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EVALUATING THE EFFECTIVENESS OF SITUATIONAL AWARENESS DISSEMINATION IN TACTICAL MOBILE AD HOC NETWORKS

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ABSTRACT

Situational Awareness (SA) dissemination in tactical mobile ad hoc networks (MANETs) plays an essential role in command and control systems for military operations. This task is particularly difficult in highly dynamic and complex environments with strict resource constraints on mobile units. In this work we present a design of SA dissemination schemes based on the multipoint relay (MPR) technique. We implement the schemes on a simulation platform and investigate their effectiveness in a real-time manner using novel metrics focusing on the completeness and freshness of SA, as well as the network traffic overhead and local processing cost. Two mobile scenarios, including one that is based on the Reference Point Group Mobility model, are set up to simulate the real-world behavior of tactical MANETs. The MPR-based methods are compared against an alternative scheme, Opportunistic Situational Awareness Passing, where the simulations highlight tradeoffs and provide insight into selection of design parameters.

1 INTRODUCTION

Operational decision making in a tactical environment relies heavily on Situational Awareness (SA) information that is required to be reliable, accurate, up-to-date and complete. Tactical operations are often conducted in areas without access to fixed communication infrastructure, and demand highly dynamic yet resilient mobile networking. To this end, mobile ad hoc network (MANET) technology is expected to play a significant role in tactical applications in the field. MANETs are self-forming and self-organizing without need of a centralized network architecture, and can be set up rapidly in complicated terrain and under adverse circumstances. The benefits of MANETs come with many challenges that need to be addressed, such as unstable links due to wireless channel conditions, handling of frequent changes in topology, overhead in maintaining the network routing, and security in open medium.

There has been increasing research interest in recent years in SA data dissemination technologies in MANETs. For example, Mason (2002) presented a framework with prototypes to compare SA technology systems. Larsen et al. (2010) investigated efficient SA dissemination techniques based on the Simplified Multicast Forwarding (SMF) protocol (Macker 2012). A comprehensive survey for situational awareness measurement techniques can be found in Salmon et al. (2006). In our recent work (Brown, Salmanian and Li 2014; Li et al. 2014), a novel Opportunistic Situational Awareness Passing (OSAP) scheme was proposed with an efficiency study, the simulation implementation and performance analysis.

Most of the SA dissemination techniques appearing in the academic literature are broadcast based. The simple broadcast scheme, called blind or classical flooding, where each node relays the same message exactly once, is prone to producing redundant transmissions and may result in serious broadcast

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storm problem (Ni et al. 1999). Improvement and optimization of broadcast techniques have been an active research topic for decades, see for example Williams and Camp (2002); Lipman, Liu and Stojmenovic (2008); and references therein. One of the efficient techniques is based on the Multipoint Relay (MPR) concept (Qayyum, Viennot and Laouiti 2002), where a quasi-minimal subset of 1-hop neighbors is selected to cover all 2-hop neighbors for message relay. The MPR method is the foundation for OLSR protocol (Clausen and Jacquet 2003), has been adapted in various broadcasting schemes, such as in Liang et al. (2006) and Song et al. (2015), and is the basis for SMF schemes as well.

The focuses of this paper are: 1) Design of SA dissemination schemes based on the MPR technique; 2) Implementation of the MPR-based schemes on the EXata (a.k.a. QualNet) simulation platform (SNT 2008–2015); 3) Investigation into the effectiveness of the schemes by simulation testing and comparison of the performance to OSAP. The simulations highlight tradeoffs and provide insight into how to properly select design and configuration parameters. We consider two variations of MPR-based SA dissemination, referred to as the source-node-flood method and the MPR-node-flood method. The software design architecture consists of the typical Hello messaging process and the greedy heuristics for the calculation of MPR sets, and an additional SA messaging process. Moreover, we focus on the completeness and the freshness of SA information, two of the most important properties of the SA in tactical MANETs.

Although the efficiency and performance of broadcasting techniques based on the MPR concept have been extensively investigated in the literature, most of the work is carried out against the accumulated data at the end of execution, while very little has been reported on the performance of concerned schemes in a real-time manner, i.e., presenting and analyzing the statistics continuously throughout the test run. For the real-time analysis of SA performance over time, we create customized functions to collect required statistics and calculate the performance metrics in a “sliding window”. This approach is particularly helpful in understanding SA dissemination performance in highly mobile applications.

The test scenarios in this paper are designed to better reflect real-world characteristics of tactical MANETs. Specifically, one scenario is set up using the well-known Reference Point Group Mobility model (Hong et al. 1999), with parameters configured to simulate infantry unit movements in the field.

We analyze the performance of the MPR-based schemes using a set of novel situational awareness metrics proposed in Li et al. (2014), which aim to evaluate SA dissemination schemes in three categories: completeness, freshness, and workload (both network-wide and local cost). In each test scenario, simulation results of the OSAP scheme are also presented for comparison with MPR-based methods.

The rest of the paper is organized as follows. We present the detailed design of the MPR-based SA dissemination schemes and their implementation on the EXata platform in section 2. In section 3 we define test scenarios, produce simulation results, analyze the performance and evaluate the effectiveness of MPR-based schemes and OSAP. Discussions and concluding remarks are made in the final section.

2 MPR-BASED SA DISSEMINATION AND SIMULATION IMPLEMENTATION

2.1 Brief Review of the Multipoint Relay Technique

For a node k in the network, all neighbor nodes within its radio range are called 1-hop neighbors of k and denoted by N_{1hop}^{k}, while the nodes that can be reached by k via exactly one intermediary hop are called 2-hop neighbors and denoted by N_{2hop}^{k}. The MPR set of k is defined as a subset of N_{1hop}^{k} such that any node in N_{2hop}^{k} can be reached by k with an MPR node as relay point. The MPR technique consists of two basic functions. First, each node maintains its 1-hop and 2-hop neighbor sets, which are populated using neighbor information carried by a periodic HELLO messaging process. The HELLO messages are never forwarded, i.e., HELLO messaging is performed locally. Second, each node updates its MPR set based on, and upon changes of, the 1-hop and 2-hop neighbor sets. Finding the minimum MPR set is an NP-hard problem and a greedy heuristic was proposed to obtain an approximate solution (Qayyum, Viennot and Laouiti 2002). We use M^{k} to denote the computed MPR set for node k. In an MPR-based flooding scheme, messages from k are forwarded by nodes in M^k only, hence reducing number of messages being forwarded across the network. The higher the ratio of N_{1hop}^k to M^k, the more savings in message forwarding can be achieved. An associated concept in the MPR technique is the MPR selector set: for an MPR node k we say a neighbor node l is in the MPR selector set of k if l selects k as its MPR node.

In a mobile scenario, the topology and connectivity status of nodes in the MANET are frequently changing. Consequently, the 1-hop and 2-hop neighbor sets as well as the MPR sets and MPR selector sets must be updated in time on each node. For an MPR-based method, there are always two types of fundamental cost: the overhead in network traffic for the HELLO messaging process; and the local processing cost of maintaining the 1-hop and 2-hop sets and subsequently calculating the MPR set by a heuristic. The efficiency and effectiveness of the MPR-based methods with regard to the above associated cost are not the focus of this work and will not be discussed further in the rest of the paper.

Note that in MPR-based methods, periodic message processes may result in simultaneous message transmissions. To mitigate the issue of collision, randomized jitters (i.e. delays) are usually implemented for the periodic messaging, and we have applied random jitters in our software implementation.

2.2 Design of the SA Dissemination Schemes

To disseminate SA across a tactical MANET, we introduce a new type of message, referred to as the SA message, which carries SA data throughout the network by the MPR-based flood mechanism. Flooding of the SA messages is managed by an SA timer with a configurable sa_flood_interval. The new SA messaging process is running in parallel with the existing HELLO messaging process that is controlled by a separate Hello timer with a configurable hello_interval. In this subsection we describe two variations of MPR-based SA dissemination scheme: Src-Flood where every node floods the SA messages; and Mpr-Flood where only the MPR nodes are tasked to flood the SA messages.

2.2.1 Src-Flood and Mpr-Flood

In the Src-Flood method, SA data dissemination proceeds independently of the HELLO messaging. Each node creates the SA message containing its own SA data, and floods at the sa_flood_interval. The SA messages are forwarded only by the MPR nodes of the originating node and relay nodes. This scheme is actually a form of the traditional MPR-based broadcasting methods for data dissemination in a MANET.

Albeit simple to implement, the Src-Flood method does not take full advantage of the MPR technique. To deliver desired data throughout a network, the typical strategy in MPR-based methods is to let the MPR node generate a message containing aggregated data from all its MPR selector nodes, rather than letting each individual node generate a separate message containing its own data. The Topology Control (TC) messaging process in OLSR protocol is a well-known example of such strategy. We design the Mpr-Flood method using the same idea, where only MPR nodes create the aggregated SA messages consisting of SA data from their MPR selector nodes, and flood the messages at the sa_flood_interval.

In order for an MPR node to generate the aggregated SA message, SA information from all its MPR selector nodes must be available. This requirement is fulfilled by an enhanced HELLO messaging process, where we augment the HELLO messages to include neighbor's SA data. Note that the augmented HELLO messages still carry out the original functionalities, and the messaging process is not to be altered.

The main differences between Src-Flood and Mpr-Flood can be observed from various perspectives:

- The originating node for SA messages – all nodes in Src-Flood vs. only MPR nodes in Mpr-Flood (since the MPR selectors deliver their SA to the MPR node in the augmented HELLO messages). As a result, Src-Flood usually requires more SA messages than Mpr-Flood, assuming they use the same sa_flood_interval.
- The SA message content – single node SA data in Src-Flood vs. aggregated SA data in Mpr-Flood. As a result, the SA message size is much larger in Mpr-Flood compared to Src-Flood.
- The mechanism used to deliver SA data throughout the network:

– In Src-Flood, the SA data is carried by the SA message only, while SA messages are flooded throughout the network at the sa_flood_interval;
– In Mpr-Flood, 1) SAs are exchanged locally between neighbors via the augmented HELLO messages at the hello_interval; 2) SAs are delivered globally by the aggregated SA messages, which are generated by MPR nodes and flooded across the network at the sa_flood_interval.

The performance differences between the two methods lie mainly in the number of SA messages to be generated and forwarded, and the size of the SA messages. Selection between the two options depends largely on the mission requirements and characteristics of the tactical network, such as the tolerance of SA data latency (note that SA data can only be disseminated at discrete time points), the density of the neighbor nodes, the wireless medium and channel conditions, and node power constraints. In section 3 we will provide some insight into the selection of the methods and configuration parameters by example.

2.2.2 Summary of the SA Dissemination Procedure

Both MPR-based SA dissemination schemes have two functional components that must be considered in the software implementation: 1) Neighbor discovery and MPR calculation; and 2) SA message generation and passing in the network. Additionally, all nodes need to create a local SA cache to keep track of SA values for all nodes in the network, and maintain several timers for operation scheduling.

For the MPR related functional component, each node carries out the following tasks:

- Create and send HELLO message at the expiration of the Hello timer.
- Upon receiving a HELLO message, populate the 1-hop and 2-hop neighbor sets.
- Apply greedy heuristics to update MPR set / MPR selector set upon changes in neighbor status.

For the SA functional component, related nodes carry out the following tasks:

- At the expiration of the SA timer, the SA message is generated by designated nodes according to the flood type (every node in Src-Flood, MPR nodes in Mpr-Flood).
- Upon arrival of an SA message, the receiving node processes the SA data contained in the message and updates the local SA cache as appropriate.
- The received SA message is forwarded according to pre-defined forwarding criteria (described in section 2.3.3 below).
- Gather message counters and timestamps and calculate the SA performance metrics.

The above steps are further detailed in the next subsection for the simulation implementation.

2.3 The Simulation Implementation

The simulation for the MPR-based SA dissemination schemes is implemented on the EXata platform (version 5.2), which is an extension of the well-known QualNet network simulator with the emulation functionality and network/cyber security add-ons. We point out that the simulation implementation of the schemes depends on neither the selection of simulation platform nor the programming language.

The wireless library in EXata includes the OLSR implementation by INRIA (referred to as olsr-inria), in files routing_olsr-inria.h/cpp. We add a new user model library (in the EXata terminology) with files routing_sadp.h/cpp (where sadp stands for SA Data Passing) to implement our MPR-based schemes with a software design similar to olsr-inria. The main components of the new code are listed below.

2.3.1 The Local SA Cache

Each node maintains a local SA cache in memory to store the dynamic SA information for all nodes in the network. There are two conditions under which the SA data in the local cache is to be updated:

1. Upon sending of a HELLO message, i.e., at the expiration of the Hello timer, every node updates its own SA data with the current timestamp, location, and other defined SA attributes.
2. Upon receiving any message that contains SA data of other nodes, the corresponding SA for the node in the local cache is examined, and updated if the received SA has a more recent timestamp.

Since the local self-SA data is updated at the expiration of the Hello timer, the granularity of the SA data is the same as the hello_interval. This is a reasonable setup since the hello_interval should be set to a proper granular value to timely reflect the network topology changes, which aligns well with the SA update requirements.

2.3.2 Neighbor Discovery and MPR Calculation

Neighbor discovery and MPR selection are based on the HELLO messaging process. We adopt the code from olsr-inria for the corresponding functions, which perform the following operations:

- Construct and send HELLO messages periodically at the hello_interval. Each HELLO message contains a list of 1-hop neighbors of the sending node.
- Process the received HELLO messages, and populate the N_{1hop}^{k} and N_{2hop}^{k} neighbor lists for the receiving node k.
- Calculate the MPR set M^k and the MPR selector set at node k by the MPR selection heuristic, upon changes in neighbor status.

Note that for Mpr-Flood, the HELLO messages are augmented to carry SA information as well, i.e., the message contains SA data of the 1-hop neighbors. The SA data in the augmented HELLO messages are processed at each receiving node as described in sections 2.2.1 and 2.2.2. A new message handler is created to deal with SA data embedded in the augmented HELLO messages.

In addition to the Hello timer, there is also a “neighbor hold timer” on each node k that controls a process to periodically purge the stale entries in the N_{1hop}^{k} and N_{2hop}^{k} neighbor lists.

2.3.3 SA Messaging Functions

New functions SadpFloodSA and SadpProcessReceivedSA are created to handle SA messaging operations in the network. The SA message flood is controlled by an SA timer with a configurable sa_flood_interval. At the timer expiration, each individual node proceeds with SA flood according to the flood type:

- For Src-Flood, every node generates and sends an SA message containing SA information of the sending (originating) node.
- For Mpr-Flood, the SA operation depends on whether or not the node is an MPR node, i.e., whether the MPR selector set of the node is empty.
  - If the node is not an MPR node, then it updates its own SA data (locally) with no further action required.
  - If the node is an MPR node, then it creates and floods an aggregated SA message. The aggregated SA message consists of SA data from all MPR selector nodes, which are available from the augmented HELLO messages for Mpr-Flood, as described in section 2.2.1.

The generated message is packed into the SA message format with a message header that includes, among other attributes, the sender’s node id and a sequence number, and a TTL (time-to-live) field. The {node id, sequence number} combination uniquely identifies an SA message and is referred to as sa_id. The SA messages are flooded in the network by the EXata messaging framework. Each receiving node n_{rc} processes an SA message in two steps. First, n_{rc} updates its local SA cache based on the received SA’s timestamp. Next, the SA message is forwarded if n_{rc} is an MPR node and meets all the following criteria:

- The SA message is received for the first time by n_{rc} based on the sa_id of the message.

- The SA message is received from the MPR selector nodes of n_{rc}, i.e., the previous hop is in n_{rc}'s MPR selector set. This is the conventional behavior of the MPR-based message forwarding.
- The SA message has a positive TTL value. The TTL attribute for the SA message is set to a pre-defined max value by the originating node, and deducted each time it is forwarded.

2.3.4 Performance Metrics and Statistics

A set of performance metrics specifically for SA dissemination was introduced in our previous work (Li et al. 2014). We define the age of an SA, denoted by T_{SA}, as the current time minus the timestamp in the SA (the time when the SA was generated). We also define two thresholds: T_{fresh} and T_{stale}, to quantify the freshness of the SA at the local node. We call the SA fresh if $T_{SA} \leq T_{fresh}$; stale if $T_{fresh} < T_{SA} \leq T_{stale}$; and expired if $T_{SA} > T_{stale}$. For each category (fresh, stale, and expired), we can get the corresponding total SA count K and the average SA age $\overline{T_{SA}} = \sum T_{SA}/K$ at each node. We can also calculate the network-wide average SA count and average SA age by taking the average over all nodes in the network.

We examine the number of transmitted (i.e., generated or relayed) messages to measure the network traffic overhead, and the number of received messages to measure the local processing cost. The network traffic volume is composed of two types of message: the HELLO messages and the SA messages. In this work we focus on the "SA-related" messages, which include the SA massages and, in case of Mpr-Flood, the augmented HELLO messages since they also contain SA data as described in section 2.2.1.

The existing Analyzer toolkit in the EXata GUI provides performance statistics only at the end of each simulation session with accumulated metric data. To get the performance metrics in a real-time manner, we implement functions to collect the performance statistics and calculate the defined metrics over a configurable "sliding window". Such running average statistics are output (in the duration of the test run) to a data file for postmortem performance evaluation and analysis.

3 SIMULATION SCENARIOS AND TEST RESULTS WITH PERFORMANCE ANALYSIS

In this section we present the simulation results for Src-Flood, Mpr-Flood, and OSAP in two typical mobile scenarios. The three SA dissemination schemes are compared and tradeoffs are highlighted, with the simulations clearly showing how the choice of design parameters influences performance.

The design parameters and performance metrics considered in this section are summarized below:

- The fresh threshold T_{fresh} to classify SAs as fresh. In this work we focus primarily on fresh SAs.
- The hello_interval and sa_flood_interval for HELLO messaging and SA messaging, respectively.
- The neighbor hold timer for MPR-based methods (see section 2.3.2) is set to 30s in all cases.
- For OSAP scheme, we will specify the SA flood interval for each OSAP round. The order of OSAP flooding is set to "interleaved", where initiating node takes turns alternately between each group. This is the most efficient scheduling in "grouped" configurations (see Li et al. 2014).
- The sliding window size for performance metrics calculation is set as the following:
  - For SA count and SA age, the sliding window size is the same as the SA flood interval;
  - For the SA-related message count, the sliding window size is set to the fresh threshold T_{fresh} , i.e., the time period required to obtain fresh SAs from the received messages.

The parameter values are specified in each scenario below. In the test results and analysis in this section, we use the term "average" to refer to the network-wide average (over the defined sliding window).

3.1 Scenario 1: Two Groups with the Waypoint Mobility

In Scenario 1 we consider two groups, each with five nodes, moving at constant speeds in a 1500m by 1000m rectangular region. The courses of node movement are configured by a waypoint mobility model in EXata. The trajectories and waypoints in the EXata GUI are depicted in Figure 1. The radio range is set to 85m using the physical layer configuration tool in EXata. Note that node 4 in group 1 and node 9 in group 2 are “scouting nodes” with a larger degree of mobility. The SA dissemination behavior of this scenario is predictable based on the given conditions, and was well documented in Li et al. (2014).

The fresh threshold T_{fresh} is set to 10s. We use hello_interval = 2s and sa_flood_inteval = 5s in MPR-based methods. For OSAP method, the SA flood interval is set to 2.5s. The total simulation time is 750s.

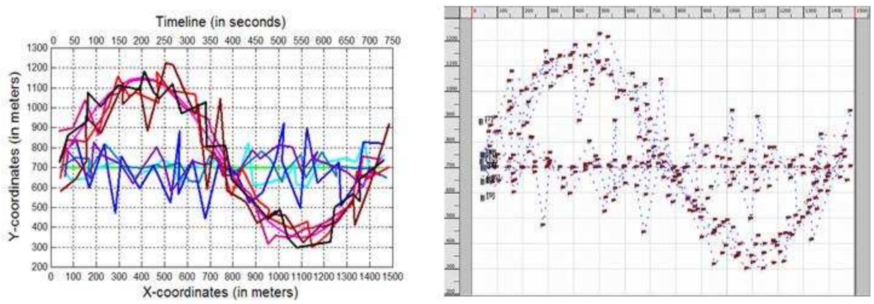

Figure 1: Scenario 1 – Mobility trajectories and waypoints.

In Figure 2 we plot the average SA count and average SA age as a function of time, comparing the two MPR-based methods and the OSAP scheme. The sliding window size is the same as the SA flood interval (5s for MPR-based and 2.5s for OSAP). From Figure 2(a) we observe that with regard to SA count, Mpr-Flood has the best performance while OSAP and Src-Flood are quite comparable. From Figure 2(b) we observe that the results of Mpr-Flood and OSAP are very close (albeit the Mpr-Flood performs slightly better), while Src-Flood gives the worst results (lower ages indicating fresher SAs).

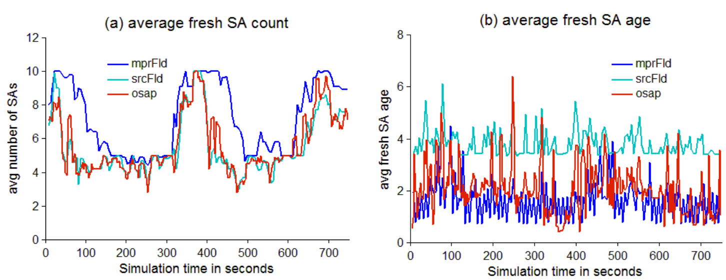

Figure 2: Scenario 1 – SA stats (OSAP flood interval = 2.5s, MPR-based flood interval = 5s).

To investigate the workload in network traffic and the local processing cost, we depict the average number of transmitted and received SA-related messages in Figure 3. To make meaningful comparison, the message counts are calculated over a sliding window of size T_{fresh} (10s) for all three methods. We see that Mpr-Flood method requires highest number of messages, due to the fact that all HELLO messages are also counted as SA-related for Mpr-Flood (see section 2.2.1). As expected, the OSAP scheme requires least messages despite the fact that it floods in shorter interval, because only one node is sending an SA message at each OSAP round.

The subplots in Figure 2 show that Mpr-Flood performs significantly better than Src-Flood. This can be explained from two perspectives. First, Mpr-Flood has the property of SA being more up-to-date (in the granularity of SA accuracy, namely the hello_interval) within a 2-hop range; in contrast Src-Flood relies on the MPR nodes forwarding the original SA message beyond one hop. Second, Mpr-Flood carries up-to-date aggregated SA messages throughout the network, which also promotes the SA count and age performance compared to Src-Flood. These two factors are further emphasized in Figure 2 because of the larger difference between hello_interval and sa_flood_interval (two and half times as much in this setup). We note that in this configuration the performance improvement in Mpr-Flood over Src-Flood comes at the cost of increased SA-related message counts as shown in Figure 3, as well as in the SA message size. Interestingly, OSAP performs quite well, achieving an age comparable to the Mpr-Flood scheme but with lower message counts and processing penalty than either MPR-based schemes.

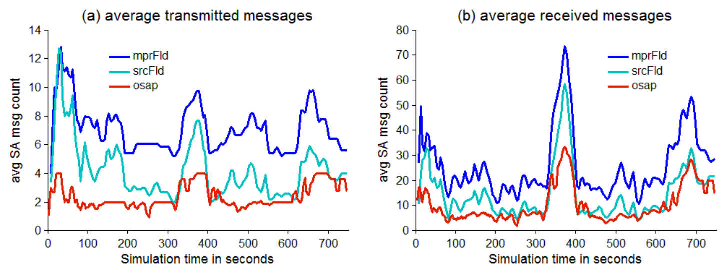

Figure 3: Scenario 1 – Message stats (OSAP flood interval = 2.5s, MPR-based flood interval = 5s).

In Figure 4 and Figure 5 we show the corresponding results when the SA flood interval is halved for MPR-based methods. Compared with Figures 2 and 3, the SA count results are almost indistinguishable, but the improvement in SA age for Src-Flood is quite significant. On the other hand, the SA-related message counts for Mpr-Flood and Src-Flood are much higher due to the more frequent SA flood, while the message count differences between the two methods are diminishing. These phenomena can be easily explained by the fact that hello_interval is now very close to sa_flood_interval in the MPR-based methods. The performance of OSAP is very strong in this case as it now achieves comparable SA age measurement with Src-Flood and Mpr-Flood, but at a significantly lower message count.

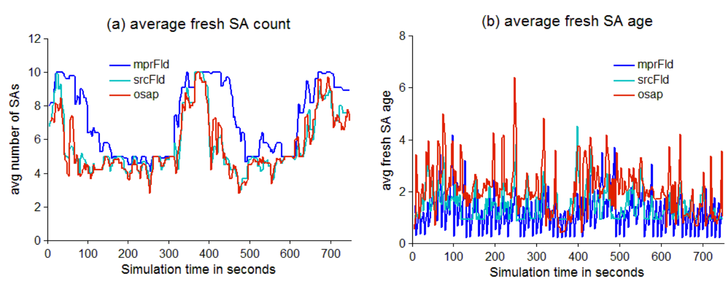

Figure 4: Scenario 1 – SA stats (OSAP flood interval = 2.5s, MPR-based flood interval = 2.5s).

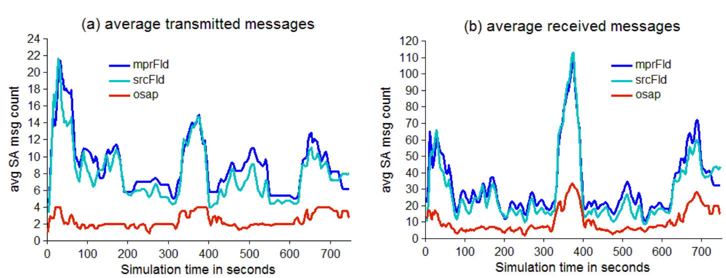

Figure 5: Scenario 1 – Message stats (OSAP flood interval = 2.5s, MPR-based flood interval = 2.5s).

3.2 Scenario 2: Four Groups with the Reference Point Group Mobility

Scenario 2 is created to model a tactical configuration, where a Platoon is assumed to consist of 4 Sections, with 10 dismounted units in each group (Section), and deployed in a 1200m by 1200m area. The mobile movements of the units are based on the Reference Point Group Mobility (RPGM) model as implemented in EXata, with the configuration parameters summarized in Table 1. To assist in visualization, in Figure 6 we depict some node placement diagrams at various points in time as taken directly from the EXata GUI at run time.

In Scenario 2 we use the 802.11b radio type, and adjust the transmission power, antenna height and antenna efficiency in EXata to obtain the following radio ranges at different 802.11b data rates: 253.2m for 1.0Mbps; 230.8m for 2.0Mbps; 223.2m for 5.5Mbps; and 207.5m for 11.0Mbps. The total simulation time is 600s, while the fresh threshold T_{fresh} is set to 20s. For MPR-based methods, hello_interval = 2s, sa_flood_interval = 4s, i.e., the SA flood takes place at every two Hello cycles. For OSAP method, the SA flood interval = 0.5s, such that within the fresh threshold all 40 nodes are able to take their turn to flood.

Table 1: Reference Point Group Mobility configuration parameters (in EXata terminology) for Scenario 2.

	group1 (node 1-10)	group2 (node 11-20)	group3 (node 21-30)	group4 (node 31-40)
group area origin	(50, 50)	(750, 650)	(110, 650)	(700, 100)
group area dimension	(400, 400)	(400, 400)	(400, 400)	(400, 400)
terrain lower-left corner	(50, 50)	(700, 700)	(50, 600)	(400, 50)
terrain upper-right corner	(500, 500)	(1100, 1150)	(900, 1100)	(1100, 600)
internal min / max speed	0 / 2 (m/s)	0 / 2 (m/s)	1 / 4 (m/s)	1 / 4 (m/s)
internal pause time	10 sec	10 sec	25 sec	25 sec
group min / max speed	0 / 4 (m/s)	0 / 4 (m/s)	2 / 5 (m/s)	2 / 5 (m/s)
group pause time	5 sec	5 sec	20 sec	20 sec

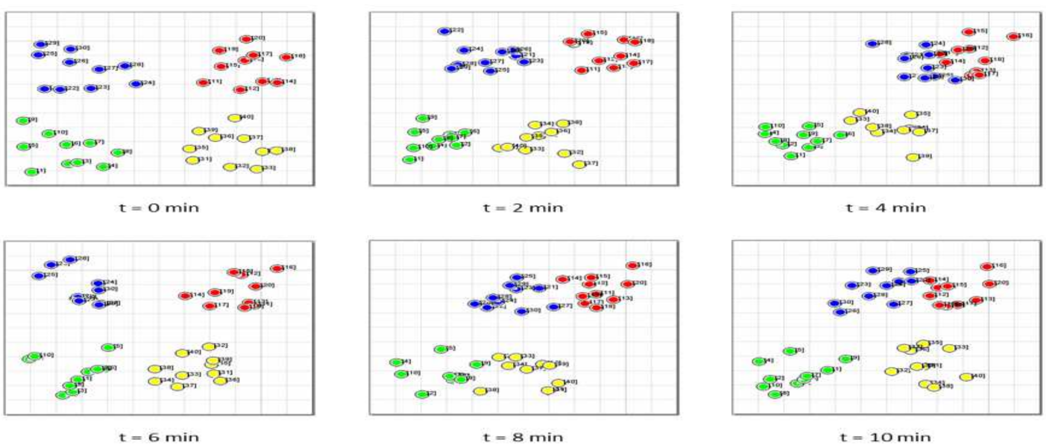

Figure 6: Scenario 2 – Reference Point Group Mobility node locations. The grid size is 100m.

We depict the results of average SA count, average SA age and average transmitted/received SA-related message counts for all three methods in Figure 7 and Figure 8 below. As in the case of Scenario 1, in Figure 7 the sliding window size is taken to be the same as the SA flood interval (4s for MPR-based methods and 0.5s for OSAP), while in Figure 8 the sliding window size is set to T_{fresh} (20s).

Scenario 2 involves more nodes, and the mobility pattern is more random and "wild", while still maintaining a "grouped" characteristic. Some interesting observations can be made from the test results for this scenario. The performance with regard to the average SA count is quite close among all three schemes as shown in Figure 7(a). The results in Figure 7(b) show that Mpr-Flood achieves the lowest (best) average SA age, followed by Src-Flood then by OSAP. It is worth noting that with more frequent SA message flooding (0.5s vs. 4s), OSAP scheme performs comparably well when every node is given a chance to flood within the fresh threshold. We also observe from Figure 7(b) that Mpr-Flood produces noticeably better results than the Src-Flood method with regard to the average SA age, where the doubled sa_flood_interval (vs. hello_interval) plays a role. We could bring the SA age in Src-Flood closer to the Mpr-Flood results by taking a smaller sa_flood_interval, however, this strategy demands much more messages, which would actually negate the benefits hence rendering it not worthwhile.

The message count results in Figure 8 reveal that for this scenario, Mpr-Flood method also requires fewer messages compared to the Src-Flood, while still achieving better SA count and age results as shown in Figure 7. Because the movements of nodes in a group are limited within a square area of 400m by 400m (Table 1), and the radio ranges are about 207m to 253m, the set of MPR nodes is a relatively small subset of all 40 nodes; therefore the total number of SA-related messages in Mpr-Flood is less than what is needed in Src-Flood, even when all HELLO messages are counted for Mpr-Flood. On the other hand, the size of the SA messages may be much larger in Mpr-Flood since they contain aggregated SA data from (bigger) MPR selector sets. Moreover, we can see that for the chosen SA flood intervals, MPR-based methods do need more messages compared to OSAP, but the differences are not excessively large. As a matter of fact, the variations in the message counts depicted in Figure 8 can help us understand the network connectivity status and topology changes, hence to infer the change in MPR node sets over time. For example, in the first 100 seconds in Figure 8 we observe high number of transmitted and received messages for MPR-based methods. Since the number of generated SA messages is constant for Src-Flood, and with very small variations for Mpr-Flood, we may assume that in that time period: 1) There were many occurrences of SA forwarding, indicating large number of MPR nodes; 2) The overall connectivity status was good, i.e., nodes often getting close to each other in the intra-group and/or inter-group manner.

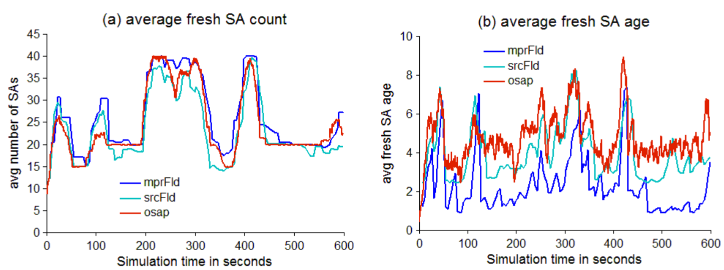

Figure 7: Scenario 2 – SA stats (OSAP flood interval = 0.5s, MPR-based flood interval = 4s).

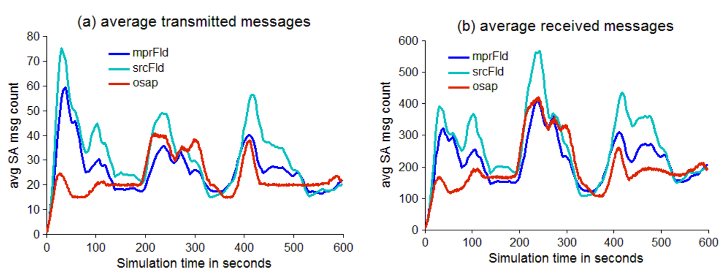

Figure 8: Scenario 2 – Message stats (OSAP flood interval = 0.5s, MPR-based flood interval = 4s).

4 DISCUSSIONS AND CONCLUDING REMARKS

The test results presented in section 3 demonstrate that our simulation implementation and evaluation strategy are effective in better understanding and characterizing the performance of SA dissemination methods. We have seen that both MPR-based methods and OSAP are well suited to tactical MANETs; and we showed that in cases where the size of the network is moderate and the topology and connectivity changes are frequent, the application of the MPR technique in SA dissemination is justified. Simulation environments such as we developed allow us to better evaluate the effectiveness of Mpr-Flood, Src-Flood and OSAP schemes and observe that each method possesses its own advantages and drawbacks, and that the choice of scheme should be made based on mission requirements and performance expectations.

For MPR-based methods, we have found that typically the sa_flood_interval can be set considerably larger than the value of hello_interval with no significant negative effect on SA performance. Generally speaking, Mpr-Flood outperforms Src-Flood in most cases. The issue of increased size for both the (augmented) HELLO message and the (aggregated) SA message in Mpr-Flood can be mitigated by two means. First, we can re-design the SA message such that it contains only SAs that have changed from the most recent flood. Second, we can package SA messages into a compact form, such that only sending the delta of those changed SA attributes. These SA messages with no fixed-length structure can be handled by customized TLVs (type-length-value) as defined in RFC 5444 (Clausen et al. 2009).

The SA messaging process in the Mpr-Flood method is in fact an extension of the TC (topology control) messaging in the conventional OLSR routing for MANETs. As such OLSR routing tables can be readily derived as an ancillary outcome of the Mpr-Flood scheme. We can even obtain enhanced routing tables with additional attributes such as policy, security and trust parameters since those values can be defined and packed into the SA data.

One might expect MPR-based methods to outperform OSAP since in MPR-based schemes the SA data are almost simultaneously flooded across the network, while in OSAP, each node initiates a flood one at time. We have run simulation tests on some scenarios set up in more dispersed and less mobile networks, and found that MPR-based methods perform better than OSAP (results not presented here). However, for highly mobile cases as we show in section 3, when SAs are flooded frequently enough (e.g., all nodes finish their OSAP round within the fresh threshold), OSAP can produce the average SA count and SA age results comparable to MPR-based methods while using much fewer messages. A potential drawback in OSAP is that the SA data are not in synch across the network (i.e., timestamps can vary up to the time difference between the OSAP rounds for the first and last node). Although this effect can be mitigated by shortening the flood interval and/or using some sort of adaptive OSAP scheduling algorithm, MPR-based methods may be more favorable if time-synchronization of SA data is a main concern.

The focus of this study is on the efficiency of SA dissemination, whatever its content may be. The SA messages could contain timestamp and location information and perhaps other mission specific data, none of which are carried by the conventional HELLO messages. The definition and content of the SA data are out of scope of this paper.

In the current work we have been using constant hello_interval and sa_flood_interval in the MPR-based schemes. Significant improvements could be achieved by incorporating some adaptive scheduling techniques, so that the flooding of SA messages is triggered by certain criteria instead of a fixed time interval. The trigger could be policy based, instructed by a commander, or could be based on observed changes in SA. The adaptive MPR-based SA dissemination is one of the related future research topics.

As mentioned earlier, the MPR-based SA dissemination scheme in this paper contains all elements required for the routing implementation in MANETs. An enhanced routing table with desired SA characteristics could be constructed, which provides routes for centralized SA functions, for example when nodes need to unicast certain special messages (e.g., the encrypted authentication messages) to a commander. We can design a hybrid SA scheme using the MPR-based framework with routing add-ons. Exploration of such hybrid SA dissemination in tactical MANETs will be carried out in our future work.

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