Metrical routing using Ad-Hoc networks in hierarchical environment

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Abstract

The need to rapidly deploy military forces in unknown areas without the ability to use existing ground-based communication infrastructure requires the use of ad-hoc communication networks. Transmission limitations motivates the use of a hierarchal routing mechanism that enables each soldier to communicate with distant soldiers using intermediate powerful nodes that hover within the transmission radius. Our research combines various types of transmitters, including short-range personal transmitters, vehicle-mounted transmitters, helicopters and a geostationary Earth-orbit (GEO) satellite. Each of these entities possesses a different communication range, velocity, and altitude. We consider the various tradeoffs rising from such a heterogeneous theater, and compare two ad-hoc protocols – AODV, which is based on dynamic updates of local cached routing tables, and MRA, which is based on dynamic updates of virtual coordinates. Our results show that for the MRA algorithm one "flat" network is sufficient, and there is no need to use clustering methods. We further show that the GEO satellite constitutes a ubiquitous mediator that contributes to the connectivity and stability of the network.

1. Introduction

Mobile ad-hoc networks (MANETs) are becoming increasingly attractive due to their instant deployment capability and independence of infrastructure. Ad-hoc networks constitute a natural solution for communication networks in a disaster zone where the fixed infrastructure is inoperative or in military applications where military forces must deploy in uninhabited areas. The ability of ad-hoc networks to preserve the connectivity among their members even when the participating nodes are moving has earned these networks with their reputation as *ubiquitous networks*.

One problem of existing ad-hoc protocols is scalability, namely how many nodes can communicate (number of ad-hoc parallel sessions) using a given ad-hoc protocol. For example, in [3] it is stated that "it has been proven that current routing protocols work well in small size networks (e.g. fewer than 100 nodes)". Most papers do not produce simulation results for more than 150 nodes and sessions. This problem of scalability is in particular problematic for a heterogonous theater where several types of transmitters/nodes with different types of transmission range, communication capacity and velocity are used.

In this paper, we study several aspects of scalability in a heterogeneous theater. We focus on "heterogeneous scalability", namely how many "more powerful" nodes are needed to "help" sessions between less powerful nodes. To that end, we consider *infantry soldiers* equipped with short-range personal transmitters; *armored vehicles* equipped with powerful transmitters; *helicopters* and a *geostationary (GEO) satellite* (see Figure 1). The personal handheld transmitters are limited by their short transmission range. The transmitters located onboard the different vehicles can handle more voice channels but are limited in their transmission range due to their ground-based position. The helicopters are flying in relatively high speeds and various altitudes and have significantly larger transmission range and communication capacity. The satellite can be used as a *relay node* containing a large number of channels.

The common routing method in such scenarios is to use hierarchical/clustered protocols such as the Hierarchical State Routing (HSR) protocol [4] or the Intelligent Hierarchical State Routing protocol (IHSR) [2]. These protocols divide the nodes in the spatial network into backbone nodes and regular nodes arranged in clusters. Every cluster uses a cluster *head node* that is a part of the backbone. The cluster head node acts as a local coordinator of transmissions within the cluster and is responsible for keeping and updating routing information beyond the cluster. The use of clusters significantly reduces the traffic of packets to the cluster heads backbone.

The use of clustered protocols, however, hampers the possibility to use a "flat/uniform" ad-hoc protocol that uniformly connects all types of nodes/transmitters in the theater without making the more powerful nodes act as cluster heads. There is a verity of flat protocols that can be used [2] including: (1) global, pre-computed routing; (2) on-demand routing; (3) location-based routing; and (4) flooding. A common assumption in these approaches is that all network elements are *homogenous* and have the *same* capabilities. This lack of ability of the flat algorithms to handle a heterogeneous theater leads to the use of clustering algorithms where, as indicated before, the traffic is significantly reduced. Quoting [2], “all these results show us that a homogeneous structure cannot be scalable to a large-size ad-hoc wireless network. Heterogeneous hierarchical structure should be the solution".

However, clustering too has several drawbacks: (1) there is a significant overhead to maintain the cluster (e.g., electing the cluster head and maintaining the cluster's members); (2) initiating a local session inside the cluster must be started using the cluster head; (3) the centralization of routes via the cluster-heads [4], i.e., sessions that can be routed through two "near" clusters must now be routed through their cluster heads; (4) clustered protocols are more sensitive to breaks and faults of the cluster heads; (5) the number of cluster heads can be larger than the actual number of powerful nodes needed for sufficient communication (6); the session path may require more nodes than a direct path; (7) leadership changes result in routing changes and hence generate routing overhead. The resulting ripple effect can have a detrimental impact on the performance of the network.

In this work, we show that the newly developed "flat" Metrical Routing Algorithm (MRA) [6] based on virtual coordinates is capable of handling a heterogeneous theater and obtain high ad-hoc connectivity *without* using a clustered backbone. Furthermore, our results confirm that Ad-hoc on Demand Distance Vector (AODV) routing working in a "flat" mode is *less* efficient than the MRA for a large heterogeneous theater.

The heterogeneous theater introduces the need to scale the network without compromising performance. There are many references in the literature to the scalability issues. However, no actual examples are given to establish the declarations that the proposed algorithms actually support scalability and the limits of the traffic load. Ref. [7] defines the scalability as "the ability of a network to adjust or maintain its performance when the number of the nodes increases". Ref. [2] describes a heterogeneous network where unmanned aerial vehicles (UAVs) are used to bridge between ground mobile entities. The claim is that IHSR improves the scalability by reducing the number of transmissions with the help of a-2^{nd} level infrastructure. The simulations were performed on heterogeneous network with three types of radio interfaces. There is no description of scalability simulations and the results of such experiments. Ref. [1] discusses a heterogeneous network with ground nodes such as troops, ground mobile nodes and UAVs that maintain a line-of-sight connectivity. The discussion on scalability does not present any simulations of heterogeneous networks and performance analysis. A simulation of a heterogeneous protocol and a Random Comparison Clustering scheme with flat and hierarchical versions of AODV is presented in [3]. The mobile nodes speed was selected to be in the range 0-10m/s, with a large network of 1000 nodes. The simulations do not include scalability tests. Ref. [5] Reports on simulations performed to compare the H-LANMAR with flat LAMAR and flat AODV. The simulations include up to 36 backbone nodes with a single UAV connected to all backbone nodes in a theatre of 3.2Km × 3.2Km. No results are given on the scalability tests.

In this work, we study scalability in a heterogeneous theater via simulation experiments, yielding the following promising results:

- The MRA working in a flat mode scales well in the heterogeneous case;
- The AODV working in a flat mode does not scale well for the heterogeneous case;
- Very few helicopters are needed to maintain global communication for all troops in the theater;
- In spite of their larger capacity, cars are less effective in maintaining global communication for troops due to their limited transmission range;
- A satellite covering a given field cannot satisfy the required Quality of Service (QoS) requirements without the support of helicopters. On the other

hand, while helicopters-only ad-hoc backbone guarantees the QoS, it cannot guarantee a global coverage of the field. Only a backbone that comprises a GEO satellite and helicopters satisfies both the connectivity needs and the QoS.

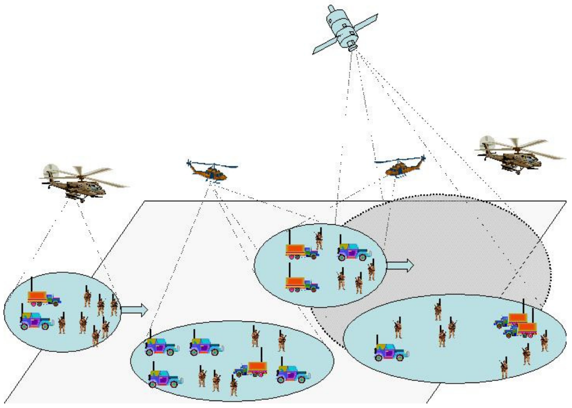


Figure 1: Theater ad-hoc network layout

We embark on our study by presenting the MRA, and continue by a presentation of the simulator, experiments, and results.

2. The Metrical Routing Algorithm

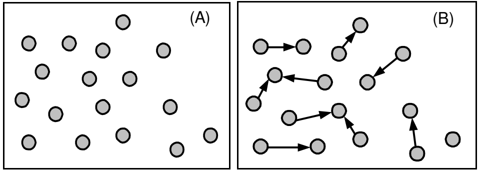
The Metrical Routing Algorithm (MRA) protocol [6] is classified as a hybrid protocol, as some traffic control is used to maintain the mapping of the nodes. The small overhead of the MRA protocol used to maintain the mapping is a worthy investment, as the MRA is capable of successfully handling a demanding traffic load under a high node density and fast node movement. The MRA organizes the nodes in rooted trees in order to find short session paths between nodes on the tree. The algorithm tries to minimize the number of trees by fusing separate adjacent trees into a single tree. As long as all nodes in one tree are not in the transmission range of all nodes in the other trees, the trees will function autonomously. As soon as a radio connection is created between two nodes, the trees will be fused into a single tree. All nodes run the same protocol implementing the MRA. As nodes emerge, disappear and move in or out of range of other nodes, there is need to update the trees. A primary goal of the algorithm is to identify these changes and adapt the trees structure to the new state. In the following discussion, we shall present an elaborate description of the MRA protocol, which will be ultimately employed for a simulation study of the MANET routing performance.

2.1 Dynamic Fusion of Spanning Trees

The MRA organizes the nodes in the field in rooted trees. Only nodes that belong to the same tree can create sessions among themselves. To ensure maximal connectivity, all nodes will try to organize themselves in a single tree. Every node in the field has a unique *node-id* (similar to a phone number or an IP address), and dynamic coordinates – the *node address* - that identify its location in the tree. Every tree is identified using a *tree name*, which is the *id* of the root node. Nodes periodically send beacons; every node that receives a beacon checks whether the node that sent the beacon belongs to a different tree. If the nodes belong to different trees, they will initiate a fusing process that will fuse the separate trees into a single tree. The fusion protocol should satisfy the follow properties:

1. The protocol should not cause active sessions to break.
2. Eventually (assuming no dynamic changes occur) all trees with nodes within transmission area must fuse into a single tree.
3. When two trees are being fused, most updates should be made to the nodes of the smaller tree (in terms of the number of nodes).
4. The protocol should maximize the number of nodes that migrate from one tree to another in every step (yielding a parallel fuse).
5. Nodes constantly attempt to shorten their distance to the root of the tree by fusing to higher level nodes.
6. Initially every node forms a separate tree of size 1.
7. The protocol is fully distributed with no central bottlenecks, namely it is defined at the level of pairs of nodes.

Every node in the tree can initiate a fusion process to a neighboring tree regardless of the node position in the tree. The fusion node gets new coordinates in its new tree according to the node's new position. Naturally, when a node migrates from one tree to a new tree, it may carry its neighboring nodes to follow it. Figure 2 presents three stages of the tree fusion protocol: The initial state, an intermediate state and final partition to trees (assuming no dynamic changes occur).



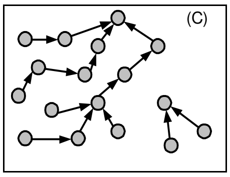


Figure 2: Tree formation process

Note that the two separate trees (C) cannot fuse because there are no two nodes within a transmission range that will start a fusion process.

3. The Simulator

A simulator for evaluating the performance of the MRA has been developed. In this section, we shall describe the simulator and the simulation scenarios.

3.1 Simulator Description

The simulator was designed and developed for testing the MRA and running comparative tests, comparing the MRA's performance to other routing protocols. Special attention was given to the following aspects: (i) enhanced visualization tools that give a full online view of the theater, node movements, voice channels, and specific node status including queue status; (ii) tracing the formation of trees in the MRA protocol; (iii) tracing the sessions in real time; (iv) configuration and simulation definition via online screens; and (v) support of logging, debugging and analysis tools.

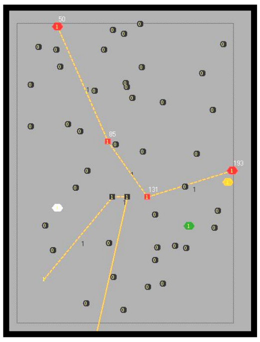


Figure 3: Intra-platoon session: 50 ⇔ 85 ⇔ 131 ⇔ 193

The enhanced visualization capabilities, unique to this simulator, contributed to the understanding of the protocol behavior, as we were able to view the progress in the field and detect unexpected behavior.

3.2 Test Entities

We simulated a test theater of 50km x 50km. In this area we defined *platoons*. A platoon is a military unit that comprises different entities such as armored vehicles and soldiers moving in specified directions. Every element in the platoon can move autonomously in any given direction. The movement speed of the individual elements may be higher than the average platoon speed. The soldiers move at a speed of 6-8 km/h and cars move at speeds of 20-70 km/h. Elements cannot cross the platoon borders and they must move within the platoon. Helicopters are not restricted to fly within a platoon, but can fly freely throughout the test area. A helicopter flies in a random speed ranging from 100 km/h to 170 km/h. We defined 5 platoons with the attributes given by Table 1.

	Elements in platoon	Size (km)	No. of elements in platoon	Platoon movement speed
Platoon 1	Soldiers, Cars	8 x 8	20	1 km/h
Platoon 2	Soldiers, Cars	4 x 4	15	1 km/h
Platoon 3	Cars	3.5 x 3.5	2	15 km/h
Platoon 4	Cars	4 x 5	8	20 km/h
Platoon 5	Soldiers, Cars	4 x 6	25	2 km/h

Table 1: Platoon details

4. Simulations and Results

In the following simulations, we defined 5 platoons in the test field as described by Table 1. Nodes in every platoon were able to communicate with each other directly when they were within the transmission range or indirectly when they were out of transmission range. Due to transmission limitations, nodes were unable to communicate in the first test with nodes located in other platoons. In Figure 3, depicting the data sessions view, we see an intra-platoon session that uses the shortest path between nodes 50 and 193, which are not in a direct transmission range. The session path is constructed of 4 nodes - 50, 85, 131, and 193. In Figure 4, we depict an inter-platoon session that uses the helicopters and a satellite to bridge the distance between the platoons. In this case, one of the platoons is not in transmission range from the satellite, so without the helicopter, bridging the sessions could not have been established. In advanced steps of the simulations, we added helicopters and a GEO satellite. While the satellite covers almost the entire test field, communicating with helicopters and vehicles, it cannot communicate with soldiers. A helicopter can communicate with soldiers, ground vehicles, the satellite and other helicopters, but all these agents must be in the transmission range limited to 24 kilometers.

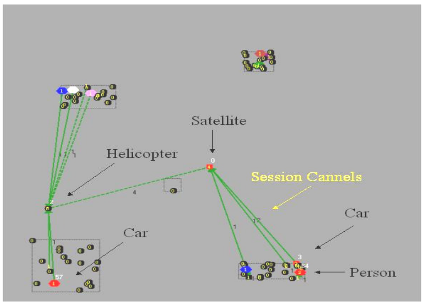


Figure 4: Inter-platoon session 57 ⇔ 2 ⇔ 0 ⇔ 3 ⇔ 64

4.1 Simulation Environment

All simulations were performed in a fixed 50 km x 50 km field. The node transmission range depended upon the following attributes: (i) transmitter type – a personal radio is limited by its transmission range and its battery power; (ii) the transmitter height above the ground - a transmitter mounted on a helicopter has a larger range than the same transmitter on the ground. We ran separate tests for different number of helicopters with and without a GEO satellite. The results show that there is a significant change in the network connectivity when a satellite is used.

The in- and out-queues of capacity of the nodes were set to 20 messages each, except for the satellite queue, where the queues were set to 50 messages. A full queue prevents the node from receiving new messages and therefore these messages will be lost. The node will get new messages when one or more messages are processed and cleared from the queue.

A session is a full duplex connection between nodes. When needed, one or more intermediate nodes will help to bridge the distance between the end nodes. A message can be lost because of an overflow of the queue in one of the chain of nodes used by the session.

Every second is constructed of 330 ticks. The status of each node is evaluated every tick and decisions are taken. A successful session is a session where at least 80% of the packets were transferred between the session parties. A session length is 5 seconds. When using a satellite in a session, the transmission packets were delayed by 0.24 seconds. As opposed to other nodes, the satellite cannot generate or terminate sessions.

4.2 Simulation Experiments

4.2.1 Bridging between Platoons by Helicopters

Figure 5 presents the field layout with the five platoons described by Table 1. This snapshot reflects only the initial position of the platoons, as the platoons are constantly moving in different speeds and different directions. This field contains a mix of heterogonous nodes having different capabilities. The personal handheld transmitters are limited by their short transmission range. The transmitters located onboard the different vehicles can handle more voice channels but are limited due to their ground-based position. The helicopters are flying in relatively high speeds and various altitudes and use transmitters which are similar to the vehicle transmitters. The satellite is used as a *relay node* containing a large number of channels, but without the capability to generate or terminate sessions. The delay in traffic due to the large distance of the satellite from earth is a factor influencing the Quality of Service of the sessions. The stable element in this chart is the GEO satellite, whose footprint constantly covers a large area. Personal transmitters and transmitters mounted on vehicles exist only in platoons. A personal transmitter cannot communicate directly with the satellite.

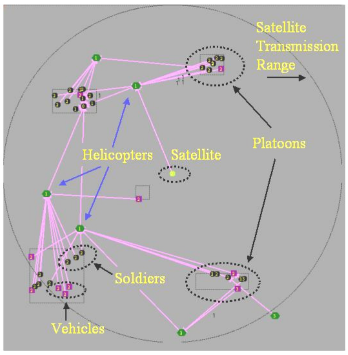
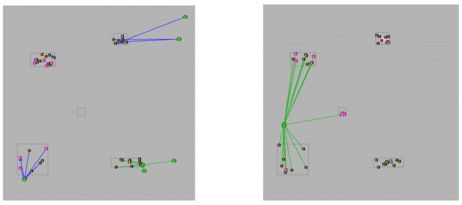


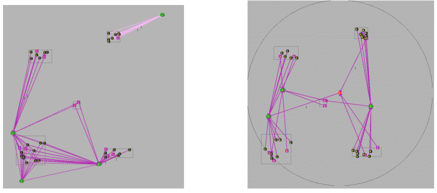
Figure 5: Field layout

The scenarios tested here simulate cases in which nodes are concentrated in platoons spread over a large area of 50km x 50 km. the connectivity level between platoons is zero. In addition, the connectivity levels inside a platoon may suffer from difficulties related to the platoon size and the number of elements in the platoon. For example, Platoon 1 (Table 1) hosts 20 elements that are spread over an area of 64km^2. Figure 6 depicts the lowest level of connectivity. The number of sessions created in this case is 50 when all of the sessions are intra-platoon sessions. Sessions are available only inside the platoons.

Adding a helicopter, as presented in Figure 6b, improves the connectivity level, due to the fact that the helicopter is used as a mediator between platoons and isolated nodes inside the platoons. Figure 6c presents the case of 4 helicopters in the field. The connectivity between some platoons is very high. However, as the helicopters are moving very fast in the field, some platoons may remain disconnected from the other platoons. Adding more helicopters does not guarantee a full coverage of the field because the helicopters may aggregate in a small zone as illustrated by Figure 6c. An addition of a satellite, shown by Figure 6d, upgrades the connectivity level. In this case, almost all nodes are connected except some isolated personal transmitters that cannot communicate with the satellite and are not within transmission range to neighboring nodes.



(a) Isolated Platoons (b) Single Helicopter



(c) 4 Helicopters (d) 3 Helicopters & Satellite

Figure 6: Inter and Intra-platoons sessions

Figure 7 presents the cumulative number of successful sessions with and without a satellite. A successful session is a session that successfully transferred at least 80% of its packets. The analysis of the results gives rise to the following important observations:

1. The absence of inter-platoon mediators such as helicopters prevents the platoons from creating inter-platoon sessions (Hel 0). All sessions generated in this case are intra-platoon sessions. The existence of a satellite which serves as an inter-platoon mediator increases the number of sessions by 90 (Figure 7). This gap stems from inter-platoon sessions.
2. The number of successful sessions grows rapidly until the number of helicopters in the field reaches 5. From the 6th helicopter, this growth becomes more moderate despite the addition of helicopters, up to the point where the area becomes saturated with helicopters. The number of mediating helicopters satisfies the bridging requirements needed to create inter-platoons sessions. Further addition of helicopters will not generate more sessions.
3. The number of successful sessions transferred by the combination of a satellite and helicopters is greater than the number of sessions transferred by helicopters only. This trend turns over after the 4th helicopter. On one hand, the satellite covers almost the entire field and enables inter-platoon sessions. On the other hand, since the satellite is unable to communicate directly with personal transmitters, every inter-platoon session initiated by a personal transmitter requires at least 5 legs: <personal transmitter> <car transmitter> <satellite> <car transmitter> <personal transmitter>.

4. The addition of helicopters to the field improves the connectivity due to the following factors:
   a. Creating an alternative to the satellite routing by using helicopters as mediators. This prevents the satellite from becoming a bottleneck to inter-platoon sessions and distribute the traffic more evenly.
   b. Shortening the average session path length. The number of the session legs drops significantly as many sessions that had used 5 legs can now be executed using the 3 legs <personal transmitter> <Helicopter> <personal transmitter> or 4 legs.

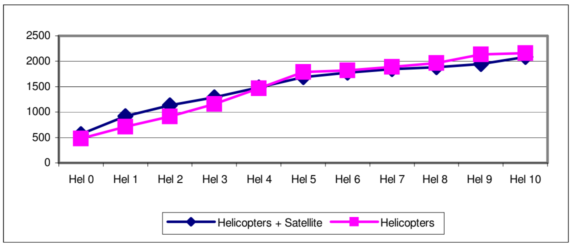


Figure 7: Successful sessions with and without satellite

Table 2 compares the number of lost messages because of queue overflow with and without a satellite. Queue overflow is caused when too much traffic attempts to use a limited resource such as the satellite. Without the satellite, we observed only a negligible number of lost messages. This is because of the relatively small coverage area of every helicopter (Figure 6b). Even more helicopters (Figure 6c) do not guarantee a full coverage of the area. The traffic volume that uses the helicopters in this case had not fully utilized the resources, and as a result only isolated cases of overflow were encountered.

The number of messages lost in the satellite because of queue overflow is very high when the number of helicopters is very small and drops significantly when the number of helicopters grows. This loss of messages reduces the quality of the sessions and may decrease the number of successful sessions. The migration of sessions from satellite to helicopters improves the quality of the sessions, as fewer messages are lost. Naturally, in the case that helicopters are absent, the bulk of the traffic is routed through the satellite, which, in turn, loads the satellite queues. When the number of helicopters passes the threshold of 4, this balance changes and more sessions use the helicopters rather than the satellite, resulting in a higher session quality.

Number of Helicopters	0	1	2	3	4	5	6
Without Satellite	0	0	5	5	0	7	7
With a Satellite	400	420	390	410	320	110	100

Table 2: Platoon details

4.2.2 Message Distribution Analysis

We divided the messages into 4 groups: Tree management messages used to manage the trees in the theater, call setup messages used to control the sessions, data messages which are the throughput of the network and Hash messages that maintain the nodes locations. Figure 8 presents the distribution of the messages in the simulations into groups.

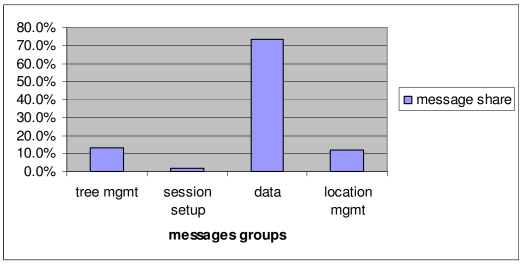


Figure 8: Message group distribution

The analysis of the message distribution shows that 73.6% of the messages in the system are pure data messages transferred during the sessions between the nodes. Additional 1.7% of the messages are used to control the sessions. The tree management utilizes 12.9% of the total number of messages running in the network. This part includes also the beacon messages which constitute about 90% of the latter constituent. The location management of the nodes in the trees requires 11.7% of the total number of messages.

4.3 Performance Comparison

Table 3 presents the results of a performance comparison between the MRA and the well-known AODV protocols. The performance is measured by the number of sessions through which more than a certain percentage of the packets passed. For example, the notation MRA 100 denotes a set of 100 simulations of the MRA protocol with 100 nodes. The success rate presents the number of sessions that succeeded in transferring more than X% packets of the session. Naturally, the sessions that succeeded in transferring 85% are included in 80% packets (sessions with less than 80% success of packets transfer were classified as faulty sessions).

Protocol	Success Rate				
	80%	85%	90%	95%	100%
MRA 100	270	267	264	257	71
AODV 100	188	188	188	184	45
MRA 140	341	325	315	289	67
AODV 140	210	210	210	197	25
MRA 180	477	462	444	410	95
AODV 180	252	226	172	90	6
MRA 220	524	489	452	383	95
AODV 220	176	134	81	31	0
MRA 260	535	491	441	377	94
AODV 260	40	23	12	4	0
MRA 300	604	558	518	442	112
AODV 300	**13**	**7**	**3**	**0**	**0**

Table 3: Successful sessions: MRA vs. AODV

The analysis of the results raises the following observations:

1. MRA generates a higher number of successful sessions. This observation holds for all densities.
2. The gap between the number of sessions generated by MRA and AODV grows as the density of the nodes grows.
3. The session's quality drops faster for AODV than for MRA as the density increases. The quality of service is defined as the weighted sum of the calls from every success rate, divided by the estimated attempts. This decrease is mainly noticeable in the high densities. For example, in the case of 300 nodes, MRA succeeded to handle 604 sessions with a success of 80% and AODV handled successfully only 13 sessions. MRA handled successfully 112 sessions with 100% messages transfer and AODV failed to handle any calls with 100% message transfer.

Figure 9 depicts the robustness of the protocols to an excessive traffic load. In this case, the requirements were to maintain 60% of the nodes in the theater occupied by sessions. The number of successful sessions that MRA succeeded to connect and maintain without any loss of messages grew until the number of active transmitters in the field reached 140. From this point on, the number of fully successful sessions decreases. AODV presents a constant decline of the number of fully successful sessions as the number of transmitters grows. The reason for this significant difference between the routing algorithms is due to the difference in the cost of creating new sessions. The high rate of creation of new sessions leads to a faster queue overflow and higher message loss in AODV compared to MRA.

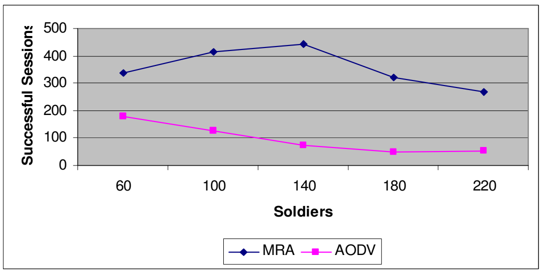


Figure 9: MRA Vs. AODV high density load efficiency

This phenomenon stems from the AODV's need to flood the network with Route Request (RREQ) messages each time a new session is initiated, while the MRA utilizes constantly a fraction of the network capacity to maintain the Hash tables without any burst of control messages during the session initiation phase.

5. Conclusions and Future Work

We described in this research a study of complex node and platoon behavior in an ad-hoc network constructed of heterogeneous nodes. The research investigated the contribution of the different entities to the connectivity and the ability of the ad hoc network based on the Metrical Routing Algorithm (MRA) to scale. The simulations were performed with a realistic mobility model of soldiers and ground vehicles organized into platoons, helicopters and an optional geostationary (GEO) satellite.

We can identify two complementary observations. On one hand, the results indicate that a GEO satellite is a ubiquitous mediator that contributes to the connectivity and stability of the network especially when the number of helicopters in the area is limited and the coverage of the field in incomplete. The ubiquity of the GEO satellite does not guarantee that users will be able to create a high-quality path between the parties. Moreover, as the anchor and a single resource for all communication sessions, the satellite cannot satisfy the communication requirements.

On the other hand, the helicopters provide high-quality communication links. These links do not ensure a global coverage of the field. Addition of helicopters to the field broadens the covered area but does not ensure full coverage. Only a combined network of a satellite and helicopters will ensure a global coverage with a satisfactory level of QoS. The addition of powerful backbone nodes such as satellites or helicopters must cross a minimal threshold. A small number of backbone nodes will collapse under the enormous number of inter-platoon control and data packets that will prevent effective communication between nodes.

The use of a satellite as an anchor provides an efficient solution for data sessions. However, for voice sessions, it is preferable to use a session path that does not include a satellite due to the inherent delay. This conclusion holds even if the length of a session path without a satellite is longer than a session path with a satellite.

We have shown in this research the ability of the MRA to connect a heterogeneous network that can scale up without degradation in performance. Moreover, we presented "reverse scalability" tests that showed how less powerful transmitters of tier 1 and tier 2 supports tier 3 entities in a large-scale theater.

The MRA algorithm attempted to allocate a short session path between the parties regardless of the session type. Future research will deal with the issue of allocating session paths that match the specific needs of voice and/or data.
Future research directions include the exploration of various regular structures for coordinate coverage as an alternative to the rooted trees presented in this paper. Another direction is the enhancement of the simulator by simulating obstacles and improvements of the simulator performance.

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