Reactive Overlays for Adaptive Routing in Mobile Ad hoc Networks

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ABSTRACT

Several emerging applications for the Internet of Things, vehicular networks, or decentralized communication using smartphones rely on Mobile Ad hoc Networks (MANETs). These networks are temporary deployments of *nodes* equipped with infrastructure-less wireless communication. MANETs operate in highly dynamic conditions where nodes move at will, interferences are a constant and density is heterogeneous. Routing is a fundamental operations in MANETs. Our evaluation of existing routing protocol for MANETs shows that, while proactive routing protocols are suitable for highly dynamic networks, reactive routing protocols perform best in dense and more static scenarios. No protocol alone can systematically perform well when density is heterogeneous. We propose RoVy, a self-aware adaptive approach for routing in heterogeneous MANETs. Based on independent estimations of density and mobility, RoVy allows nodes to automatically switch between AODV, a reactive routing protocol and DSDV, a proactive protocol. Interoperability protocols support the integration of AODV and DSDV in a single heterogeneous MANET. RoVy maintains a dissemination overlay to speed-up route discovery and improves the emergence of alternative routes to destination nodes. Our simulations of the full network stack with 1,000 nodes shows that RoVy outperforms singular routing protocols in terms of performance, costs and reliability.

KEYWORDS

MANET; Routing protocols; Self-organization

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1 INTRODUCTION

We observe the emergence of new decentralized communication networks, e.g. using smartphones and proximity networking, built up in a bottom-up fashion and powered by Mobile Ad hoc Networks (MANETs) protocols. For instance, in September 2019, the city of Hong Kong experienced several protest where thousands of citizens took the streets. To avoid using traditional systems of communication such as SMS or email, which would surely be monitored by the state and mobile infrastructure operators, citizens relied on ad hoc communication to exchange with each other using a smartphone application that requires no Internet access [11]. In different contexts, implementations of ad hoc routing protocols for low-power IoT devices in the network layer of ZigBee, the IEEE 802.15 wireless technology, have been used for applications in smart cities, drones networks and sensors-based monitoring systems in the private sector.

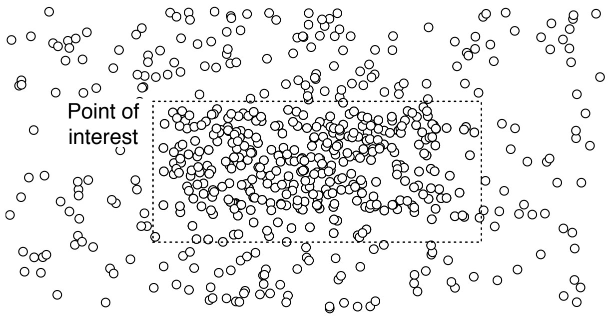

Figure 1: Snapshot of an heterogeneous MANET where nodes mimic humans movements to represent a protest.

MANETs are temporarily deployments of battery-powered wireless devices with short range of communication—e.g., up to 10m with technologies such as Bluetooth, as used during the protests in Hong Kong. Figure 1 depicts an example scenario of a protest where each node is a moving human holding one smartphone. In this context nodes do not follow random movements. In fact, models of mobility for humans [21] characterize two aspects of such a dynamic network: *density* and *mobility*. Certain nodes might form dense clusters indicating a point of interest, where mobility varies between low to moderate. Other nodes may leave the network or navigate between points of interest, leading to regions with sparse density and high mobility.

In addition to network dynamics, communication between nodes in a MANET is subject to faults and uncertainty. Nodes follow a multi-hop routing approach due to the short transmission range of wireless devices. The on-demand routing process in a MANET is typically composed of two phases. The source starts with the dissemination of a route request. This network packet will be disseminated in the entire network requiring every node other than the destination to relay the packet. When the destination "hears" about the request, it replies back to the source with an acknowledgment. This reply aggregates a list of nodes that have relayed the request in the first phase; the source is then aware of the route between the pair of nodes. At this point source nodes start sending messages

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to their destinations, but the dynamics in the network might affect connectivity between nodes, creating *stale routes.* Routing is a fundamental operation to discover and maintain reliable paths between nodes. This operation can be a challenge in a heterogeneous MANETs.

In the past three decades several routing protocols for MANETs were proposed [3, 5]. These protocols can generally be classified in two groups: *proactive* protocols and *reactive* protocols. Proactive protocols use preemptive approaches that estimate the network topology in advance of routing requests, with the maintenance of routing tables. Reactive protocols, on the other hand, discover routes on demand. The literature overwhelmingly considers that a single routing protocol runs in the entire network. This might be suboptimal in heterogeneous MANETs. Discovering routes in advance in a dense region of the network might result in storing large routing tables in nodes with limited RAM and also might be unnecessarily, because nodes remain mostly static in these regions; as the point of interest depicted in Figure 1 shows. On the contrarily, using a reactive protocol in sparse regions where nodes move frequently may increase the traffic required to repair unreliable routes and increase the loss rate of messages. We believe that adaptive routing approaches are more adequate for heterogeneous MANETs. In this context, adaptation refers to the ability to dynamically select and configure the protocol used for routing. It is important to note that this adaptation and protocol selection should be possible not only for the entire system but also, and more interestingly, just for a part of it.

We propose RoVy, a decentralized adaptive approach for routing in heterogeneous MANETs. Based on independent estimations of density and mobility in the network, nodes in dense zones use AODV, a reactive protocol. In contrast, in dynamic zones of the network with sparse density, nodes use DSDV, a proactive protocol. Our approach follows a coordinated policy of adaptation to switch from AODV to DSV (or vice-versa). Interoperability protocols enable reliable routing between zones using different protocols. RoVy also maintains a dissemination overlay for two main reasons:

- **Speed-up the phase of route discovery**. Widely used implementations of AODV and DSDV uses pure flooding as a broadcast mechanism to discover routes. Evaluation studies to broadcast in heterogeneous MANETs suggest that choosing an appropriate dissemination approach is key to avoiding network overhead [4]. Overlay-based protocols for broadcast may, indeed, reduce considerably the traffic overhead in the network [17].
- **Support to fix unreliable routes on demand**. When nodes detect a broken link in a route, instead of notifying the source, an alternative reliable route might be fetch from an overlay node. With this approach, a message can continue its way to the destination and immediately after, the new reliable route can be announced back to the source node.

To the best of our knowledge there exist only very few works [2, 12] that combine routing approaches in a single MANET deployment and several research questions still remain open. Some of these questions are: **(i)** how nodes running different protocols interoperate with each other?, **(ii)** what is the overhead of control network packets per delivered messages to maintain and create routes?

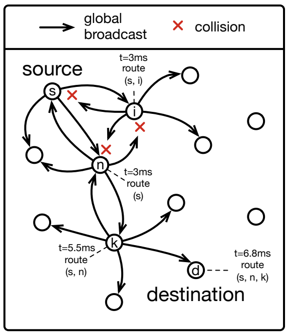

Figure (2) Route discovery in AODV. Flooding approach to disseminate route request.

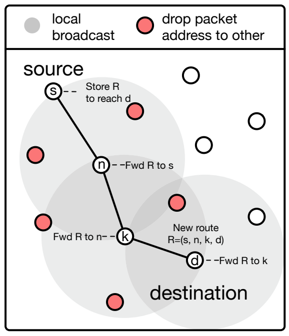

Figure (3) Route discovery in AODV. A route to the destination reaches the source node.

and **(iii)** what is the impact on route discovery and route maintenance of adaptive approaches?. We tackle these questions in the present work.

The rest of the paper continues as follows. We describe the two state-of-the-art protocols that our adaptive routing approach (RoVy) requires, provide a discussion of their importance and assess how they perform in a MANET deployment (Section 2). This early evaluation motivates the design of main building blocks in RoVy, the interoperability aspects to deploy more than one protocol in a network as well as the coordinated policy of adaptation (Section 3). After presenting the evaluation of our approach (Section 4), we finally discuss existing hybrid routing approaches (Section 5) and present our conclusions (Section 6).

2 BACKGROUND

Routing protocols rely on two fundamental operations, route discovery and route maintenance. Reactive and proactive routing protocols differ in the way they implement both operations. RoVy reduces the latency of discovering routes and speeds up the maintenance of reliable routes of two widely used routing protocols, AODV and DSDV. This section discusses how both protocols operate and presents a benchmark of their performance in a simulated deployment mimicking a flock of mobile humans holding wireless devices.

2.1 Ad hoc On Demand distance Vector (AODV)

Perkins and Royer proposed AODV, a reactive routing protocol [16]. In AODV, a source node looks for a route to reach a destination following the steps shown in Figures 2 and 3. The source sends a route request packet (RREQ). This packet of control spreads in the entire network using a simple flooding technique—i.e., every node relays RREQ packets at most once. Nodes other than the destination receiving a RREQ extend the content of this packet with their identifier. When the destination finally receives the RREQ request, it replies to the source with a route reply packet (RREP). These replies are acknowledgments of route requests that will reach the source by letting every node in the new discovered route act as *router* for future *messages* (or content packets). The route discovery phase in AODV concludes when the source node stores the route contained in the route-reply acknowledgment. At this point, a source node can start sending messages to its destination, but the operating

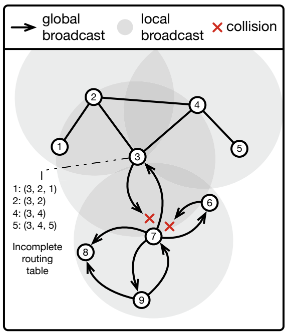

Figure (4) Discovery phase in DSDV. Nodes periodically broadcast beacons to their neighbors and disseminate data about the network topology.

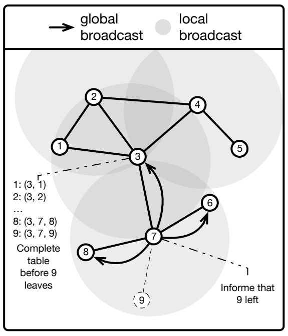

Figure (5) Route maintenance in DSDV. This process result in having an overlay where every node maintains via a global routing table.

conditions in the network might result in destination nodes stop receiving messages. Nodes in AODV maintain reliable routes by monitoring network packets at the level of the MAC layer. An unreliable connection between two nodes in a route will result in a node relying a message not hearing the corresponding acknowledgment of correct reception from its adjacent neighbor. This triggers an announcement back to the source to inform about the unreliable route. The source replaces the route with an alternative one or starts with a new phase of route discovery.

2.2 Destination Sequenced Distance Vector (DSDV)

Inspired by the Bellman-Ford algorithm, a widely used routing protocol for wired networks, Perkins and Bhagwat proposed DSDV [15]. This proactive protocol estimates the underlying topology of the network through the periodic dissemination of control packets that contain the lists of one- or two-hop neighboring nodes as well as route update messages. As Figure 4 shows, nodes periodically disseminate control packets to the entire network using simple flooding. In other words, the phase of route discovery in DSDV approximates a global routing table for the entire network with every node maintaining a copy of it. Apart from the list of nodes to reach a certain destination, an entry in the routing table contains the distance to it (number of hops) as well as a sequence number that will be given by the destination itself. Sequence numbers serve to identify stale routes or update them if there is a new route with a shorter distance. DSDV implements an incremental mechanism in the phase of route maintenance, illustrated by Figure 5. When a node detects a change in its list of neighboring nodes (e.g., a faulty neighbor or a radical change in its position), it performs the following steps: **(i)** identify the nodes affected by the change, **(ii)** update the sequence number in the corresponding entry of the routing table and **(iii)** announce the update to affected nodes.

2.3 AODV and DSDV as milestones of routing protocols

AODV and DSDV characterize themselves for their simplicity, robustness and being positioned as two of the most representative protocols in the category of reactive and proactive solutions respectively. Several other protocols rely on the designed concepts of AODV or DSDV.

Associativity-based routing [22] (ABR) is a reactive protocol that assigns weights to links between nodes of routes as a discretization technique of reliable routes. It is up to destination nodes to chose a set of routes with the highest degree of reliability. Apart from this metric, ABR performs the phases of route discovery and route maintenance as originally proposed in AODV. Another example of a protocol that relies on DSDV, this time in the category of proactive protocols, is Optimized Link State Routing [6] (OLSR). This protocol builds an overlay of dissemination in a MANET deployment by letting every node periodically broadcast its list of one-hop neighbors. The use of an overlay in OLSR allows replacing the simple flooding approach to message dissemination, which has been proven to easily overwhelm the network with *broadcast storms* [24]. This overlay is indeed a graph with the properties of a connected dominating set where nodes are either relays or pure receivers [8]. Only relay nodes in OLSR store a copy of the global routing table, in contrast to DSDV where every node keeps a copy of it.

The design of routing protocols must address the following aspects: avoid cycles in routes, speed-up route discovery, repair unreliable routes, as well as reducing the overall network traffic to ensure these properties. The simplicity of how AODV and DSDV operates comes to the cost of being baselines in the category of reactive and proactive protocols, and interestingly, these two protocols are also upper bounds when it comes to assess their performance in MANETs deployments. Over the years these two protocols have been recognized as milestones in the computer science community[1]. Our research suggest that there is still a gap in the evaluation of these protocols in heterogeneous networks where nodes follow humans mobility patterns.

2.3.1 Overestimations in the performance of routing protocols. Some surveys and evaluation studies suggest that source-initiated reactive protocols are more adequate in highly dynamic MANETs deployments [3, 5]. This generalization is not completely accurate. Intuitively, in a network where nodes move more frequently, it will be more likely to observe unreliable routes and therefore, a reactive protocol will need to spend more time maintaining routes. This will in turn decrease the achievable throughput for regular messages. A previous improvement to AODV corroborates this intuition [20]; this work proposes to store several routes as backups during the route discovery phase.

2.3.2 Modeling real-life MANET deployments. Several routing protocols present the results of an experimental set-up that implements some layers of an standard networking model (such as the OSI model) or a mathematical analysis of the protocol complexity; this is the case for the following reactive protocols: AODV [16], ABR [22], TORA [14] and SSA [7]. An evaluation study of proactive and reactive protocols over different mobility models [13] simulates only the network and physical layers. Other studies propose to model the networking stack via complex mathematical frameworks [25]. None of these protocol evaluation actually considers the

[1]For instance, in 2018 the protocol AODV received the SIGMOBILE Test-of-Time award (see https://beta.sigmobile.org/articles/test-of-time-awards).

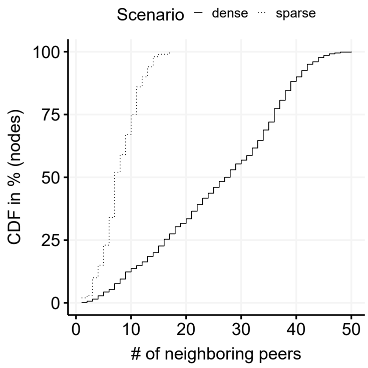

Figure 6: Heterogeneous number of neighboring peers per node in two network deployments.

full network stack, e.g. including the MAC protocol, the existence of collisions, and the resulting inaccuracies in the broadcast process. It is worth noting that the Dynamic Source Routing approach (inspired by AODV) is an exception because its testbed models the full network stack with 50 nodes [10].

2.4 Benchmarking AODV and DSDV

Our first contribution is a benchmark whose goal is to assess the performance of AODV and DSDV. We focus on: the latency to discover routes, the latency for receiving messages and the message delivery fraction[2] as a measure of throughput. While a further description of the technical details in our simulations will be shown in Section 4, this benchmark models the following aspects:

- **Full network stack simulation.** The physical layer models a single tranceiver per node where the range of transmission is set to 10m and remains invariable. The data-link layer follows the complete Distributed Coordination Function MAC protocol of the IEEE 802.11 wireless standard [1]. As Address Resolution Protocol we have either AODV or DSDV in the network layer, and in the higher layer we use a ping-like probing application that sends TCP datagrams and measures round-trip latency.
- **Humanlike MANET deployment.** Nodes are initially positioned in a random way over a 100x100 m area. When the simulation starts nodes mimic humans movements performing *truncated levy walks* [19] that is, continuous frequent short walks with occasional rides to distant locations at a pace of up to 1.5 m/s.
- **Dynamic network conditions.** A single experimental execution lasts for 6 minutes where a source node pings a destination every 1.5 s. This configuration is repeated 10 times using a different simulation seed for each iteration. To add nodes density as another element in the network, there are two deployments per iteration in our experiments. The first one with sparse density contains 200 nodes and the second one with higher density contains 1,000 nodes. Figure 6 shows the degree of nodes as a CDF, that is, the number of surrounding neighbor peers within the transmission range of every node per MANET deployment.

[2]Ratio of the numbers of received messages over the number of sent messages between source and destination.

2.4.1 *Performance of discovering routes.* Figure 7 and Figure 10 report the cost of establishing routes for AODV and DSDV, respectively. We distinguish, as for the other measurements, the routes based on the shortest path between the source and the destination (as measured offline–i.e. there is no guarantee that this shortest route will be the one selected by the algorithm). This is the time a source node waits until it receives an acknowledgement from the destination prior to start sending messages. More specifically, in AODV this is the cost of discovering a route through flooding and acknowledgments collection while in DSDV this is simply the time for an acknowledgment to reach the source node using a reliable route, given that nodes already contain a copy of the global routing table. The dissemination of route requests using simple flooding explains the high variance in AODV. The mean of the latency systematically grows with the density. It is also worth pointing out that discovered routes in AODV are not necessarily the ones with the shortest distances—number of hops—because paths on route requests are chosen in the order in which they arrive at the destination. In contrast, the latency of ARP sessions in DSDV are in average two times faster. This reflects the advantage of having topological information of the network as well as the use of a decentralized implementation of the Bellman-Ford algorithm to find the shortest routes—with few variations as consequence of mobility.

2.4.2 *Reliability of routes and throughput.* Figures 8 and 9 show that having reliable routes in AODV comes to the price of latency. In average, it takes at least ten hundred milliseconds to exchange messages between a pair of nodes but the advantage is that the highest lost of messages is 5% in the sparse deployment, while no message loss is observed in the dense one. In DSDV, as Figures 11 and 12 depict, there exist a higher lost of messages varying between 20% and 60% in the dense deployment and between 4% to 20% in the sparse one. We observe a higher number of collisions and contentions in the data-link layer due to the simple flooding technique to disseminate updates of routes. This is also the case during the exchange of control packets to update the list of neighboring peers.

Our findings suggests that AODV is resilient to node spatial density. In particular, we observe no loss of messages in networks with moderate to high density. We corroborate that a reactive approach for routing shows highest throughput besides the density in nodes. Despite of what have been suggested in previous studies [3, 5], DSDV shows poor throughput when the density also goes from moderate to high in zones where nodes remain mostly static. On the other hand, there is a substantial amelioration in the throughput for sparse networks. We believe, therefore, that the design of routing protocols in MANETs must take into consideration nodes mobility and density.

3 ADAPTIVE ROUTING WITH ROVY

Our main contribution is the design and implementation of RoVy, an adaptive approach for routing in heterogeneous MANETs. Nodes in RoVy choose a routing protocol following this rule of thumb: the use of DSDV in sparse zones of the network with high mobility or the use of AODV in dense zones where mobility is low to moderate. The rationale behind this rule is twofold. Firstly, a preemptive approach that periodically approximates the topology of highly dynamic zones in the network is adequate to maintain reliable

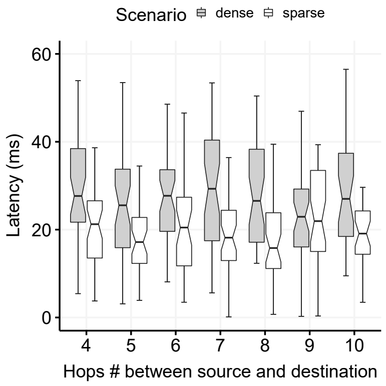

Figure (7) Route discovery latency (AODV). The high variation in latency is the result of using a pure flooding approach to find routes independently of the number of hops between nodes, and independently of density.

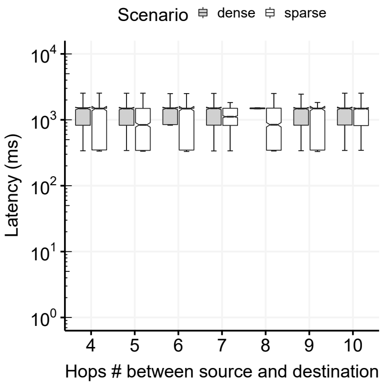

Figure (8) Messages latency (AODV). Mobility remains the main factor that delays the reception of messages (packets of data).

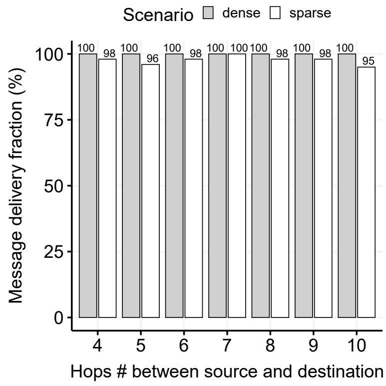

Figure (9) Throughput (AODV). Reactive approaches are fairly resilient to density variations thanks to the small number of packets required to maintain routes.

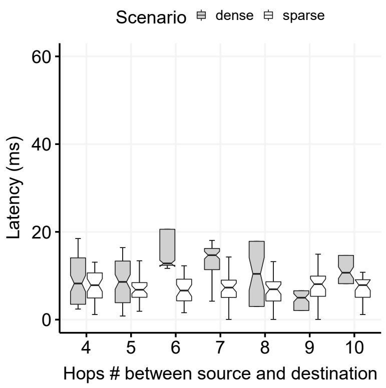

Figure (10) Route discovery latency (DSDV). Once nodes posses a global routing table, we observe that the time to monitor reliable routes remains within an interval of 20ms.

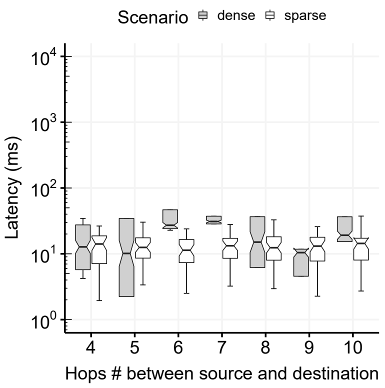

Figure (11) Messages latency (DSDV). Preemptive approaches that approximate the network topology find shortest routes to destinations and latency depends on the length in routes.

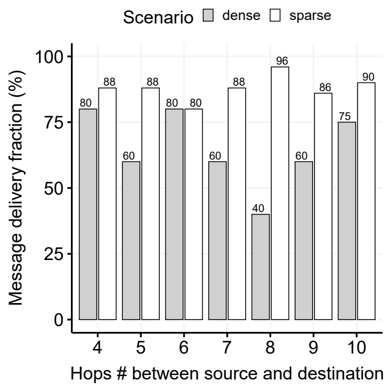

Figure (12) Throughput (DSDV). Probing provokes collisions/contentions that impact the delivery of messages. In more dynamic zones probing increases throughput.

routes. Secondly, on-demand routing reduces the traffic to maintain routes in dense zones of the network avoiding to store (possibly) large routing tables. The use of RoVy aims at reducing the latency of messages reception, leading to an increase in throughput and at the same time, avoiding network overhead; as our evaluation in the previous section has shown, there is still room for improvement in these metrics of performance by combining two representative routing protocols.

Nodes in RoVy maintain a dissemination overlay in the entire network by announcing themselves using best-effort broadcast, these probing packets bypass the MAC protocol. The overlay reacts to mobility, using passive probing in dense zones of the network and active probing in sparse ones, in order to aid the native route maintenance procedure in AODV and DSDV. RoVy requires the following building blocks: the characterization of density and mobility, the maintenance of a dissemination overlay, the bootstrap of coordinated adaptation in the entire network, and guaranteeing interoperability between native network packets of AODV and DSDV. This section details these building blocks.

3.1 Monitoring density and mobility

We use periodic probing, as used in proactive protocols, to gather an approximation of the number of neighboring peers within the transmission range of nodes. The size of this set of peers is also known as *degree*, which we use to characterize mobility and density.

The density around a node n is measured by its degree. The measurements over a time window for n form a sequence $d_1, d_2 \ldots, d_t$, where $t \leq 10$ is the time of the latest measurement. Using only one measurement (e.g. d_{10}) may lead to sudden fluctuations that do not reflect medium-term increases in density around the node. We compute instead an average over four periods of time, e.g. $\bar{d}_1, \bar{d}_2, \bar{d}_5, \bar{d}_{10}$. As measurements are not taken with a fixed frequency, we weight each measurement using its validity window (e.g., $d_{10} - d_5$). Mobility is measured indirectly as the average time unique neighbors are observed. Again, we compute mobility over four periods of time, resulting in $\bar{m}_1, \bar{m}_2, \bar{m}_5, \bar{m}_{10}$.

The interval of time t_{hello} for probing remains within the following range $[0.5, 2.5]$s. These values are lower and upper bounds

Algorithm 1 Selection of relays at node n_i with MPR

1: **input**
2: OneH : *set* ▷ one-hop neighbors
3: TwoH[ ] : *map* $(n_{j \neq i} \in \text{OneH}) \rightarrow \{n_k, \ldots\}$ ▷ two-hop neighbors
4: **procedure** chooseRelays()
5: uncovered = $\bigcup_{n_j \in \text{OneH}} \text{TwoH}[n_j]$ ▷ all two-hop neighbors
6: relays $\leftarrow \emptyset$
// Phase 1: select 1-hop neighbors connecting isolated 2-hop neighbors
7: **for every** n_j **in** OneH **do**
8: **if** $\exists\ n_{\text{iso}} \in \text{TwoH}[n_j]$ s.t. $\forall n_{k \neq j}$, $n_{\text{iso}} \notin \text{TwoH}[n_k]$ **then**
9: relays $\leftarrow$ relays $\cup \{n_j\}$
10: uncovered $\leftarrow$ uncovered - TwoH$[n_j]$
// Phase 2: select high-degree 1-hop neighbors until coverage
11: **while** uncovered $\neq \emptyset$ **do**
12: select $n_j \in$ OneH maximizing $|\text{TwoH}[n_j] \cap \text{uncovered}|$
13: relays $\leftarrow$ relays $\cup \{n_j\}$
14: uncovered $\leftarrow$ uncovered - TwoH$[n_j]$
15: **return** relays

Algorithm 2 Coordinated adaptation on node n_i

1: **constants**
2: d_{switch} ▷ density threshold
3: **variables**
4: t_{hello}: time ▷ period of probing to maintain overlay
5: $\bar{d}$ ▷ observable (density) maintained using probing
6: $P \in \{$ AODV, DSDV $\}$ ▷ currently running protocol
7: t_{AODV} ▷ when running AODV, dissolution timer
8: **procedure** switch(): **return** $(\bar{d} \leq d_{\text{switch}})$ ▷ low to moderate density
9: **upon** creation or reception of a switch request s for the first time
10: **if** switch() **or** s.switch **then** ▷ react to proposal
11: s.switch $\leftarrow$ `true` ▷ disseminate proposal
12: useDSDV()
13: **else**
14: s.switch $\leftarrow$ `false` ▷ do not disseminate proposal further
15: **procedure** useDSDV()
16: **if** P = AODV **then**
17: DSDV.init() ▷ initialize t_{hello} to 0.5s (default value)
18: wait($3 \times t_{\text{hello}}$), then $P \leftarrow$ DSDV ▷ stabilize then switch
19: $t_{\text{DSDV}} \leftarrow$ currentTime() $+10 \times t_{\text{hello}}$ ▷ set dissolution timer
20: **when timer t_{DSDV} expires or if no DSDV probing received in**
21: DSDV.terminate()
22: $P \leftarrow$ AODV ▷ return using AODV

of time for Levy walks of 1m—to remain within the boundaries of the mobility model [19]. In order to have an adaptive probing that reduces the likelihood of collisions in heterogeneous MANETs, t_{hello} is a function of density as well as mobility. That is, t_{hello} tends to 2.5s when $\bar{d} \geq d_{\text{threshold}}$ and $\bar{m} \leq m_{\text{threshold}}$. Inversely, t_{hello} tends to 0.5s when $\bar{d} < d_{\text{threshold}}$ and $\bar{m} > m_{\text{threshold}}$. Where $d_{\text{threshold}}$ and $m_{\text{threshold}}$ are fixed thresholds for density and mobility, respectively; we find adequate values for these thresholds through experimentation (see Section 4).

3.2 Reactive Overlay with MPR

In their work [23], Tomar G. S. *et al.* evaluate different dissemination strategies for AODV. In our benchmark we observed loss of messages in DSDV even in the deployment with low density; in several occasions, the reason of this loss was the slow propagation of changes in routes. These findings let us decide to maintain a dissemination overlay in order to replace pure flooding but also to reduce the route discovery latency in AODV as well as to speed-up the maintenance of a global routing table in DSDV.

We chose the Multipoint relaying technique (MPR) to maintain an overlay, for being a decentralized approach that requires a local approximation of nodes degree [17]. The goal is to form a *connected dominating set*: the combined coverage areas of all relays must contain all nodes in the network. An overlay should be connected but at the same time contain as few relays as possible. The selection of relays is shown in Algorithm 1. The goal is to ensure that all two-hop neighbors are *covered* by at least one relay. The selection is in two phases. The first phase (lines 7–10) selects relays that are *necessary*, i.e. one-hop neighbors that with a single two-hop neighboring peer. The second phase (lines 11–14) selects relays that are *sufficient* to complete the coverage. The heuristic is to add as relay the one-hop neighbors that cover the largest number of two-hop neighbors until all nodes are covered. As the set of uncovered nodes is the union of all two-hop neighbors (line 5), the `while` loop on lines 11–14 always terminate.

MPR is a decentralized heuristic that may not obtain the optimal selection of relays. Maintaining an overlay with this technique ensures that any node is either a relay or that at least one of its neighboring peers is a relay. We leverage this property for three purposes: (i) to aid AODV and DSDV to disseminate network packets in the entire network, (ii) to speed-up the maintenance of routes and (iii) to leverage interoperability between packets of both protocols (as we develop in Section 3.4). Nodes running AODV disseminate route request using their adjacent relays to discover routes and announce unreliable routes; that is, nodes in routes are no longer responsible to forward acknowledgment addressed to sources or destinations. As we corroborate in our evaluation (Section 4) this is useful when a route is several hops long. Similarly, DSDV nodes spread updates to routes or changes in the network topology using its adjacent relay.

3.3 Coordinated adaptation

RoVy requires a phase of bootstrap to let nodes have a first approximation of density and mobility, during this phase nodes use AODV as routing protocol. After three intervals of probing have passed, an overlay will be built using MPR. In two more intervals of probing ($5 \times t_{\text{hello}}$ seconds) nodes will have the first computation of weighted average for density within a validity window of at least ten seconds (see 3.1); by default t_{hello} is set to 2.5s. There is now enough information to start the adaptation process, i.e., to make nodes in sparse-dynamic regions switch to the use of DSDV and those in dense-static regions keep using AODV.

RoVy uses a simple probabilistic approach to chose certain nodes for initiating the procedure of adaptation. That is, a non-uniform random-binary function weighted at 10% of chance to be chosen as node to start the adaptation procedure. These nodes disseminate a *switch-request* network packet and every other node in the network follows the coordinated adaptation shown in Algorithm 2. Nodes receiving a switch request (line 10) assess whether their threshold of density is below d_{switch}. If this is the case, nodes *propose* others to switch or keep using AODV (line 11) and a warming phase starts to the eventual use of DSDV (lines 18). This phase serves to propagate a switch request among nodes with equally sparsely density as well as to coordinate the use of DSDV among them. To cope with sudden changes towards densely clusters in the network, notice that the mobility of DSDV nodes varies from moderate to high, when a node has not heard a DSDV packet of control for a while (lines 20-22) it switch to the use of AODV. Finally, nodes with density higher than d_{switch} stop the propagation of the switch request (line 14) and keep using AODV.

d_{switch} is an upper bound that characterize nodes with low density. Indeed, this threshold depends on the operating conditions in the network and we explore several values for this threshold through experimentation (see Section 4). Our evaluation also confirms that the weighted average to approximate density (see Section 3.1) is sufficient to deal with nodes moving between sparse and dense zones in the network because we observed a minimum impact in the overall throughput and latency of routing messages.

3.4 Interoperability

RoVy enables a MANET where nodes might use AODV or DSDV. The design of these protocols were thought to operate in network deployments where nodes use a single protocol, meaning that network routing packets from foreign protocols will be dropped. In our context, this result in limiting routing only within zones of the network using the same protocol. We need to ensure that messages will be delivered to destinations independently of the protocol nodes use for routing in the different regions.

Interoperable nodes are relays from the overlay maintained by RoVy running DSDV that are located at the edge of dense zones. They are responsible for converting AODV network packets into DSDV ones (and *vice versa*) in order to guarantee continuity to deliver messages in the entire network. The connectivity properties of an overlay built with the MPR technique ensure that there exist interoperable nodes between the frontier of a dense zone and an sparse one with at least one other adjacent overlay relay using AODV. The interoperable node extends its DSDV routing table with the AODV relay, in fact this is a gateway to reach any other peer in sparse areas.[3] For the matter of clarity, in the rest of the text we use the term *gateway* as a relay running AODV–positioned at the edge of a sparse zone—and an *interoperable node* as a relay running DSDV—positioned at the end of a dense zone, respectively. With the aim of avoiding any disruption in the way both routing protocols discover routes, our mechanism of interoperability copes with the following two cases:

(1) **AODV node as source and DSDV as destination.** Keeping in mind that the dissemination overlay serves to flood route requests, an interoperable node will eventually hear from such AODV request and will consults in its DSDV routing table whether there exist a route to the destination. In case such a route does not exist, the interoperable node drops the route request. Otherwise, the interoperable node concatenates the existing route with the path the request has followed and forwards the discovered route back to its gateway; note that there is no alteration in the format of an AODV route request.

(2) **DSDV node as source and AODV as destination.** This case takes place when there is no entry in the local DSDV routing table to reach the destination. Given that there might be more than one gateway in a routing table, the source node chooses one at random and delegates the creation of a new AODV route request to this selected gateway. This node will discover a route, store it as an on-demand route, and forward any message to its adjacent interoperable node, which will forward messages to the DSDV source.

Our current technique only guarantees interoperability for the phase of route discovery. To maintain routes, once a node detects an unreliable route the resulted notifications will be delivered to the corresponding source via the dissemination overlay.

4 EVALUATION

We assess the performance of RoVy using full-stack simulations in Omnet++ (v5.6.1) with its plug-in INET (v4.2.0) to model wireless communication. RoVy is a program for the network layer that relies on the native implementations of AODV and DSDV.[4] This section complements the experimental setup and evaluation discussed in Section 2.4.

4.1 Use case and experimental model

We approximate the conditions of a large gathering to model a real-life scenario. Our MANET deployment contains 1,000 nodes. Originally, every node is located at a random position in a 100 m x 100 m area. At the center of this area there is a 50 m x 50 m zone that represents a Point of Interest (POI), as depicted in Figure 1 (Section 1). Nodes mimic humans movements by performing truncated levy walks [19]. When located at the PoI nodes move at a slow pace (velocity interval [0, 1.5) m/s) and out of this zone nodes move faster (velocity interval [1.5, 3.0] m/s). These values are representative of mobility in large gatherings. In order to have high density within the PoI, the walks of nodes are biased to remain in that area. Specifically, the direction of walks within the PoI follows the Reference Point Group Mobility (RPGM) model [9]. This model not only gives us a deterministic approach to create a dense region but it also serves as a guideline during the evaluation of routing approaches because the performance of AODV and DSDV have been assessed using RPGM.

Similarly to our benchmark in Section 2.4, the transmission range of every node remains invariable and is set to 10 m. The MAC protocol follows the IEEE 802.11 wireless standard, in the network layer we have either AODV or DSDV, and we use a ping application that sends UDP datagrams of 140 Bytes (i.e. the size of a social media message such as a "tweet") allowing segmentation of packets. A single simulation lasts for 6 minutes where a source node pings a destination every 2 s. We repeat each simulation 10 times, using different simulation seeds.

Given that our simulations rely on artificial traces of mobility, we known in advance the initial length of any route between two nodes as well as their initial position—whether these nodes are at the PoI or out of this zone. This information is of great importance to assess the interoperability mechanism in RoVy. Therefore, in every

[3] Similar to the way routers in wired networks operate: packets of the network layer are forward to gateways when the IP address of a destination belongs to another network.

[4] Both implementations have been made available by the INET community (see https://inet.omnetpp.org/docs/users-guide/ch-adhoc-routing)

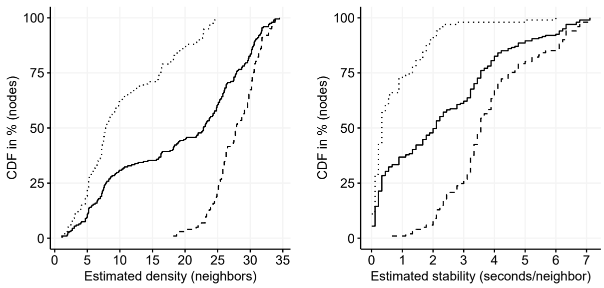

Figure 13: Distributions of density $\bar{d}_{10}$ (left) and mobility $\bar{m}_{10}$ (right) in the 3 regions: for all of the communication area (solid line), at the POI (dashed line) and out of the POI (dotted line).

simulation five source nodes ping their corresponding destinations, the number of initial hops between each route varies between 4 to 10 and routes between every pair of nodes contains at least one node at the PoI and other node out of this zone.

4.1.1 Quality of observables. We evaluate the quality of observables collected at the level of the MAC protocol, as defined in Section 3.1. Figure 13 presents the distribution of observed density ($\bar{d}_{10}$) and observed mobility ($\bar{m}_{10}$) over an observation period of 10 seconds.[5] We present the distribution for both the entire system and regions at and outside the POI.

We confirm that the distribution of density outside the POI differ, with the former ranging from as low as 1 and up to 25 neighbors, while the latter ranges from 18 to 34 neighbors. We only observed a slight deviation to lower density estimates for nodes at the POI, that we explain as a result of collisions leading to missed packets of probing. Average mobility ranges from 0 to 6 and 1 to 7 neighbors changes per second outside and at the POI respectively.

4.2 Performance of RoVy

After several tests and based on the estimations of density and mobility, we set the thresholds RoVy requires reporting those values that result in the lowest average latency to deliver messages (see Section 4.2.2). That is, sparse regions contain no more than 15 nodes where mobility is below 1.5m/s—setting the threshold of adaptation as $d_{\text{switch}} = 15$. Our tests also suggest that having seen at most 4 nodes per second let us chose an interval of probing between 1.5 s and 3.5 s in zones with high mobility. Meaning that having a probing between 3.5 s and 5 s it is enough to maintain the overlay of dissemination in dense zones.

4.2.1 Route discovery. Figure 14 depicts the latency to discover routes over several lengths, the average latency with our approach remains between 20s and 23s with a tendency of observing a higher variance when the minimal distance between nodes increases. We also observe an important improvement in the 95% confidence interval (represented by the notch in every box plot) in comparison with the high variance in the individual evaluation of AODV and DSDV (Section 2, Figures 7 and 10). This also confirms that replacing a pure flooding approach to broadcast will have substantial benefits to maintain routes.

4.2.2 Latency and throughput of delivered messages. Figure 15 depicts the latency for delivering messages and shows that our approach inherits the advantage of knowing the connectivity in the network to find alternative reliable routes (from DSDV) in order to compensate repairing routes on demand (from AODV). Reporting an average latency of almost 110 ms outperforms some state-of-the-art approaches [2, 12]. The overall achievable throughput of messages shown in Figure 16 suggests that our mechanism of interoperability enable reliable routes independently on the routing algorithm that each node runs.

5 RELATED WORK

Park and Corson propose TORA (Temporally Ordered Routing Algorithm) one of the earliest works that pointed out the need of adaptation in routing for ad-hoc networks [14]. This protocol disseminates route requests (similarly to AODV) keeping copies of discovered routes in nodes that forward route-replies packets. Faulty nodes trigger a repair mechanism that adapts the weight of reliability in links of routes, that is, a record of time stamps about faulty links. Routes will be repaired according to this metric avoiding an immediate notification all the way back to the source node. This protocol requires an external service, like a GPS, to keep track of synchronized time stamps in the entire network. In this context, adaptation means to update the metric of route reliability and disseminate this value to certain nodes.

Radhakrishnan et al. propose an adaptive routing approach that maintains an overlay in the entire network as a Distributed Spanning Tree (DST), nodes positioned in zones with sparse density follow a store-and-forward approach and those nodes in regions with high density relay on the overlay for routing [18]. Another contribution in DST is an heuristic to reduce the number of relays nodes on this overlay. The evaluation of DST relies on a simulation with 100 nodes, the results of this experiment are shown as a categorization of when to use a controlled flooding approach or a spanning tree based on the degree of nodes; no distribution of latency of messages nor throughput is reported. While RoVy uses on-demand routing (with AODV) in dense zones, DST relies on an overlay without providing a discussion about the impact on active probing.

Bamis et al. propose a framework for MANETs that combines three routing protocols based on the mobility of nodes [2]. This approach recommends the use of DSDV in networks with low mobility and when the velocity of nodes augment from low to moderate nodes use AODV. In highly dynamic networks the recommendation is to use a cluster approach where a group of nodes will be chosen to change frequently their position, with the aim of augmenting the connectivity in the whole network. Another contribution in this work is the use of a metric to characterize mobility as a function of the density of nodes; in comparison with RoVy, this characterization is also a moving weighted average that copes with sudden fluctuations in nodes degree. Several simulations were conducted to evaluate this approach modeling up to layer three of the network stack. The MANET deployment consist of 20 nodes deployed in a

[5]We do not present distributions for other aggregation periods due to space limitations. Our experiments confirm that short periods (e.g. 1 second) yield similar distributions, but measurements for individual nodes are subject to higher noise. Longer periods (e.g. 10 seconds) do not bring significant benefits.

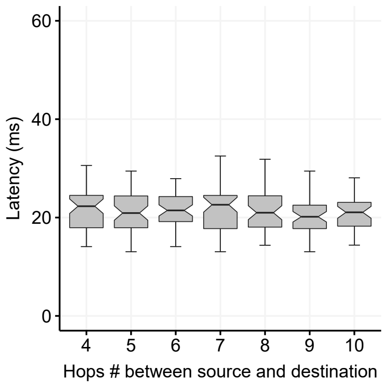

Figure (14) Latency to discover routes with RoVy.

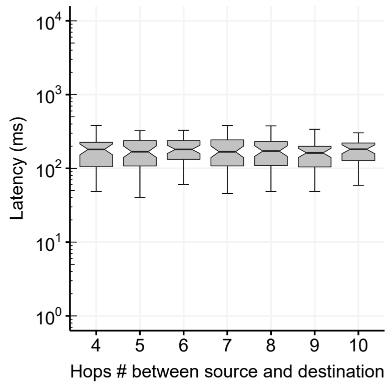

Figure (15) Latency of messages with RoVy.

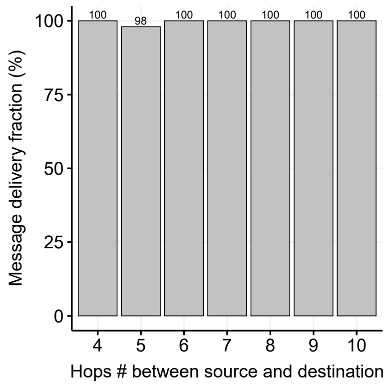

Figure (16) Throughput with RoVy.

1000mx1000m area, every node posses a fixed transmission range of 250m and they follow the random waypoint mobility model.

Lakkakorpi et al. also propose an adaptive approach that combines AODV and TCP-DTN for routing in opportunistic networks based on the density of nodes [12]. Similarly to DST [18], this approach relies on a store-and-forward approach to cope with highly mobile networks. Several simulations were conducted modeling the complete network stack, on the contrarily there is no discussion about how networks packets of the Bundle protocol interoperate with AODV packets to maintain reliable routes.

In comparison with RoVy, any of the previous works propose a mechanism of interoperability nor a coordinated (and decentralized) adaptation policy to trigger the creation or dissolution of clusters running state-of-the-art routing approaches.

6 CONCLUSIONS

The main contribution in this research work is an adaptive approach for routing in heterogeneous MANETs that enables the use of AODV in dense zones of the network with low mobility and the use of DSDV in sparse zones with high mobility. Based on the operating conditions in the network, our decentralized approach let nodes switch from AODV to DSDV and vice-versa. Interoperability algorithms maintain reliable routes in the entire network. Our evaluation shows that our approach offer good delivery guarantees in comparison with individual deployment of two state-of-the-art routing protocols.

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