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Research Article

A Software Defined Networking-based Routing Algorithm for Flying Ad Hoc Networks

Berat Erdemkılıç[1], Mehmet Akif Yazici[2]
[1]Istanbul Technical University, Electronics and Communication Engineering Department; berdemkilic@itu.edu.tr;
[2] Corresponding Author; Istanbul Technical University, Informatics Institute, Information and Communications Research Group, Istanbul, Türkiye; yazicima@itu.edu.tr; Tel: +90 212 285 71 94

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Abstract

Flying Ad-Hoc Networks (FANET) are wireless mobile ad-hoc networks composed of unmanned aerial vehicles (UAV) as communicating nodes. As with any computer network, routing is an essential problem that has to be solved efficiently for high performance. FANETs present unique challenges with respect to routing, due to their structures. FANET systems have high dynamicity as the nodes move at very high speeds and UAVs can behave in accordance with various mobility models. The nodes usually have line of sight between them, but FANET systems frequently operate on large topologies with low node density. Hence, the structure of the topology changes rapidly, and the frequency of link disconnections between UAVs increases. Traditional topology-based and position-based routing algorithms do not work well in the face of this problem. In this study, we propose a novel SDN-based Routing Protocol which comprises both proactive and reactive components in order to improve the performance. Software Defined Networking technology is used as the network management architecture. To investigate the performance of the proposed protocol against legacy MANET routing protocols, a comparison study was conducted in terms of throughput, end-to-end delay, and control packet overhead. Simulation results show that the proposed SDN-based Routing Protocol performs better than the selected legacy protocols.

Keywords: unmanned aerial vehicle, flying ad-hoc network, software defined networking, openflow protocol, routing algorithm

1. Introduction

Ad hoc networks are networks without dedicated infrastructure, often formed temporarily for certain purposes. Such networks are usually wireless, and the hosts may be mobile, in which case the network is named a mobile ad hoc network (MANET). MANETs consisting of vehicles are called vehicular ad hoc networks (VANET), which are studied as a special case due to their certain properties and use cases. Similarly, flying ad hoc networks (FANET) are special types of VANET/MANETs that are made up of unmanned aerial vehicles (UAV). FANETs are used mainly in search and rescue operations, traffic and surveillance applications, military and law enforcement, and natural disaster scenarios. A typical FANET consists of UAVs moving with very high speeds (compared to earth-bound vehicles), in a variety of mobility patterns leading to highly dynamic network topologies, which is usually detrimental to routing performance. On the other hand, FANET nodes usually communicate via line-of-sight transmissions as they do not see many obstacles in the air matching their speeds [1].

The major difficulty regarding routing in MANETs is the dynamicity of the network topology. Routes become obsolete much more frequently in MANETs compared to wireline or infrastructure networks. Therefore, there exist specialized routing algorithms for MANETs [2]. In FANETs, this is an even more profound problem as nodes move much faster and use larger areas, which lead to highly dynamic but sparse networks, making routing more difficult. Depending on the use case [3], UAV nodes in a FANET might move in predetermined paths, that can be modeled using the semi-random circular movement model [4] or the paparazzi model [5]; or they might move randomly, which are usually represented by stochastic mobility models such as the random waypoint model [6].

In general, routing protocols for MANETs can be topology-based or position-based. Topology-based routing protocols can be:

(i) static, where all routes to destinations are predefined and do not change,

(ii) proactive, where routes to all possible destinations are discovered before any need for transmission and refreshed periodically,

(iii) reactive, where routes are only discovered for a destination when a transmission is to be made to that particular destination, and

(iv) hierarchical, where nodes use a proactive protocol for a subset (usually a neighbourhood) of the topology and use a reactive protocol for the rest.

On the other hand, position-based routing protocols generally rely on position services such as the global positioning service (GPS).

In this study, we propose a novel routing algorithm for FANETs. The proposed algorithm is based on the software defined networking (SDN) paradigm and exploits central SDN controller(s). We provide simulation-based comparisons with existing and widely known algorithms from the literature to demonstrate the performance of the proposed algorithm. In the sequel, we give an overview of existing routing algorithms for MANETs and FANETs in the second section. We describe the proposed algorithm in the third section, whereas we present simulation results for the performance evaluation in the fourth section. Finally, we conclude in the fifth section.

2. An Overview of Routing Algorithms for MANETs and FANETs

Routing is one of the essential problems in MANETs, VANETs, and FANETs. As FANETs are special cases of MANETs, many FANET routing protocols are based on MANET routing protocols. A comprehensive survey of routing protocols for UAV networks is given in [7]. Static/deterministic protocols are useful if the flight path and the formation of the FANET is known beforehand and no change is expected. However, overwhelmingly, FANETs require dynamic routing protocols in most use cases. FANET routing protocols can be roughly classified into topology-based and position-based protocols, although there are stochastic routing protocols based on estimation [8] and node movement [9], and cluster-based approaches such as mobile infrastructure based VANET routing [10], modularity-based dynamic clustering [11], and the hybrid self-organized clustering scheme [12]. Based on the use cases, there are routing protocols supporting multicast [13] [14], which we do not consider in this study.

Among the topology-based routing protocols, proactive algorithms such as the destination-sequenced distance-vector routing (DSDV) [15], the optimized link state routing protocol (OLSR) [16], the better approach to mobile ad hoc networking (BATMAN) protocol [17]; reactive algorithms such as the ad-hoc on-demand distance vector routing (AODV) [18] and dynamic source routing (DSR) [19]; and hierarchical protocols such as the zone routing protocol (ZRP) [20] and the temporally-ordered routing algorithm (TORA) [21] can be mentioned. Proactive routing protocols keep the topology information and the routing tables at the nodes fresh by updating them periodically, whereas the reactive routing protocols discover routes when necessary. Hierarchical protocols define clusters or neighbourhoods inside which the protocol act proactive, maintaining routes, whereas to the outside of the cluster, the protocol behaves as a reactive protocol. The advantage of the proactive routing protocols is low latency but they suffer from high overhead and reduced throughput. On the other hand, reactive routing protocols avoid high control overheads at the cost of considerably larger latencies. Hierarchical protocols are a hybrid of both approaches, trying to combine the best aspects of both worlds. The effectiveness of such hybrid protocols highly depend on their definition of the clusters. These algorithms are better suited for systems such as sensor networks where communication between nodes in close proximity to each other is much more frequent than the communication between nodes that are further apart.

Position-based routing algorithms use geographical location information obtained through positioning methods such as GPS, which provides position information every second within 10 to 15 m accuracy. This can be made more accurate via assisted GPS (AGPS) or differential GPS (DGPS), and more speedy using an inertial measurement unit (IMU) [22].

Location-aware routing for delay-tolerant networks (LAROD) [23] is a position-based routing algorithm that is equipped with a location service that keeps a local database of node locations, which is updated using broadcast gossip and routing overhearing. LAROD uses partial knowledge of geographic position to decrease latency and overhead. The greedy perimeter stateless routing (GPSR) algorithm [24] makes greedy forwarding decisions using only information about a router's immediate neighbors based on their geographical positions. The decisions are greedy in the sense that at every forwarding, the packet is sent to a node that is closer to the destination. When that is not possible, GPSR routes the packet around the perimeter, and goes back to its greedy behaviour when possible. GPSR performs well in terms of routing speed and scale. An algorithm based on GPSR was proposed in [25], which works using adaptive (as opposed to periodic) beacons to reduce overhead and position prediction. The Adaptive Density-based Routing Protocol (ADRP) is described in [26]. ADRP adjusts the transmission probability of nodes, giving preference to those with fewer neighbours to increase the probability that their packets get through. Ad-hoc Routing Protocol for Aeronautical Mobile Ad hoc Networks (ARPAM) [13] is a protocol rooted in AODV that also employs geographical location information as well as proactive functions in specific circumstances. The position aware, secure, and efficient mesh routing (PASER) [27] is a position-based routing algorithm that puts special emphasis on security.

A typical FANET is considerably more dynamic than a typical MANET, both in node speeds and coverage area. FANETs may also have less node density, giving rise to packet loss issues. Therefore, legacy MANET routing protocols such as AODV, DSR, OLSR etc. may not always perform well in a FANET setting. Protocols designed specifically for FANETs are expected to perform better, but this also depends on the scenario. On the other hand, comparing specially designed protocols for FANETs is not straight-forward, as most of these protocols are not readily-available in major wireless network simulators.

3. The SDN-based Routing Algorithm for FANETs

The proposed algorithm is a position-based routing protocol that runs at the SDN controller. It has both reactive and proactive components, thus mitigating the disadvantages of both kinds of protocols. The SDN controller keeps track of the positions of each node, and makes routing decisions accordingly. For the communication between the SDN controller and the nodes, OpenFlow protocol [28] is used. Accordingly, the OpenFlow packet types listed in Table 1 are adapted and used for the purposes of the proposed protocol.

Table 1 Adapted OpenFlow packets for the implementation of the proposed algorithm

Packet Type	**Packet Purpose**
Hello	Packet sent from the nodes to the controller during initialization
Configuration	Configuration updates for the nodes
Echo	Request/reply packet pair to maintain connectivity of the nodes to the controller
Barrier	Ensuring message order and dependencies
Error	Notifying the controller of any problems at the nodes
Role-Request	Assigning roles to a node by the controller, particularly when there are multiple controllers a node can connect to
Packet-in	Transferring the control of a packet to the controller, when there is a miss in the rule table of the node, or the rule requires forwarding the packet to the controller
Packet-out	Forwarding packets that are received via Packet-in messages, along with the associated rules

The controller executes the following services:

- *Data layer unit configuration service*: This service consists of initializing the nodes in the FANET, as well as updating the timer period value at the nodes.
- *Topology mapping service*: Nodes in the FANET share their location information periodically every second with the SDN controller, and the controller builds an internal map of the topology of the FANET on which the routing decisions are made.

- *Table control service*: The routing tables are built based on the location data obtained from the nodes. Then, any modifications are communicated to the relevant nodes. Instead of the entire tables, only the changes are sent in order to minimize the protocol overhead.
- *Proactive routing service*: Routes are found and refreshed periodically based on the topology map built by the topology mapping service. Dijkstra's shortest path algorithm is used to find the minimum hop route.
- *Reactive routing service*: In case of asynchronous route request arrival due to an absence of a valid route to a destination in the routing table, this service is used along with the topology mapping service to provide up-to-date routing information to the requester node. Similar to the proactive routing service, the reactive routing service uses Dijkstra's shortest path algorithm.
- *Timer management service*: The timer for the proactive routing service is initiated with a period of 1 second. Afterwards, the dynamicity of the network is determined based on the location data received from the nodes. As a result, the period of the timer is either decreased or increased. Then, the updated period value is broadcast to the nodes via the data layer unit configuration service.

A general flow diagram summarizing the behaviour of the proposed algorithm is given in Figure 1. After the initial configuration of the nodes, the topology mapping service builds a map at the controller, who builds the routing tables both periodically in a proactive manner, and reactively when the rule table of a node does not have an entry for an incoming packet with a certain destination. The period of the timer is adaptively controlled by the timer management service. The routing tables produced at every proactive cycle are compared to the previous table, as indicated as "Service 4" under the topology mapping service in Figure 1. If the table remains the same three consecutive times, it is concluded that the dynamicity of the FANET does not require the current frequency of refreshing, and hence the period of the timer is reduced by 200 ms. Similarly, if the table changes three consecutive times, it is concluded that the dynamicity of the FANET requires more frequent route updates, and thus the period of the timer is increased by 200 ms.

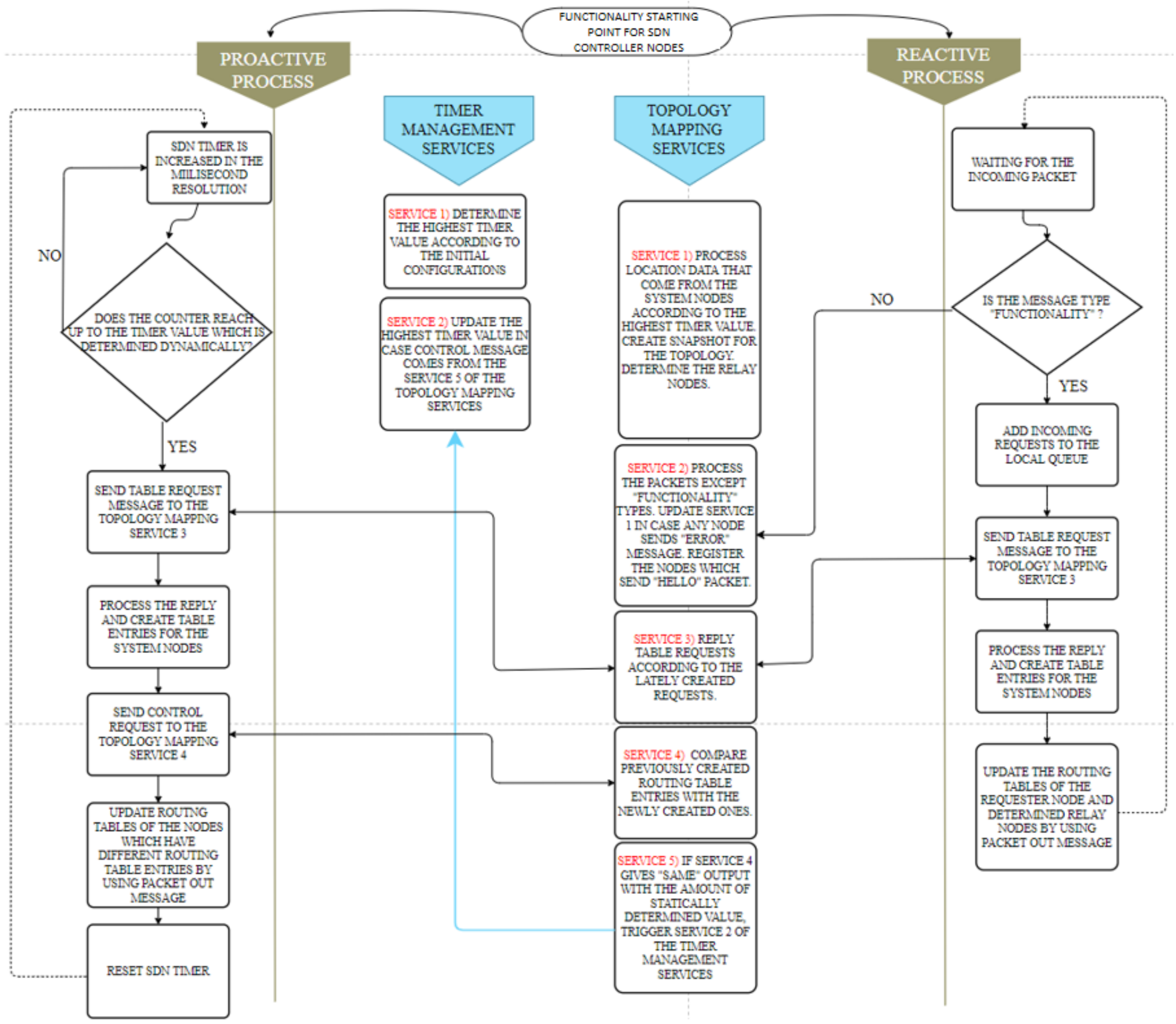

Figure 1 The flow diagram of the proposed routing algorithm.

4. Performance Comparison

The performance of the proposed algorithm is compared with three well-known routing algorithms for MANETs, namely AODV, a reactive topology-based protocol, DSDV, a proactive topology-based protocol, and GPSR, a position-based protocol, with respect to the throughput achieved, end-to-end latency, and control messaging overhead. As stated in section 2, more specialized protocols for FANETs are mostly unavailable in wireless network simulators such as OMNeT++ [29]. Therefore, comparison of the proposed algorithm with such protocols is left as future work. We provide a comparison with three representative protocols from the main families of routing protocols for MANETs to indicate a general performance level. For this purpose, a simulation study has been conducted on OMNeT++. AODV, DSDV, and GPSR have already been implemented on OMNeT++, whereas we implemented the proposed algorithm by defining and/or modifying the necessary packet types and writing the functionality for the services as defined in section 3.

A scenario with a FANET consisting of 8 user nodes and 2 SDN controllers is simulated on a geographical area of 3.2 km by 2.2 km. 4 of the nodes are assigned as two source-destination pairs. 1500-byte UDP packets are generated at each source according to independent Poisson processes with a rate of 1 packet per second. All nodes move according to the random waypoint model with 200 ms pause time between direction changes. A snapshot of a sample topology under the scenario is presented in Figure 2. In four different experiments conducted for each of the protocols, the nodes are moved with constant speeds of 5, 10, 15, and 20 m/s. The simulation parametres are summarized in Table 2. The four protocols are compared with respect to the throughput obtained, end-to-end latency, and the total protocol overhead due to the control messaging.

Figure 2 The snapshot of a sample topology under the simulation scenario.

Table 2 The summary of the simulation parametres and the environment.

Parametre/Property	Value
Topology model	Unit Disk Radio Medium
Detection range (m)	Uniformly distributed in [995, 1005]
Communication range (m)	1000
Interference range (m)	1000
Link layer protocol	IEEE 802.11ah
Network layer protocol	IPv4
Transport layer protocol	UDP
Application layer packet size (B)	1500
Packet generation model	Poisson arrival process (mean rate: 1 packet/s)
Node mobility model	Random waypoint model (200 ms pause time)
Number of nodes	8 terminal nodes and 2 SDN controller units
Node speeds (m/s)	5, 10, 15, 20
Simulation iterations (per speed value)	10
Total simulation time (hours)	5
Topology area (m^2)	3200 × 2200

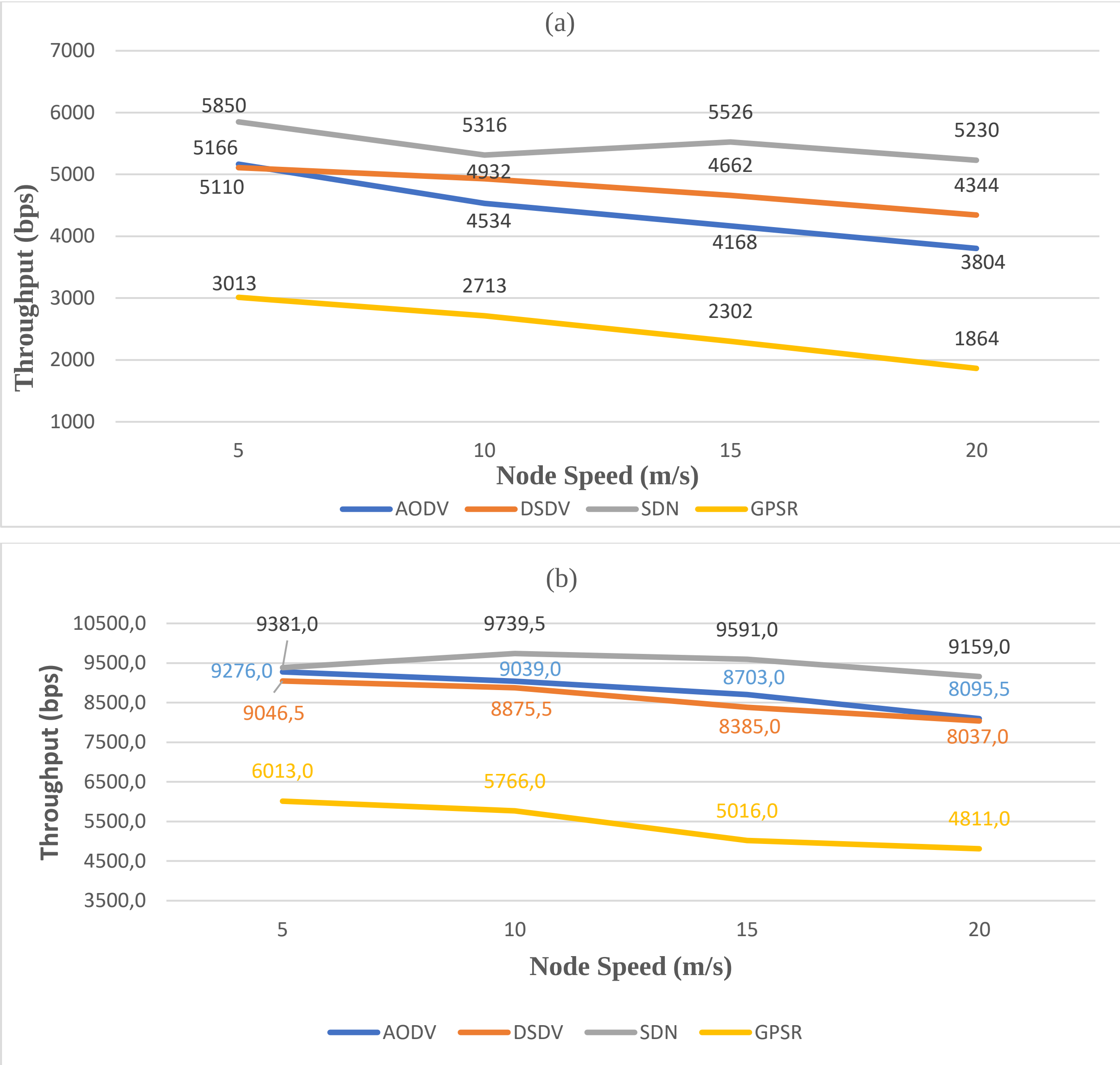

Figure 3 Throughputs achieved by the protocols for (a) Source1 - Destination1 pair, (b) Source2 – Destination2 pair, under the described scenario

The throughputs achieved by the protocols for each node speed value is given in Figure 3. For both source-destination pairs, it is observed that the proposed protocol performs the best, while AODV and DSDV are not far behind. Another important observation is that the throughput obtained with the proposed protocol is more or less maintained, whereas the other protocols, especially GPSR has a decreasing trend with increasing node speeds.

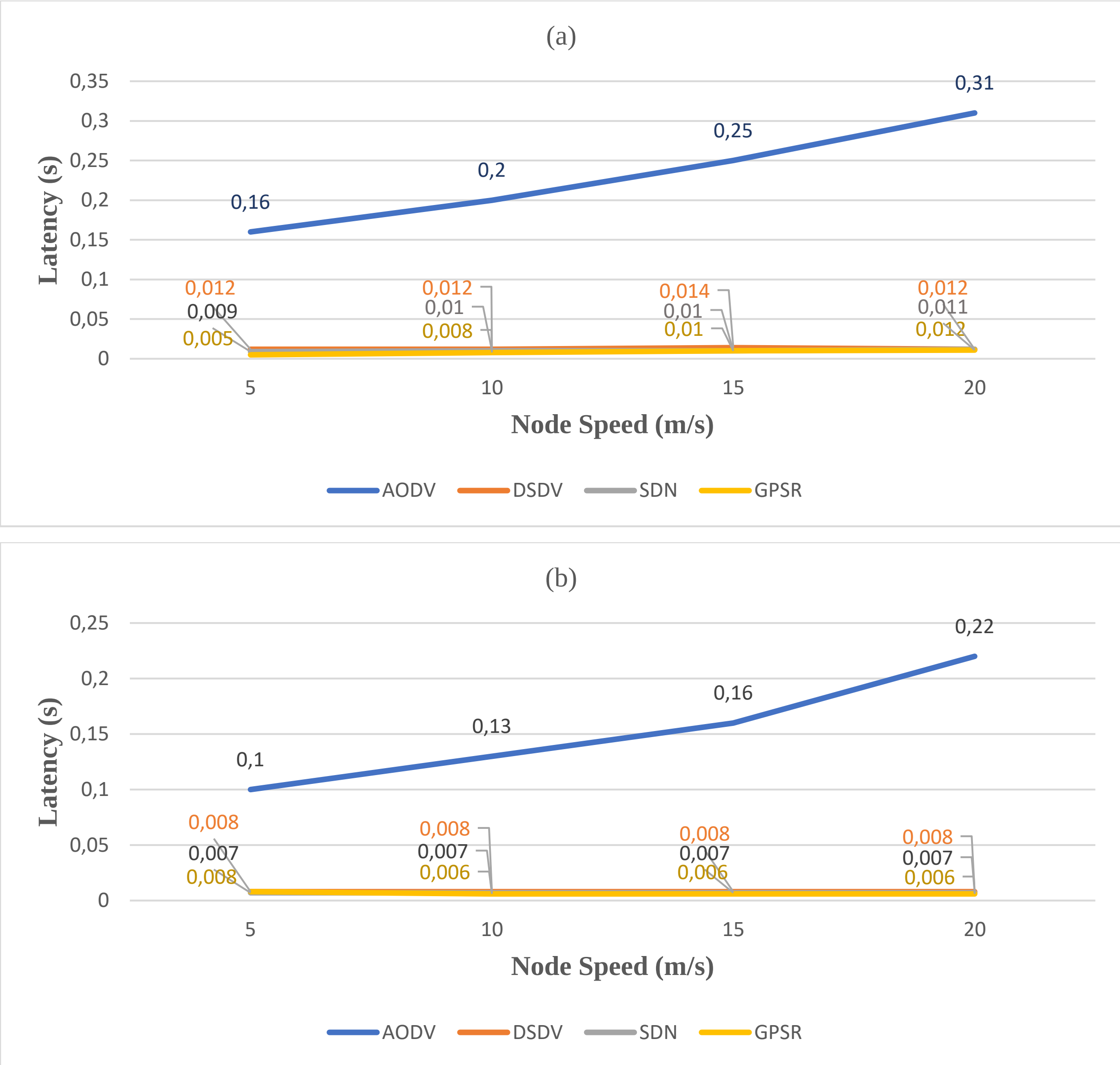

Figure 4 Average end-to-end latency values experienced by the packets for each of the protocols for (a) Source1 – Destination1 pair, (b) Source2 – Destination2 pair, under the described scenario.

The average end-to-end latency values experienced by the packets for each of the protocols is given in Figure 4. The proposed algorithm achieves latency values no more than 11 ms and this seems to be insensitive to the topology dynamicity (in terms of node speeds). The proactive component of the proposed algorithm makes sure that the routes are fresh. DSDV and GPSR behave similarly, whereas AODV, being a pure reactive protocol, leads to delays that are an order of magnitude larger and that increase with increasing node speeds. This demonstrates that any protocol used for especially highly dynamic FANETs must have a proactive component in order to keep the latency under a certain value.

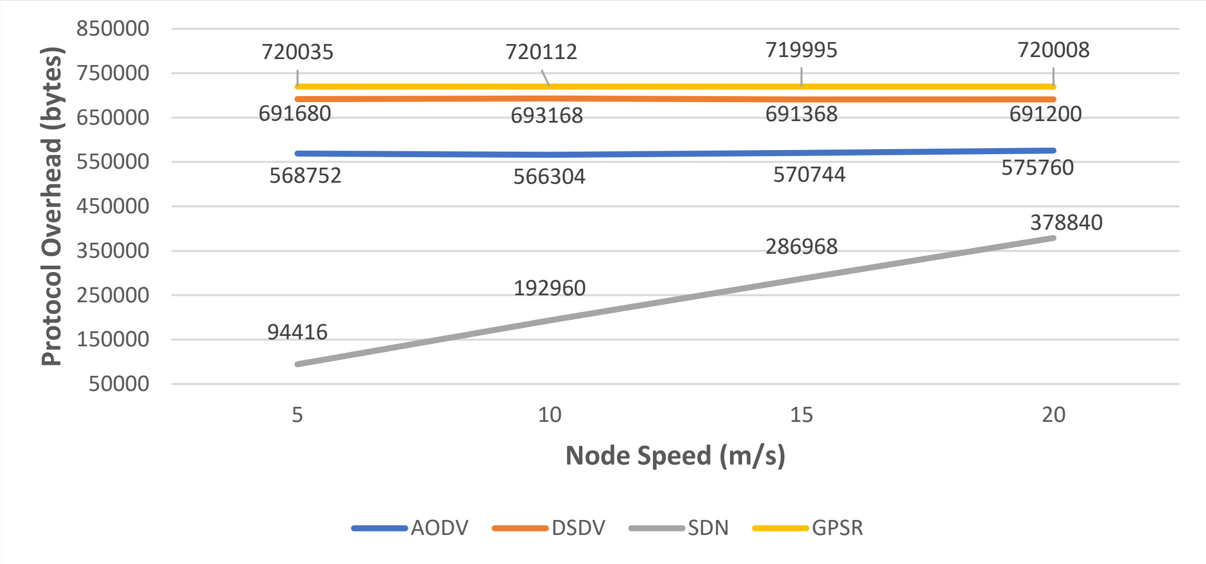

Figure 5 The total protocol overhead in bytes for each of the protocols.

The total protocol overhead for each of the protocols due to control messaging is presented in Figure 5. The proposed algorithm outperforms the others, especially when the dynamicity of the network is relatively low. As the proposed algorithm takes precautions against unnecessary overhead, such as the table control service checking for changes in the routing tables before broadcasting the fresh routes to the nodes, it achieves the best performance in this regard among the investigated algorithms. Although the amount of protocol overhead for the proposed algorithm is increasing with the network dynamicity as opposed to the other three protocols, it is still well below the others even at the speed of 20 m/s, which is very close to the optimal speed of a drone in a delivery scenario described in [30]. It requires further research to determine at what speed the proposed algorithm ceases to be the best in terms of protocol overhead. However, taking the Figures 3 and 4 into account, it could be expected that at such speeds, the proposed algorithm would offer better throughput and/or latency performance.

5. Conclusion and Future Work

In this paper, we proposed an SDN-based position-aware routing protocol for FANETs. The algorithm has proactive and reactive components, and merges the low latency advantage of proactive routing protocols with the low control overhead advantage of reactive routing protocols. Being SDN-based, the algorithm runs on the SDN controllers, which keep track of the geographical topology via periodic position updates and informs the nodes of any changes in the routes. The period of the position updates is dynamically adapted in order to keep up with highly dynamic scenarios, while keeping control overhead low for less dynamic systems.

The simulation results show that the proposed algorithm outperforms AODV, DSDV, and GPSR in terms of throughput, latency, and control overhead. Although the control overhead for the proposed algorithm is below that of the others for all of the investigated scenarios, it increases with the node speeds, owing to the fact that routes become obsolete more frequently in such scenarios. This means that there exists a speed value above which the control overhead will exceed that of AODV, DSDV, and GPSR. However, at such high speeds, these three protocols will suffer in terms of throughput and latency. As future work, scenarios with higher speeds can be investigated to determine how these protocols perform. A composite metric that is a function of the three figures investigated, namely the throughput, the latency, and the control overhead, can be defined to measure the overall performance. Another direction that can be further investigated is scenarios with higher node density.

Finally, a comparison with more position-based routing protocols that have been specifically designed for FANETs should be executed to demonstrate the effectiveness of the proposed algorithm. However, this requires a considerable amount of effort as these protocols are not available as predefined functionality in simulation tools such as OMNeT++.

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