, regardless of the increased number of connections. The conclusion is that, although AODV and DSR generate a lower number of routing control messages, the utilization of the wireless medium is better in OLSR, especially in a network in which the number of connections increases over time.

Finally, Figure 2(d) shows the average end-to-end delay of the protocols. OLSR has the lowest end-to-end delay, which increases almost linearly with the number of connections. DSR has lower end-to-end delay than AODV, although AODV employs a similar chasing mechanism to that of DSR. This is because the timeout value for erasing routes that has been used previously in AODV is not optimized to cover all possible mobility and traffic scenarios. We observe that DSR has higher end-to-end delay for 30 connections for the same reason.

6.2. *Varying the network load*

In the second set of simulations, we increase the number of data packets sent by the sources from 5 packets/s (20.480 kbps) to 20 packets/s (81.920 kbps), keeping all other network parameters unchanged. The demand for efficient routing and wireless medium utilization for data traffic is higher in this scenario; we will observe how the three protocols can scale in that demanding network. In this scenario, we observed that with a packet rate of more than 25 packets/s (102.400 kbps) all protocols present a very low packet delivery ratio (below 50%), making any comparison at those rates meaningless.

Figure 3(a) shows the packet delivery ratio of the protocols. All protocols have an identical performance at low rates (5 packets/s). DSR outperforms AODV and OLSR in all cases, whereas OLSR has, again, the worst performance. Although we placed 50 nodes in an area of 2000×1000 m to avoid

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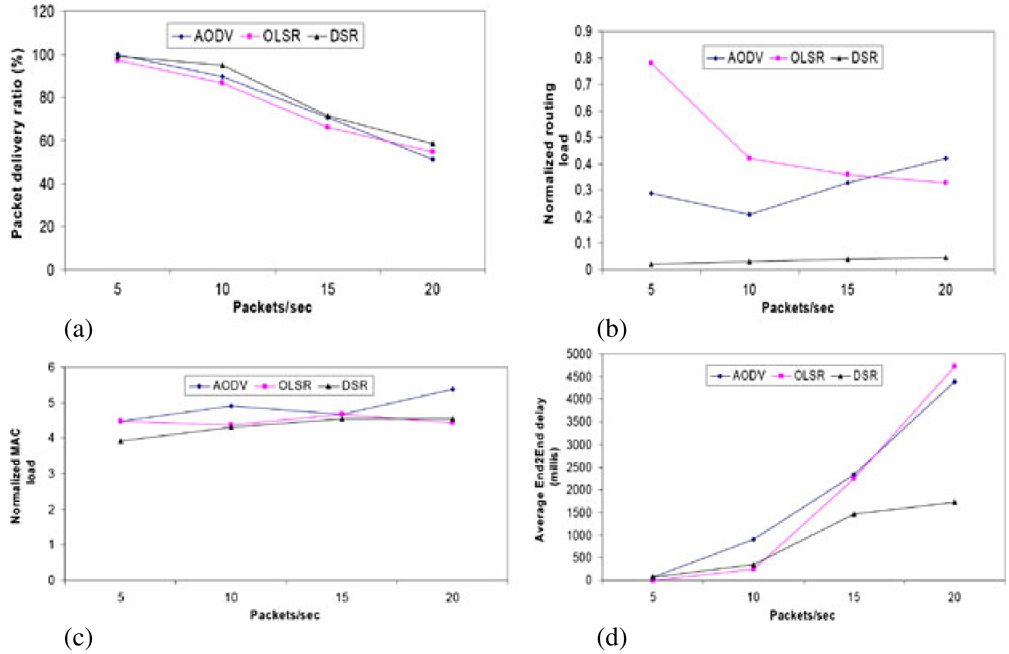

Figure 3. Varying the network load

interference, nodes are still in close proximity, especially within the clusters. This scenario does not favor OLSR: we noticed by analyzing the ns-2 trace files that OLSR produces a large size of route update packets that require higher transmission time than that of AODV and DSR. Neither AODV nor DSR suffers from that periodic exchange of link state information, as routes are discovered in an ad hoc fashion. By analyzing also the trace files, we observed that data packets are dropped by AODV for the following reason: in AODV, the source node will send an RREQ message if a route to the destination node does not exist. After the second transmission of the RREQ message, if the source node does not receive a RREP message within a time interval it will drop the first packet in the queue and repeat the same procedure for the second data packet in the queue. However, when any intermediate node cannot find a valid route to the destination node by repeating the above procedure, it will drop not only the first packet but also all data packets from its queue, thereby degrading the protocol's performance.

Figure 3(b) shows the normalized routing load. DSR has the lowest routing load at all packet rates, showing that it scales well in networks with low mobility in which data traffic increases over time. OLSR presents high routing load in low traffic (5 packets/s), which drops significantly in higher traffic. The reason why is that OLSR generates the same amount of routing packets regardless of whether AODV has a higher routing load than DSR, although, like DSR, it employs an expanding ring and caching mechanism. However, AODV was designed for networks with a larger number of nodes and higher mobility than that in our simulation.

Figure 3(c) shows the normalized MAC load. DSR has the best performance at all rates. We observe also that AODV has a higher MAC load than OLSR, although the AODV routing load is lower than that in OLSR. We explained in the previous section why that happens.

Figure 3(d) shows the end-to-end delay. We expected OSLR to have better performance than the other two reactive protocols. However, the end-to-end delay in OLSR increases when the data traffic increases. The explanation lies in the low mobility of the network. As nodes do not change their positions very frequently, there exists a high level of network congestion at certain regions of the network because none of the three protocols employs any mechanism for load balancing, data traffic is not evenly distributed in the network, and high end-to-end delays result.

6.3. Distributing the network load

In the third set of simulations, we approximate a real situation scenario in military operations in which a node within each cluster, called the cluster head, communicates with its neighboring nodes within the

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cluster and with other nodes at a central position in the simulation area,. The cluster head represents the headquarters (HQ) of the unit. We distribute the network load so that 66% of the data packets are destined within the clusters and 33% are destined to a cluster at a central position in the simulation area. Figure 4 depicts this simulation scenario. We can observe how the clusters are created (dotted lines) and the exchange of packets between the clusters.

As none of the routing protocols employs any mechanism for balancing the network load, we expect all the protocols to have a lower performance than in our previous scenario. This is because nodes around the central cluster behave as 'bottlenecks' of the network, dropping data packets. However, this is a common scenario in military communications, and we wish to analyze the behavior of the tested protocols under this scenario.

Figure 5(a) shows the packet delivery ratio. All protocols present almost identical performance, which is lower than the previous scenario. That at least indicates that all three protocols can be used for any traffic scenario in a network with a low number of nodes, medium data traffic, and medium mobility.

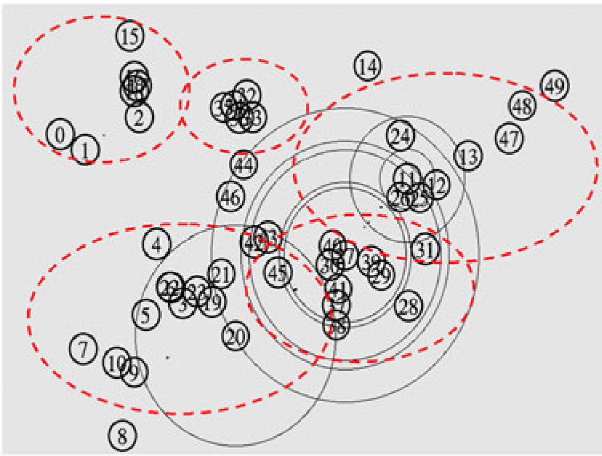
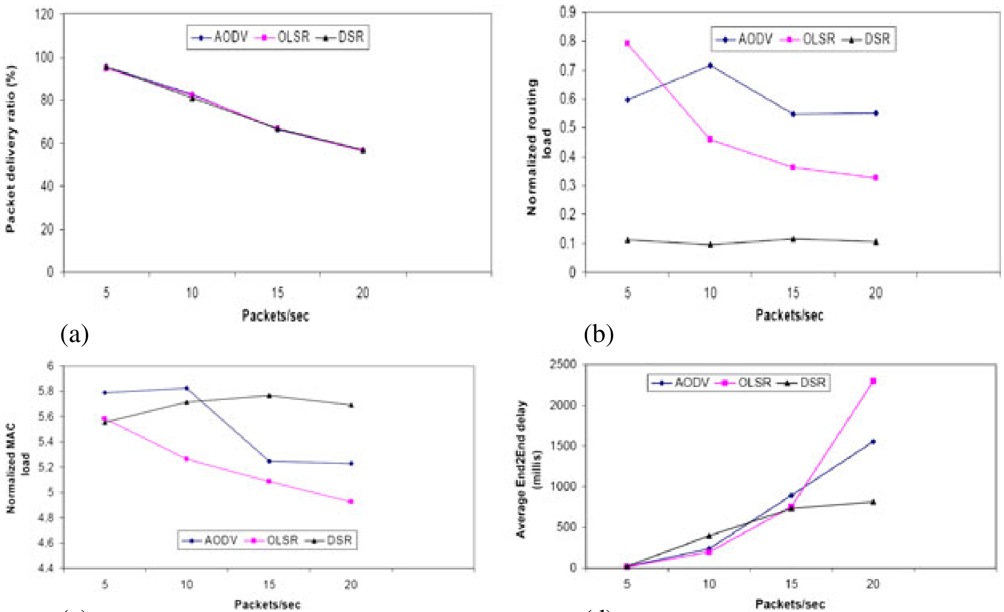


Figure 4. Exchange of packets between clusters



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

Figure 5. Distributing the network load

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Figure 5(b) shows the normalized routing load of the protocols. We observe that DSR has the lowest routing load, which remains stable regardless of the data packet rate. AODV, in contrast, presents the highest routing load. We explained in the previous section that the reason for AODV's high routing load lies in the design of AODV, which performs better in larger networks with a higher mobility.

Figure 5(c) shows the normalized MAC load. OLSR again presents the lowest MAC load, while the DSR performance is the most stable. AODV has the highest MAC load at lower data packet rates, which drops when the data rates increase.

Finally, Figure 5(d) shows the average end-to-end delay of the protocols. OLSR has the lowest end-to-end delay at lower rates, while DSR has the lowest end-to-end delay at higher rates.

What is interesting in the above results is that OLSR presents the highest end-to-end delay at higher data packet rates. By analyzing the simulation trace files, we observed that the size of OLSR TC messages is within the range 48 2020 bytes. Every 5 s all MPR nodes flood the network with TC messages. In our ns-2 implementation, we configured the node's interface queue in such a way that all routing control messages have the highest priority amongst other types of packets, so routing protocols can adapt the network changes in a timely manner. However, that size of TC messages in OLSR causes high end-to-end delay for data packets due to processing, transmission, and propagation delays at the intermediate nodes. In conclusion, the proactive attribute of a protocol does not necessarily guarantee a lower end-to-end delay. Routing control packets size, mobility, and data traffic all affect protocol performance and, under scenarios similar to the one above, a proactive routing protocol may introduce higher end-to-end delay than a reactive routing protocol.

6.4. Varying network mobility

In the fourth set of simulations, we vary the mobility of nodes. We start with a mobility scenario in which the nodes have a low velocity of 5 m/s (18 km/h). We then increase the node velocity up to 20 m/s (72 km/h). Our intention is to investigate the behavior of the three protocols in networks with varied mobility, although the high mobility (72 km/h) cannot be easily found in military movements. We keep a constant data rate of 10 packets/s (40.960 kbps) and a constant number of 20 connections. We observed that, at higher data rates with increasing mobility, the performance of the protocols decreases. The decreased performance is large, mainly due to network congestion, in a way that makes any comparison meaningless.

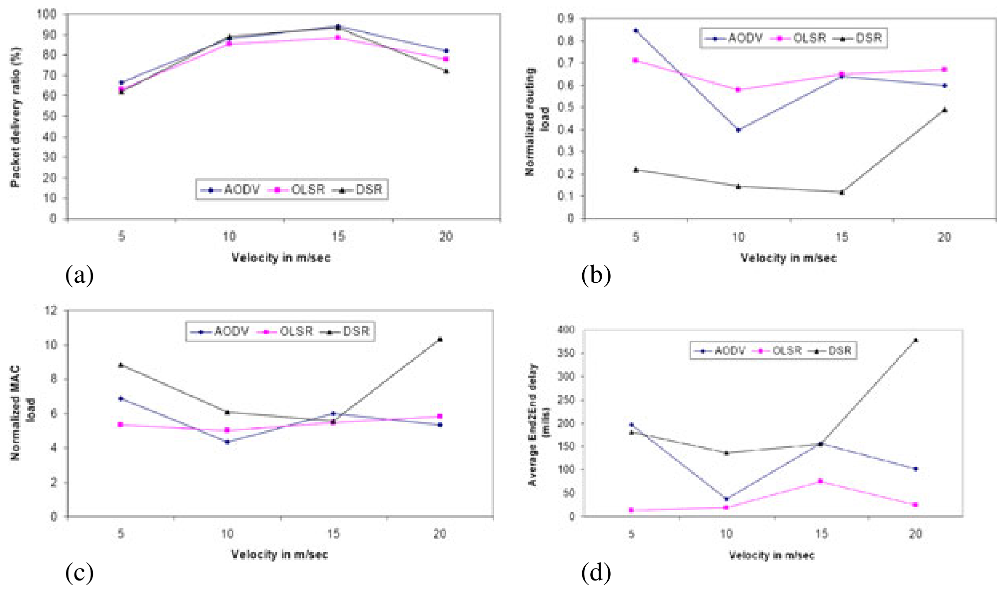

Figure 6. Varying network mobility

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Figure 6(a) shows the packet delivery ratio of the protocols. All protocols present a similar performance as AODV, having the best performance at all mobility rates. We observe again that protocols have a better performance when the speed of the nodes is 10 m/s and 15 m/s, because the network load is more evenly distributed among the nodes at higher mobility rates.

Figure 6(b) shows the normalized routing load. DSR has the best performance, with an increase of the routing load at a higher mobility. That stable behavior of DSR is a desirable property of a protocol as it indicates that it can scale well in networks in which the mobility changes over time. OLSR has the same behavior, while the AODV performance increases when nodes move at higher speeds.

Figure 6(c) shows the normalized routing load. AODV has lower normalized MAC load than DSR, despite having a higher normalized routing load. The explanation is that under this simulation scenario the route discovery in AODV is more accurate than in DSR. DSR, as a result, generates a higher number of routing control messages than AODV to discover alternate routes at the intermediate nodes. OLSR is the most stable protocol in terms of the normalized MAC load in networks with varying mobility.

Figure 6(d) shows the end-to-end delay of the protocols. OLSR has the lowest end-to-end delay at low and high mobility, while AODV outperforms DSR. That high end-to-end delay in DSR in all cases can be explained by our previous observation for the DSR-normalized MAC load, because intermediate nodes need to repair all invalid routes between a source/destination pair in the network, which increases network delay.

6.5. *Varying node density*

In the final set of the simulation, we vary the number of nodes in the network. Our objective is to investigate the impact of node density on the protocol's performance. We use the same simulation area as in our previous simulations and gradually increase the number of nodes in the network. A desirable property of a protocol is to have stable behavior regardless of the number of nodes in the network. However, due to wireless medium limitations, we do not place an inadequate number of nodes in the simulation area. A small number of nodes in a large simulation area will result in low connectivity due to the large distances between nodes. In contrast, a large number of nodes in a small simulation area will result in signal interference, as nodes are located very close to each other.

All protocols have a similar packet delivery ratio, except in the case of 90 nodes, in which OLSR performance drops significantly compared to that of AODV and DSR (Figure 7a).

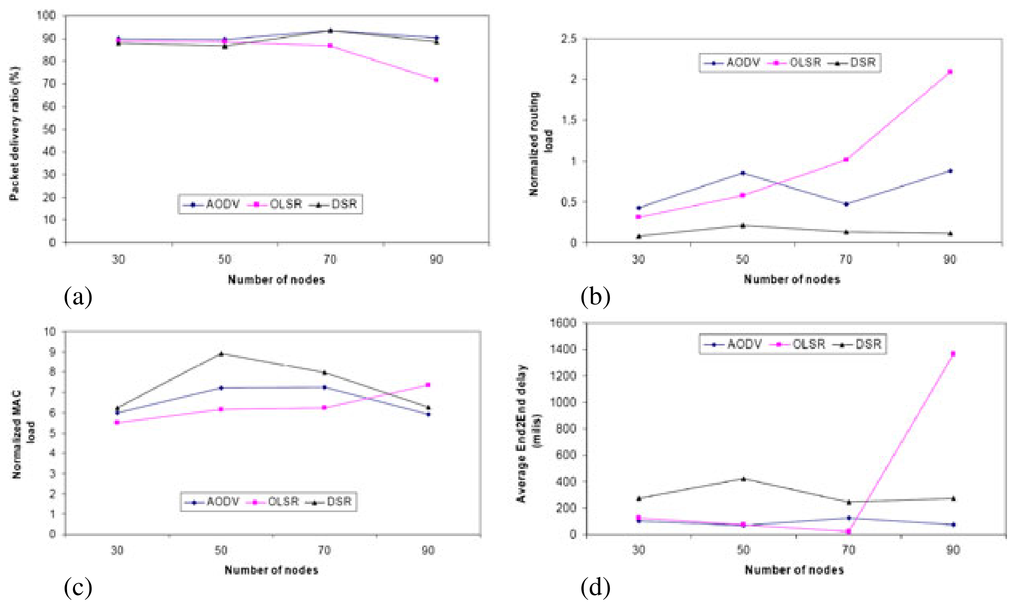

Figure 7. Varying node density

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Figure 7(b) shows the normalized routing load. DSR has the lowest normalized routing load, which is almost independent of the number of nodes in the network. AODV has a higher normalized routing load than DSR and OLSR in the case of 30 and 50 nodes. However, AODV scales well when the number of nodes in the network increases. OLSR has a lower normalized routing load than AODV in the case of 30 and 50 nodes, which increases exponentially with 90 nodes. This is not a desirable property of a protocol, as that high routing load reveals the OLSR inefficiency to operate properly in a network with an increasing number of nodes. This is a direct result of the OLSR proactive behavior, but we expected that the proposed optimization of the Link State algorithm with the implementation of the MPRs would result in a much lower normalized routing load, thereby increasing OLSR performance.

Figure 7(c) shows the normalized MAC load. OLSR has the lowest normalized MAC load except in the case of 90 nodes, in which OLSR generates a higher number of control packets. That high number of normalized MAC load reveals that the network is congested, not by data packets, as we keep the data rate constant, but from the routing packets generated by OLSR. The direct result of a congested network is a high end-to-end delay, which increases exponentially in the case of 90 nodes, as we see in Figure 7(d). Both AODV and DSR present small fluctuations in terms of the end-to-end delay, but generally their performance is stable in all cases.

7. CONCLUSIONS

We presented in this article a complete performance evaluation of ad hoc routing protocols that may be suitable in military communications. Our performance evaluation was based on both qualitative and quantitative metrics as recommended by RFC 2501.

OLSR had the lowest performance in terms of the packet delivery ratio in all of the simulations. The reason lies in the proactive behavior of OLSR, because the Multipoint Relay (MPR) nodes flood the network with Topology Control (TC) packets every 5 s (default value). Therefore, when the network load increases, data packets are dropped by the mobile nodes due to network congestion caused by the periodic transmission of TC packets.

OLSR presented the lowest end-to-end delay in almost all of the simulations, and in most cases the end-to-end delay was independent of the varying simulation parameters. OLSR is a good compromise when combining the protocol performance, in terms of the packet delivery ratio and the end-to-end delay. It is concluded that OLSR is the most efficient protocol for time-sensitive applications such as voice and video transmission. However, a few cases were observed in which OLSR had a higher end-to-end delay than the other two reactive protocols. This is a direct result of the high network congestion in certain areas of the network. By adjusting the TC packet interval and the nodes' willingness default values to the network attributes (mobility, topology, number of nodes, transport protocol), one could reduce network congestion and end-to-end delay.

AODV had a lower packet delivery ratio, higher normalized routing and MAC loads, and a higher end-to-end delay than DSR. In networks with a small number of nodes and low mobility, AODV did not suggest a good solution as a routing protocol. However, AODV had better performance in networks with higher mobility and a greater number of nodes. Simulation results in those networks suggest that AODV presented a higher packet delivery ratio and a lower normalized MAC load than DSR and OLSR. In addition, AODV performance in terms of end-to-end delay was very close to that of OLSR. It was concluded that AODV was the appropriate protocol for any kind of application (voice, video, file transfer, etc.) in networks with high mobility that consist of up to 90 or more nodes.

DSR presented the best performance in terms of packet delivery ratio and end-to-end delay. In most cases, DSR presented the lowest normalized routing and MAC loads, showing that source routing proves to be an efficient routing mechanism in networks with a small number of nodes and high connectivity because it utilized the wireless medium for data traffic in a better way than the other tested protocols.

However, DSR performance decreased in networks with higher mobility, disclosing that source routing could not efficiently adapt the network topology changes that were caused by the frequent movement of the mobility nodes. The same set of observations was obtained when comparing DSR performance in networks with an increasing number of nodes. Under that scenario, DSR presented lower performance than AODV in terms of the packet delivery ratio and end-to-end delay.

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To summarize the above results and observations, it was concluded that DSR was a good candidate as the routing protocol in networks with high connectivity, a small number of nodes (up to 100), and low mobility. The high packet delivery ratio and the low end-to-end delay in those networks enabled the efficient use of time-sensitive applications, such as voice and video streaming.

8. RECOMMENDATIONS FOR FUTURE WORK

8.1. Optimized Link State Routing (OLSR)

It is recommended that further experiments be conducted on the value of the TC packet interval to optimize the performance of OLSR when the attributes of the network are known in advance. In a network with low mobility, for instance, one should increase the TC time interval, as network topology does not change so frequently and routing tables have valid routes to any source/destination pair for a longer period. Alternatively, in a network with high mobility, one should decrease the TC time interval, as network topology changes more frequently and valid routes expire in short periods. In this way, one could control the number of TC packets in the network, balancing network congestion, and thereby optimizing OLSR performance.

A second optimization of the protocol is recommended by adjusting the nodes' willingness value to reflect network topology. In our simulations, the value of the nodes' willingness is set to three, which is the default value in accordance with RFC 3626. That means that a node is willing to act as an MPR for all nodes within a distance of three hops away. In a cluster-like network, one can set that value in such a way that a node will not act as an MPR for nodes that lie outside its cluster. Thus one could reduce the dissemination of OLSR control packets in the network, reducing network congestion and optimizing OLSR performance.

8.2. Ad Hoc On Demand Distance Vector (AODV)

The main design flaw of AODV is the high number of RREQ and RREP messages, which are generated by the mobile nodes. That high number of messages increases routing overhead in the network, which results in higher network congestion.

An optimization of the AODV protocol is recommended by adjusting the time-out value, which is defined as ACTIVE_ROUTE_TIMEOUT in RFC 3561, for routes that have previously been used by a node, to reflect a given network topology and mobility. However, to do that, one should know in advance the network mobility and topology, so that one can estimate the optimal time-out value by experimenting with different time-out values. Generally, in networks with low mobility, a large time-out value should be chosen, as network topology does not change so frequently, whereas a small value is more suitable in networks with high mobility.

8.3. Dynamic Source Routing protocol (DSR)

The main disadvantage of the protocol is the high end-to-end delay, which is caused by the way the mobile nodes reply to RREQ messages.

A modification of the protocol is recommended in the way the mobile nodes reply to incoming RREQ messages. AODV design can be used as an approach to address this particular problem, by forcing the mobile nodes to reply only to the first incoming RREQ message sent by a node in the network. In this way, DSR can discover the least congested path between a source/destination pair and therefore decrease end-to-end delay. An additional benefit of this modification will be a better utilization of the wireless medium, as a lower number of RREP messages will flow through the network.

8.4. General recommendations for routing protocols for MANETS

It is the authors' understanding, after studying the routing protocols and running several simulations for this work, that no protocol exists which can be applied to all 'kinds' of networks. In other words,

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there is no routing protocol for MANETs that can provide efficient routing to any size of network, commercial or military, with a small or large number of nodes and varying network load and mobility. What needs to be done is to adjust these protocols to the network attributes. No protocol can be seen as the best solution for all mobility and traffic models. The bottom line: when one knows in advance the mobility of the nodes, the network topology, the degree of connectivity, the type of the transport protocol (UDP or TCP), and the application that is to be used (email, ftp, video, voice, etc.) one can adjust the internal parameters of the protocol (route updates interval, HELLO interval, etc.) to get the best performance from the protocol. Here is where the problem for finding and standardizing just a single protocol, which can solve the routing problem in MANETs, is located. None of the proposed protocols can be *the* solution to the routing problem. On the other hand, if one takes any of the proposed routing protocols and adjusts its internal parameters to network attributes, one will have a very good protocol, but only for a specific network or similar networks.

A second approach would be a self-configurable routing protocol that would be able to adjust its internal parameters to network attributes. This protocol would collect a number of statistics, such as observed end-to-end delay, packet delivery ratio, node velocity, and degree of network connectivity, and would make decisions to adjust its behavior and therefore optimize its performance.

All the observations and recommendations are left for evaluation and future work.

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