Geographical Routing with Location Service in Intermittently Connected MANETs

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***Abstract*—Combining mobile platforms such as manned or unmanned vehicles and peer assisted wireless communication is an enabler for a vast number of applications. A key enabler for the applications is the routing protocol that directs the packets in the network. Routing packets in fully connected mobile ad hoc networks (MANETs) has been studied to a great extent, but the assumption on full connectivity is generally not valid in a real system. This means that a practical routing protocol must handle intermittent connectivity and the absence of end-to-end connections. In this paper we propose a geographical routing algorithm LAROD enhanced with a location service LoDiS, together shown to suit an intermittently connected MANET (IC-MANET). Since location dissemination takes time in IC-MANETs LAROD is designed to be able to route packets with only partial knowledge of geographic position. To achieve a low overhead LAROD uses a beacon-less strategy combined with position-based resolution of bids when forwarding packets. LoDiS maintains a local database of node locations which is updated using broadcast gossip combined with routing overhearing. The algorithms are evaluated under a realistic application, namely unmanned aerial vehicles (UAVs) deployed in a reconnaissance scenario, using the low level packet simulator ns-2. The novelty of the work is the illustration of sound design choices in a realistic application, with holistic choices in routing, location management, and the mobility model. This holistic approach justifies the choice of maintaining a local database of node locations is both essential and feasible. The LAROD-LoDiS scheme is compared with a leading delay-tolerant routing algorithm (Spray and Wait) and shown to have a competitive edge, both in terms of delivery ratio and overhead. For Spray and Wait this involved a new packet level implementation in ns-2 as opposed to the original connection level custom simulator.**

***Index Terms*—Disruption tolerant networking, Location service, Mobile ad hoc networks, Routing protocols**

I. Introduction

ROUTING in systems of mobile nodes with no infrastructure support has received a lot of attention in the last decade. This began in the field of mobile ad hoc networks (MANETs) and then carried over to the field of delay-tolerant networks (DTNs). Despite the solid body of work on routing schemes there is a lack of momentum in applying them in real-world systems. Lindgren and Hui [1] suggest some applications where DTN routing is more attractive than conventional infrastructure-based solutions. Two areas that can be added to their review are disaster scenarios and military operations, areas we believe can spearhead the application of DTN technology. Works on disaster area networks are emerging [2][3] and the Unmanned Aircraft Systems Flight Plan 2009-2047 for the US Air Force [4] envisions swarming unmanned aerial vehicles (UAVs) communicating with MANET technology. This paper addresses one such military mission, namely reconnaissance operation using swarming UAVs.

In a reconnaissance operation the goal is to monitor a selected area and to report all interesting activities within the area. In most cases the complete area cannot be continuously monitored. Instead one has to repeatedly cover the area using mobile units. We have deployed the pheromone reconnaissance mobility model which has shown to provide high coverage while still meeting the military reconnaissance requirements.

The early studies of the reconnaissance mobility [5] reveal that the UAVs will most often not form a completely connected network. Instead they will form connected partitions that constantly change their topology. This class of network is a type of DTN [6] that we call intermittently connected MANET (IC-MANET). To successfully route packets in IC-MANETs, where partitions are considered as a normal phenomenon, a store-carry-forward technique is used to overcome communication interruptions. When wireless transfers cannot forward the packet node mobility is exploited. To be able to navigate all UAVs have to be aware of their geographical position and this knowledge can be taken advantage of by the routing protocol. Routing packets towards a geographical position has been shown to work well in IC-MANETs [7][8], including our algorithm LAROD (Location-Aware Routing for Delay-tolerant networks), an early version of which has been studied in isolation from the location service [9].

Clearly, a geographical routing protocol needs to be complemented by a location service that can provide the current physical location of the destination node for a packet. A location service can be as simple as flooding the network

Manuscript received December 3, 2009; revised March 30, 2010, July 9, 2010 and September 9, 2010; accepted October 12, 2010.

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with a request that the destination answers to using quorum based techniques for updates and requests. For MANETs there have been many suggestions on how to provide a location service [10], but to our knowledge, there have been no suggestions on how to provide this service in an IC-MANET or DTN setting.

This paper bridges the gap between an application area and MANET/DTN research by providing a holistic approach to routing and location services in a realistic setting. The routing and the location update problem is rooted on the application-driven pheromone mobility for which the whole system is illustrated to provide a competitive edge. The contributions of this paper are in particular:

- We propose the first location service for IC-MANETs, the Location Dissemination Service (LoDiS) evaluated in a conceivable setting and illustrate the challenges of this setting compared with the standard random waypoint mobility model.
- We present the integrated LAROD-LoDiS scheme and show that it is more effective and efficient compared to a leading non-geographic scheme, Spray and Wait [11].

An early version of LAROD has been shown to work well with mobile sources and static receivers [9]. This paper extends the reach of this beacon-less geographical routing protocol for IC-MANETs. The missing building block to enable routing towards mobile receivers is a location service. LoDiS disseminates node locations in the network using a gossip inspired technique [12] with a constant per node overhead. While local gossiping may seem an inefficient method on the face of it, we demonstrate that in combination with updates from the routing protocol it is both effective and efficient. Due to the disconnected nature of IC-MANETs the dissemination takes time which means that the location state maintained by LoDiS could be stale. To overcome this problem our approach builds on an incremental update of the location knowledge as a packet travels through the forwarding chain. The intermediate routers update the location information in a packet if their local LoDiS service has more recent information about the destination's location. It is based on the simple idea that the nodes closer to the destination have better information on the correct location of the destination. Thus the knowledge about the destination position will incrementally be improved as the packet is routed towards the destination.

Our evaluation of the combined LAROD-LoDiS scheme shows that in the reconnaissance scenario Spray and Wait fails to provide an acceptable delivery ratio within a reasonable delay, whereas LAROD-LoDiS can provide over 95% delivery ratio. The significance of the more realistic mobility model is further illustrated by comparison to the standard random waypoint mobility. Another major result in the paper is that the LoDiS element of the combined scheme comes surprisingly close to a perfect location service (an oracle), but only contributes to a constant and modest increase in overhead.

The rest of the paper is organized as follows. In Section II we give an overview of routing algorithms for IC-MANETs, location services and the military reconnaissance mobility model. This is followed in III by a presentation of LAROD and LoDiS. In Section IV we present our evaluation of LAROD with LoDiS and compare the results to Spray and Wait. The paper ends with some conclusions and ideas on future work.

II. Background and Related Work

Proposals on how to route packets in MANETs comprise a massive body of research in ad hoc networks. In the last decade this interest has broadened into networks with intermittent connectivity. In this section we give an overview of relevant research in the MANET and DTN area regarding geographical routing and location services. We also present the military reconnaissance mobility model used in the evaluations.

A. *IC-MANET Routing*

In a wireless ad hoc network where a contemporaneous path can never be assumed to exist between any two nodes, mobility can be used to bridge the partitions. When no suitable forwarding opportunity exists a routing node can choose to temporarily store a packet until node mobility presents a suitable forwarding node. This routing paradigm is called store-carry-forward.

Cerf et al. have described an architecture for DTNs [13] where a large and heterogeneous system transports data bundles between custodians that temporarily store the bundles until they can be forwarded again. The main difference between their view of a DTN and our view of an IC-MANET is in the size and diversity of the systems. We see an IC-MANET as a relatively homogeneous system with a relatively modest spatial distribution. This difference in system properties leads to the proposal that the routing should be done on the network (i.e. IP) layer instead of on top of the transport layer. This choice is in line with how routing is done in MANETs.

A major factor influencing the design of an IC-MANET routing protocol is the amount of information available regarding node contacts. If all node encounters are known in advance (also called scheduled contacts) then an optimal packet route can be computed by the source and if needed be updated by intermediate routers. If there is no information available on future node contacts then the routing becomes more challenging. At each node contact the routing protocol must decide whether a packet shall be handed over to the other node or not. Factors that can influence this decision are probability that the peer can move the packet closer to the destination, available buffer space in the two nodes, relative priority to forward this packet compared to other packets the node holds, and available energy in the nodes. If nodes are location-aware then the relative position of the nodes can be used to influence the forwarding decision, a property used by LAROD.

The conceptually simplest protocols maintain no knowledge about how the nodes move, where they are, or the nodes they have previously encountered. Two very simple protocols are Randomized Routing [14] where a packet randomly jumps around between nodes until it reaches the destination and Epidemic Routing [15] where every node in the network receives a copy of a packet. Another conceptually simple scheme, but one that uses node mobility actively and limits it overhead, is Spray and Wait [11]. In Spray and Wait a packet is distributed to a limited number of nodes who hold on to the packet until they (potentially) meet the destination. As a leading non-geographic delay-tolerant routing scheme we have chosen Spray and Wait as a comparative baseline when evaluating LAROD-LoDiS.

If the nodes are location aware and the (approximate) location of the destination is known then the packets can be forwarded by geographic routing. To the best of our knowledge there are, in addition to LAROD, only two other delay-tolerant geographical routing protocols published. These protocols are motion vector (MoVe) [8] and GeoDTN+Nav [7]. Both these protocols have been evaluated using vehicles moving along streets with static destinations. In MoVe a message is handed over to a peer if, given their current directions, the peer is expected to come closer to the destination than the current custodian of the packet. To limit the overhead MoVe uses a request-response mechanism. This means that only nodes holding a message transmit HELLO messages. When another node hears a HELLO message it responds with a RESPONSE message. Once a link is established using this exchange, the nodes start to exchange information to determine whether the message shall be handed over or not.

GeoDTN+Nav is designed for routing in a network of streets and it has three forwarding modes. When possible it takes greedy forwarding decisions at road junctions and then forwards the packets along the roads between junctions. When greedy forwarding is no longer possible it uses perimeter forwarding. In the perimeter mode a switch score is calculated and if it is beyond a certain threshold the protocol switches over to the DTN mode. In DTN mode GeoDTN+Nav exploits the fact that most vehicles know where they are heading. Commuter busses have scheduled routes and taxis have known destinations where they will deliver their passengers.

Most proposed MANET routing protocols transfer packets between nodes using a link layer unicast transfer mode. This enables error correction at the link layer, but it does not exploit the broadcast nature of wireless transmissions. In opportunistic routing (OR) [16] a packet is sent in a broadcast mode to several eligible forwarders and the best forwarder who received the packet will continue to forward it. The challenge in OR is how to distribute knowledge about the best forwarder. One way to do the selection of the forwarder is by geographical selection, an approach taken in Contention-based Forwarding (CBF) [17] and Beacon-less Routing (BLR) [18]. LAROD builds upon these principles and extends them to meet the requirements of an IC-MANET.

B. Location Services

For a geographical routing protocol to be successful it must be supplemented by a location service that can provide position information for all potential destinations. There is a substantial body of research treating location services for MANETs (see the survey by Das et al. [10]), but as indicated through the use of static receivers in MoVe and GeoDTN+Nav there are to our knowledge no proposals on how to provide a location service in a delay-tolerant setting. In this section we will provide an overview of the principles used for location services in MANETs and discuss why most of them are not directly transferrable to an IC-MANET.

For connected MANETs there have been several suggestions for location services ranging from simple flooding based services to hierarchical services. These location services have been classified according to Fig. 1 by Das et. al [10][1] based on how location servers are selected and queried. A major difference between the flooding-based location services and the mapping based services are the number of nodes acting as location servers. In the mapping-based services a subset of the nodes in the system act as location servers and location information requests have to be routed to one of these nodes. In the flooding-based services all nodes act as location servers.

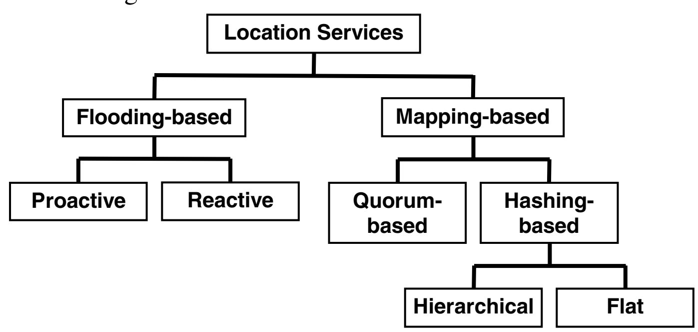

Fig. 1. A taxonomy of location services.

If we study the architectural concepts used by the location services from a delay-tolerant perspective we will see that most concepts will have significant problems when full network connectivity is not available. In a mapping-based service the node requesting location information needs to access one node in the subset of nodes acting as location servers for the destination node. In a delay-tolerant setting this will significantly delay the time until a message can be sent towards its destination due to the transport time for a location query and its response.

In the flooding-based services there is no delay for reaching the location service since it is located in the source node, but the time to acquire the location information differs significantly between proactive and reactive services. A reactive location service first tries to obtain the position of the destination when it is requested. If the information is not available in the local cache then the location server broadcasts an information request over the network. Due to the disconnected nature of the network there will be similar problems with delays as for the mapping-based location services. A protocol that attempts to limit the cost of a location request by having a proactive component is Brownian Gossip [19]. In Brownian Gossip

[1] Das et al. [10] called the mapping-based group rendezvous-based, but since rendezvous indicates that two tasks meet in time, which is not the case here, we have renamed the group to mapping-based.

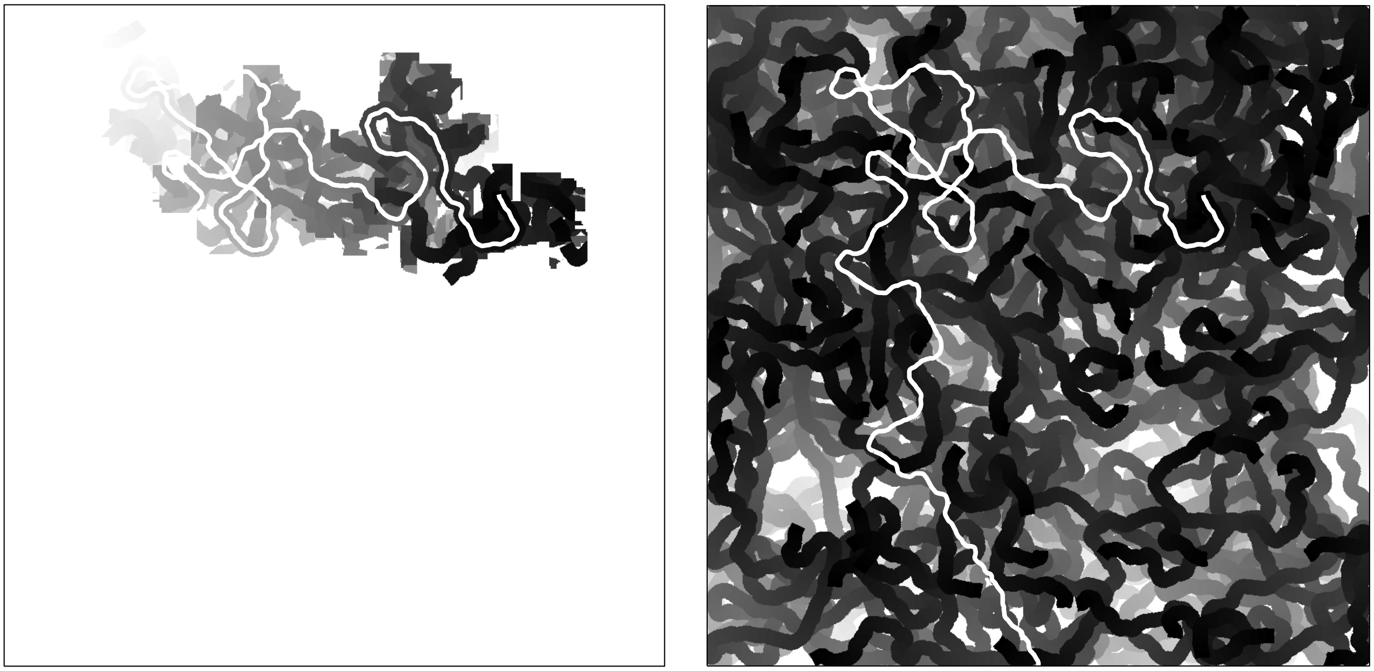

Fig. 2. Local and global pheromone map after 7200 seconds of simulation.

nodes exchange information on previous encounters when two nodes meet. This information is used to guide a location request towards the destination node's position. We have taken the principle of how Brownian Gossip routes location requests by continuous refinement of the destination's position when routing data packets within LAROD-LoDiS.

A proactive location service continuously distributes the position of all nodes in the network which means that location information will be available immediately when needed in the source node. The problem with this system-wide distribution of location information is that it can consume large amounts of system resources if not properly designed. Two location services with very different proactive elements are the DREAM Location Service (DLS) [20] and the Simple Location Service (SLS) [20]. In DLS a node broadcasts its position to nearby nodes at a given rate, and to nodes further away at a lower rate. The rates depend on a node's speed, but a minimum rate is guaranteed if a node moves very slowly or not at all. In SLS, on the other hand, location data is only exchanged between neighbors. By exchanging location tables between neighbors communication is kept local while permitting the location data to be globally distributed in the system. Both DLS and SLS have a reactive component that inquires a node location by broadcasting a request if the required location data is not available in the source node. As discussed earlier these system wide broadcasts are problematic in an IC-MANET.

We believe that to minimize routing delays in an IC-MANET all nodes need to have a location service that has data about the location of all other nodes in the system. Due to the disconnected nature of IC-MANETs this information might be old for some nodes, but as we will show in the evaluations even inaccurate data can be used successfully with a proper design of the routing protocol. We will base LoDiS on the proactive element of SLS and modify the concept as required to meet the demands of an IC-MANET environment.

C. *Mobility Models*

The choice of mobility model when evaluating IC-MANET routing protocols is important since the performance of a routing protocol will change depending on how the nodes move [21][22]. We have chosen a military reconnaissance operation mobility model as the main model used in the evaluations [5]. For comparative reasons we have also used the random waypoint mobility model [23]. Extensive surveys on mobility models can be found in articles by Camp et al. [24] and Aschenbruck et al. [25].

The goal of a reconnaissance operation is to monitor an area and to detect defined types of activities. Due to high costs it is generally not possible to monitor the entire area continuously and instead all parts of the area need to be regularly scanned. In a military setting it is also a requirement that the scanning shall not exhibit any apparent pattern (to make it harder to avoid detection), and the system must be robust upon loss of some of the scanning nodes. The mobility model we use utilizes distributed pheromones to guide the scanning nodes, the UAVs, to areas not recently scanned.

In the pheromone reconnaissance mobility model all UAVs place pheromones on the areas they have scanned. Since it is not possible to place these pheromones in the environment as would be done in a natural system a UAV places them in a local pheromone map. As pheromones we use timestamps which means that the information slowly fades away. To share the information about scanned areas with the other UAVs each UAV regularly broadcasts a local area pheromone map to the other UAVs within its radio range. All UAVs that receive the broadcast merge this information into their pheromone map. The broadcast frequency and size of the map broadcasted can be adjusted to control the bandwidth required for the transfer of the pheromone information.

Based on the information in the local pheromone map a UAV regularly evaluates if it should continue straight ahead, turn left, or turn right. The selection is probabilistic and it is more probable that it will select an area not recently visited. The selection of where to go is made using only pheromone information relatively close to the UAVs. A global search is never made to determine where to go. The benefit of only using local data is that a global view of the system does not need to be distributed to all the nodes in the network making the scheme more scalable. Fig. 2 illustrates the difference between the local pheromone map held in a UAV and the total pheromone data present in the system. In the figures black represents fresh pheromones and white represents no pheromone information, or pheromones older than one hour. Also drawn on the maps is the path of the UAV whose local pheromone map is shown. The pheromone maps are taken from simulations where the probability of a successful transfer of pheromone data was set to 50%. For a detailed description and experimental evaluation of the mobility model see [26].

III. ROUTING WITH LOCATION SERVICE

In this section we first describe an enhanced version of the IC-MANET geographical routing protocol LAROD [9] and how it integrates with a location service. This is followed by a description of the novel IC-MANET location service LoDiS. The ns-2 source code for LAROD and LoDiS is freely available for scholarly research [27].

A. *Location Aware Routing for Delay-Tolerant Networks (LAROD)*

LAROD is a geographical routing protocol for IC-MANETs that combines geographical routing with the store-carry-forward principle. It is a beacon-less protocol and uses greedy packet forwarding when possible. When greedy forwarding is not possible the node holding the packet (the custodian) waits until node mobility makes it possible to resume greedy forwarding.

In order to forward a message towards the destination a custodian simply broadcasts the message. All nodes within a predefined forwarding area are eligible to forward the packet and are called tentative custodians. All tentative custodians set a delay timer (t_d) specific for each node, and the node whose delay timer expires first is the selected new custodian. Upon becoming a custodian the node forwards the message in the same manner as the previous custodian. The old custodian that sent the message and most other tentative custodians will overhear this transmission and conclude that a new node has taken over custody of the packet. If no such transmission is heard the current custodian repeats (and keeps repeating) the broadcast of the message (with an interval of t_r) until a new custodian becomes available due to node mobility. The rebroadcast time (t_r) is randomly chosen for each transmission between two configured values. The values should be chosen so that forwarding opportunities are not missed, but also avoid wasting bandwidth. It is possible that not all nodes in the forwarding area will overhear the broadcast made by the new custodian thereby producing packet duplicates. This will increase the load in the system but also enable exploration of multiple paths to the destination. When the paths of two copies cross, only one copy will continue to be forwarded. To prevent a packet from indefinitely trying to find a path to its destination all packets have a time to live (t_{TTL}) expressed as a duration. When the TTL expires a packet is deleted by its custodian.

The forwarding area can have many shapes, but it should be designed in such a way that progress towards the destination is guaranteed. An attractive property is the potential for all nodes within the forwarding area to hear each other's transmissions. This will reduce the risk of tentative custodians failing to receive the packet transmitted by the new custodian. Examples of shapes that meet these criteria are a 60° circle sector, a Reuleaux triangle or a circle (see Fig. 3a-c). The longest distance between two points within these shapes must be the assumed radio range. If overhearing is not a critical property and we want to maximize the probability of finding a new custodian then the forwarding area should include all nodes that guarantee progress towards the destination (see Fig. 3d). To avoid too small hops and to cater for inaccuracies in the positioning service (such as GPS) a minimum forward distance may be prudent (the small gap between the custodian and the progress forwarding area in Fig. 3d). All these forwarding areas can be used in LAROD as a parameterized input. In this paper we have chosen the progress forwarding area and we will return to the rationale for this choice in Section IV.B.

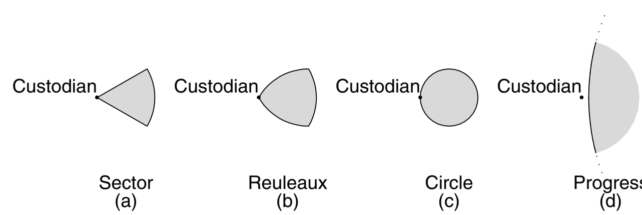

Fig. 3. LAROD forwarding area examples.

The delay timer (t_d) for each node can be set based on many principles where two natural ones are to favor short hops or long hops towards the destination. Short hops are advantageous if much data is to be exchanged between the nodes since the transfer probability is higher with a shorter distance. The downside is that more hops create higher overhead. Long hops will reduce the number of hops, but the downside is that the transfer reliability between distant nodes is lower. As a middle ground one can consider a delay timer that prioritizes nodes at some set distance from the custodian. Graphical illustrations of these three principles are provided in Fig. 4 (r is the nominal radio range and distance is measured as progress towards the destination). The gray area for the long hops indicates that the delay is randomized for these distances. The function that sets the delay timer is a configuration parameter in LAROD, but for the purpose of this paper we have chosen a mechanism that provides long hops towards the destination. Details on the delay timer function is found elsewhere [28] and are omitted due to space restrictions.

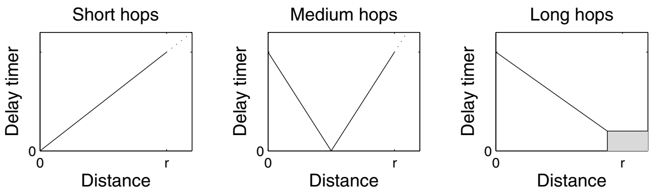

Fig. 4. LAROD delay curve examples.

The proposed delay timer functions do not take the direction of node movement into account, although this would have been feasible. The main reason is that even if the next custodian might move in the wrong direction the hope is that it can forward the packet to a node closer to the destination. Another reason is that node directions are not stable and a node might turn and move towards the destination. For these reasons a packet is always forwarded towards the destination even if it in some cases might be returned to the old custodian due to node movement.

```
Source node at data packet generation
  Get destination location from location service
  Broadcast data packet
  Set up timer for rebroadcasting packet to t_r

Destination node at data packet reception
  If the packet is received for the first time
    Deliver data packet to application
  //Inform of delivery to destination
  Broadcast ack packet

All intermediate (non-destination) nodes at data
packet reception
  Update location service with data packet location
  information
  //Packet has been delivered to the destination
  If an ack has been received for the packet
    //Inform of delivery to destination
    Broadcast ack packet
  //The node is a tentative custodian
  Else if the node is in the forwarding area
    If the node does not have a copy of the packet
      Set up timer for rebroadcast to t_d
  //If the custodian is ahead of the node
  Else if custodian is in node forwarding area
    Remove packet in node if it has one

At ack packet reception
  Update location service with ack packet location
  information
  If the node has a copy of the packet
    Remove packet

When a data packet rebroadcasting timer expires
  If the packet's TTL has expired (t_TTL)
    Remove packet
  Else
    Update location information in packet with
    location server data
    Broadcast data packet
    Set up timer for rebroadcasting the packet to t_r
```

Fig. 5. LAROD pseudo code with location service interactions.

To stop further transmission of a packet by custodians and tentative custodians when it has been delivered to the destination an acknowledgement packet (ack) is sent by the destination at reception. All nodes hearing an acknowledgement packet will store the acknowledgement information until the packet times out. If a node receives a packet for which it previously has received an acknowledgement then it broadcasts an acknowledgement to stop the transmission of the packet. Acknowledgements are not intended to reach the source, only to prevent further forwarding attempts by nodes holding the acknowledged packet.

To manage the inaccuracies inherent in an IC-MANET location service, LAROD inquires the location service at each packet hop, and if more accurate (more recent) position data is available then the routed packet is updated. This way the quality of the location data is incrementally improved as the packet approaches the destination. To further improve the quality of the location data in the location service LAROD provides it with the location data available in received packets. For a full description of the routing protocol see Fig. 5.

Fig. 6 illustrates one actual LAROD-LoDiS routing example with the progress forwarding area. Solid lines are wireless forwards, dotted lines are movements by custodians when a packet could not be forwarded and the dashed line is the movement by the destination. When the packet is generated by the source we see that the actual location of the destination differs from the one stored in the source's location service. Also while the packet is routed the destination moves and the destination position in the routed packet has to be updated to reflect the movement. When the source node transmits the packet there are two tentative custodians that are too far from each other to overhear the others transmission which means that two copies of the packet are created and sent via different paths. After a while these paths cross and one copy is discarded.

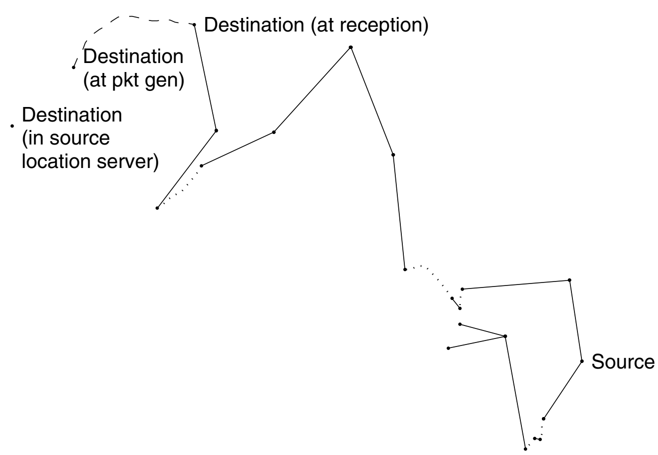

Fig. 6. LAROD-LoDiS path visualization example.

B. *Location Dissemination Service (LoDiS)*

In MANETs it is generally assumed that the relative movement of a node compared to the radio range is small during the interval from a node location request to the data packet delivery at the destination. If this is not the case then either the location of the destination must be updated in the routed packet as it approaches the destination or some other routing mechanism must be used after the packet has reached the assumed location of the destination.

In an IC-MANET environment we know that information exchange can be delayed by partitions in the topology which means that any time-dependent information that is received is more or less inaccurate. This means that any location service in an IC-MANET will generally only provide inaccurate location information due to the time taken for a location update to reach the server and/or the time taken for a location request to be answered by a location service. These issues force a designer of a location service in an IC-MANET to decide on how to manage the location errors that the system will inevitably have.

1) The LoDiS Protocol

In LoDiS every node is a location server and location data is updated by data exchanges as nodes encounter each other. The reason that all nodes are location servers is to avoid delaying the packet at the source node. If only a limited set of nodes were location servers then the transmission of a data packet will be delayed by the time it takes for a location server to respond to the location request. Due to the disconnected nature of IC-MANETs this delay could be long. With the low cost of memory, maintaining location tables that contain data on all nodes in the system should not be a problem in a UAV even for fairly large systems (thousands of nodes). If we assume that each location entry requires 30 bytes then 1000 nodes would require 30 kbytes, a very small requirement by modern standards.

When the routing protocol requests a location from LoDiS one thing it can be relatively sure of is that the location will be wrong, but if the provided location points the packet in the approximate right direction it should be possible to use it as an initial estimate. To reduce the location error the geographical routing protocol should update the location data in a packet for each node that the packet traverses. This is done by inquiring that node's local LoDiS server whether it has more accurate information about the destination. As nodes closer to the destination should have better information on the destination's location, the accuracy of the destination position is incrementally increased. This position update approach does to some extent resemble the query routing in Brownian Gossip [19]. While Brownian Gossip uses the distributed location information to guide location queries towards the destination LAROD-LoDiS uses the location information to route the actual data packets due to the disconnected nature of IC-MANETs.

LoDiS builds on the conceptual solution used by SLS [20] and employs the principle of MANET broadcast gossip [12] to distribute the continuously changing location data. A LoDiS location server regularly broadcasts the information it has in its location table. Any node hearing this broadcast merges the information with the one it has itself and the most recent information will be propagated when that node makes its LoDiS broadcast. In this way location information is spread like rings on water. In addition to the broadcasts, LoDiS also accepts location updates from the routing protocol. The routing protocol will have some location information in the packets it routes that could improve the data in the location service. The pseudo code for LoDiS is shown in Fig. 7.

To limit the overhead generated by LoDiS each node is only allowed to generate one packet worth of location data at a set rate. If we assume a packet size of 1000 bytes and that 10 bytes are required for each node (which includes some compression) then an update can transfer information on 100 nodes. If all location information stored in the node can fit in one packet then all is well. If that is not the case then a selection has to be made. The selection could range from simple round-robin algorithms to selection based on distance and information age. In the results presented in this paper the number of nodes has been less than the data limit in a packet and the use of different selection techniques has not been explored. The reason to have a fixed broadcast interval is that it will limit the per node overhead. If a dynamic interval would be used then it should be influenced by factors such as how often the neighbors change, the number of neighbors and how much new data there is to distribute. As an example, Brownian Gossip approximates these factors with the speed of the node. In Section IV.B we will show that the overhead introduced by LoDiS is small compared to the routing overhead from LAROD.

There are several reasons why we have chosen to regularly broadcast the location data instead of using an exchange each time two nodes meet. If an encounter exchange scheme is chosen then the nodes need to broadcast regular beacon messages instead of location data broadcasts. When a beacon message is received a node needs to determine whether it is a new encounter or not, and if it is, initiate an information exchange. This is a more complicated scheme and it also has the drawback that the exchange may not be finished properly due to node movement or changed transmission conditions [29]. With the broadcast technique, if the data is received by a node then all is fine and well, and if it is not, then the information will be broadcasted again relatively soon. Another advantage with the chosen scheme is that each LoDiS node consumes a predictable amount of bandwidth.

We have experimented with using timeouts for location entries to reflect aging as is done in SLS, i.e. that location data older than a set time period is inaccurate and should not be used. The results indicated that it is better to start to route a packet with existing location data rather than to wait until reasonably fresh location data becomes available.

```
At a set interval broadcast location data
  Select location data: vector with elements
  (node, location, timestamp)
  Broadcast the data

When a LoDiS broadcast is received
  For each received location data that is more
  recent
    Update the entry in the LoDiS server

When location data is received from the routing
protocol
  If the supplied information is more recent
    Update the entry in the LoDiS server
```

Fig. 7. LoDiS pseudo code.

2) The Requirements on Clock Synchronization

In LoDiS all location data is time-stamped to be able to determine if some location information for a specific node is more recent than some other information on that node. Since the local clocks always somewhat differ in different nodes (independent of clock synchronization technology used), it is important to know the clock precision requirements for LoDiS to provide a good service.

Assume that we can accept a position error of 10% of the nominal radio range, then the maximum allowed clock offset between two nodes is 10% of radio range divided by maximum speed. For the main scenario used in this paper (see Section IV.A) this would mean a maximum clock error of $0.1*250/1.4 \approx 18$ seconds. This is a precision most clock synchronization protocols should manage to live up to. Since it is generally the angular precision and not the absolute precision that is important, let's then instead say that we can accept an error of 1°. This would permit a position error of 1.7% (sin(1°)) of the distance. Using the same example then at a distance of 1 kilometer the clock error may be $1000 * \sin(1°) / 1.4 \approx 12$ seconds. The conclusion is that LoDiS does not have high requirements on a clock synchronization protocol and that an approximation of global time can be used to determine the newer of two location items.

IV. Evaluation

In this section we present the results from our evaluations of LAROD-LoDiS. The routing protocols have been evaluated in the network simulator ns-2 using both the pheromone reconnaissance mobility model and the random waypoint mobility model (for comparative purposes). The setup of the simulator for the evaluations is detailed in Section IV.A. The configuration parameters for LAROD and LoDiS are studied in Sections IV.B and IV.C and this is followed in Section IV.D by an evaluation of how the choice of mobility model impacts LAROD-LoDiS. Finally, in Section IV.E we compare the performance of LAROD-LoDiS to Spray and Wait.

The two main evaluation metrics used are delivery ratio and effort required for each generated data packet (overhead). The delivery ratio is the most important evaluation criteria since it determines the quality of service as perceived by the user or application. The effort used to transfer a packet is also important since lean protocols will allow either a higher throughput or lower power consumption by the nodes. This will be measured as the number of transmissions performed per generated data packet.

A. Scenario Parameters and Set Up

The basic simulation parameters are given in Table I. The real-world parameters are based on reasonable assumptions made by UAV domain experts. For our simulations in ns-2 we have chosen to keep the default ns-2 radio range and scale the other parameters accordingly to ease comparisons with other work. For the random waypoint mobility model we have used two speed settings; slow and fast. We have used both a constant speed of 1.4 m/s (slow) to match the pheromone reconnaissance mobility model and a variable speed between 1.0 and 10.0 m/s (fast). The variable speed setting is similar to what is used in many MANET simulations.

TABLE I
BASIC SIMULATION PARAMETERS

Parameter	Real-world	ns-2
Reconnaissance area	64x64 km	2000x2000 m
Node density	0.020 nodes/km²	20 nodes/km²
Node speed	161 km/h	1.4 m/s
Radio range	8000 m	250 m
Data generation rate	36 pkt/hour/node	36 pkt/hour/node
Packet life time (TTL)	1000 s	1000 s

The node density is a very important parameter since together with the mobility model it determines how well connected the system is. A study of node densities used in a range of earlier works has shown that a wide range of relative densities are used by various researchers. The density used in this paper produces small groups of connected nodes (partitions). The chosen density gives a degree of connectedness in the network that is below the percolation threshold [30] meaning that it is very likely that no large dominating partitions exist at any point in time. In particular, we are still at a degree of connectedness that is comparable to some literature in the DTN area [30].

All nodes generate data packets at a set average rate and send each of them to a randomly chosen destination. The reason to have this abstract communication setup is that it challenges the routing protocol to provide communication paths between all pairs of nodes.

To get as relevant results as possible data should only be collected during system steady state unless initiation and startup phenomena shall be studied. To come as close as possible to this ideal state the data presented in the results below are collected during 3600 seconds at full network activity and with the mobility models at steady state. To guarantee full network activity during the measurement period, the simulation was run at least 1400 seconds (maximum packet life time) before and after the measurement period. When evaluating LAROD-LoDiS the simulation was run for 3600 seconds before the data collection interval to populate the LoDiS location data.

For simulations with the random waypoint mobility model node position, speed and initial destination have been initiated according to the procedures and equations proposed by Navidi and Camp [31]. For the pheromone mobility model the nodes have initially been uniformly randomly distributed and then the simulation was run for 3600 seconds before the data collection interval to populate the pheromone maps. For all data points 10 runs have been recorded and the average value with 95% confidence interval is presented.

B. LAROD Parameters

The performance of LAROD is influenced by the forwarding area and the delay timer. To evaluate the impact of these parameters we evaluated LAROD with two different forwarding areas and two different delay timer functions. In Table II we show the delivery ratio for the different settings and here we note that while the delivery ratio is greatly impacted by the forwarding area, it is only marginally impacted by the delay timer function. The reason for this is the low node density dictated by our application. The larger area of the progress area (from Fig. 3) means that the probability of finding a node that can forward a packet is larger than for the smaller circle area.

Table III shows the overhead of LAROD for the forwarding areas and timers as the average number of transmitted packets per generated data packet. Here we see that the choice of the timer indeed matters. In the progress area the difference between selecting the closest and the furthest node is seen with the increased overhead for the short hops compared to the long hops. For the circle area both delay functions give the same overhead. The reason is that low node density gives lower probability to have more than one node within the circle forwarding area, which means that irrespective of delay function the same node will be selected. For the rest of the evaluations we have used the progress forwarding area and the long hop delay timer.

TABLE II
DELIVERY RATIO FOR DIFFERENT LAROD PARAMETERS.

Forwarding area	**Short hops**	**Long hops**
Circle	86.1%±4.3%	86.8%±6.0%
Progress	98.1%±1.7%	97.5%±1.8%

TABLE III
OVERHEAD FOR DIFFERENT LAROD PARAMETERS.

Forwarding area	**Short hops**	**Long hops**
Circle	64.6±5.7 trans./data packet	61.5±7.8 trans./data packet
Progress	53.4±4.9 trans./data packet	45.3±5.8 trans./data packet

C. LoDiS Parameters and Performance

The major configuration parameter for LoDiS is the broadcast interval. Fig. 8 shows the delivery rate of LAROD using LoDiS with four different broadcasting intervals from 5 to 100 seconds and LAROD using an oracle location service. The oracle location service is a perfect baseline since it simulates the case where the location service information is always correct. It is very interesting to note that delivery ratio is essentially identical for all configurations. In simulations with the random waypoint mobility model we get the same type of results. This somewhat surprising result can be explained by the fact that geographical routing can cope with positional errors as long as the angular error is low, as we will see later in this section.

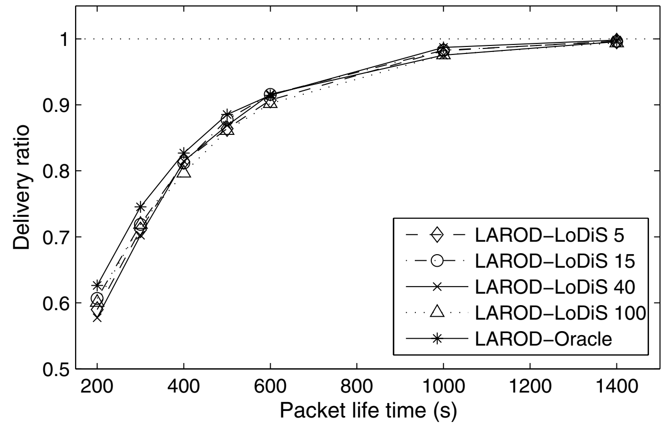

Fig. 8. Delivery ratio with parameterized LoDiS and Pheromone mobility.

In Fig. 9 the overhead of LAROD-LoDiS under the pheromone mobility with different packet life times and broadcast intervals is plotted. Not unexpectedly we find that having a longer broadcast interval decreases the transmissions generated by a packet. Each curve shows the overhead with a given broadcast interval (5 seconds, 15 seconds, etc). The variance analysis (not shown here) shows that there is no statistically significant difference between the overheads at the broadcast intervals 15, 40 and 100 seconds. At some point the error introduced by having long broadcast intervals means that the routing will require more transmission since the packet is routed for too long in the wrong direction. This has been confirmed in evaluations with a broadcast interval of 300 seconds and where updates from the routing protocol was not used. For these reasons we have chosen to use a LoDiS broadcast interval of 40 seconds for the rest of the presented results. Note that this is the same interval we chose for the Spray and Wait beaconing. We also evaluated LoDiS in a sparser network and the relative performance results for a node density of 10 nodes/km² were the same as for 20 nodes/km² (graphs not shown).

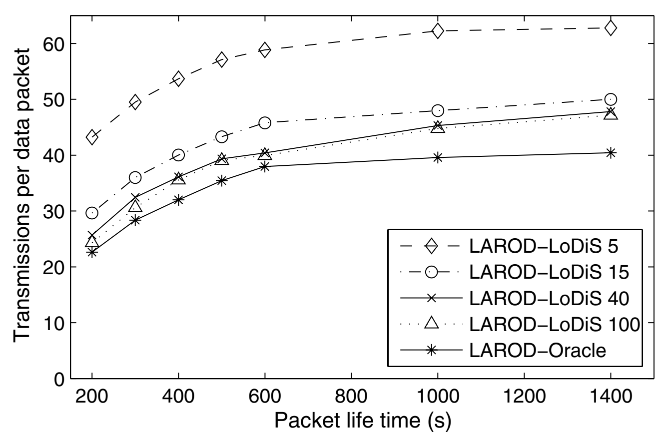

Fig. 9. Overhead with parameterized LoDiS and Pheromone mobility.

In a geographical routing protocol the important thing is not always to know exactly where the destination is, but to know approximately the direction to the destination. As the packet moves closer to the destination the position information can be updated by intermediate routers to a more accurate position for the final routing steps. In Fig. 10 the average direction error at the source node for different LoDiS broadcast intervals is plotted. Not unexpectedly the error increases with longer broadcast intervals, but for all scenarios except for the fast random waypoint the error is small (below 11°) which means that the packets will be sent in the right direction. With a very long broadcast interval of 300 seconds and with no location service updates from the routing protocol, an average direction error of 29° was measured together with a significant drop in the delivery ratio. Due to the more disconnected nature of the pheromone mobility compared to random waypoint mobility location distribution takes more time and for that reason the direction error is larger for pheromone mobility with the same speed profile. This indicates the challenging nature of the pheromone reconnaissance mobility model which is induced by the application scenario.

Analysis of the distribution data for all runs shows that for the pheromone mobility scenario 94% of the packets are sent with an angle error of less than ±20º. For the slow random waypoint scenario the value is 98% and for the fast 86%.

These results show that the overhead (cost) of LoDiS is low compared to an oracle location service and that the impact on delivery ratio because of location errors is insignificant. We have also shown that the directional error when a packet is sent from its source is low which partially explains the good overall results.

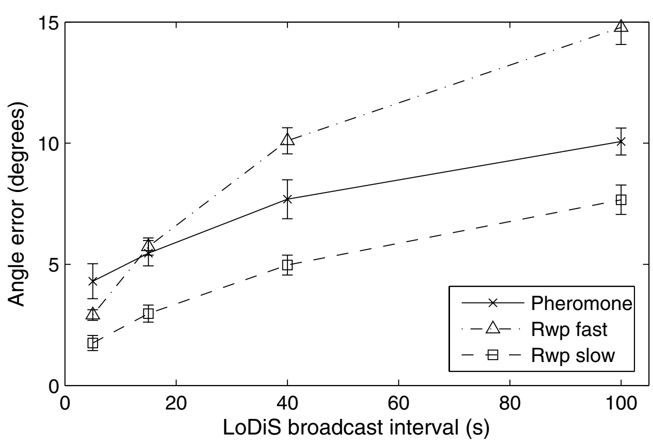

Fig. 10. Average direction error at source node.

D. *The Impact of the Mobility Model*

Evaluating the routing protocols under three different mobility scenarios reveals the importance of selecting a relevant scenario when studying a routing protocol. In Fig. 11 we see the impact of the delivery ratio for LAROD-LoDiS for the pheromone reconnaissance mobility model and the random waypoint mobility model with two speed profiles. All scenarios have the same average node density as defined in Table I, but the difference in distribution, movement pattern and movement speed greatly impacts the results. The overhead for the same setup is shown in Fig. 12. Not unexpectedly the overhead increases for the scenarios with a lower delivery ratio. The reason is that more packets live longer before they either reach their destination or time out. We have also done the corresponding simulations for Spray and Wait and the relative results were similar to LAROD-LoDiS. This confirms earlier reports [21][22] that the choice of relevant mobility model is important when evaluating routing protocols.

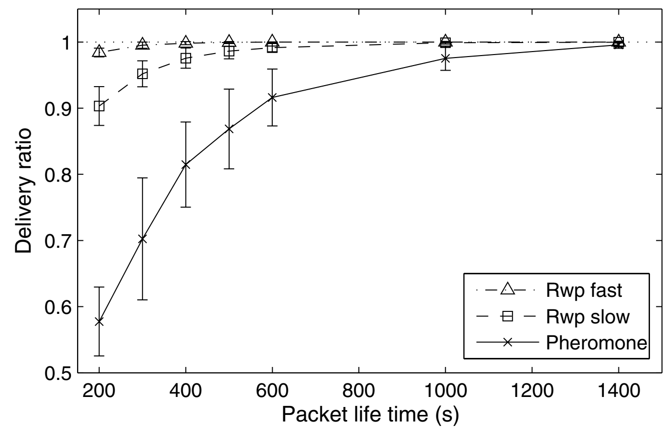

Fig. 11. LAROD-LoDiS delivery ratio for different scenarios.

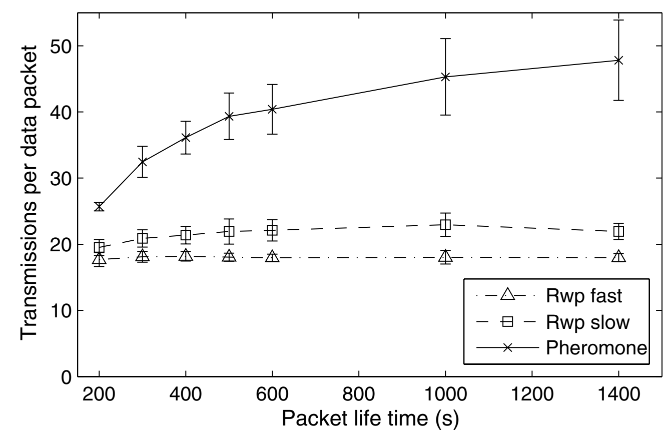

Fig. 12. LAROD-LoDiS overhead for different scenarios.

E. *LAROD-LoDiS Compared to Spray and Wait*

In order to show the merit of LAROD-LoDiS compared to other routing schemes we have compared it to Spray and Wait [11]. Spray and Wait is reportedly an efficient routing protocol with good delivery properties. It would also be interesting to compare LAROD-LoDiS to another geographical IC-MANET routing protocol. However, since both MoVe [8] and GeoDTN+Nav [7] are designed for road based scenarios and lack a location service we have not found it worth the effort to re-implement them in ns-2. In a previous paper we have compared LAROD to an epidemic routing protocol and showed that LAROD gave essentially the same delivery ratio as the epidemic protocol under low load scenarios, but with a 4 to 8 times lower overhead [9]. As Spray and Wait originally was implemented for a custom simulator we have re-implemented it in ns-2. Implementation details are provided in an on-line technical report [28] and the code is freely available for scholarly research [27].

Comparing the delivery ratio and overhead of LAROD-LoDiS to Spray and Wait we see that the benefit of using geographical information and active forwarding is very high (see Fig. 13-16). Under the pheromone reconnaissance mobility model Spray and Wait does not provide an acceptable delivery ratio. In Fig. 13 we see the impact of the packet life time on the delivery ratio. As expected both routing protocols benefit from having more time to find a path from source to destination. The relative performance of the two protocols is not surprising since Spray and Wait mainly uses node mobility to forward packets while LAROD actively forwards the packet via peers towards the destination. As long as node encounters are frequent then protocols that actively forward should outperform protocols relying on node mobility as the main delivery mechanism. What is also interesting to note is that the overhead for Spray and Wait is about double that of LAROD-LoDiS for a spray factor of 10 and almost four times higher with a spray factor of 20 (see Fig. 14). Significant factors in the Spray and Wait overhead are the beacons and the query and response packets, packets not present in LAROD-LoDiS.

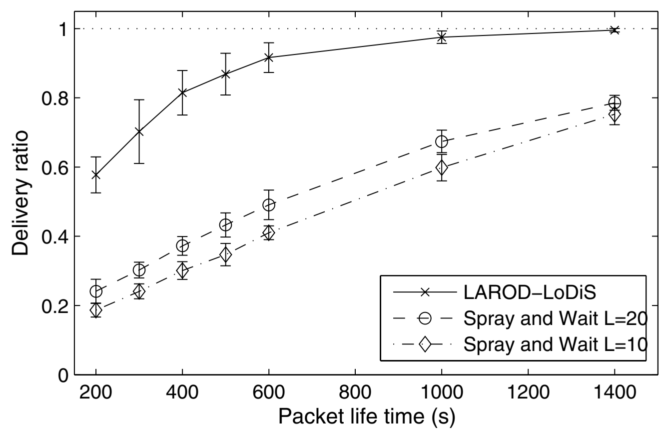

Fig. 13. Delivery ratio for different packet life times under Pheromone mobility.

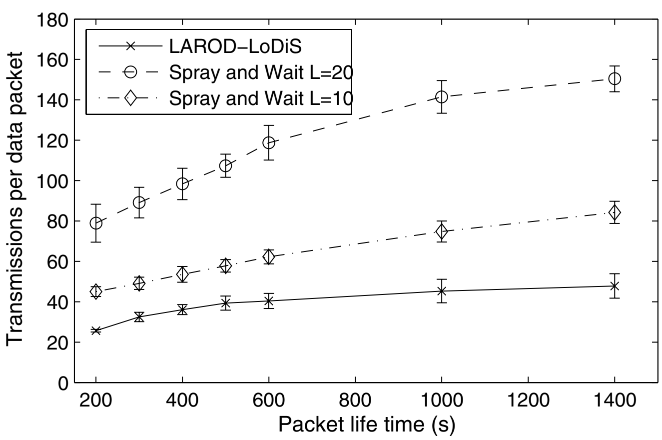

Fig. 14. Overhead for different packet life times under Pheromone mobility.

Comparing the two routing protocols with respect to varying load we see that both LAROD-LoDiS and Spray and Wait with 10 copies maintain a constant delivery ratio meaning that neither routing protocol overloads the network over a wide load spectrum (see Fig. 15). However, increasing the Spray and Wait spray factor to 20 packets, we see that the system becomes overloaded and the delivery ratio drops.

Looking at the overhead in Fig. 16 we observe that the overhead for LAROD-LoDiS is essentially constant for varying load. The reason is that the transmissions from LAROD are proportional to the number of generated packets. Also, the node-linear overhead from LoDiS is so low that amortizing is hardly noticeable. For Spray and Wait the overhead per generated packet is reduced with increased load as the query exchanges are amortized over more data packets.

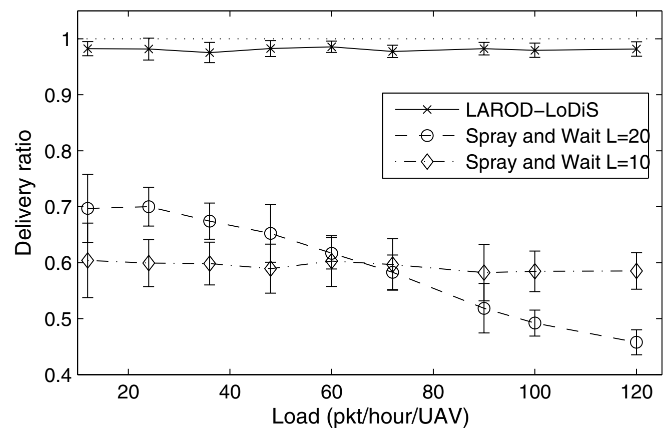

Fig. 15. Delivery ratio for different transmission loads under Pheromone mobility.

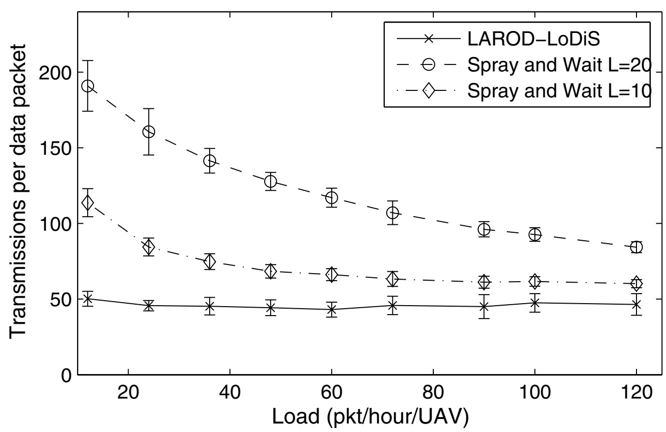

Fig. 16. Overhead for different transmission loads under Pheromone mobility.

If we study the performance of the two routing protocols under varying node densities we can make some interesting observations. For both routing protocols the delivery ratio improves with increased node density (see Fig. 17), but the change is more pronounced for LAROD-LoDiS than for Spray and Wait. The reason that the delivery ratio for Spray and Wait is only marginally improved with increased node density is that its main routing mechanism, waiting until a node holding the packet meets the destination, is not affected by the node density. The improvement with increased node density results from the initial distribution of the packet taking less time. LAROD on the other hand, actively tries to forward a packet towards the destination via wireless forwards and with increased node density the forwarding opportunities are increased.

The overheads in the two protocols, presented in Fig. 18, illustrate what is expected from the protocol designs. For LAROD-LoDiS the overhead increases with a decreased node density as delivery latency increases and more packets exist in the network for their maximum lifetime (TTL). For Spray and Wait the overhead increases with increased node density since the node encounter rate increases; for each new encounter some data has to be exchanged towards possible message replication.

These results and the influence of the mobility model presented in Section IV.D show the impact that system parameters have on the network performance. For these reasons we think that it is very important to determine the system parameters and required performance before the routing protocol is selected. In some systems it might be trivial to achieve the required performance, while in others it might be impossible even with oracle knowledge.

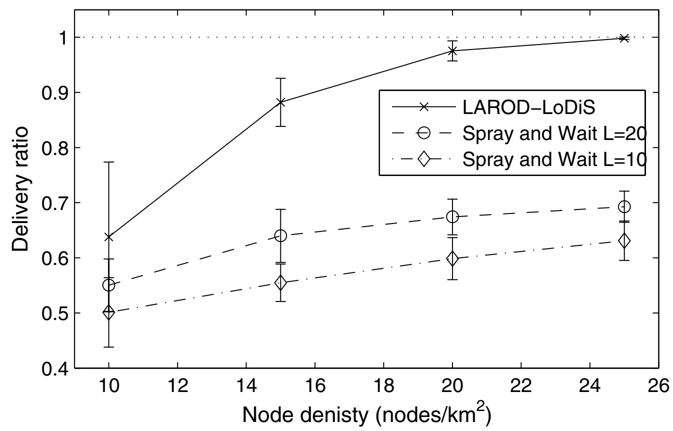

Fig. 17. Delivery ratio for different node densities under Pheromone mobility.

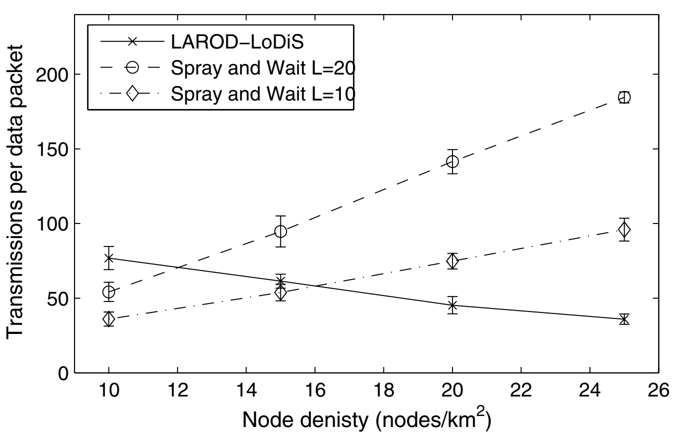

Fig. 18. Overhead for different node densities under Pheromone mobility.

V. Conclusion

The availability of node location information enables the use of efficient geographical routing protocols in MANETs and IC-MANETs. A major component for a geographical routing protocol is a well performing location service. The location service will provide information on where a destination is located in order to have a point to route a packet towards.

In this paper we have shown that by using a MANET broadcast gossiping technique and continuous modification of packet location information, geographical routing in IC-MANETs is feasible. The proposed location service (LoDiS) has then been integrated with a routing protocol (LAROD), and thoroughly studied in comparison with a high performance baseline. We have also shown that the delivery ratio for LAROD-LoDiS is the same as that obtained using LAROD with an oracle location service; a very important result. The cost of LoDiS is also relatively small compared to the basic cost of routing using LAROD. Since the cost of LoDiS is constant per node, the more traffic there is in the network the lower the relative cost will be.

We have also shown that LAROD-LoDiS gives a much higher delivery rate at a much lower overhead compared to the efficient topological routing protocol Spray and Wait at a node density relevant to a realistic UAV reconnaissance application. That LAROD-LoDiS would have a better delivery ratio than Spray and Wait was not that surprising. What was a bit more unexpected was the large difference in overhead to the benefit of LAROD-LoDiS. One reason for this difference is that Spray and Wait uses message replication to exploit the mobility of several nodes to reach the destination. Another reason is that Spray and Wait uses more packets to transfer each data packet. While LAROD uses overhearing as acknowledgement, Spray and Wait transmits an explicit acknowledgement packet.

VI. Future Work

LoDiS is a very good base to use for further studies of location services in IC-MANETs and DTNs. Depending on what one considers a reasonable scenario for an IC-MANET further studies and improvements of the LAROD-LoDiS routing algorithm should be done for very sparse systems (nodes normally lacking a neighbor) or a mixed scenario with both dense and sparse areas. Current work includes evaluation of a manycast algorithm in disaster area networks where pockets of intense activity and large sparse areas can be simultaneously present [3]. Also, the location service performance should be studied for very large systems (thousands of nodes). For the very sparse systems information dissemination will probably be very slow and it is not certain that geographical routing is the best choice in such a scenario. For very large systems the challenge will be how to distribute the location information for all the nodes in the system. To do this one probably has to employ some kind of data compression or approximation methods for nodes located far away.

If parts of the network become very dense the transfer of location data may start to consume too much bandwidth locally at the dense spots. It might be interesting to study some throttling techniques to free up bandwidth. As found in the experiments reported in this paper it is important to start to route a message even if the exact location is not known. It would be interesting to study the best approach to use if you have no or very old location data for a node that you want to communicate with.

Another topic that should be studied is how to handle areas permanently void of nodes (for example no fly zones for UAVs). If these zones do not have a convex shape then it is possible that packets get stuck in local minima and never manages to navigate past the empty area.

To better understand the properties of LAROD and LoDiS ongoing work analyzes the algorithms mathematically. Using the mathematical descriptions it is possible to predict the behavior of LAROD-LoDiS in settings such as those described above.

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