DELAY TOLERANT ROUTING IN SPARSE VEHICULAR AD HOC NETWORKS

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ABSTRACT

Low density of network nodes in Vehicular Ad Hoc Networks (VANETs) outside the rush hours and in peripheral areas limits usability of traditional ad hoc networking, which requires end-to-end connectivity between communicating parties. In this article, we survey how usability of vehicular networks could be escalated with delay-tolerant networking, in which vehicles store and carry network data while waiting opportunities to forward it. With delay-tolerant networking applications are able to get eventual data delivery even in sparse networks. We address the routing problem in delay-tolerant vehicular networks and introduce a novel geographical routing scheme, which is based on movement predictions. As our simulations show, the presented protocol attains efficient results even in sparse networks.

Keywords: *Vehicular Ad Hoc Network, Delay Tolerant Network, routing protocols, geographical routing.*

1. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) face highly variable density of traffic, which affects drastically to connectivity and coverage of the ad hoc networking. During the rush hours, ad hoc networking attains high probabilities for successful data delivery. Unfortunately, when the traffic quiets down, end-to-end connections via intermediate nodes cannot be established any more. In outlying districts situation is even worse, since traffic in those areas is always sparse. In this paper, we study how vehicular networks could be utilized even when the traffic is sparse and direct end-to-end paths between communicating parties do not exist. Communication systems that we study fall into a category of Delay Tolerant Networks (DTNs), which cover wide area of applications from a deep space exploration to tactical military networks [6]. Instead of requiring direct connectivity, DTNs in a mobile environment attain eventual delivery by store-carry-forward fashion, where messages are saved in nodes' storage buffers and forwarded when devices encounter each other as a result of their movement.

Vehicular networks belong into one of the most challenging class of DTNs due to vehicles autonomous motion. In ordinary DTNs opportunities to communicate with other intermediate nodes are scheduled [6] or can be predicted with high probabilities [12]. In vehicular DTNs contacts between nodes appear without any a priori knowledge, and therefore routing protocols do not have any certain information available for means to make routing decisions. There have been efforts to utilize scheduled and fixed movement in vehicular networks in purpose to offer limited communication capabilities for peripheral areas, for example by using public transportation vehicles as digital couriers [1] or utilizing existing postal services for data delivery [17]. These systems, however, cannot employ autonomously moving vehicles as mobile routers.

This article focuses on a special roadside-to-vehicle-to-roadside communication system, in which vehicular networks operate as a transit system for roadside devices, relaying delay-tolerant messages into data sinks. The application scenarios may contain, for example, collection of data from environmental sensors. Shah et al. [14] have earlier studied related communication systems as a three-tier architecture, according to which mobile elements named Data MULEs act as a transport channel between static network nodes.

In this paper, we present Predictive Graph Relay (PGR), which is a novel geographical routing scheme for mobile and vehicular DTNs. In PGR autonomous software components, *smart routing agents* predict their hosts' movement and co-operate to attain eventual data delivery.

We study emerging research area and application scenarios, which have not been addressed much in previous research. Hence, several contributions are made. On one hand, we introduce a novel routing scheme, which shows promising results regardless the complexity of an environment. Coupling the movement prediction with a trajectory-based forwarding gives us means to make intelligent routing decisions which achieve efficient results in terms of scalability, energy consumption, delay and delivery percentage. We also examine and analyze performance of existing proposals and show that delay-tolerant geographical routing schemes are very sensitive for presumptions about devices' mobility, network density and especially infrastructure.

This paper has the following structure. The next section is an overview to related work in this area. Section 3 introduces PGR and section 4 describes the simulation environment, the mobility model and implemented routing schemes. Simulations results are presented and analyzed in section 5. Finally, our conclusions are summarized in the section 6.

2. RELATED WORK

Geographical routing has been earlier studied mostly in a context of connected ad hoc networks. Localized geographical routing methods apply location information when passing messages hop-by-hop closer to their destination in a given network topology [8, 13]. In localized routing, message headers contain required information to determine locally after each hop to which adjacent node the message should be forwarded. If a connected path does not exist, localized routing methods fail and messages are dropped.

Chen et al. [3] have proposed possibility to couple the store-carry-forward paradigm with the localized geographical routing schemes. In an optimistic forwarding (also called opportunistic forwarding [10, 18]) strategy, a message is forwarded closer to its geographical destination until a possibility for a next hop does not exist. Instead of dropping the messages, they are held and forwarded again if some node closer to the destination is detected. Authors in [3] have studied performance of optimistic forwarding only in a single segment of a highway, in which node movement is implicitly predictable.

LeBrun et al. [10] have proposed another opportunistic forwarding strategy, which utilizes motion vectors in delay-tolerant geographical routing. Authors present MoVe algorithm, which relays messages to a node whose motion vector points closer to the message's destination. MoVe is closely related to our work, since it exploits movement prediction in the delay-tolerant geographical routing.

Wu et al. [18] have introduced delay-tolerant geographical routing algorithm for vehicular networks, which disseminates messages along a defined trajectory between sender and receiver. In MDDV, nodes advertise last known location of the most forwarded copy and message carriers nearby that location form a group, which actively disseminates messages to encountered nodes.

Other studies concerning routing in mobile DTNs have not been considered directly for VANETs. Basic approach to implement routing in mobile DTNs is message replication, which propagates messages into a large group of nodes hoping that one of them will eventually reach the destination. Vahdat and Becker [16] did one of the very first studies in this area and introduced Epidemic routing, which diffuses messages into the network like an epidemic disease. The disadvantage of this approach is the stress for the network, as the number of transmitted copies will increase rapidly and exhaust nodes' storage capacity.

The waste of network resources that epidemic diffusion causes can be reduced, if diffusion is limited some way. Harras et al. [7] have studied different approaches to limit the epidemic diffusion by controlling the number of retransmissions and preventing epidemic spread with acknowledgement messages they called a cure. The message receiver sends a cure when the first copy arrives. Cures heal the epidemic by erasing original messages as they spread into the network. Moreover, Spyropoulos et al. [15] have proposed Spray&Wait protocol, which is another method to limit epidemic diffusion. Spray&Wait exploits counters to control the number of copies in the network. None of these schemes, however, makes any effort to select between distinct nodes while forwarding copies. Instead, they employ numerous randomly selected nodes as message carriers.

In some networks, routing protocols can benefit from contact history of the nodes by using it in order to predict future contacts. For example in networks employed by human carried devices in collective communities, the contact history reflects social aspects of the network. Thus, nodes encountering each other are more likely to encounter again in the future than the nodes that have never met each other. There exist several proposals that are based on or closely related to a contact prediction [4, 12]. In practice, the contact prediction schemes do not fit well in such environments as VANETs, which may contain a vast number of nodes and the probability to meet a previously encountered node again is very low.

Finally, some projects in mobile environment have studied situations where nodes may change their movement in order to deliver messages, for example [11, 19].

3. PREDICTIVE GRAPH RELAY

3.1. Geographical addresses

PGR is an interface between smart routing agents that have the ability to predict their hosts' movement. The routing decisions in PGR are based on messages' *geographical address*. Due to the complexity of the infrastructure, routing metrics that PGR uses cannot rely on a straightforward Euclidean distance between two points. The geographical address contains required information to resolve message's path trough a complex infrastructure. We define the geographical address as an n-tuple of plane points, representing some known route from the roadmap

$$(a_1, a_2, \ldots, a_n), \quad a_i = (x_i, y_i) \in R^2 \tag{1}$$

where a_1 is the receiver's location. Obviously, the address may represent a full trajectory to the destination, if a_n is the sender's location. However, due to lack of mobile devices resources, we do not want to expect that any device – not even the message sender – could actually define the whole required path from the roadmap. Instead, a static geographical address can be shared inside a wider district. In this paper, we do not discuss further how these addresses can be obtained.

3.2. Metrics

PGR offers two distinct metrics for agents. First, the *graph distance* can be used in the case of long-term movement predictions, where an agent has the information of the path it follows (fig. 1). To solve the graph distance, we have to determine the line segments' intersections between the address and a predicted route. We are, however, interested in only the first intersection after recipient's location as it defines how close the host will eventually go, and therefore the rest of intersections can be omitted. Thus, when the first intersection $C = (c_X, c_Y) \in \boldsymbol{R}^2$ is found from the line segment $[a_q, a_{q+1}]$, the graph distance is

$$D = \sqrt{(c_X - x_q)^2 + (c_Y - y_q)^2} + \sum_{i=1}^{q-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \tag{2}$$

when $q > 1$, otherwise $d(g, a_1)$, i.e. the Euclidean distance between g and a_1. In practice, we need some accepted inaccuracy for comparisons, because the resolution of these graphs may differ. Since in geographical routing the radio transmission range δ defines how precisely data needs to travel, we can use it as the resolution when an intersection point is resolved.

The second metric, a *direction angle* is for purposes of short-term predictions. The direction angle is a metric that can be used when only the direction of current movement is known. Due to continuousness of motion, the current direction gives some insight into the future position of the host, but as shown later, it has also some serious flaws.

The direction angles have similarities with motion vectors (MoVe) studied in [10]. The basic idea of the direction angles is to forward a message to an agent, which is currently moving toward a desired direction. The difference with the above mentioned MoVe method is that we take advantage of geographical address information by relaying the angle comparison points in the address graph. With given agent position h we select a comparison point by finding the closest line segment $[a_q, a_{q+1}]$ from the address. The point a_q is defined as the comparison point x_c, if the distance $d(h, a_q) > \delta$ or $q = 1$, otherwise a_{q-1}. This gives us an effect where the comparison point "moves" ahead as data travels along its path. The direction angle is used by drawing a vector $\boldsymbol{m}$ from h to comparison point x_c and resolving the cosine of an angle between $\boldsymbol{m}$ and the known motion vector $\boldsymbol{w}$ (fig. 2 (ii)).

The cosine of the angle actually contains enough information and therefore we do not need to resolve the value of the angle itself. Particularly, if $cos(\theta) > 0$ an agent's host is moving towards the comparison point, i.e. the host is moving along the address graph.

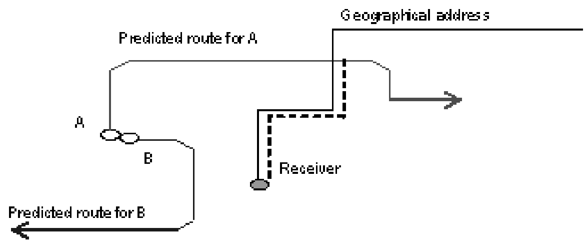

Fig. 1 Resolving message's carrier with long-term movement prediction.

3.3. Routing decisions

The imprecise information of direction angles may cause incompetent decisions and routing loops which trap messages into traffic flows. For example in the fig. 2 (i), agents at the upper road would compare their motion vectors to the address point a_i, causing an effect where messages bounce around point c, as agents coming from both directions will carry messages always back (supposing the transmission range is not adequate to help messages jump from one street to another).

Agents capable of long-term predictions survive better in the complex situations which can be expected since long-term prediction has more information to exploit, and therefore long-term match always dominates the direction angle information. In addition, if an agent stands still, it takes messages from agents moving away, which prevents messages escaping from the defined path.

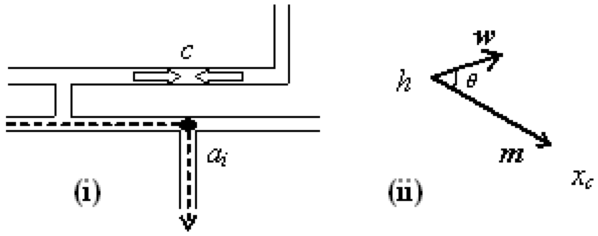

Fig. 2 Routing decision.

3.4. Smart agents

Depending on the host characteristics and the available resources, the implementation of routing agents may vary. In some cases, the agents may have external sources of information about their movement. Cars using navigation software, for example, may know where their drivers intend to go. Moreover, many vehicles such as city busses use scheduled or fixed routes. In these cases, it is convenient to design agents that specialize in using the above mentioned information sources. Unfortunately, most devices do not have that kind of information available. We have designed a Greedy Mobility Pattern (GMP) agent to meet the needs of those general devices. GMP-agents predict movement by learning the host's individual *mobility pattern*, which represents the characteristics of the host's motion.

As several DTN-routing studies have pointed out, people in a real environment do not move randomly. Both infrastructure and our habits narrow the area we generally use. We regularly use certain routes between home, work, lunch restaurant, and other similar locations. By observing these locations and routes between them, a GMP-agent can form the node's mobility pattern.

The learning takes place in two parts. First, a GMP-agent learns the regularly visited areas by observing the locations where the host's movement stops for longer periods of time. When movement resumes, the agent stores the followed route. A route will become a part of the agent's pattern, if both the start and the end point were previously known visiting areas. To save memory resources, agents combine traced points to line segments with heuristic that allows routes to vary within the transmission range, which defined the resolution in PGR. Both the visiting areas and the routes are parts of the pattern only for a limited period of time. A pattern part will expire and be removed if the host is not using it at certain intervals.

During a host movement, the agent frequently checks if the routes are still valid. By using the valid routes, the encountering agents can solve the graph distance metric for delivered data. The agents we implemented are greedy since they always select the best possibility from a valid set of routes.

During the movement agents also create a routing table entry for each carried message. The function of these entries is to observe when calculated routing locations are not valid anymore and distances in messages need to be changed. If the routing table does not contain an entry for some target, i.e. an intersection between the address and the valid routes cannot be found, the agent resolves the direction angle for that header on each encounter.

4. SIMULATION ENVIRONMENT AND SETUP

4.1. Mobility model and simulation environment

Since one of our interests was to simulate the earlier described smart agents, we developed a location-based mobility model in order to model behaviours that can be learned. In the location-based mobility model, each node has an individual location pattern containing several positions that the node visits frequently. The movement of the nodes takes place within a graph representing a roadmap, where nodes roam between their known or randomly selected locations. In addition, the model consists of a few locations representing shops and other favoured visiting areas which are preferred in nodes' location patterns. We assume that this leads into a more realistic traffic flow distribution.

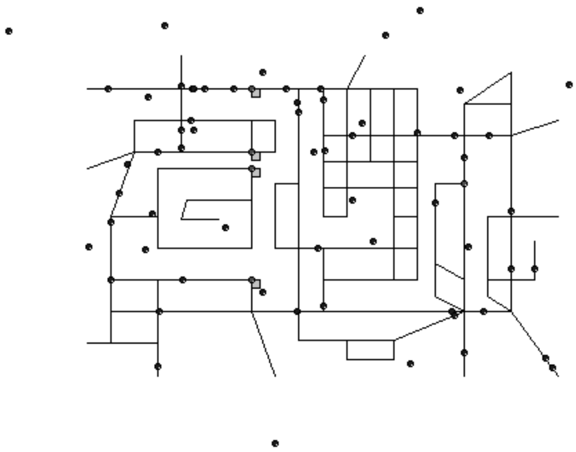

Fig. 3 Simulation environment.

We implemented a custom Java simulator to study PGR statistics. The roadmap lies at the centre of the total simulation area (9 km^2) and the size of that graph is 1 km^2 (fig 3). This gives us an opportunity to observe situations in which nodes may leave the simulated routing area, i.e. we can simulate incoming and outgoing traffic flows on the graph. Most of the previous studies have examined DTN-routing with some random mobility model in a closed environment where nodes cannot leave the simulation area, see for example [10, 15]. This assumption, however, does not hold in the context of VANETs. In DTN-routing messages will be lost when a node carrying them leaves the area. We implemented some DTN-routing schemes to see how they would behave in unbounded networks like VANETs. We made our simulation to reflect the behaviour of vehicular traffic flows in an open environment by dropping the messages that the nodes carried outside the map. In order to compare results, we also ran one series of simulations representing closed environment, in which messages were not dropped.

In simulations, the velocity of nodes varies between 1 – 16 m/s. Each node has a randomly selected interval of 3 – 10 seconds, after which the speed is updated. When a node arrives at a waypoint, it stops for random time of 62.5 to 125 seconds. Queries to find other nodes are sent twice in a second. In our study, the approach is not limited to one single networking technology, and therefore the behaviour of network and the physical layers are not implemented. Details about some suitable wireless short range technologies can be found, for example, in [5].

In the studied application scenario, four sensors generated traffic, each sending one message every 5 seconds. All traffic was targeted at the single sink. The simulations first ran 1000 seconds in order to get the node distribution balanced. After that, total 1000 messages were sent in the period of 1250 seconds. Sensors had a 'send and forget' policy, i.e. they did not use any retransmissions nor stored copies once a message was successfully forwarded. In DTN-architecture, corresponding policy is called as *custody transfer* [6]. If the message's designated lifetime in the network expired before forwarding or sensor's buffer storage was full, the message was dropped.

Anastasi *et al*. [2], who have measured actual transmission ranges of common IEEE 802.11 devices in ad hoc mode, reveal one question we were paying attention in simulations. The authors point out, that commonly used transmission ranges in simulations are up to three times more than actual devices are able to reach. Hence, we selected transmission ranges for our simulations on basis of what the authors have measured in [2]. The authors show that a packet loss rate begins to rise rapidly as early as after 25 m distance in 11 Mbps bandwidth even when buildings between the streets are not taken into account. Therefore we will observe the network system by limiting the transmission range to 20 m, which is so low that messages have to detour every street block. These simulations construct similar environment compared to *Mobile Encounter Networks* (MENs) [9], in which all connections are pair-wise encounters between individual nodes.

4.2. Implemented methods

The following routing schemes were implemented in order to compare PGR statistics and to analyze the behaviour of different methods in the context of VANETs:

Epidemic: A variation of Epidemic routing [16] with an unlimited hop count. On each encounter, a node forwards copies of all messages to an adjacent node, if it does not hold them already. A time-stamp is attached to each message when it is created and nodes remove copies when their timeout expires. With an unlimited buffers and bandwidth, the Epidemic model gives us always the smallest delay.

S&W: Spray&Wait [15] uses a simple counter to spread *n* copies to the network. When a message is created, the counter is set as *n* and afterwards divided by two on each encounter. A copy of the message is forwarded to an adjacent node until the counter equals one. After this spraying phase, nodes wait for a contact with the receiver until the message's timeout expires. The value of *n* was 32, which spreads copies from 19 to 100 percentages of mobile nodes, depending on the total number of nodes in different simulation executions.

MoVe: MoVe [10] exploits motion vectors to perform geographical routing. During an encounter, a message is forwarded to another node if its motion vector points closer to the geographical destination. The exact routing metric is calculated by resolving the $sin(\theta) \cdot d(h, x_c)$ according to variables described in fig. 2 (ii). The recipient's location is here always the static x_c. Exact comparisons, including nodes standing still and heading away, are described in [14].

FK: PGR's Full Knowledge agents each know the followed path. Agents can resolve the graph distance at any time if an intersection point between the geographical address and the followed route exists. In order to compare metrics, FK-agents do not use direction angles if an intersection cannot be found. With all PGR agents, a single static address is shared within all sensors. It should be noted, that in practice the information that FK-agents exploit would require maps and therefore each agent could also modify the address before resolving the graph distance, which is not, however, considered here.

DIA: PGR's Direction Angle agents that use only the direction angles to predict host's movement. Within both MoVe and DIA, motion vectors were measured from the previous second movement.

GMP: PGR's Greedy Mobility Pattern agents that use both above mentioned metrics. The graph distance is used if an agent follows some route from its pattern and the route has an intersection with message's address. If the graph distance is unknown, GMP-agents use direction angles.

5. SIMULATION RESULTS

5.1. Performance in Mobile Encounter Networks

We will present two series of simulations with 20 m transmission range. The first case was intended to appear easy for all implemented schemes. The sink was located at a place that several nodes passed frequently, the environment was closed and the capacity of storage buffers unlimited. At the second series of simulations the sink was located in a position that only a few nodes occasionally passed. The environment was unbounded and the size of storage buffers was limited at 10% of the total message traffic. We refer to these simulations as closed and open environment respectively.

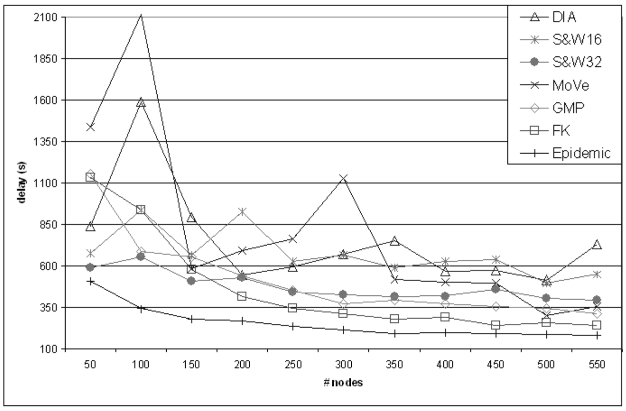

Fig. 5 Delivery delay.

In the closed environment, timeout values for messages were adjusted for Epidemic to 1000 seconds and for S&W to 2000 seconds in order to minimize unnecessary overhead. For single-copy schemes timeout was 3500 seconds. It is worth noting that with a single copy adjusting timeout is not as critical as in diffusion-based schemes, because network does not need to be cleaned from unnecessary copies. These timeouts were sufficient for all the schemes to achieve nearly 100% delivery even with a low number of nodes. The only exception was MoVe. Due to sensor locations, not any comparable timeout was adequate as a set of messages were caught in routing loops described earlier in fig. 2 (i). Therefore, as shown in fig. 4, the delivery rate of that particular scheme was poor. It performed better with a low density of nodes since in a sparse traffic routing loops can not catch messages as easily. On the basis of visual observations, the favoured visiting areas in our mobility model caused the worst routing loops.

Epidemic was superior in delays as it finds always the shortest path from the network's contact graph with the unlimited storage capacity (fig. 5). What is remarkable is that FK-agents achieved surprisingly good results, an average of only less than 1.7 times more than the optimal. In addition, GMP-agents performed also well but DIA-agents attained only similar levels to those of MoVe. Delays of FK- and GMP-agents reduced faster than other schemes, when amount of nodes increased.

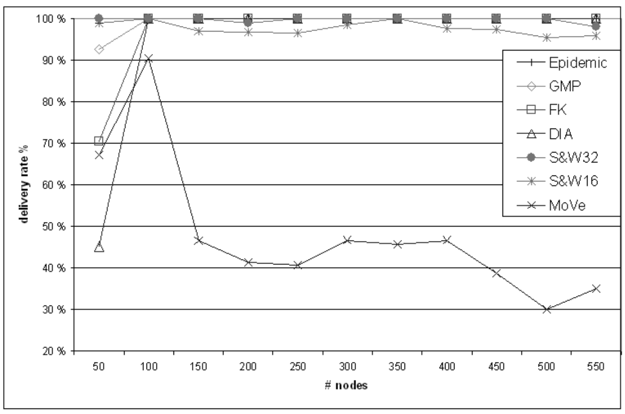

Fig. 4 Data delivery rate.

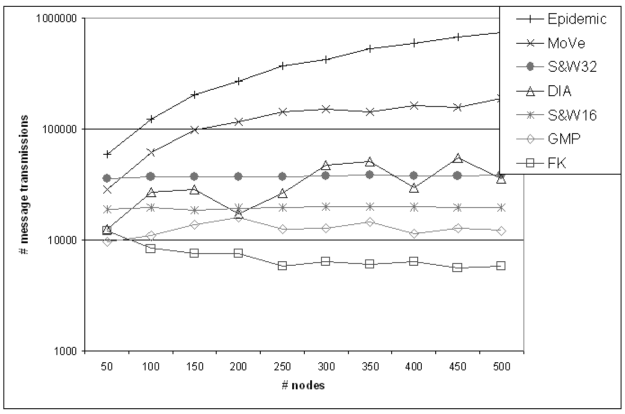

Fig. 6 Network system stress.

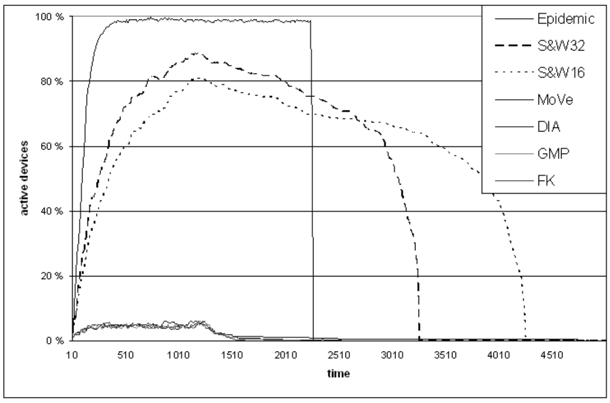

Fig. 7 Network system stress.

In figs. 6 and 7 we can see different measurements about the overhead and the total stress of the network system. From the fig. 6, we can see that FK- and GMP-agents caused far less message transmissions than other schemes did. DIA-agents achieved only similar levels to those of S&W, but outperformed rest of the routing schemes. The Epidemic caused far more than one transmission per every node because the sink received numerous copies of the same messages. Since nodes do not remember what messages they have already delivered, they received the same copies again after delivering them at the sink. In MoVe, messages trapped in routing loops caused several unnecessary transmissions as messages bounced in traffic flows.

The fig. 7 shows another point of view for network stress levels, representing how many devices were active message carriers during the transmissions in a simulation run with 450 nodes. Differences between single-copy and diffusion schemes are remarkable, as expected.

In the second series of simulations, representing more complex as well as realistic open environment, success rates of all schemes were deprived in low network densities. When network density increased, PGR clearly outperformed other schemes (fig. 8). In Epidemic routing, the limited buffer size prevented diffusion and caused message drops as timeout expired before messages spread into the network. This result was expected on basis of other studies, for example [4, 15]. The additional simulations we ran showed that increasing the timeout gave no benefit for the Epidemic routing as message copies blocked the network in any case. Actually, extended timeout only raised delivery delays because some messages had to wait longer in the sensors' buffers before they had an opportunity to propagate into the network.

With S&W, limited buffers were not as critical as with Epidemic. It seemed that both the unbounded environment and the difficult sink location affected drastically S&W as the probability to find the correct message carrier randomly was compromised. In these simulations, the timeout for S&W was the same 3500 seconds as for PGR. Results of S&W indicate that a random selection of nodes is not adequate in an open network, especially if traffic flows are not equally distributed.

Based on the results we may also conclude that as complexity of routing task increases the greater is the benefit from long-term movement predictions. In addition, results draw attention to the importance of trajectory information in geographical DTN-routing.

The stress for the network remained relatively similar between the schemes compared to simulations in the closed environment. The most significant difference is that even though the total message transmissions between the nodes stayed low with FK- and GMP-agents, DIA-agents had great difficulties to find proper message carriers. The main reason for difficulties with DIA was the sink location. This caused a number of unnecessary message hops between the nodes as messages bounced in traffic flows nearby sink. These results show again the differences between efficiency of routing metrics in PGR. However, DIA-agents still outperformed other schemes in delivery success rate, especially after network density increased.

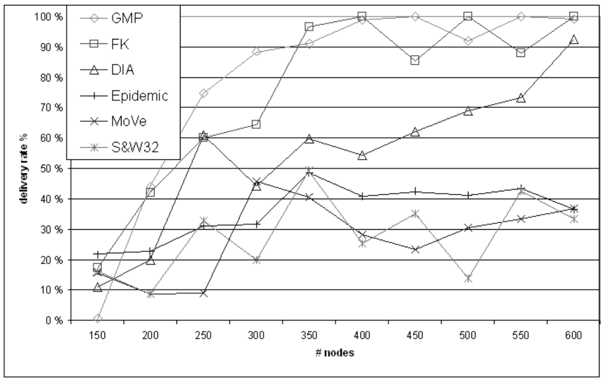

Fig. 8 Network system stress.

6. CONCLUSION AND FUTURE WORK

We studied delay-tolerant routing in vehicular networks with varying network density and presented a novel geographical routing scheme for sparse mobile and vehicular ad hoc networks. Predictive Graph Relay (PGR) is an interface between smart routing agents, which are capable of predicting their hosts' movement. Agents can utilize both long and short-term movement predictions and we demonstrated that as network density decreases and intervals the nodes are carrying messages expand, the more important long-term predictions became. PGR was more effective than other geographical routing schemes in the sparse network and especially in the complex environment, where infrastructure entailed routing loops for carried messages. Simulation results were promising and pointed out that smart agents attain efficient network usage even when information sources are limited or hosts' behaviours have to be learned. Transport delays were in the best cases near optimal and at the same time, the protocol overhead was far less than with other implemented methods. Agents needed only a fraction of network resources compared to the diffusion-based routing schemes and caused less message transmissions as the other single-copy methods.

We compared pure epidemic diffusion [16] and randomly limited diffusion [15] to geographical proposal [10] in the context of VANETs by forming an unbounded network, in which messages were easily lost in traffic flows. Epidemic diffusion attained excellent results if total data transmissions were less than nodes' storage capacity, but scalability for more intensive data flows was poor. On the other hand, limited diffusion offered good tradeoff between network stress levels, scalability and performance in the closed environment, but in the open network random selection was not adequate to find proper message carriers. In practice, adjusting diffusion parameters like messages' timeout and number of copies can be distressed task for real applications in an open environment. On the basis of presented simulations we may conclude that geographical routing schemes are the best choices for vehicular networks. However, geographical DTN-routing requires other approaches than straightforward greedy metrics than traditional localized routing methods are currently using. We presented how topology of infrastructure causes routing loops for carried messages and confirmed that combination of trajectory-based forwarding and movement predictions, which PGR uses, is able to solve those problems.

Our current simulations separated differently behaving agents and at present we are examining internetworking between distinct agents using varying radio interfaces. In addition, further studies of parameters in presented mobility model are required. In the next phase we will study the behaviour of method with a more complex environment.

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