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Geolocation Assisted Routing Protocols for Vehicular Networks

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***Abstract*—The class of flooding-based DTN routing protocols that leverage (transitive) encounter probabilities have been shown to perform well in selected simulations and scenarios, however they are especially sensitive to heterogeneous mobility models in which some nodes' mobility pattern is on a significantly different timescale than others. In particular, military and disaster response scenarios can exhibit abrupt topology changes. We analytically show that the worst-case inputs to these existing DTN routing algorithms can drastically reduce their performance. In light of such scenarios, we develop new protocols that inherit the benefits of existing schemes, while leveraging geographic assistance to enable faster recovery from abrupt topology changes.**

I. INTRODUCTION

In the last decade, the network research community has developed a variety of special-purpose routing protocols to support delay- and disruption-tolerant networking (DTN). These protocols cover a wide spectrum of design choices – in terms of forwarding, from an epidemic-style flooding of messages [1], [2] to single-copy forwarding [3], [4], with selective replications [5]–[7] in between; in terms of buffer management, from simple FIFO and drop tail buffering [6] to elaborate per message utility based schemes [2]. Frequently, these design choices are specific to the envisioned deployment environment and underlying mobility assumptions.

The performance of existing encounter-based DTN routing protocols has been evaluated mostly under homogeneous mobility models where nodes move at similar speeds and in a similar pattern. Even in real deployment scenarios (e.g., DieselNet [2]), no sudden change of mobility patterns is explicitly considered. It remains an open question whether existing DTN routing protocols can perform well in scenarios where the traffic mobility pattern is *irregular*, i.e., where some nodes may suddenly change from one mobility pattern to another. Such scenarios are not uncommon in emergency relief and military DTN settings. E.g. mobile platforms (vehicles or helicopters) that may move in and out of locations abruptly, on demand. Worse, these platforms, usually well equipped and strategically located, may be relaying a disproportionally large amount of messages at the time of re-deployment.

Based on these insights we develop the Geolocation-Assisted Predictive Routing (GAPR) protocol. A fundamental finding of our work is that while maintaining and distributing encounter information in the network can provide significant benefit and exploit extant temporal and spatial locality, such information is not robust to abrupt topology changes – changes that can frequently occur in realistic DTN deployments. We therefore design GAPR to inherit the benefits of existing schemes, while leveraging geographic assistance to "unlearn" encounter probabilities when they are unlikely to be correct. Unlike prior work on geographic routing, our protocol only employs geolocation to ascertain positional state changes, not direct forwarding decisions. Our contributions are three-fold:

1) We simulate current DTN routing protocols across a variety of scenarios to understand their performance amid heterogeneous and irregular mobility. Our results show that their performance may have large fluctuations from scenario to scenario, raising concern about the generality of some of these approaches.
2) We isolate components of existing DTN routing protocols that contribute most to their performance. We discover that bundle queue strategy and drop policy can dominate observed performance.
3) We propose and demonstrate a new, general DTN routing approach that leverages lightweight geo-positional information to adapt to various kinds of mobility more effectively than the state of the art.

II. BACKGROUND

Our simulation study focuses on four existing routing protocols: PRoPHET, MaxProp, RAPID, and Encounter-Based Routing (EBR). They represent the state of the art for a class of DTN routing protocols that utilize historical contact and forwarding information to predict future contacts and make forwarding and buffer management decisions accordingly. This section briefly reviews and compares these protocols using the notation and terms adopted by the respective protocol developers. In the rest of the paper, we refer to this class of routing protocols simply as *predictive* DTN routing protocols.

A. PRoPHET and PRoPHETv2

In PRoPHET [8], a node's routing decisions are based on a per-peer metric of *delivery predictability*, or the prior probability of encounter between nodes. $P(A, B)$ represents

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an estimated probability of successfully forwarding a message from A to peer B, either directly or indirectly. For each data bundle, a node compares its own P value for the destination with the P values of its neighbors and forwards the message to the neighbor with the highest probablity of delivery success. If the node itself has the highest P, it buffers the message until a new contact opportunity arises.

1) PRoPHETv2: Certain flaws in PRoPHET that became apparent with specific mobility patterns led to the development of PRoPHETv2 [6]. To summarize the issues found, whenever the frequency of encounters was not spread evenly throughout the network, the P values of some nodes would grow disproportionately to the real topology leading to routing failure. To account for this, the equations for updating P values were modified [6].

B. MaxProp

The MaxProp [1] DTN routing protocol also uses historical encounter data to aid routing decisions. Each node performs epidemic forwarding, but uses connection history to prioritize messages on new peer connection events, or drop bundles if the local buffer fills.

Specifically, each node A maintains a table of probabilities $f(A, i)$ for encountering every other node i in the network. $f(A, i)$ is initialized to $1/(N - 1)$ where N is the size of the network. Upon encountering a peer, say B, node A first increments the corresponding f value by 1 and then renormalizes the entire table so that the sum of all encounter probabilities remains to be 1.

C. RAPID

RAPID [2] also performs epidemic forwarding. In contrast to MaxProp, RAPID prioritizes messages for both forwarding and dropping through the use of utility functions, instead of ad-hoc rules, with the goal of intentionally optimizing specific metrics (e.g., minimizing the average or maximum delay, and minimizing the number of packets that miss a deadline). For example, to minimize the average message delay, RAPID uses a simple utility function $U_m = -D(m)$ where $D(m)$ is the estimated end-to-end delay for message m.

D. EBR

Unlike the other protocols discussed, the Encounter Based Routing (EBR) [5] protocol performs selective replication. It is also referred to as a quota-based protocol because it sets an upper bound on the number of replicas allowed for each message in the network.

Similar to RAPID, the protocol targets networks where the future rate of node encounters can be roughly predicted by past data. Specifically, each node is responsible for maintaining an exponentially weighted average rate of past encounters (EV), which is used as an indicator of likelihood of future encounters. When two nodes A and B meet, the relative ratio of their respective rates of encounter determines the appropriate fraction of message replicas the nodes should exchange [5].

III. GAPR DESIGN

The main objective of the GAPR design is to leverage node location information to better adapt to heterogeneous and irregular mobility patterns. While several design approaches are possible, we have chosen to first identify from the existing predictive protocols those features that are generally applicable to most scenarios and then augment them with new primitives for nodes to exchange and process geolocation information. Our rationale is as follows. Classic geographic routing protocols that make local forwarding decisions are often susceptible to dead-end (local maxima) conditions where a node does not have a “better” (closer) neighbor based on GPS information. Predictive routing protocols may be effective in mitigating such conditions because (i) their routing metric is based on historical encounters with the destination node, and (ii) they replicate or flood multiple copies of a message. We therefore utilize geographic assistance to “unlearn” encounter probabilities when they are unlikely to be correct.

A. Baseline Features

We have identified the following design features from existing DTN routing protocols to form a baseline for GAPR:

- Acknowledgments for delivered data are flooded throughout the network in order to free buffer space. This feature should be effective in most scenarios, particularly those where buffer overflow is a concern, and data bundles are large relative to the size of the acknowledgments, and time-to-live is long.
- Nodes estimate the delivery probability P_{direct}, for each buffered message based on direct encounters with the destination node. Upon an encounter, each involved node computes a transitive delivery probability through the other node (denoted by P) using the modified Dijkstra’s algorithm proposed in [1].
- Nodes forward messages to a peer in the decreasing order of the P values for that peer. This feature allows nodes to make the best use of short-lived contact opportunities.
- If it is necessary to delete messages, nodes delete those with the lowest P_{direct} first, ensuring that the messages more likely to be delivered are maintained.

B. Geolocation Assistance

In addition to the baseline features, we require two nodes to exchange their geographic locations (along with timestamps) upon an encounter. Furthermore, each node records in a table the historical location information for all the nodes it has encountered and exchanges this table with other nodes. Such information allows a node to promptly detect a change in network topology if a previously “nearby” node has suddenly moved away. Consider a node A and a destination node i. Let $l_{\text{old}}(i)$ be the recorded location for node i at A’s historical location table, with a timestamp value of $T_{\text{old}}(i)$. Suppose node A has just learned a new location of i, $l_{\text{new}}(i)$ with timestamp $T_{\text{new}}(i)$, from another peer. Node A would now be

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TABLE I
HELSINKI SCENARIO PARAMETERS

Parameter	Value
simulated duration	12 hrs
warmup time	1000 s
timestep resolution	0.1 s
number of runs	4
radio bandwidth	1 Mb/s
transmit range	10 m
buffer size	5 MB
number of pedestrians	80
pedestrian speed	0.5–1.5 m/s
pedestrian pause time	0–120 s
number of cars	40
car speed	2.7–13.9 m/s
car pause time	0–120 s
number of trams	6
tram speed	7–10 m/s
tram pause time	10–30 s
message rate	1 / 25–35 s
message size	0.5–1.0 MB
message TTL	5 hrs

TABLE II
SUDDEN SCENARIO PARAMETERS

Parameter	Value
simulated duration	10 days
warmup time	1 day
timestep resolution	0.1 s
number of runs	5
radio bandwidth	250 Kb/s
transmit range	100 m
buffer size	5 MB
number of stations	10
number of buses	7
bus speed	10-25 m/s
bus pause time	10–30 s
number of truck	3
truck speed	5 m/s
truck pause time	10–30 s
message rate	1 / 2600–4600 s
message size	0.5–1.0 MB
message TTL	12 hrs

able to detect a sudden movement of i and reset P_{direct} for i if the following two conditions hold.

$$\begin{aligned} \text{Distance}(l_{\text{new}}(i), l_{\text{old}}(i)) &> \alpha \times R, \quad (1) \\ T_{\text{new}}(i) - T_{\text{old}}(i) &\leq T_0, \quad (2) \end{aligned}$$

where R is the radio transmission range, α a tunable parameter with a default value of 1, and T_0 another tunable parameter.

Specifically, to enable this functionality, nodes maintain a *location table* containing the timestamped GPS coordinates of the nodes they have encountered, and a *transitive location table* containing node locations and timestamps learned via peers. At each encounter, they exchange their current locations and transitive location tables. When a node receives this information from a peer, it updates its own location and transitive location tables with the peer's location and current time, and copies any new locations from the peers table into its own transitive location table. It then compares its updated transitive location table with its own location table. For any node existing in both tables, if the timestamp in the transitive table is newer than the one in the location table, the entry in the location table is removed and the P_{direct}-value for that node is reset to zero.

C. GAPR Operations upon Node Encounter

Combining geolocation assistance with probabilistic modeling, as well as queue management optimizations, GAPR operation is as follows when a node encounters a peer node.

1) Exchange acknowledgments of delivered data, and clear acked messages from buffers.
2) Forward messages destined to the peer.
3) Exchange routing and location information including P-value tables.
4) Reset P_{direct}-values for nodes that have moved abruptly since last update.
5) Forward messages for which the peer has a higher P-value, in descending order starting with the highest of their computed P values.

D. GAPR2 Variations

We also propose a variation on GAPR, called GAPR2, which is more fully explained and analyzed in [9]. GAPR2 seeks to reduce message replication and thus improve efficiency boy considering not only node locations and the time of encounters, but their direction of travel. Messages are forwarded to neighboring nodes with increasing probability proportional the the difference between their velocity vector in two dimensions.

$$P_{\text{forward}} = \sin(\theta) \quad (3)$$

Equation 3 shows the probability of forwarding to a given neighbor, where θ is the smallest ($< 180°$) angle between the trajectories of the two nodes. In the case that one or both of the nodes are stationary, $P_{\text{forward}} = 1$. This probability is applied in series with P_{direct}, so the final probability is the product of the two. Intuitively we see that the result is reduced message forwarding.

IV. DTN SCENARIOS FOR EVALUATION

We use several scenarios to compare the performance of the DTN routing protocols we consider, including a map-based model of the streets of Helsinki, a trace-based scenario from the DieselNet testbed, and a synthetic model designed to test performance with heterogeneous mobility. All simulations are performed in the popular ONE DTN simulator [10].

A. Helsinki Scenario

This scenario, based on a street-map of Helsinki, Finland has become popular for DTN simulations due to its inclusion as the default mobility model in the ONE DTN simulator. It includes pedestrians, cars, and trams, all of which follow a

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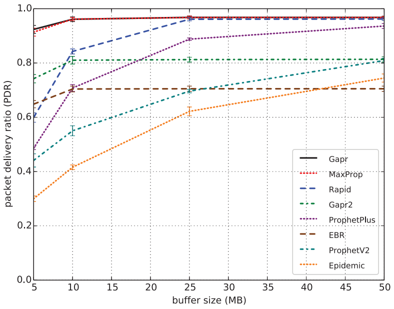

Fig. 1. Helsinki scenario delivery probability vs. buffer size

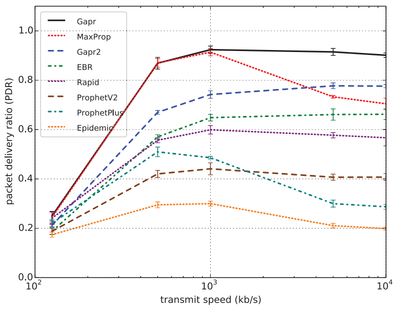

Fig. 2. Helsinki scenario delivery probability vs. radio bandwidth

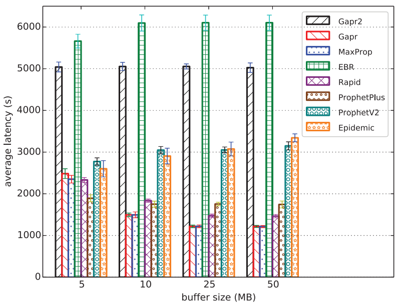

Fig. 3. Helsinki scenario average latency vs. buffer size

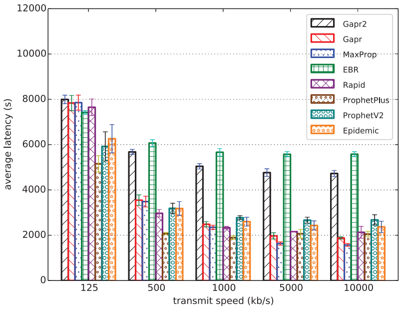

Fig. 4. Helsinki scenario average latency vs. radio bandwidth

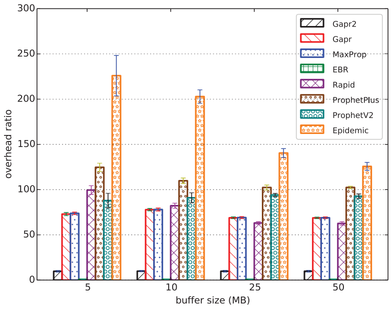

Fig. 5. Helsinki scenario overhead ratio vs. buffer size

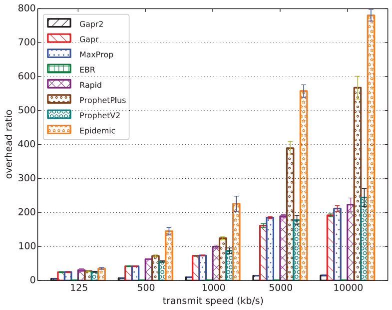

Fig. 6. Helsinki scenario overhead ratio vs. radio bandwidth

map-based mobility pattern. We use the default mobility and traffic parameters in order to promote comparison with other studies using the Helsinki scenario.

B. *Sudden-Movement Scenario*

Both the Helsinki and DieselNet scenarios are relatively homogeneous in terms of the mobility of individual nodes, and in particular pause times are relatively short. In contrast, varying, lengthy pause times are often used in evaluating MANET routing protocols, producing a positive correlation between duration of pause times and message delivery probability.

To better reflect this type of mobility, we develop a new scenario, inspired by a real military application, that we dub “sudden-movement.” In this scenario we focus on the ability of the DTN routing protocols to deliver packets to nodes with long pause times and with brief periods of movement. The sudden-movement scenario includes 10 fixed stations, 7 buses, 3 trucks, and 1 chopper. Each of the vehicles deterministically traverses a set path among the series of stations.

The helicopter moves only occasionally, while the rest of the mobile nodes maintain regular map-based mobility patterns. We analyze the performance of the protocols in delivering messages to the helicopter.

V. EVALUATION

To evaluate the GAPR protocol we have constructed a model of it in the ONE simulator [10], in order to compare it to several other DTN routing protocols on the scenarios described in Section IV. Throughout these simulations the value of α is set to 1, and T_0 is set to ∞ for the GAPR protocol.

A. *Protocol Comparisons*

We compare GAPR against several known approaches with available ONE simulator models: Epidemic [11], PRoPHET [8], PRoPHETv2 [6], MaxProp [1], RAPID [2], and EBR [5]. Besides these we created a modified version of PRoPHETv2 called PRoPHET+, in order to explore the contribution of buffer-management optimizations.

1) PRoPHET+: Early-on in our evaluation process we noted that MaxProp performed much better than the PRoPHET variants in several simulation cases. To further investigate the cause we added all of the buffer-management optimizations from MaxProp to PRoPHETv2. The result was a protocol with *identical* performance to MaxProp. Experimenting with each optimization individually showed that data acknowledgments were the most significant. Unfortunately showing plots of each optimization is impossible within the space constraints of this paper, so we chose to include a version of PRoPHET+ with all the MaxProp buffer management optimizations *except* acknowledgments. Figures 1 and 2 show the improvement provided by the buffer management over PRoPHETv2 (in most cases), but also the additional advantage gained by MaxProp by using acknowledgments (keeping in mind that PRoPHET+ *with* acks achieves performance identical to MaxProp).

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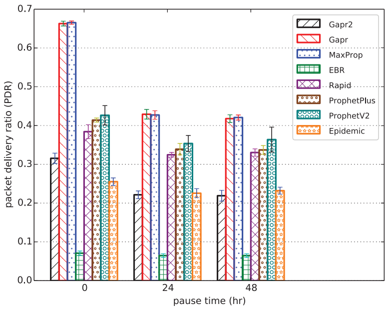

Fig. 7. Sudden scenario delivery probability vs. wait time

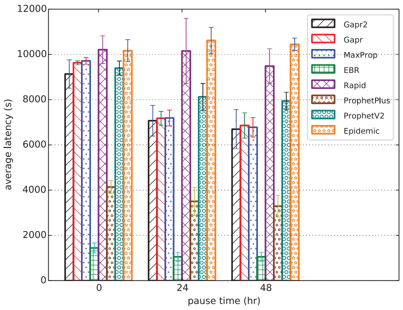

Fig. 8. Sudden scenario average latency vs. wait time

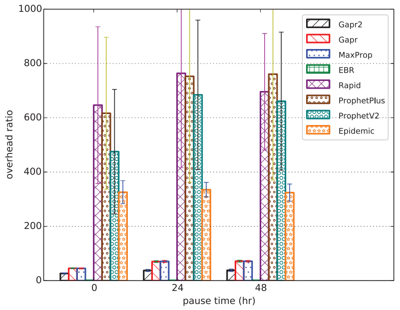

Fig. 9. Sudden scenario overhead ratio vs. wait time

B. Simulation Results

First we examine the fraction of packets that are delivered to the destination before timing out.Figure 1 shows this on the Helsinki scenario as we vary the buffer size of the nodes. We see that Epidemic, PRoPHET, and PRoPHETv2 are the most affected by constrained buffer sizes, due to their flooding-based design and lack of buffer-management optimizations. We see that PRoPHET+ performs significantly better, and RAPID better still, however the top performers with constrained buffers are GAPR and MaxProp due to data acknowledgements, with GAPR showing a small edge due to geolocation assistance. EBR also does well, since it it not flooding-based, however its peak performance even with large buffers never matches GAPR and MaxProp, and given large enough buffers even Epidemic and PRoPHETv2 surpass it. Figure 2 also shows the delivery probability on the Helsinki scenario, this time while varying the bandwidth of the radios. As expected all the protocols perform badly a low data rates (128 kb/s), however at 500 kb/s all are at or near their peak performance. GAPR achieves the best delivery performance at each measured bandwidth, reaching peak performance at 1 Mb/s. Of note is that MaxProp and PRoPHET+ both decrease significantly in performance as the bandwidth is *increased*. We suspect that this is an artifact of MaxProp adapting to the average number of bytes transferred per encounter.

The secondary metric for evaluating DTN performance is latency. From Figure 3 we note that the worst performing protocols (in terms of delivery probability) show an upward trend in latency as buffer size increases, while the best performing (GAPR, MaxProp, and RAPID) are able to utilize increased buffer space to decrease latency. EBR, while performing well has nearly constant latency across the range of buffer sizes. Figure 4 shows a trend on decreasing latency as bandwidth increases for all protocols. In both of these figures, we see that in every case where GAPR has more latency than MaxProp, GAPR is delivering more packets than MaxProp, while in every case where MaxProp matches GAPR's delivery performance, GAPR has the same latency as MaxProp.

Lastly we look at the overhead incurred by each protocol in this scenario. In Figure 5 we see the overhead decreasing for each protocol as a greater fraction of packets are delivered. As expected, Epidemic has the most overhead, and EBR has the least, since it is non-flooding based. This would make EBR very appealing, except that we observe that due to its algorithm it *never* delivers messages to certain destinations, even with unlimited resources. Figure 6 shows that the flooding-based protocols incur more overhead with increasing bandwidth, however the really interesting thing is that MaxProp incurs significantly more overhead than the others, even than Epidemic, as its performance decreases at high-bandwidths. This is the result of the MaxProp encounter algorithm which transfers high-priority packets *before* exchanging acknowledgements, resulting in duplicate message deliveries. GAPR does not suffer from this additional overhead due to exchanging acknowledgements first.

When evaluating the sudden-movement scenario, instead of looking at resource constraints we are interested in the effect of heterogeneous mobility on the routing protocols. We see that due to the light traffic load, epidemic and similarly greedy protocols all perform well, however two protocols in particular have trouble with this scenario. EBR (which performed well on Helsinki) and PRoPHET (which outperformed Epidemic on Helsinki) both perform extremely poorly in this case (Figure 7). We expect that this type of behavior was part of the motivation for PRoPHETv2, which is much improved, however it is surprising to see it in EBR, which is considered a state-of-the-art DTN protocol. Overall, we see that GAPR, MaxProp, and PRoPHET+ all perform comparable to Epidemic in this lightly-loaded case, while Rapid and PRoPHETv2 both perform slightly worse.

Similarly when we look at the average latency in the sudden-movement scenario (Figure 8) GAPR, MaxProp, PRoPHET+, and Epidemic all show comparable latency, while RAPID and Epidemic have significantly higher latency. EBR and ProphetPlus have low latency, however they are delivering a much smaller fraction of messages. The overhead results follow a similar trend (Figure 9) with GAPR and MaxProp generating significantly less overhead the RAPID, and the PRoPHET variants.

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VI. RELATED WORK

Our GAPR design was inspired by a number of location-based routing protocols developed for mobile ad-hoc networks, including APRAM, DREAM, SIFT, and GRID [12]–[16]. APRAM [17] utilizes GPS coordinates to discover the geographically shortest path to the destination, while DREAM uses the cached node locations to make local forwarding decisions that forward packets in the direction of the destination. Similarly AeroRP [18], [19] uses both the coordinates and velocity of neighbors to locally determine the best next hop. LAR [20] uses location information to bound the area of the route discovery phase, thus reducing overhead. Beaconless geographic routing [21] exploits the broadcast nature of wireless channels to overhead the location of neighboring nodes, and use this information to discover the best route. Other protocols such as IGF [22], BOSS [23], and BLR [24] have been proposed that vary in the algorithm used to select the forwarding node.

VII. CONCLUSION AND FUTURE WORK

In this paper we explored the limits of existing DTN routing protocols by performing simulations across a range of realistic mobility scenarios. We also introduced GAPR, presenting its design and evaluation on these scenarios, showing it to perform well across a broad spectrum of mobility patterns and resource constraints while other protocols' performance suffered under certain conditions.

In the future we plan to explore more sophisticated algorithms to leverage the geographic assistance mechanism, as well as further exploring the utility of velocity on the performance of GAPR/GAPR2. Lastly we are working on an implementation of GAPR to work with DNT2 and compatible DTN bundling protocol agents.

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