Social and Geographical Routing for Vehicular Delay-Tolerant Networks

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***Abstract*—Vehicular Delay-Tolerant Networks (VDTN) address the communication challenges inherent in vehicular environments characterized by intermittent connectivity and dynamic mobility patterns. This paper investigates the simultaneous use of social and geographical routing mechanisms in VDTNs. Social information can be learned automatically from previous contact history, while geographical information is assumed to be received on each node from a GPS system and exchanged with neighboring nodes. The routing protocol variants studied are variants of the spray-and-wait protocol, where both the spray and wait phases use either social or geographical information. The simulation results show that the mechanism used in the search phase has more impact on the routing performance. GreedySocial, a combination of Greedy spraying of messages followed by Social (dLife-based) search of the destination had the best (higher) delivery probability for higher node density situations, although for lower density scenarios its spray mechanism is not aggressive enough.**

Keywords—Vehicular Delay-Tolerant Networks, Social Routing, Geographical Routing

I. Introduction

There are numerous scenarios where network infrastructure is insufficient, intermittent, or entirely absent. These challenges are evident in remote rural areas, disaster zones, large-scale events, and even some urban settings with high device density. In such situations, where access to traditional infrastructure is limited, Delay-Tolerant Networks (DTN) emerge as a resilient alternative to ensure communication. Nodes in vehicular networks can benefit from DTN concepts to support non-urgent data transfers such as maps and software updates, infotainment contents for passengers, etc., in what is called Vehicular Delay-Tolerant Networks (VDTN) [1].

The motivation for this paper lies in the opportunity to explore the integration of the geographical information that most vehicular nodes have with social information that nodes can learn from their previous encounters. By combining social and geographical data, nodes are expected to have more efficient, adaptive, and resilient communications, which are essential for the emerging digital world.

This paper has the following contributions:

• Present a survey of current routing protocols designed for DTNs with a focus on the integration of social and geographical aspects, in section II.

• Develop an innovative routing framework tailored to the dynamics of VDTN by incorporating both social and geographical-aware mechanisms, emphasizing the efficient utilization of social ties and vehicular movements for improved message delivery, in section III.

• Implement the proposed routing framework in a simulation environment and evaluate its performance metrics, and compare the outcomes with existing protocols to validate the effectiveness of the proposed approach, in section IV.

Finally, section V presents conclusions and further work.

II. State of the Art

A. Delay-Tolerant Networks

Traditional ad hoc routing protocols assume that hosts are always available, so that when links are down or hosts are offline, no strategy exists to deliver data once the destination is available again [2]. Thus, traditional routing protocols perform poorly in DTNs.

For DTNs, a Store, Carry, and Forward (SCF) mechanism is used, where nodes take advantage of contact opportunities to progressively forward messages until their destination. So, there is no need for a permanent end-to-end path from source to destination as in Mobile Ad Hoc Networks (MANET), making DTNs appropriate for non-real-time traffic [3].

In DTNs, a specialized message-oriented layer known as the "Bundle Layer" is introduced above the transport and network layers it connects. The Bundle Layer takes application data units and converts them into one or more protocol data units, referred to as "bundles". The key concept is to consolidate all the necessary data for a transaction within these bundles, minimizing the need for multiple round-trip exchanges. To aid in routing and scheduling decisions, bundles contain information like an origin timestamp, a useful life indicator, a class of service assignment, and a length indicator [1].

B. DTN Basic Routing Protocols

Routing protocols are the backbone of communication in DTNs, enabling the efficient delivery of messages across networks where connectivity may be sporadic, delayed, or unreliable. The primary goal of routing in DTNs is to maximize the successful delivery of messages while minimizing delays and resource usage [4,5]. Two of the core concepts underpinning these protocols are replication and forwarding, which play crucial roles in determining how data is propagated through the network.

Replication involves creating multiple copies of a message and distributing them across different nodes. By increasing the number of copies of a message, the chances that at least one copy will successfully reach the destination are enhanced. This method is particularly useful in networks where the likelihood of direct and consistent paths between source and destination nodes is low.

Forwarding implies that a message is not duplicated but only transferred to another node till the final destination using a SCF mechanism. Unlike replication, forwarding typically involves fewer message copies, relying instead on intelligent decision-making to move the message closer to its target [2].

Epidemic Routing Protocol [6] operates without the need for prior knowledge about the network. When two nodes come into contact, they exchange all messages that are not already shared between them. This exchange results in the replication of multiple copies of each message throughout the network, including the destination node [7]. However, common scenarios involve limitations on buffer size, finite transmission rates, and other resource constraints, so that Epidemic routing may result in network congestion.

The Spray-and-Wait [8] protocol effectively manages the extent of message replication within the network by limiting the number of copies of each message to *L*. This protocol encompasses two distinct steps: the Spray step and the Wait step. In the initial Spray step, the source transmits *L* copies of the message to the first *L* nodes met in the network. Subsequently, in the Wait step, each node that has received a copy of the message awaits to meet the destination node to deliver the data.

C. DTN Social-based Routing Protocols

Social-based routing protocols leverage social relationships and patterns of human mobility to make routing decisions. They aim to optimize message delivery by understanding and predicting how nodes are likely to encounter each other based on past social behaviors [9].

The Bubble Rap [10] protocol focuses on two issues: community and centrality. These two are related to human beings. Together, with both community and centrality forwarding methods, is called Bubble forwarding.

Community [11] is used to divide the nodes into specific communities or groups. It is used to represent a group of nodes where nodes inside the community have more internal connections than external connections - a group in which nodes frequently meet each other. The k-clique algorithm [12] is employed to identify communities within the contact graph.

Centrality [13] is related to forwarding messages to nodes which are more popular than the current node. Nodes with higher centrality values can more effectively disseminate information throughout the entire network compared to nodes with lower centrality measures. However, there are several alternative definitions of centrality, leading to various proposed measures. Among them, degree centrality and betweenness centrality are the most prominent methods. Degree centrality is determined by the number of links a node has with other nodes, i. e., their direct neighbors. Betweenness centrality assesses a node's contribution to the shortest paths between every pair of nodes in the network.

In the Bubble Rap strategy, if a node has a message intended for a specific destination node, it initiates a process of 'bubbling' the message up through the hierarchical ranking tree, using global centrality rankings, until it encounters a node within the same community as the destination node. Subsequently, the local ranking system takes over, further advancing the message through the local hierarchy until it reaches its destination or expires. This approach does not require each node to have knowledge of the ranking of all other nodes in the system; rather, it compares rankings with encountered nodes and sends the message using a greedy approach.

dLife (daily life) [14,15] is an opportunistic routing protocol designed around the daily routines of individuals, taking into account the time-evolving social structures. The calculation of the time-evolving social structure by dLife is based on representing dynamic social structures to indicate the duration of connection between pairs of nodes over different periods of time using two utility functions: Time-Evolving Contact Duration (TECD) and Time-Evolving Contact Duration Importance (TECDi). TECD serves to capture the evolution of social interactions between pairs of users during the same daily period over consecutive days. On the other hand, TECDi captures the evolution of user importance. This importance is determined by factors such as the node degree and social strength towards its neighbors over different periods of time. In the context of dLife routing, the decision to replicate messages relies on TECD/TECDi. If the encountered node has a stronger relationship with the destination in the current daily sample, it receives copies of the message. Replication of the message occurs only when the relationship to the destinations is unknown, and it happens if the encountered node has higher importance than the carrier.

A second iteration of the dLife algorithm, known as dLifeComm [14], has been developed to facilitate a more straightforward comparison between solutions focusing on network dynamics (centered on users' daily routines, like the dLife protocol) and solutions emphasizing network structure (centered on node communities, like the Bubble Rap protocol). In dLifeComm, the TECD and TECDi are used to harness communities formed through social interaction. Community detection relies on the k-clique algorithm, mirroring the approach in Bubble Rap. When a user needs to send a message to another user in a different community, the message is forwarded towards the destination's community using TECDi. Users with higher importance are more likely to reach the destination's community faster. Upon reaching the destination's community, forwarding occurs towards the destination by replicating the message to users with higher social strength (TECD) toward the destination, rather than higher centrality as seen in Bubble Rap. The links used for forwarding within and between communities evolve over time, reflecting varying degrees of social strength during different time intervals.

D. DTN Geographical-based Routing Protocols

The GeoSpray [16] routing protocol assumes that nodes in a VDTN are aware of their geographical position, obtained through a positioning device such as a GPS navigation system. This allows node to calculate routes, distances, and travel times between two points on the map. Additionally, the protocol presupposes that the locations of destination nodes are known in advance, and that mobile nodes possess information about their speed and current route. Unlike blind replication found in protocols like Spray-and-Wait, GeoSpray ensures that bundle copies are selectively distributed to nodes approaching the destination more closely or arriving sooner. GeoSpray heavily depends on accurate mobility information, including node speed and direction. In dynamic scenarios where nodes' movements are unpredictable or where mobility data is imprecise, the effectiveness of the protocol may be compromised.

Spray and Locate [17] uses a distributed localization mechanism, where nodes maintain dictionaries of the last known position of other nodes, lifting the requirement of accurate mobility information that GeoSpray has.

E. Hybrid DTN Routing Protocol

M-Dimension [18] is a DTN routing protocol, specifically designed for Human-Associated Delay Tolerant Network (HDTN). It distinguishes mobile nodes based on attributes in multiple dimensions, including both geographic and social aspects. The protocol utilizes a greedy routing scheme, combining attributes from diverse dimensions to determine the optimal route. In the M-Dimension routing scheme, the network structure is reorganized. Each node is assigned a unique ID represented by a vector that combines attributes from different dimensions. The protocol assumes each node is aware of its own ID, which includes characteristics from different dimensions like geographic location and social status. The protocol calculates the distance between nodes using a weighted sum of differences in each dimension. Routing decisions are based on factors like distance and network status, followed by multicasting of messages to available intermediate nodes to eventually reach the destination.

The fundamental concept behind Price [2] (Periodicity based Routing in Intermittently-Connected Environments), involves integrating a greedy geographic forwarding approach with contact-based forwarding. Nodes employ geographic forwarding in scenarios where direct communication between the source or relay node and its associated neighbors and the destination is not feasible through contacts. Alternatively, the system should switch to contact-based forwarding in other situations. In general terms, each node compiles agendas based on locally gathered histories of contact and position information. Agendas serve to anticipate mobility-related events within a predefined prediction period, which is divided into equal-duration time slots. Predictions are generated for each time slot. For location-based agendas, a predominant expected position is forecasted for each time slot. On the other hand, contact-based agendas provide a set of contacts with a high probability of occurrence. Nodes maintain contact agendas, listing expected contacts for each time slot, allowing the estimation of a recontact delay. Similarly, location agendas provide information on anticipated positions, estimated using a barycenter-based algorithm with pause duration weights, facilitating the prediction of delays before the next visit.

III. Social and Geographical Hybrid Protocols

The methodology employed in the development of our hybrid protocols involved an exploratory approach, where various combinations of social and geographic parameters were tested. The primary goal was to create an efficient hybrid protocol that could address the specific challenges of VDTNs.

The implementation and simulations were conducted using The ONE Simulator [19,20]. The social parameters used in this work were built upon the open-source implementation by JP Dillon [21], whose contributions were fundamental to this research. Dillon developed a community detection module on top of the default version of The ONE Simulator - allowing an easier creation of protocols that leverage community properties.

The strategy to achieve an effective hybrid protocol was to experiment with various combinations of social and geographic parameters. Through simulations in different scenarios, the impact of each combination on routing efficiency was observed.

A. Social Parameters

The main social parameters considered were:

Community [11] detection: By analyzing previous and frequent encounters between nodes, groups that share similar paths can be detected, increasing the likelihood of message delivery within these communities.

Centrality [13]: This parameter measures the importance of a node within the network, based on its position and number of interactions with other nodes. Nodes with high centrality are more likely to act as effective intermediaries in message forwarding.

TECD/TECDi [14]: These parameters explore repetitive behavior patterns of nodes throughout the day. TECD serves to capture the evolution of social interactions among pairs of users during the same daily period over consecutive days, while TECDi captures the evolution of user importance.

B. Geographical Parameters

In addition to social parameters, integrating geographic information plays a critical role in the development of hybrid protocols. Metrics related to the spatial mobility of nodes allow for more precise routing, particularly in scenarios where physical proximity to the destination is a determining factor. The main geographic parameters considered were:

Location: The location of nodes is determined through a previously implemented GeoLocation dictionary [17], allowing the protocol to continuously monitor the current position of nodes.

Direction: This parameter considers the movement vector of a node, allowing the prediction of its future path and the identification of nodes moving towards the message destination.

Angle of Movement: The angle of a node’s movement relative to the destination can indicate whether the node is approaching or moving away from the destination.

C. Hybrid Protocol Operation

The main drawbacks of the current hybrid protocols stem from their unsuitability for environments that are not well-behaved or predictable. In such scenarios, predictive models that rely on certain patterns or regularities in the environment, struggle to accurately forecast future movements or interactions. As a result, the delivery of messages may become less reliable, and the protocols may face difficulties in adapting to the network. Conversely, some of them also depend on highly personal information, rather than being centered around the collection of anonymized data from past interactions.

The novel DTN routing protocols of this work had inspiration from the Spray-and-Wait protocol.

The hybrid routing protocol combines two key phases: **Spray** and **Search**.

It starts with a replication phase (spray phase) to increase the likelihood of encounters and deliveries when the environment is not well-behaved or predictable. The second phase, instead of just waiting for the destination node, focuses on the search for the destination (search phase), and will also rely on social, geographical and temporal information. These protocols aim to leverage both social behaviors and geographical data to optimize communication and data transfer within vehicular networks.

Multiple strategies were explored. This exploration led to the creation of several variants, each targeting different aspects of message replication and forwarding. The combination of these variants allowed comprehensive testing.

Below, the variants explored in both phases are outlined considering the simple following algorithm: *Upon the encounter of node x with node y, for each message m intended for node d, if node y represents the destination node d, transfer message m to node y; otherwise, retain message m within node x.*

D. Phase 1: Spray

In the spray phase, message copies generated are replicated among nodes according to different strategies:

Binary Spray: If there is more than one copy of message *m*, deliver half of the copies to node *y*, while retaining the remaining half within node *x*.

Angle Spray: If there is more than one copy of message m, and node *y* is moving in a direction that deviates by more than 30 degrees from the moving direction of node *x*, deliver half of the copies to node *y*, while retaining the remaining half within node *x*.

Greedy Spray: If there is more than one copy of message *m* and the last known position of node *d* is closer to node *y* than node *x*, deliver half the copies to node *y* and keep the other half in node *x*.

Community Spray: If there is more than one copy of message *m* and node *y* belongs to the same community as node *d*, deliver half the copies to node *y* and keep the other half in node *x*.

Centrality Spray: If there is more than one copy of message *m* and node *y* has a higher global centrality than node *y*, deliver half the copies to node *y* and keep the other half in node *x*.

Social Spray (dLife-based): If there is more than one copy of message *m* and node *y*'s has a higher weight than node's *x*, deliver half the copies to node *y*, while retaining the remaining half within node *x*. Otherwise, if node *y* has a higher importance than node *x*, deliver half the copies to node *y* and keep the other half in node *x*.

E. Phase 2: Search

Once only one copy remains in a node, specific strategies are employed to find the destination node. The variants for this phase are:

Angle forwarding: If node *y* is moving in a direction that deviates by less than 30 degrees from the direction of node *d*, transfer message m to node *y*.

Greedy forwarding: If the last known position of node *d* is closer to node *y* than node *x*, transfer message *m* to node *y*.

Community forwarding: If node *y* belongs to the same community as node *d*, transfer message *m* to node *y*.

Centrality forwarding: If node *y* has higher global centrality than node *x*, transfer message *m* to node *y*.

Social forwarding (dLife-based): If node *y*'s has a higher weight than node *x*, transfer message *m* to node *y*. Otherwise, if node *y* has a higher importance than node *x*, transfer message *m* to node *y*.

The combination of the previous variants resulted in the following seventeen protocols: BiAngle, BiGreedy, BiComm, BiCentral, BiSocial, AngleComm, AngleCentral, AngleSocial, GreedyComm, GreedyCentral, GreedySocial, CommAngle, CommGreedy, CentralAngle, CentralGreedy, SocialAngle, SocialGreedy

F. Evaluation metrics

The most common metrics to evaluate the effectiveness of the routing protocols include: delivery ratio, overhead, hop count, and latency [18]. *Delivery ratio* quantifies the percentage of messages successfully conveyed from their source to the intended destination within the network. A high delivery ratio is indicative of the routing protocol's efficiency in accomplishing successful message delivery, even in the presence of network disruptions and delays.

IV. PROTOCOLS EVALUATION AND ANALYSIS

To evaluate the implemented hybrid protocols, a simulation scenario was used to "extract" the previous key metrics described in section III.F. The simulations provide a structured way to compare the new protocols with several well-established ones, ensuring that the evaluation is consistent.

The scenario chosen simulates daily routines, resembling a real-life city setting. In this case, nodes follow more predictable routines, such as commuting routes or daily activities, which align with patterns commonly found in urban areas.

The reference protocols chosen for this comparison were: Epidemic, Spray-and-Wait, DLife, DLifeComm and GeoSpray - which were described in Section II.

A scenario with the midtown area of Manhattan, USA, was used, as available in The ONE simulator [19]. The area modeled covers 10 km by 8 km .Table I and Table II summarize the main settings of the simulations.

Pedestrians use the Working-Day Movement (WDM) model, which simulates a complex and realistic model with daily activities like going to work, shopping, and visiting meeting points. This model is configured to reflect an 8-hour workday, closely resembling the real-world routines of people in an urban setting. Additionally, each pedestrian has a 50% probability of owning a car and a probability of going shopping / going to a meeting spot after work of 50%, in which they can spend between 1 and 2 hours. 10 offices and 15 meeting spots were considered on the map, both randomly positioned. On the other hand, cars are restricted to roads using the Shortest Path Map-Based Movement (SPMBM) mode, while buses follow fixed, pre-programmed routes that simulate real-world public transport using the Routed Map-Based Movement (RMBM) model.

TABLE I. NODES' SIMULATION SETTINGS FOR THE MANHATTAN SCENARIO.

Group	Movement Model	Nr. Of Nodes	Speed [m/s]	Buffer [MB]
1: Pedestrians (p)	WDM	30, 55, 80, 105, 130, 155, 180	[0.5, 1.5]	5
2: Buses (b)	RMBM	10	[7.0, 10.0]	5
3: Cars (c)	SPMBM	10	[2.7, 13.9]	5

TABLE II. NODES' SIMULATION SETTINGS FOR THE MANHATTAN SCENARIO.

Parameter	**Values**
Simulation map	Manhattan downtown map (10 x 8 km)
Hosts groups	3
Number of Nodes	50, 75, 100, 125, 150, 175, 200
Message size	200 KB
Message generation interval	60 s
Transmission range / speed	30 meters / 4.5 MBps
Message copy limit	6
TTL	1433 min (approx 1 day)
Simulation time	700ks (approx 8 days)

A. *Protocol Variants Comparison*

Fig. 1-4 show four separate graphs that will be used to analyze the routing performance based on both Spray (social and geographical) and Search (social and geographical) strategies. This allows for a detailed comparison of how each combination impacts the most critical metric: message delivery success.

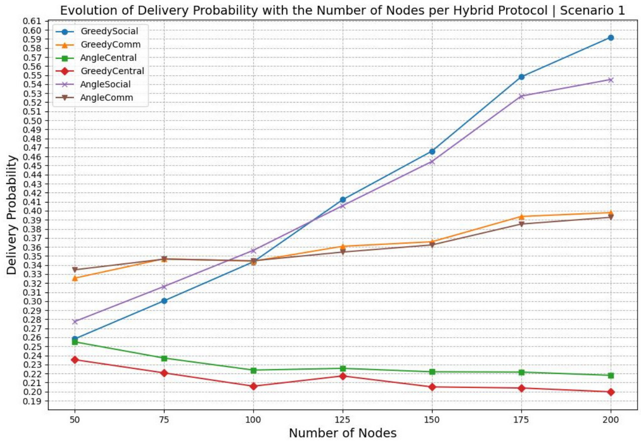

Fig. 1. Delivery probability analysis of Geographic Spray-based Hybrid protocols

No protocol demonstrated clear evidence of outperforming the others across all scenarios. However, there is a clear indication that the hybrid protocols' performance improves as the number of nodes increases, as a sparse network results in few contact opportunities.

Focusing on protocols that utilize a geographic spray-based approach (such as GreedySocial, GreedyComm, AngleSocial, and AngleComm), we can conclude that the most determining factor in their performance is the search strategy. Protocols with the same search strategy exhibit similar behavior, as seen with GreedySocial closely matching AngleSocial, and GreedyComm behaving similarly to AngleComm.

Protocols that incorporate the social (dLife-based) variant search outperform those using the community variant search in terms of delivery probability. In sparser scenarios, where the simulation map is large and nodes are sparsely dispersed, the community variant initially has an advantage because nodes are not closely connected through social ties. This simpler search method works well in less dense environments, where central nodes constantly change.

However, as the number of nodes increases, the social variant begins to show a significant advantage. With more nodes, there are more connections and stronger social ties, which enhance the performance of the social variant. Starting from around 100 nodes, the social variant exhibits a rapid increase in delivery probability, while the community variant remains relatively stagnant, showing little improvement.

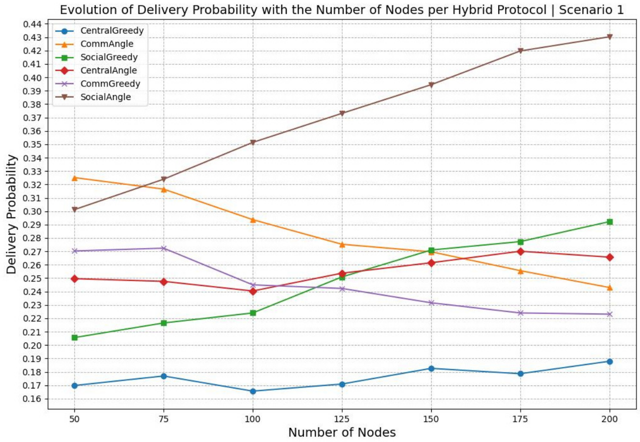

Fig. 2. Delivery probability analysis of Social Spray-based Hybrid protocols

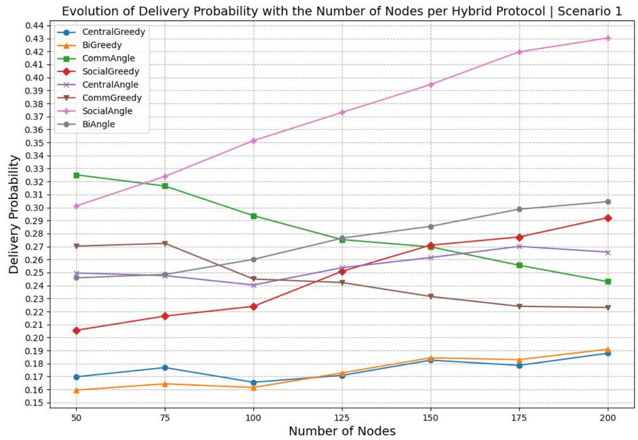

Fig. 3. Delivery probability analysis of Geographic Search-based Hybrid protocols

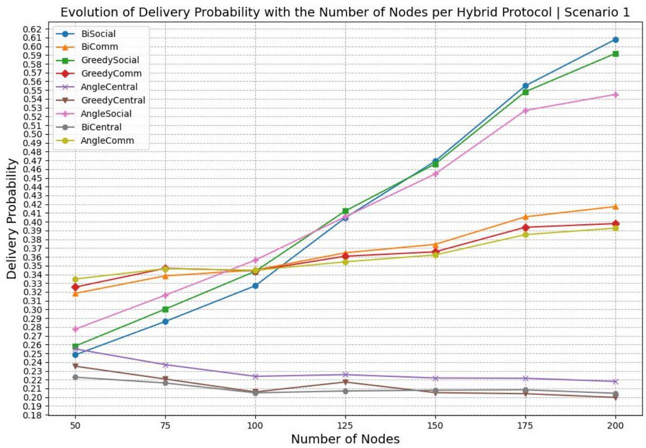

Fig. 4. Delivery probability analysis of Social Search-based Hybrid protocols

GreedySocial had the best (higher) delivery probability for higher node density situations, although for lower density scenarios its spray mechanism is not aggressive enough. AngleComm had the best (lower) hop count and overhead, so these two protocols were considered for comparison against state-of-the-art protocols.

Figure 5 show the delivery probability of the main state-of-the-art protocols referred to in section 2 as compared with GreedySocial and AngleComm. GreedySocial has the best delivery probability for denser network cases, while Spray-and-Wait is the best for sparser scenarios. This means that for sparser scenarios, being aggressive in the spray phase, as Spray-and-Wait is, compensates. The other protocols lag behind, with Epidemic being the worst, due to the congestion caused by its unlimited message replication algorithm

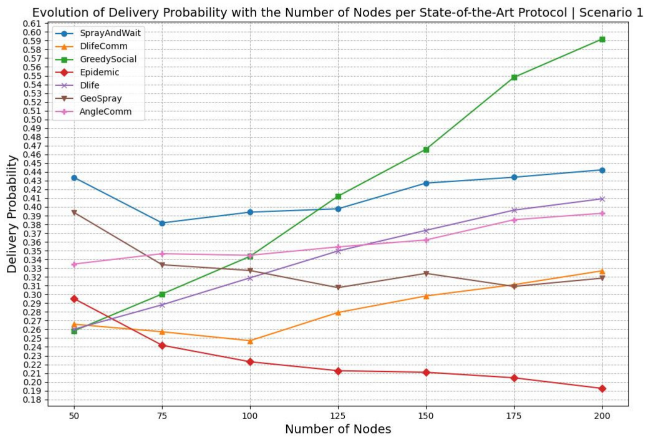

Fig. 5. Delivery probability analysis against State-of-the-Art protocols

V. Conclusions

As the number of nodes increases, the overall performance — particularly in terms of delivery probability — also improves. This finding suggests that larger, denser networks naturally benefit from more effective message dissemination.

The search strategy used plays a very important role in the routing protocol performance. Geographic-based search tends to increase the hop count and overhead, as messages circulate around the network searching for their destination. Social based search strategies have less overhead and hop count, as they learn and use the structured social interactions. The social (dLife-based) search strategy was the one that achieved the best performance, with the best delivery rate.

GreedySocial, a combination of Greedy spraying of messages followed by Social (dLife-based) search of the destination had the best (higher) delivery probability for higher node density situations, although for lower density scenarios its spray mechanism is not aggressive enough so Spray and Wait results better as its spray phase is more aggressive. However, the additional complexity inherent in GreedySocial protocol brings additional challenges in latency.

For future work, the focus should be on making the hybrid protocol more adaptive and intelligent, particularly to address its challenges in sparser or less dense networks. This adaptability could be achieved by continuously monitoring the encounter rate and re-calibrating the spray strategy throughout the network's operation, e. g., by having a more aggressive spray in sparse networks. Combining geographic and social information in the search phase algorithm could also be beneficial and should also be explored in the future.

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