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Original Article

A Cluster Based Directional Forwarding Routing Protocol for Bandwidth Constrained Networks

T. O. Kebeng[1], S. M. Sheikh[2], M. Kgwadi[3]

[1,2,3]*Electrical & Electronics Engineering, University of Botswana, Gaborone, Botswana.*

[1]*Corresponding Author : tippykebeng@outlook.com*

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Abstract *- Routing protocols in wireless ad hoc networks use control messages to learn the network, discover paths, and keep up with network changes. For bandwidth-limited networks, too many control messages severely impact data delivery performance. Therefore, reducing the number and broadcast scope of control messages is important. It can be done using different broadcast techniques, Location Services (GPS), data aggregation, and directional antennas. Options like GPS or directional antennas are costly. Therefore, this paper aims to present an alternative protocol that directs or limits route request messages along some path between the source and destination without using GPS or complex antennas. The protocol modifies Ad-hoc Distance Vector Routing (AODV) and Dynamic Source Routing (DSR). Still, it is called Cluster Based AODV (CLUBAA), and this paper has evaluated only against AODV at different route-discovery-request rates and network sizes. The novelty of the protocol is that it uses DSR-like pathfinding at a cluster level, not a node level. Simulations were carried out on Network Simulator 3, and it was found that for some configurations, CLUBAA uses fewer control messages; the difference is statistically significant. CLUBAA also had a better data delivery ratio, above 40%, compared to below 30% for AODV at 150 nodes. One of the negatives is that CLUBAA failed to find routes successfully more often than AODV did, for example, failing 45% of route discoveries at a request rate of 2 route discovery requests/second.*

Keywords *- Ad-hoc Distance Vector Routing (AODV), Cluster, Cluster Based AODV (CLUBAA), Directional Routing, Dynamic Source Routing (DSR), Normalized Routing Overhead (NRO).*

1. Introduction

Much research has been done on bandwidth-limited wireless ad hoc networks to minimize the number of routing protocol control messages or reduce their broadcast scope [1-16]. Doing so improves the bandwidth utilization efficiency; a smaller fraction of messages propagating in the network is occupied by control messages, and a good fraction goes to data delivery instead. For this paper, the different bandwidth-efficient protocols have been divided into 2 main classifications; Those that channel/direct control and data messages between sources and destinations [1-9] and those that do not have directional forwarding [10-16]. From these studies, there appears to be a gap in directional routing protocols that do not use Global Positioning System (GPS) or complex directional antennas, which is the inspiration behind this paper.

Even as technologies like WIFI 6 or 5G become more popular, not all devices in the Internet of Things/Everything (IoT/IoE) sphere [17-18] will immediately use them; there are still applications for which using older, less efficient technology is cheaper and better. Examples of IoT technology not using WIFI 6 or 5G; the author of [19] presents a communication protocol for use in smart grids and homes to facilitate the operation of heating and air-conditioning (HVAC). The authors in [20] present a new protocol for improving bandwidth utilization within a bandwidth-constrained water telemetry management system that implements IEEE 802.15.4 standard. For ad hoc networks like Wireless Mesh Networks (WMNs) and Wireless Sensor Networks (WSNs) that do not use the most cutting-edge technologies, limited bandwidth, energy and computing power are some of the relevant challenges [21-24]. It is against this backdrop that this paper is presented.

The next section is the Related Literature, which goes in-depth on the different bandwidth conserving routing protocols, and then the novel protocol algorithm is discussed in the subsequent section. Chapter 4 is the Materials and Methods, and it details the settings used during the simulations. Next, chapter 5 presents the Results and Discussion, where comparisons between the novel protocol and AODV are presented. Following that is chapter 6, the Conclusion.

2. Related Literature

This paper divides routing protocols into 2 groups based on whether they can directionally forward messages. This, however, is not the only classification criteria; for example, routing protocols can also be divided into three broad categories; proactive [16, 24-26], reactive [24-25, 27-28] and hybrid [24-25, 29]. Proactive protocols are energy and bandwidth-intensive as the nodes always have to maintain up-to-date paths to other nodes using periodic control messages. In contrast, reactive protocols only initiate path formation when a request is made. Hybrid protocols combine properties from both protocols, as mentioned above.

Firstly, papers related to protocols capable of directional forwarding will be reviewed. These protocols aim to send request messages or data in the general direction of where the destination node is, simultaneously avoiding other parts of the network, thus conserving network bandwidth. After that, protocols that are not capable of such directional forwarding but instead use some other technique to reduce the number of control messages will be reviewed for a complete presentation.

2.1. Directional Protocols

2.1.1. Using Complex Antennas

Some protocols take advantage of devices that have sophisticated directional antennas, beam forming and Multiple-Input-Multiple-Output (MIMO) capabilities [1-4]. Directional antennas concentrate their radiation pattern over a smaller angle, unlike omnidirectional antennas, which ideally have a uniform radiation pattern in all directions [1,30]. The ability to cast a message in a specific direction while avoiding other areas around the node is quite a bandwidth efficient.

Authors in [2] present Directional Dynamic Source Routing (DDSR) and Directional Ad-hoc Distance Vector (DAODV) protocols, which use directional antenna technology. In addition to hop count, metrics such as beam overlap and power budget are used to select routes. Using these antennas, the protocols can send messages in the general direction of where they are needed and avoid flooding regions of the network not close to the source or destination.

The authors of [4] propose a reactive routing protocol for ad hoc networks that utilize directional antennas and estimate the angle/direction of arrival (DOA) messages from neighboring nodes. Using this DOA estimate, the antenna array can maximize the power radiated toward the receiving node. The array can also introduce nulls in the radiation pattern, where they are needed, to avoid interference.

2.1.2. Using Location Services

Directional Flooding Based Routing Protocol (DFR) [5] is used in underwater applications. Underwater sensor networks (UWSNs) do not use radio technology to connect but instead use sound because light (RF) quickly attenuates underwater. The proposal from [5] is to devise a protocol that delivers packets to a sink node using controlled flooding. Defining the flooding zones based on location services information (geographic data) and the link quality between nodes.

Location Aided Routing (LAR) [10, 31] is a reactive routing protocol which uses the position information to improve the efficiency of the route discovery process by limiting the scope of route request flooding. The source node estimates an expected zone (a region where the destination node is most likely to be, given past knowledge about it). It uses the destination's last reported location and the destination node's mobility pattern. Requests are only broadcast within that zone.

Distance Routing Effect Algorithm for Mobility (DREAM) [7, 10] is a proactive routing protocol in which nodes keep a record of the location information of all the nodes in the network, and they use this information when sending out messages in the direction of the destination. Quadrant-Directional Forwarding (Q-DIR) [2] is a limited flooding protocol that uses location services to specify a zone in which query flooding is done, restricting the broadcast region to just the nodes in the same area as the source and destination nodes. Other similar protocols include Greedy perimeter stateless routing GPSR [32].

The authors of [8] present an energy-efficient routing scheme called Adaptive Location Update (ALU) for WSNs. Unlike other geographic routing protocols with nodes sending periodic updates (beacons) about their location and velocity, ALU only does broadcasts based on the mobility dynamics of the node and the presence of a new node in the vicinity. Meaning that slower moving nodes, whose location is maintained within some threshold, will send fewer beacons, thus saving bandwidth.

2.1.3. Data Aggregation

For networks that need to send data to a central site, such as sensor networks, data aggregation protocols like Low Energy Adaptive Clustering Hierarchy (LEACH) are good at improving bandwidth efficiency and power utilization. 8 varieties of LEACH are presented in total by the authors of [33]. These show that data aggregation can reduce the number of messages circulating in the network if only some nodes (Cluster Heads - CHs) are given the ability to communicate outside their clusters. However, data aggregation is not an option for multi-hop WMNs in which many devices form independent source-destination pairs.

The basic form of LEACH works by dynamically clustering nodes and selecting a CH among them. The CH is an aggregation point for data collected from the sensors/other nodes. The CH would then forward this data to the base station; this way, the other devices save energy as the CH contacts the base station. To keep energy levels evenly distributed among all the nodes, CH devices are changed regularly based on residual energy [34].

2.2. Non-Directional Protocols

2.2.1. Broadcasting Techniques

Limiting the scope of a broadcast control message to a part of the network, even if the messages are not directional, leads to better bandwidth efficiency. An example is Q-DIR, which is explained under subheading 2.1.2. The Expanding Ring Search (ERS) [24-25, 27] is also a broadcast limiting algorithm employed by AODV. In ERS, query messages (RREQs) are sent out by the source with a larger time-to-live (TTL) value each iteration in the search process until the destination is found.

If the destination is relatively close to the source, ERS will find a path while limiting RREQs to a smaller network area. However, in the case of a larger network and if the destination is a bit further away, then a few more RREQ waves would be needed to discover a path. Enhanced Expanding Ring Search (EERS) [12] addresses this issue by avoiding smaller initial TTL values not likely to lead to a path discovery. Instead, the initial TTL value is dependent on the diameter/size of the network. For example, one network will have an initial TTL of 2, and a larger network diameter would call for a TTL value of 3. The process after setting the initial TTL is the same as for ERS.

Another issue with ERS is that when the search radius increases, the same source device sends out a new RREQ, so devices within the previous search radius are queried about the same destination despite not having a route to it. Blocking-ERS [35] addresses this by having intermediate nodes send out the RREQ messages on behalf of the source device. Other alternatives include; Hop-Prediction-ERS-AODV (HP-ERS-AODV), which bases its TTL on previous hop counts/ TTL used [36], and another, which sets the TTL value at each node, depending on the number of RREQs a node has in the queue waiting to be processed for routing [13].

Messages can be broadcast either in a greedy fashion or a gossiping fashion. Greedy broadcasting is when a packet is sent to all the nodes in the radio range of the sender. Gossiping is the selectively sending out messages that would otherwise be broadcast to all neighbors, to just some randomly selected few, which go on to do the same and so on [11]. Gossiping uses bandwidth better and saves energy.

2.2.2. Hierarchical or Cluster Based Protocols

Arranging devices into clusters is one way to limit the extent to which query messages can propagate; the examples of hierarchical routing protocols in this paper mostly use the Cluster Head device as a communication nexus. Doing so concentrates control messages around the CH and away from other parts of the network, thus freeing up bandwidth elsewhere at the expense of congestion at the CH. An example is LEACH which was explained in subsection 2.1.3. The design of CLUBAA protocols like these provided great inspiration.

ClusterHead Gateway Switch Routing Protocol (CGSR) [10, 16] is a proactive protocol because nodes periodically broadcast their member tables; a node also has a record of the other devices in the same cluster. Gateways are those devices that are members of two or more clusters and act as a bridge for communication between those clusters. All communications between the source node and destination node travel through their respective CH devices and the gateway devices connecting those clusters. The disadvantage of CGSR is that it concentrates a lot of the communication going outside and into the cluster through the CH and gateway device, leading to a bottleneck.

In Cluster Based Routing Protocol (CBRP) [10], all devices keep a neighbor table, storing the link states of these neighbors, making it proactive. When a source makes a query, it sends the message to its CH and other neighboring CHs, which check their records to find out if the destination is a member of their cluster. If not, the CHs will send this query to its neighboring CHs and so on, but if the CH knows the destination is in its cluster, it will forward the query to it, and then the destination will follow the path back through the CHs and gateways back to the source node. The query message uses source routing to record the addresses of the CH devices it has passed through. The disadvantage to point out here is that keeping routing tables up to date is bandwidth-intensive.

Packet bottlenecks at CH or gateway nodes are poor for bandwidth efficiency, leading to collisions and packet loss. So the proposed protocol uses CH devices a little differently. CHs will, for the most part, only be involved in pathfinding but will not be directly involved in forwarding messages in and out of the cluster unless it is efficient. CGSR has interlocking/interconnected clusters, which leads to the need for gateway devices, which present as another bottleneck; what the proposed protocol does differently because clusters are separate; a node can only be part of one cluster at a time, thus avoiding the need for gateways.

2.2.3. Other Techniques

Another way of classification, according to the authors of [14], is; Attribute-based or Data-centric Routing Protocols examples include protocols like Sensor Protocol for

Information via Negotiation (SPIN) [14, 15], which uses metadata labels on the different types of data packets and negotiate with other nodes to remove from the network redundant packets based on the metadata tags.

3. The Proposed Routing Protocol - CLUBAA

3.1. Cluster Formation

The Cluster Heads (CHs) are randomly elected when the network first comes online. The administrator sets the number of CHs so that, on average, there are 10 nodes per CH (currently, the election is done using a pseudo-random number generator in NS3).

The CH devices send joint messages to their neighbors, creating different clusters. Join messages are repurposed RREQ messages that contain the join flag and the cluster ID of the CH. A device only joins the cluster of the CH from which it receives the first join message; it ignores other join messages. Cluster boundaries do not overlap, meaning each node can only belong to one cluster simultaneously. By not overlapping clusters, CLUBAA avoids the problem of gateway bottlenecks such as those experienced by CGSR.

After a node joins a cluster, it sends a join-acknowledgement message (repurposed RREP) to the CH to build an inventory of the devices it has under its jurisdiction, similar to CBRP. The node also broadcasts a Join message with one hop TTL on behalf of the CH, similar to blocking ERS. A clusterless node cannot participate in network routing. If they have a message to send, they must wait for or initiate the formation of new cluster boundaries. This cluster formation process is shown in Fig. 1, and clusters can form by the faint black lines connecting the different nodes. The clusters have amorphous shapes, depending on the other clusters' boundaries.

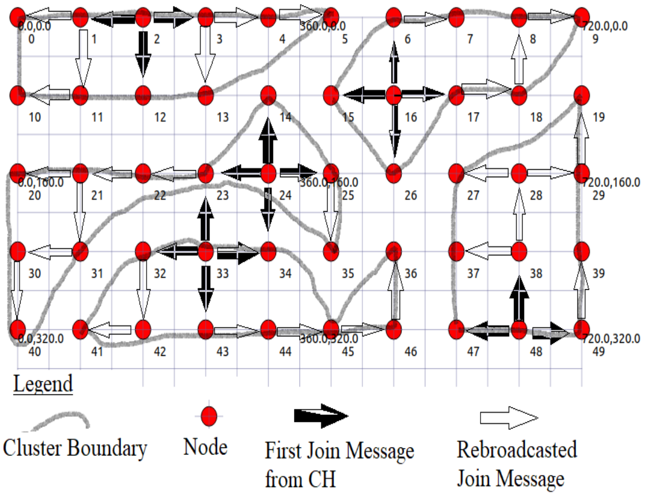


Fig. 1 Cluster formation process.

3.2. Intra-Cluster Route Discovery

A source node is looking for a destination and sends an RREQ message. This message does not have a maximum TTL hop count but is only confined within the cluster that the source is a part of. If the destination node is in the same cluster as the source, an intermediate node or the destination itself will respond to the request. The reasoning is that in a small limited area such as a cluster of 10 nodes, it is more bandwidth efficient not to use ERS but instead greedy broadcasting.

3.3. Extra-Cluster Route Discovery

Using the cluster inventory, a CH device (say CH-33) can notice if one of the intra-cluster RREQs (from node 44) is destined for a device not under its control. CH-33's response depends on whether it has a valid route to at least one other CH or not. If CH-33 does not have a route to any other CH, it will send a CH2CH broadcast message (repurposed RREQ) that can propagate between clusters. As this CH2CH message propagates, it records the different cluster IDs it has passed through, for example, Cluster 33, then 24 and 16; see Fig. 2; alternate paths are ignored. When an external CH receives this message, it records the path to CH-33 and response. It responds with an RREP containing the cluster path taken to reach it, and if it has the destination (node 8) in its inventory, it responds with an appropriate flag.

For the case, CH-33 has at least one path to one other CH; it would send a unicast message called a direct CH2CH to ask about the destination. The recipient CH (say 24) would then send a reply back to CH-33 to reset the timer keeping the path between them active. In the same RREP, if the destination were in CH-24's inventory, it would also set the appropriate flag. Otherwise, the flag is inactive. Failing this, CH-33 would resort to the broadcast CH2CH method above to find other CH devices.

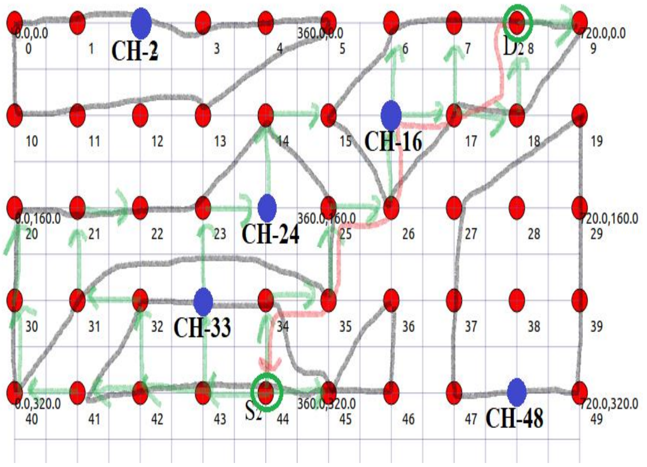


Fig. 2 Extra-cluster route discovery between S2 and D2

Whichever way is used, when the originating CH (CH-33) has the cluster path (path 33-24-16) leading to the destination (D2-node 8), it would share this path with the source device (S2-node 44). S2 would then construct an RREQ message (pathfinder message) that is only able to propagate along the cluster path outlined. Unlike other clustering protocols that need the CH to be a part of the path leading outside the cluster, CLUBAA avoids congesting the CH by having different independent path discoveries. CH-33 would then temporarily store this cluster path to device D2 for future use to shorten the discovery process the next time a different device looks for D2.

See Fig. 3, which summarizes the process from cluster formation until path discovery.

4. Materials and Methods

4.1. Simulation Description

This paper presents 3 tests: how CLUBAA responded to different route discovery request rates, how CLUBAA responded to different network sizes, and a hypothesis testing experiment. The simulations were implemented on the Network Simulator (NS3.30.1); the layer4 protocol was used as User Datagram Protocol (UDP). Since UDP does not have packet re-transmissions, it is the best way to test L3 performance [37]. CH devices were selected randomly, and so was the source-and-destination pair needing route discovery. For every 10 nodes in the network, 1 CH was randomly selected.

This paper's objective was to design a more bandwidth-efficient directional protocol than AODV. However, looking at conclusions from literature such as [39,42], AODV is more bandwidth efficient than DSR and Destination-Sequenced Distance Vector (DSDV); it didn't seem necessary to include those protocols. The performance of CLUBAA compared to the other directional protocols will be studied in future publications.

The first set of simulations focuses on the Normalized Routing Overhead (NRO), data-delivery-ratio-percentages and path-discovery-failure-percentages against average route discovery request rates while keeping the network size (50 nodes) and other factors constant. The average route discovery request rate is defined here as the number of source-destination pairs sought after divided by the total simulation time. The nodes were arranged in a 5 by 10 grid – because a grid presents a better way to test cluster formation than a line or star topology.

Requests for route discoveries happened randomly during the simulation time. They were not constant or evenly spaced because having the requests randomly occur is a better model for what happens in a real network; the number of requests was varied as the simulation time stayed constant over different tests. For example, to get an average of 0.2 requests/second, there were 20 requests made within 100 seconds; to get an average of 1 request/second, 100 requests were made within 100 seconds and so on.

The next test shows NRO, data delivery ratio percentages, and path-discovery-failure percentages against network size. In this test, the average request rate was kept constant at an arbitrary 0.5requests/second, and the simulation time was constant at 100 seconds. The tests were done such that there is, on average, 10 nodes per cluster, meaning for the 50-node network, there were 5 CH nodes; for the 150-node network, there were 15 CH nodes and so on. The network size was increased from 50 nodes up to 250 nodes.

For the last test, the null hypothesis is that the changes made to AODV to make CLUBAA did not improve bandwidth efficiency (NRO). It was tested by running the simulation 100 times and then using AODV and CLUBAA's results to calculate the p-value [41].

These tests help ensure that the other test results were not just good and favorable results for the authors but that the positive results were scrutinized. For these tests, the network size was kept constant at 50 nodes (5CHs), the simulation time was set at 90 seconds, and the number of requests was kept constant at 30, thus giving an arbitrary average rate of 1 request/3 second or 0.333requests/second. Different source-destination pair requests were made on every single iteration to prevent all the results from being the same. The x-axis of these figures represents the different individual runs performed; they are labeled as "tests".

4.2. Network Parameters

The results will be presented under these three subsections; Normalized Routing Overhead, Data Delivery ratio and Route discovery failure. The first two parameters are taken from the works of [33, 34]. The last is a percentage of how many routes were found relative to all the routes that could have been found.

$$NRO = \frac{\sum control\ messages}{\sum data\ packets\ received} \quad \ldots (1)$$

$$Data\ Delivery\ Ratio\ = \frac{\sum packets\ received\ by\ target \times 100}{\sum data\ packets\ sent\ by\ source} \ \ldots\ (2)$$

$$Route\ discovery\ failure\ rate\ = \frac{\sum targets\ not\ found\ \times\ 100}{\sum targets\ sought\ after} \ldots (3)$$

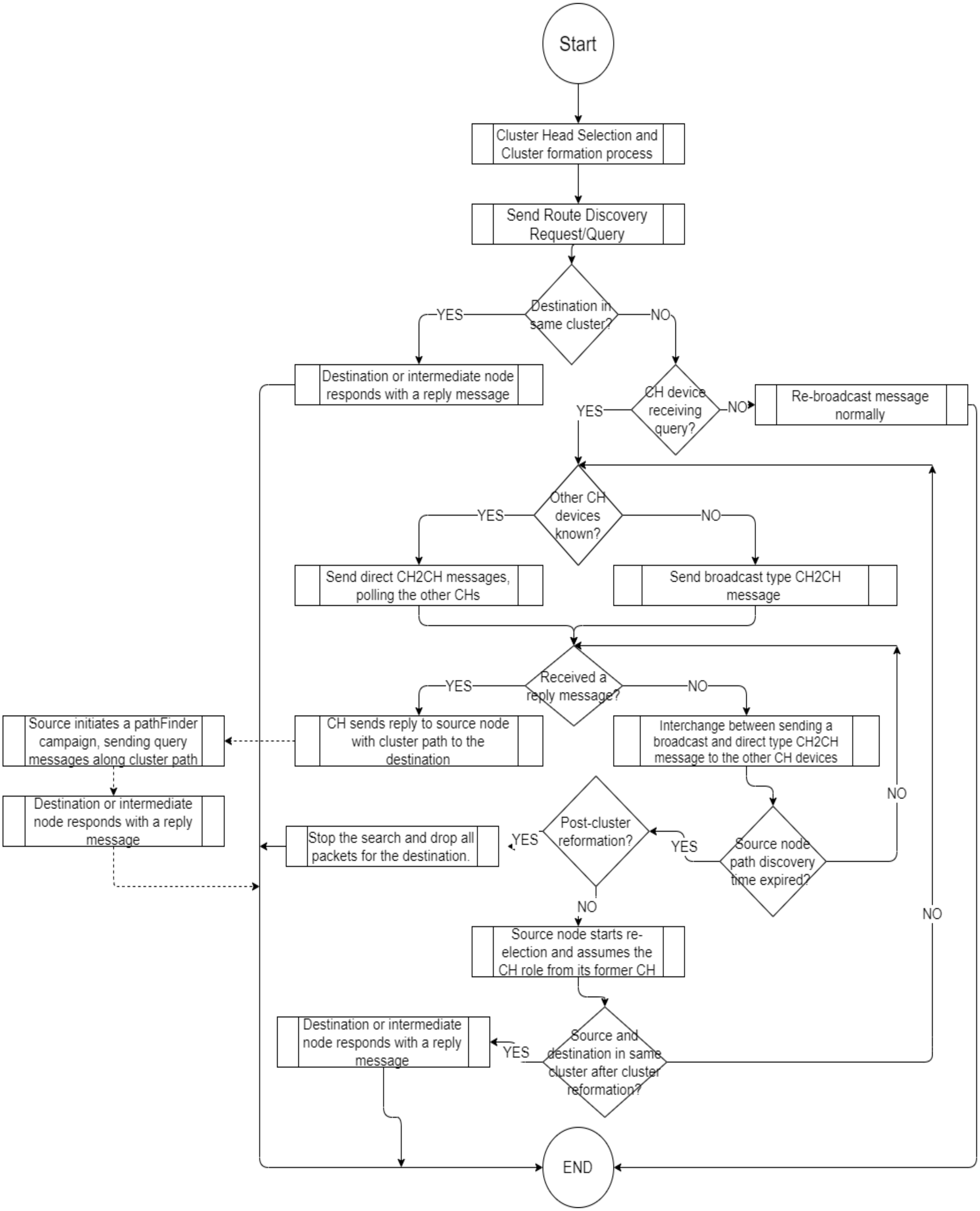


Fig. 3 Summary of CLUBAA algorithm

Table 1. Summary of simulator settings
(Settings for the 3 different tests are presented here)

Property	Request rate test	Network size test	100 test
IP address	10.1.1.0/24	10.1.1.0/24	10.1.1.0/24
WIFI (ad hoc)	802.11b	802.11b	802.11b
Bandwidth	1Mbps	1Mbps	1Mbps
Loss model	Friis	Friis	Friis
L3 protocol	AODV, CLUBAA	AODV, CLUBAA	AODV, CLUBAA
L4 protocol	UDP (port 654)	UDP (port 654)	UDP (port 654)
Simulation time (s)	100	100	90
Number of requests (60 ICMPs)	20,40,60,80, 100,120,140, 160,180,200	50	30
Topology (row x column grid)	5x10	5x10,10x10 15x10, 20x10,25x10	5x10
Node spacing (m)	80m	80m	80m
Node speed (m/s)	0	0	0

5. Results and Discussion

5.1. Normalized Routing Overhead

Since NRO is defined as control messages over data packets, if a protocol produces a lot of control messages relative to the data packets received, it would have a high NRO. On the other hand, if a protocol delivers more data packets relative to the control messages it produces, it will have a lower NRO. Fig. 4 shows the NRO values of AODV compared to CLUBAA while testing how these values respond to a change in route discovery request rate. The requested rate varied from 0.2 route discovery requests/second to 2 route discovery requests/second.

The main observation is that CLUBAA has a lower NRO than AODV for slower request rates, below about 0.8 requests/second. It means that when the requests are not so frequent, CLUBAA uses fewer control messages to discover routes than AODV. A speculative reason CLUBAA becomes more inefficient as the request rate increases is that more cluster re-formations are triggered by nodes that fail to find a route to their destination devices. Cluster re-formation involves more join messages, join acknowledgement messages and new CH2CH broadcast messages to look for new cluster paths.

Tables 2 and 3 show the raw data captured from the simulation. Data packets are regarded as ping/icmp echo messages successfully delivered to their intended destination and control messages as all messages are sent minus the total number of pings sent. The quotient of the two was then divided by 100 to scale down the values on the y-axis, but this does not affect the shape of the graphs, just the numbers appearing on the y-axis.

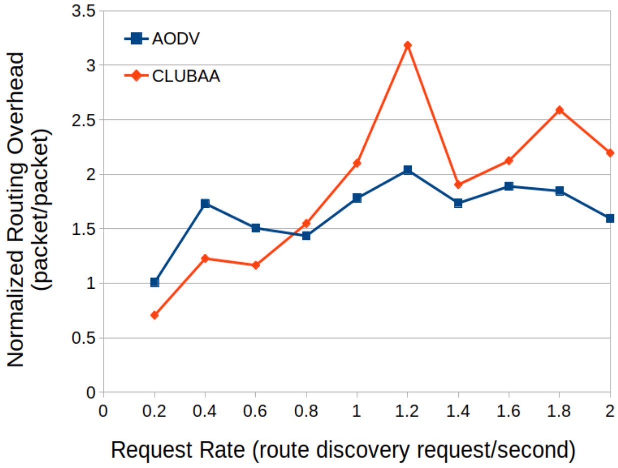


Fig. 4 Route request rate vs NRO

It can be observed that CLUBAA is more affected by the change in request rate compared to AODV, increasing from an NRO of 0.7052 to as high as 3.1832. In contrast, AODV increased from a low of 1.0065 to a high of 2.0367.

Table 2. NRO vs Request rate AODV data
(If 20 requests were made during the simulation, then 1200 ICMP/data packets were sent, but not all arrived at their respective destinations)

	AODV		
Request rate	∑(messages sent) - Data packets sent	∑Data Packets Received	NRO / 100
0.2	75280 - 1200	736	1.01
0.4	178640 - 2400	1018	1.73
0.6	237354 - 3600	1553	1.51
0.8	316054 - 4800	2170	1.43
1.0	386404 - 6000	2137	1.78
1.2	456710 - 7200	2207	2.04
1.4	442114 - 8400	2500	1.73
1.6	553599 - 9600	2880	1.89
1.8	579388 - 10800	3080	1.85
2.0	612992 - 12000	3771	1.59

Fig. 5 shows how AODV and CLUBAA NRO values compare when the network size varies. AODV is more affected as the network size increases from 50 to 250 nodes, starting from a low of 1.6135 to a high of 10.6890. The interesting thing is that CLUBAA is fairly stable in performance regardless of the network size, NRO ranging from 1.7821 up to 2.9747. It corroborates with results from the paper [38]. As the network size increases for AODV, so does the NRO.

Table 3. NRO vs Request rate data
(If 80 requests were made in 100 seconds, then 4800 ICMP/data packets were sent, but not all arrived at their respective destinations

	CLUBAA		
Request rate	∑(messages sent) - Data packets sent	∑Data Packets Received	NRO / 100
0.2	64882 - 1200	903	0.71
0.4	140188 - 2400	1124	1.23
0.6	155534 - 3600	1305	1.16
0.8	258383 - 4800	1638	1.55
1.0	306878 - 6000	1432	2.10
1.2	364991 - 7200	1124	3.18
1.4	327189 - 8400	1674	1.90
1.6	342828 - 9600	1569	2.12
1.8	388033 - 10800	1457	2.59
2.0	427244 - 12000	1892	2.19

This could be because, for AODV, the further away the destination is from the source, the larger the TTL value of the query messages becomes. This repeated increase of the search radius leads to a rise in NRO. CLUBAA, however, adjusts to a larger network by having more clusters. It means longer cluster paths between source and destination but not an increase in the number of messages, hence a more stable NRO.

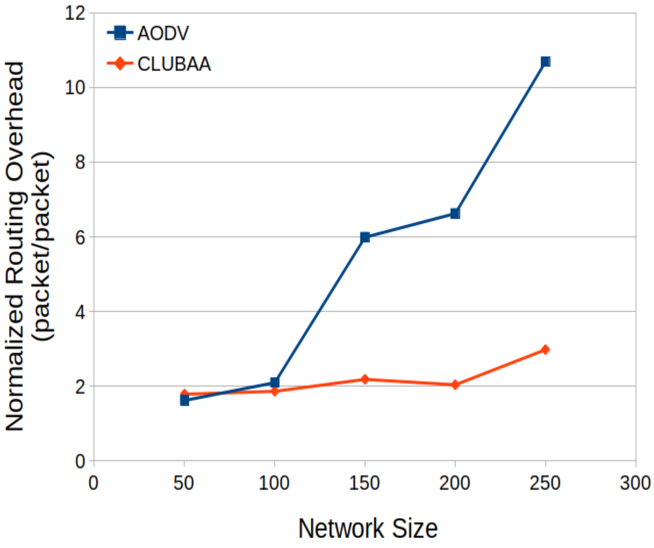


Fig. 5 Network size vs NRO

Fig. 6 shows a larger pattern emerging; the pattern that CLUBAA has a lower NRO than AODV more often than not. These results were fed into an online statistical p-value calculator to test if the outlined pattern is significant and not just due to random chance. See Fig. 7.

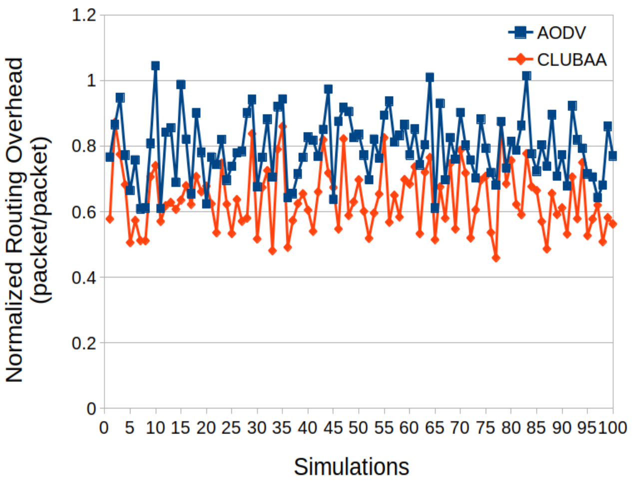
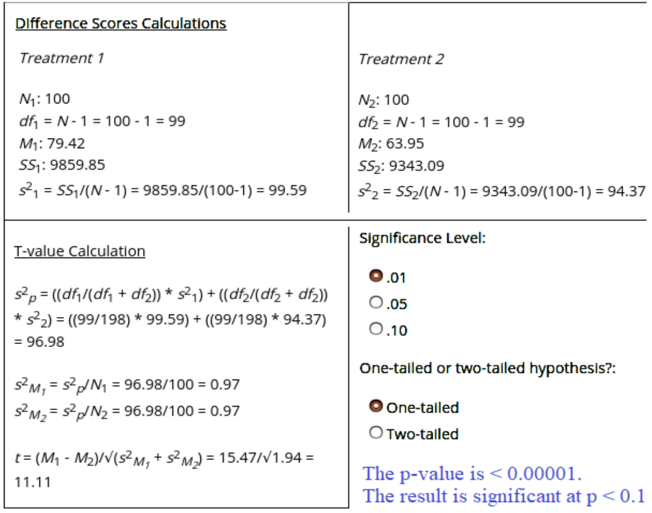


Fig. 6 Repeated runs testing NRO

The values of the NRO were not divided by 100 when running the p-tests; the raw values were used. Figure 7 shows that CLUBAA NRO values are lower and statistically significant than AODV NRO values. Treatment 1 is the data associated with AODV and has a mean of 79.42, while CLUBAA is treatment 2, having a mean of 64.01. Figure 7 shows that the p-value is less than 0.00001. It allows for the rejection of the null hypothesis. The null hypothesis is that: *CLUBAA offers no improvement in bandwidth efficiency (NRO) compared to AODV.*


Difference Scores Calculations

Treatment 1

N_1: 100
$df_1 = N - 1 = 100 - 1 = 99$
M_1: 79.42
SS_1: 9859.85
$s^2{}_1 = SS_1/(N - 1) = 9859.85/(100-1) = 99.59$

Treatment 2

N_2: 100
$df_2 = N - 1 = 100 - 1 = 99$
M_2: 63.95
SS_2: 9343.09
$s^2{}_2 = SS_2/(N - 1) = 9343.09/(100-1) = 94.37$

T-value Calculation

$s^2{}_p = ((df_1/(df_1 + df_2)) * s^2{}_1) + ((df_2/(df_2 + df_2)) * s^2{}_2) = ((99/198) * 99.59) + ((99/198) * 94.37) = 96.98$

$s^2{}_{M_1} = s^2{}_p/N_1 = 96.98/100 = 0.97$
$s^2{}_{M_2} = s^2{}_p/N_2 = 96.98/100 = 0.97$

$t = (M_1 - M_2)/\sqrt{(s^2{}_{M_1} + s^2{}_{M_2})} = 15.47/\sqrt{1.94} = 11.11$

Significance Level:

● .01
○ .05
○ .10

One-tailed or two-tailed hypothesis?:

● One-tailed
○ Two-tailed

The p-value is < 0.00001.
The result is significant at $p < 0.1$

Fig. 7 P-value results for NRO

5.2. Data Delivery Ratio

Fig. 8 shows that CLUBAA has a better data delivery ratio than AODV when the request rate is about 0.5requests/second and below. Despite the lower delivery ratio above 0.5requests/second CLUBAA remains comparable to AODV. Both protocols experience a drop in performance as the route discovery request rate increases. For AODV, the packet delivery ratio decreases as the network load increases [38].

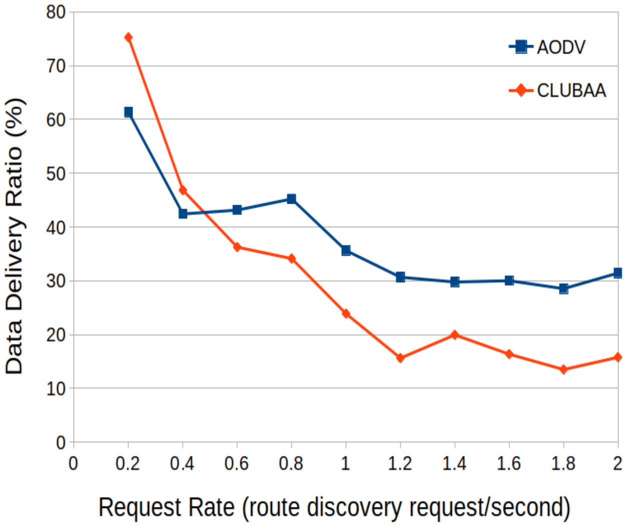


Fig. 8 Request rate vs Data delivery ratio

Fig. 9 shows that CLUBAA emerges with a better data delivery ratio as the network size increases, keeping above a delivery ratio of 35% at its lowest. AODV's data delivery ratio suffers greatly as the network size increases above 100 nodes, dipping to as low as 23.23% at a network size of 250.

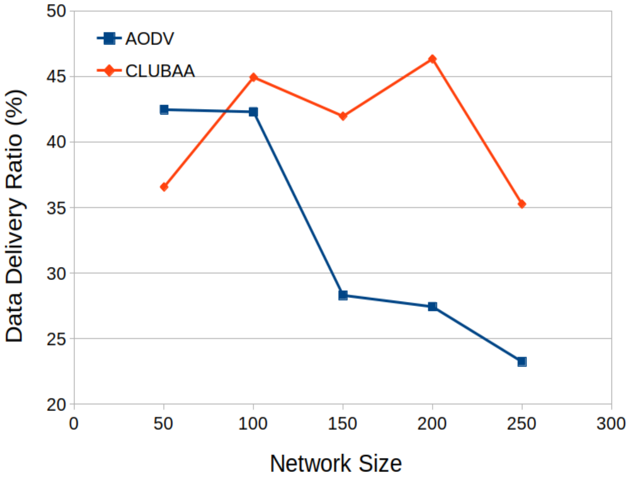


Fig. 9 Network size vs data delivery ratio

Fig. 10 shows a lot of overlap in the data delivery ratios of CLUBAA and AODV, even when run multiple times.

5.2. Route Discovery Failure Rate

Fig. 11 shows that CLUBAA experiences more 100% ICMP route discovery failures than AODV at all request rates. Below 0.8 requests/second CLUBAA has a reasonable failure rate, below 16.25%. Above that point, the failure rate increases to 44.5% at a request rate of 2 requests/1 seconds. Both AODV and CLUBAA experience an increase in request failure as the request rate increases.

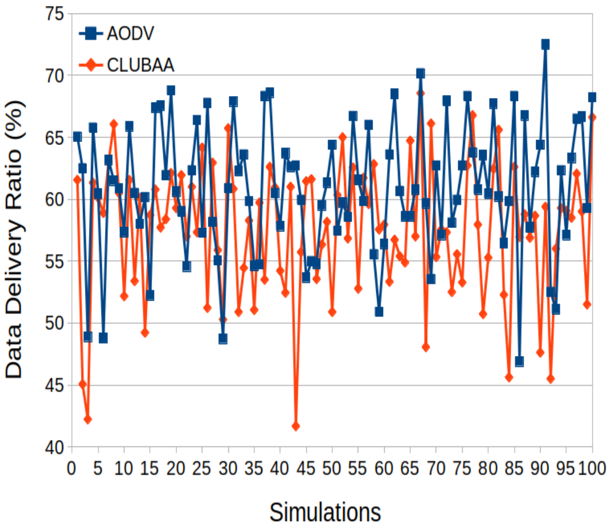


Fig. 10 Repeated runs testing data delivery ratio

The failure rate rises so much for CLUBAA compared to AODV because after a cluster re-formation, and the destination device has not been found yet, CLUBAA will abandon the search, leading to a high failure rate when re-formations are frequent. AODV, on the other hand, tries searching for the destination device at a maximum TTL of 35 at least twice before giving up the search [28], so there are more chances of finding the destination even if collisions increase

Comparing Fig. 4, 7 and 11, one notes that below 0.8requests/second, despite failing to find up to 16.25% of destination devices, CLUBAA was able to deliver more packets to the destinations it did find. For example, say there were 3 destination devices to find, and AODV found all of them, but CLUBAA found two; CLUBAA would have a higher discovery failure rate. If 10 pings were sent to each of the three destination devices, and AODV managed to deliver; 40%, 60% and 50%, but CLUBAA delivered 75% and 75%, the delivery ratios would be similar.

Shown in Fig. 12 is that, as the network size increases, both protocols experience an increase in route request failures, where CLUBAA reaches a high of 38% at a network size of 250 nodes and AODV at 18% at the same network size.

The pattern that emerges from 100 runs is that AODV has fewer 100% route discovery request failures than CLUBAA. It is shown in Fig. 13.

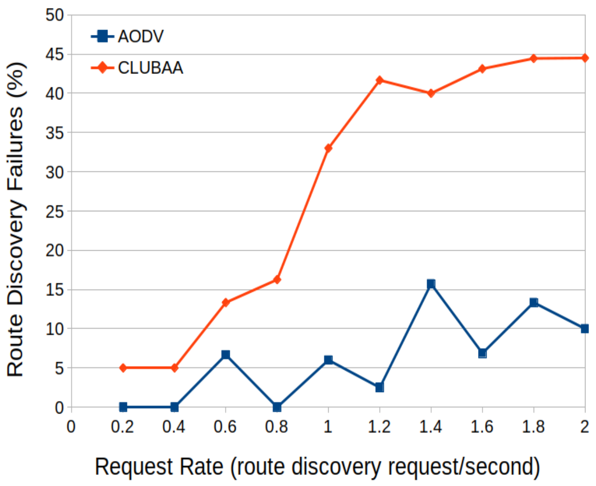


Fig. 11 Request rate vs route discovery failure rate

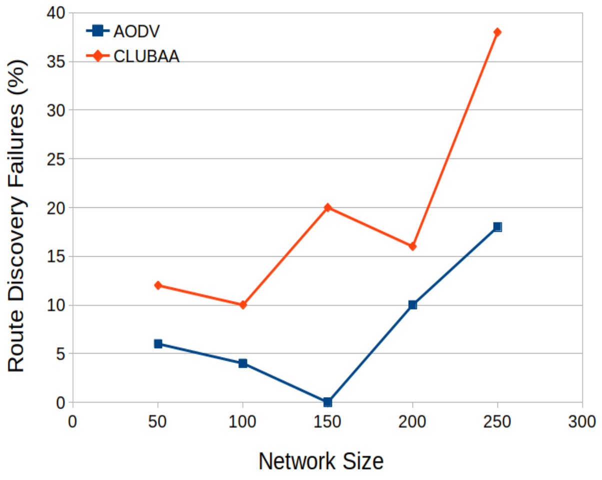


Fig. 12 Network size vs route discovery failure rate

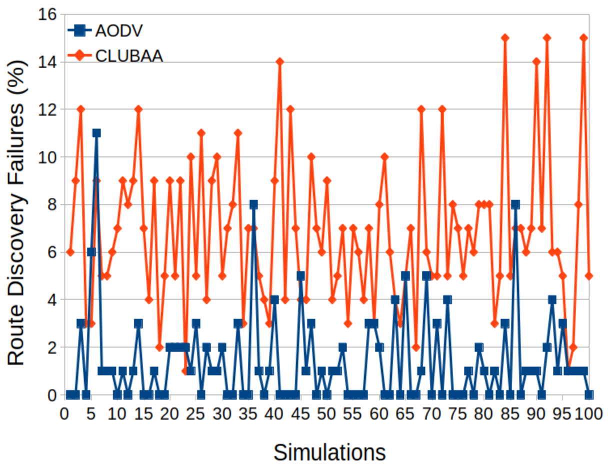


Fig. 13 Repeated runs testing route discovery failure rate

6. Conclusion

It can be concluded that CLUBAA can successfully direct/confine control messages (pathfinder RREQs) along a designated cluster path during the route discovery process (for extra cluster destinations). It achieves this without the use of GPS or complex antennas.

It can also be concluded that for slower request rates, below 0.8requests/second, CLUBAA is more bandwidth efficient because it has a lower NRO than AODV, as shown in Figure 4. The difference in NRO is statistically significant (p-value less than 0.00001), so the null hypothesis can be rejected.

Fig. 5 and 6 show that CLUBAA is more scalable than AODV, maintaining a better NRO and data delivery ratio even as the network size increases.

For future work, CLUBAA might be implemented on actual devices on a test bed because simulations are not 100% representations of the real world, only approximations and different results may be found.

Also, several improvements can be made to the algorithm to improve CLUBAA, such as adding a CH selection and clustering process. Furthermore, several other tests can be done with CLUBAA to determine how the parameters change as the network size increases but at different request rates, not just the 0.5 requests/second rate.

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