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Position-Based Multicast Routing in Mobile Ad hoc Networks: An Analytical Study

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Abstract

With the prevalence of multimedia applications and the potential commercial usage of Mobile Ad hoc Networks (MANETs) in group communications, Quality of Service (QoS) support became a key requirement. Recently, some researchers studied QoS multicast issues in MANETs. Most of the existing QoS multicast routing protocols are designed with flat topology and small networks in mind. In this paper, we investigate the scalability problem of these routing protocols. In particular, a Position-Based QoS Multicast Routing Protocol (PBQMRP) has been developed. PBQMRP builds a source multicast tree guided by the geographic information of the mobile nodes, which helps in achieving more efficient multicast delivery. This protocol depends on the location information of the multicast members which is obtained using a location service algorithm. A virtual backbone structure has been proposed to perform this location service with minimum overhead and this structure is utilized to provide efficient packet transmissions in a dynamic mobile Ad hoc network environment. The performance of PBQMRP is evaluated by performing both quantitative analysis and extensive simulations. The results show that the used virtual clustering is very useful in improving scalability and outperforms other clustering schemes. Compared to On-Demand Multicast Routing Protocol (ODMRP), PBQMRP achieves competing packet delivery ratio and significantly lower control overhead.

Keywords: MANETs, multicast, routing, protocol, position-based, GPS

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1. Introduction

Mobile Ad hoc networks (MANETs) are composed of a collection of mobile nodes that communicate with each other over wireless links in the absence of any infrastructure or centralized administration. MANETs have gained significant interest and popularity since they have enormous potential in several fields of applications. Over the past few years, the necessity of applications that require close association of the member nodes over mobile Ad hoc networks gained high popularity [1]. Multicast communication is fundemntal communication mechanism in such type of applications to reduce the routing overhead. At the same time Quality of Service (QoS) issue has been regarded as an essential requirement for group-oriented applications over MANET.

Supporting QoS for multicast routing protocols is a challenging task compared to unicast routing protocols. In unicast QoS protocols, the resource reservation is done between a source and a destination, while multicast QoS routing protocols should provide suitable QoS paths to all destinations of the multicast group [2]. Also, the heterogeneous nature of paths to the destinations makes it difficult to design QoS multicasting protocols [3]. Several QoS multicast routing protocols have been proposed [1][4]. However, there still exist many unresolved problems, especially the scalability and QoS issues, which need further investigation.

With the development of wireless communications and decreasing cost of wireless hardware, a mobile device is able to obtain its location information [5]. This awareness of location information has been utilized to improve scalability and efficiency through restricting the broadcast region and reducing the routing packets of MANETs routing protocols. As a result, location-based routing has emerged as a promising routing technique. However, combining location-based with QoS during routing discovery is confronted with extra difficulties to guarantee finding the optimal routes.

Clustering algorithms are proposed in Ad hoc networks as an attractive approach to improve routing protocol scalability [6]. A clustering algorithm is usually used to divide the network into smaller sub-groups. The idea of using clustering is not new. Previous efforts in this issue are discussed in [7][8][9][10][11]. In general, clustering can provide scalability and reduce signaling traffic [12]. This is essential in networks with large number of nodes (e.g. hundreds or thousands). For example, if a flat structure is used in a large network, routing tables and location updates would grow to a huge size. Therefore, partitioning the network into multiple clusters can limit the size of routing tables. Moreover, detailed topology information for a particular cluster is only exchanged among local cluster members whereas aggregated information is propagated between neighboring clusters in a higher hierarchical level [12]. Distributing the load among multiple nodes improves performance and scalability of the routing protocol. It also helps in achieving robustness and solving the single point of failure problem. Whenever multicast routing is applied in large-scale networks, the problem will become worse if all nodes maintain routing tables. Thus, clustering is utilized to address the scalability issue in multicast routing.

In this work, a new Position-Based QoS Multicast Routing Protocol (PBQMRP) has been developed. The main objective of this protocol is to design a lightweight scalable QoS multicast routing scheme irrespective of the number of multicast members and network size. This is achieved by applying the following strategies: First, developing a novel and scalable virtual architecture that makes use of the nodes' location information, which provides an efficient cluster management to handle dynamic movement of mobile nodes. Second, developing a new location service algorithm which reduces redundant propagation of packets between clusters.

Third, proposing a simple and efficient hierarchical structure to manage the multicast members to further enhance the scalability. And finally, creating a multicast forwarding tree through developing a route discovery algorithm guided by the geographic information which incurs lower overhead.

In MANETs, evaluating and testing a routing protocol is a mandatory phase to ensure its success in the real world applications. To perform this evaluation, researchers have four options: using test-beds, emulators, analytical modeling or using simulation tools. The performance of the proposed protocol is evaluated through developing both an analytical investigation and extensive simulation using the GloMoSim simulator environment [13]. Part of our simulation results that study wide range of scenarios (node mobilities, multicast group size, node density, network area size and the bandwdith requirement) has been published in [14]. Results demonstrate that PBQMRP has higher packet delivery ratio in large and dense networks and maintains lower normalized packet overhead. In fact, it is observed that PBQMRP out performs On-Demand Multicast Routing Protocol (ODMRP) [15] in most of the studied metrics and scenarios. In this paper we presents an analytical model and perform extensive simulations to show the scalability and effeicency of PBQMRP.

The rest of the paper is organized as follows: In the consequent section, an overview about the proposed protocol is introduced. Section 3 provides a detailed description of the resulted control overhead. Section 4 presents our simulation results. In section 5, a discussion of the generated results is provided. Finally, concluding remarks are summarized in section 6.

1.1 Paper contributions

In this paper, we address the scalability problem of QoS multicast routing protocols in MANETs. Designing a scalable multicast routing protocol in the presence of frequent topology changes and shared wireless channel is a challenging task due to several difficulties including: (1) difficulties in multicast packet forwarding, (2) handling large number of nodes and receivers, and (3) maintenance of large network size. Most of the existing protocols focus on multicast routing in small-scale networks and do not take scalability into consideration when holding a multicast session. These protocols incur large control overhead when the network gets large, dense and with large number of destinations. These problems motivate developing PBQMRP protocol, which can scale to large network size with large group size and can support efficient multicast packet transmissions in a dynamic network environment.

In summary, the major contributions of this paper are the following:

1) Designing a clustering strategy that can adapt to MANET mobility to form a stable topology that supports various network functions such as multicast routing, security, resource utilization and QoS support.
2) Developing an efficient location service algorithm to gather information about subscribers in the multicast sessions by utilizing geographic partition to reduce location service overhead.
3) Utilizing the position information to design a scalable multicast routing protocol that maintains efficient packet forwarding and meets specific QoS requirements in large networks.
4) Making a quantitative analysis of the control overhead of the protocol, and conducting a simulated performance analysis to show the scalability and efficiency of the protocol.
5) Comparing the performance of the proposed protocol with ODMRP. ODMRP is selected for comparison since it is still considered as de facto baseline and its performance outperforms most of the existing Ad hoc multicast schemes.

2. PBQMRP Overview

PBQMRP is a source-tree multicast routing protocol proposed to enhance scalability of QoS multicast routing over MANETs. PBQMRP aims to be implemented in large networks with large number of multicast members. To achieve this, a virtual clustering strategy has been introduced. This strategy is based on partitioning the whole network into several hexagonal cells. Hexagon-based clustering is selected because it outperforms other clustering scemes, due to its geometric features. The idea of using cluster-based routing using hexagonal shape has appeared in several previous works such as [11]][12][13][14]. However, establishing a cell coordinate system and node location management for hexagonal clustering is an important problem that needs to be solved. In this protocol, we have developed a self-mapping algorithm and cell coordinate assignment system for hexagonal clustering to enable each mobile node to know exactly the cell it belongs to during the network life time without the need to contact any other node.

Each hexagon cell has a Cell Leader (*CL*) node elected to maintain information about all nodes in its cell (till they join a new cell) and to assist in performing the location service algorithm. Also, each cell has a Cell Leader Backup (*CLB*) node to avoid single point of failure when the *CL* fails or leaves the cell. A general overview of the network architecture is shown in **Fig. 1**.

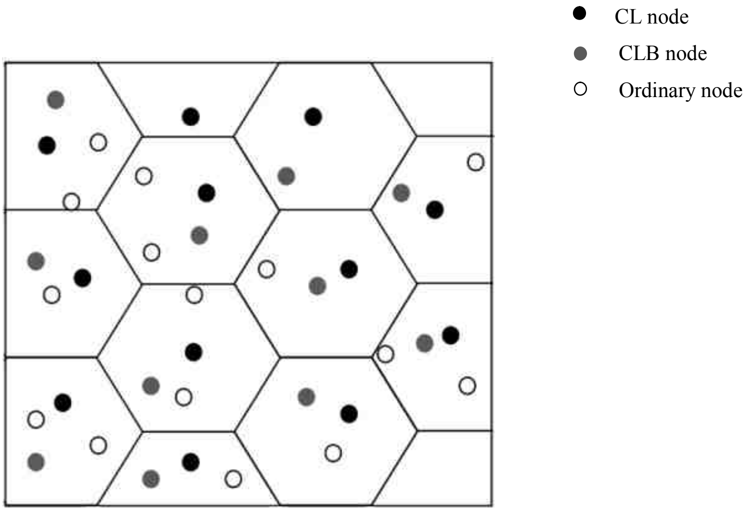


Fig 1. General overview of the network architecture.

The proposed protocol assumes that mobile nodes are aware of their positions through certain positioning system such as GPS receivers. The protocol exploits nodes' positions information to reduce the number of nodes participating in forwarding control packets in the network. This is achieved through using Restricted Directional Flooding (*RDF*). Based on nodes' positions and location information of the destination (obtained through location service algorithm), nodes in *RDF* forward the packets only if their positions are closer to the destination (than their previous hops). Using this mechanism eliminates broadcast storm and efficiently utilizes the network resources.

The protocol operation is divided into multiple phases. These phases include network construction, network maintenance, location service, multicast group division, routing discovery and maintenance as well as data transmission. Network construction phase includes dividing the network area into several hexagon cells and electing *CL* and *CLB* nodes for each cell. Network maintenance provides efficient solutions to nodes mobility and failure to obtain a stable structure. When a source node wishes to send data packets to a particular multicast group, location service phase is initiated by efficiently utilizing the cluster structure to gather information about the subscribing nodes and provide the source node with this information. After that, the source starts the multicast group division phase by partitioning the multicast group members into manageable subgroups. In each of these subgroups, one of the group members is selected to be a coordinator. The coordinator nodes have two functions. First, they establish a sparse multicast tree among themselves and the source node. Second, they deliver the multicast packets to other group members in their group. This structure is scalable in term of increasing the number of multicast members and it reduces the number of nodes that participate in forwarding the data packets. This will significantly reduce the resulting overhead. Also, this structure maximizes the advantage of broadcast nature of the wireless medium since the destinations in the same local area can receive the data packets in single broadcast operation.

After the source node identifies the coordinators for each sub-group of destinations, a route discovery and maintenance process is initiated. In this phase, the source and the coordinators co-operate to search for QoS routes to all destinations. Once the route discovery procedure is completed, data transmission phase takes place by sending data packets from the source to different destinations. In the following section, we will focus on analytically analyzing the control overhead of the proposed protocol.

3. Analytical Results

In this section, the control message overhead is derived and analyzed to estimate the upper bound of the control packets generated in each protocol phase. Initially, illustration and analysis of the clustering shape are presented. Then, the control overhead of different phases of the proposed protocol is discussed. Finally, the control overhead analysis is summarized. In this analytical model, we follow the other researchers and we try to measure the packets that are sent in each algorithm. Therefore, this quantitative model can help to estimate the control overhead generated in each phase, which may be utilized in the future to improve the routing protocol function. For ease of reference, **Table 1** summarizes notation used in this paper.

Table 1. PBQMRP notations

Notation	Meaning
CL	Cell Leader node.
CLB	Cell Leader Backup node.
RDF	Restricted Directional Flooding.
A	The network area.
H	Height of the network area.
W	Width of the network area.
R	Transmission range.
L	Side length of hexagon cell.
C	The number of cells in the network area.
N	The total number of nodes in the network.
n	The average number of nodes per hexagon cell.
Ah	The area of a single hexagon cell.
As	The area of a single square cell.
At	The area of a single triangle cell.

3.1. Cell Shape Analysis

In this subsection, we justify the selection of the clustering shape by considering hexagon, square and triangle shapes. It is assumed that the nodes are uniformly distributed in a network MANET area A. Considering the assumption that the farthest possible distance between two nodes in a hexagon cell must not be larger than the radio propagation range (R) of each node, the side length of the hexagon cell is set to:

$$L = \frac{R}{2} \tag{1}$$

Hence, the area of one hexagon cell (A_h) can be calculated as:

$$A_h = \frac{3\times\sqrt{3}}{2}\times L^2 = \frac{3\times\sqrt{3}}{2}\times\frac{R^2}{4} \tag{2}$$

The number of cells in the network (C) can be estimated as:

$$C = \frac{\textit{Network area}}{\textit{Cell area}} = \frac{A}{\frac{3\times\sqrt{3}}{2}\times\frac{R^2}{4}} = \frac{A}{0.6495\times R^2} \tag{3}$$

Therefore, with network size A and total number of nodes N, the average number of nodes per hexagon cell (n) is calculated as:

$$n = \frac{\textit{Number of nodes in the network}}{\textit{Number of cells in the network}} = \frac{N}{C} = \frac{N}{\frac{A}{0.6495\times R^2}} = \frac{0.6495\times R^2\times N}{A} \tag{4}$$

Considering the case of the square shape, the area of a single square cell (A_s) and the side length (L) are defined as:

$$A_s = L^2, L = \frac{R}{\sqrt{2}} \tag{5}$$

Hence, the number of square shape cells in the network (C) and the average number of nodes/cell (n) are presented respectively as:

$$C = \frac{A}{L^2} = \frac{A}{0.5\times R^2} \tag{6}$$

$$n = \frac{N}{C} = \frac{N}{\frac{A}{0.5\times R^2}} = \frac{0.5\times R^2\times N}{A} \tag{7}$$

Considering the triangle as the clustering shape, the area of a single cell (A_t) and the side length (L) are defined respectively as:

$$A_t = \frac{\sqrt{3}}{4}\times L^2,\ L = R \tag{8}$$

Accordingly, the number of triangle cells in the network (C) and the number of nodes/cell (n) are calculated as:

$$C = \frac{A}{\frac{\sqrt{3}}{4}\times L^2} = \frac{A}{0.433\times R^2} \tag{9}$$

$$n = \frac{N}{C} = \frac{N}{\dfrac{A}{0.433 \times R^2}} = \frac{0.433 \times R^2 \times N}{A} \tag{10}$$

From the aforementioned analysis, it is clear that using hexagon shape reduces the number of cells in the network; which effectively reduces the control overhead due to reducing the leader election overhead. Also, the hexagon cell shape covers more area in a single transmission, which will increase the number of nodes that are affiliated with the leader of each cell. This would reduce the communication overhead between nodes and improve the propagation delay in performing location discovery (to be discussed in subsection 3.2.3). **Fig. 2** shows the difference between square, triangle and hexagon shapes in terms of number of cells with respect to network size assuming the value of R is set to 250m. **Table 2** summaries the side length, cell area, number of cells and number of nodes/cell considering the three cell shapes.

Table 2. Cell shape analysis.

	Hexagon	**Square**	**Triangle**
Side length (L)	$L = \frac{R}{2}$	$L = \frac{R}{\sqrt{2}}$	$L = R$
Cell area (A_h, A_s and A_t)	$A_h = \frac{3 \times \sqrt{3}}{2} \times L^2$	$A_s = L^2$	$A_t = \frac{\sqrt{3}}{4} \times L^2$
Number of cells (C)	$C = \frac{A}{0.6495 \times R^2}$	$C = \frac{A}{0.5 \times R^2}$	$C = \frac{A}{0.433 \times R^2}$
Number of nodes/cell (n)	$n = \frac{0.6495 \times R^2 \times N}{A}$	$n = \frac{0.5 \times R^2 \times N}{A}$	$n = \frac{0.433 \times R^2 \times N}{A}$

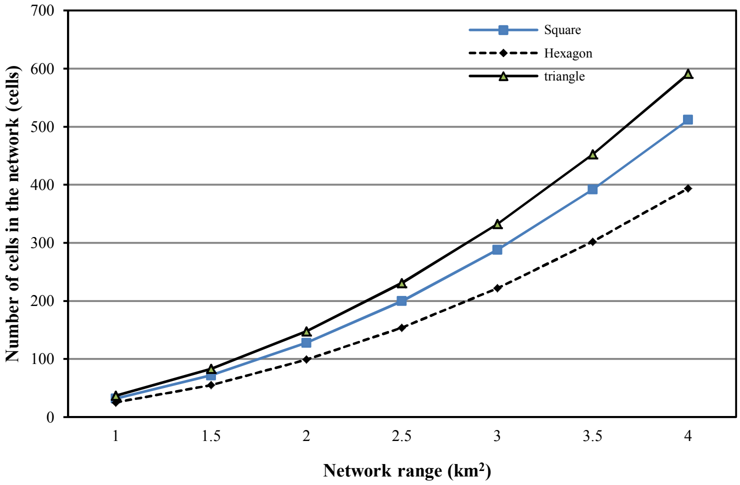


Fig. 2. Comparison between different clustering shapes.

3.2. Control Overhead Analysis

In this subsection the messaging overhead for PBQMRP is investigated. For clarity purposes, the control overhead of each phase is independently analyzed. Therefore, the total control message overhead is calculated as follows:

Total control message overhead =

overhead of network construction (OH_{NC}) + overhead of network maintenance (OH_{NM}) +
overhead of location service (OH_{LS}) + overhead of routing discovery (OH_{RD}) +
overhead of routing maintenance (OH_{RM})

$$T_{OH} = OH_{NC} + OH_{NM} + OH_{LS} + OH_{RD} + OH_{RM} \tag{11}$$

The messaging overhead of each phase is discussed separately in the following subsections.

3.2.1 Network Construction

In this phase, the entire network area is partitioned into an arbitrary number of equal-size virtual cells with hexagonal shape. This virtual structure is used as underlying backbone to facilitate packet routing. The novelty of this structure is twofold: First, it is efficientlly utilized to perform the location service algorithm instead of flooding packets in the network, specially in large-scale networks. Second, the virtual structure is used to handle the multicast group membership management, which will be discussed in future publications.

An election algorithm is executed later inside each cell independently. Some of the most-valuable nodes among all nodes in the network are selected to take the role of cells leaders and form the virtual backbone. Upon electing the leader nodes, it is important to select the nodes that expected to survive the longest possible time to keep the network construction stable as possible. In the election process, all network nodes are involved in sending their capabilities to be leader nodes inside each cell (i.e. 1-hop cluster broadcast). Each node calculates its capability factor and broadcasts it to its neighbors within the cell. Thus, the overhead of capability broadcast (OH_1) is:

$$OH_1 = O(N) \tag{12}$$

Where N is the number of nodes in the network. Here, each elected *CL* declares its leadership by sending a *NEW_CL* packet to the nodes inside its cell. It also sends a *NEW_CL_NBR* packet to the *CL* nodes of the six neighbor cells; rather than flooding it to all the *CLs* in the network. Therefore, the number of packet transmissions needed for leadership advertisement (OH_2) in all cells is computed as follows:

$$\begin{aligned} OH_2 &= C \times (1 \text{ packet inside cell} + 6 \text{ packets for neighbor cells}) \\ &= C \times (1+6) = O(C) \end{aligned} \tag{13}$$

Where C is the number of cells in the network. Accordingly, the overhead of leadership advertisement is $O(C)$. Thus, the resulted control overhead from network construction phase (OH_{NC}) will be:

$$\begin{aligned} OH_{NC} &= OH_1 + \mathrm{OH}_2 \\ &= O(N) + O(C) = O(N) \end{aligned} \tag{14}$$

It is clear that the network construction depends on the total number of nodes in the network (N) because all the mobile nodes are involved in constructing the network structure. However, this operation is performed only once during the network setup.

3.2.2 Network Maintenance

Network clustering incurs maintenance overhead, which is the amount of control packets needed to maintain a stable cluster structure. To maintain the network structure, the following scenarios should be considered: the communication between the *CL* and ordinary nodes, communication between the *CL* and the *CLB*, handling *CL* and *CLB* failure (or movement outside the cell), handling new joining nodes and handling empty cells. In the proposed protocol, these operations have only local effects on the network topology, which effectively reduce the resulting overhead. For simplicity, the resulting overhead for each cell is computed and then the overall control overhead is obtained for all cells. The messaging overhead of each scenario is discussed separately as follows:

- **Periodic leader election**: Each *CL* node declares its leadership state through sending *LEADER_ELECTION* packet to the local cell every *Leader_Ref_Time* interval and only the nodes with higher capabilities respond to this notification packet. Thus, the resulting overhead is $O(n)$. Where n is the number of nodes/cell.
- **Periodic *CL-CLB* backup**: To enable network recovery and to avoid single point failure, the concept of backup node is proposed (*CLB*). Periodically the *CL* updates the *CLB* with changes happened on the status of nodes inside its cell. This operation is performed using 1-hop communication. Assuming that any node may change its information, the cost of the *CL-CLB* backup is $O(n)$.
- **Intra-cell movement of ordinary nodes**: When a node moves to a distance larger than *Dist_move_th*, it needs to update its location information with the local *CL* node. It can be seen that the location update cost is limited to the number of nodes in each cell. These update packets are unicasted to the local *CL* node rather than flooding them to the network. Thus, the location update cost is $O(n)$.
- **Inter-cell movement of ordinary nodes**: To handle nodes movement between neighbor cells, the following communication operations take place: one leave packet sent from the moving node to the original *CL* node, one reply packet sent from the *CL* to the leaving node and one join packet sent from *CL* of the old cell to *CL* of the new cell. Hence, the overhead of inter-cell movement of a node is $O(1)$. Considering that all nodes inside the cell (n) may leave their cell, the resulting overhead of inter-cell movement is $O(n)$.
- **Intra-cell movement of *CL* nodes**: When a *CL* node moves to a distance larger than *Dist_move_th*, its location information needs to be updated with the six neighbor cells. Therefore, the maximum location update overhead is $O(1)$.
- **Inter-cell movement of *CL* nodes**: When a *CL* node moves to another cell, the needed packet transmissions are as follows: one packet from *CL* to *CLB* ($O(1)$), information about n nodes in the cell ($O(n)$), one packet to join the new cell $O(1)$ and one packet from *CLB* inside the cell to six neighbors ($O(1)$). Thus, the overhead of inter-cell movement of a *CL* node is $O(n)$.
- **Intra-cell movement of *CLB* nodes**: As any ordinary node, the *CLB* updates its location information with the local *CL* node if it moves to a distance larger than *Dist_move_th.* The cost of this overhead is $O(1)$.
- **Inter-cell movement of *CLB* nodes:** When the *CLB* crosses the boundary of its original cell, the needed packet transmissions are as follows: one leave packet, one leave reply packet and one cell join packet. Hence, the overhead of *CLB* inter-cell movement is $O(1)$.
- **Empty cell**: A cell may become empty when all the nodes move away. In this case, the last moving node (i.e. *CL* node) notifies the six neighbor cells. So, the resulting overhead is $O(1)$.

From the aforementioned analysis, the communication overhead for network maintenance on the cell level is $O(n)$. Therefore, the total cost of network maintenance (OH_{NM}) phase is:

$$OH_{NM} = O(C \times n) \tag{15}$$

It is obvious that the upper level of packet overhead depends on the number of nodes in each cell. This indicates that the re-clustering operations have local impact only and does not involve all the network nodes. This which makes the protocol more applicable to be implemented in large-scale networks.

3.2.3 Location Service Discovery

Position-based routing based on the availability of location information about the destination nodes. Typically, this needs a location service algorithm or availability of location server in the network to enable the source node to map the geographical positions of the destinations, which is one of the challenges facing position-based routing in MANETs.

Many of the previous researches assume that the information about the destinations positions are available at the source node or they incur large overhead to maintain these positions [16][17]. In fact, the simulation results presented for these research works shows that the location information is typically provided to all mobile nodes without cost [18][19].

For example, A Distance Routing Effect Algorithm for Mobility (*DREAM*) [20] is based on using *RDF*. *DREAM* assumes that each node maintains a position database that stores position information about all other nodes in the network. This assumption leads to large overhead due to the position updates and large position information maintained by each node. Consequently, the protocol is not scalable. Another example is Location-Aided Routing (*LAR*) protocol [21], it also based on using *RDF* in route discovery. Unlike *DREAM*, *LAR* does not require all nodes to maintain position information about every other node. Instead, it uses the available position information from a route that was established earlier. In case the locations are not available, it performs selected flooding.

In PBQMRP protocol, new location service algorithm is developed with reduced overhead. This it to facilitate the routing task without relying on availability of underlying location service algorithm. In PBQMRP, when a source node decides to initiate a multicast session, a location query packet (*INCELL_INV_REQ*) is first directed to its local *CL* node to ask for possible participating nodes in the held multicast session. This packet needs only 1-hop communication operation, since all nodes inside a particular cell are within the transmission range of each other. The local *CL* node then forward *OUTCELL_INV_REQ* packet to the six neighbor *CL*s. After that, the *OUTCELL_INV_REQ* packet is propagated until it reaches all the network cells. In our analysis, for simplicity, we consider the number of location discovery packets (*OUTCELL_INV_REQ)* issued from the orginal *CL* node, note that the forwarding of these packets between the neighbor *CL* nodes is performed using restricted directional flooding.

The cost of performing the location service may be zero if the destinations locations are available at the source node cache. In this analysis, let us consider the worst scenario, where the source node does not have location information about the destination nodes. In this case, the overhead resulted from the location request and reply packets is the summation of the overhead inside the source cell (OH_1) and that resulted from communication among the other cells (OH_2).

The source firstly unicasts the *INCELL_INV_REQ* packet to local *CL* node. The *CL* replies to this packet if there are local multicast members. Thus, the cost of the communication inside the source cell is:

$$OH_1 = O(1) \tag{16}$$

Then, the source *CL* initiates *OUTCELL_INV_REQ* packet to six neighbor cells. As shown in

Fig. 3, each neighbor *CL*, upon receiving such invitation packet for the first time, continues forwarding the packet only to a specific set of neighbor *CLs* rather than flooding it to all neighbor cells.

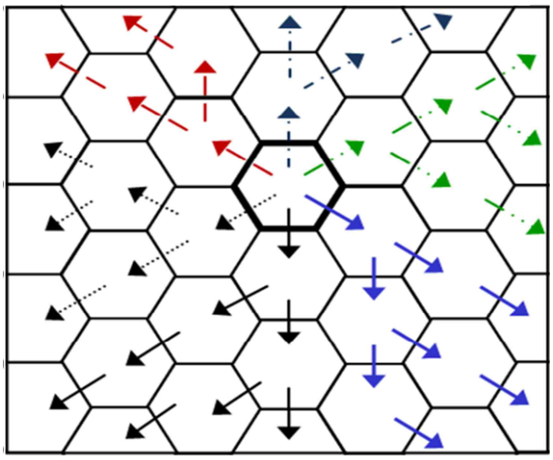


Fig. 3. Forwarding of *OUTCELL_INV_REQ* packets.

The proposed forwarding strategy enables the *CL* of each cell to take part in delivering the packet to at most two neighbor cells. This is based on both the border number that the packet comes from and the coordinates of the sending cell. This strategy insures that the *OUTCELL_INV_REQ* packet is propagated through the network with no duplicates and all the network cells are visited only once.

The overhead of sending *OUTCELL_INV_REQ* packet is as follows: initiating *OUTCELL_INV_REQ* packet by the source *CL* and forwarding the *OUTCELL_INV_REQ* packet by other *CL*s. Thus, the cost of these request packets is:

$$\text{Location request overhead} = 1\times 6 + (C\text{-}1) \times 2 = O(C) \quad (17)$$

Where C is the total number of cells in the network. The *CL* nodes that maintain multicast members reply to the *OUTCELL_INV_REQ* packets. Note that the source *CL* has already replied to *INCELL_INV_REQ* packet. Thus, the cost of the reply packets sent outside the same cell is as follows:

$$\text{Location reply overhead} = (C\text{-}1) \times 1 = O(C) \quad (18)$$

Hence, the overhead of location request and reply packets sent outside the source cell is:

$$\begin{aligned} OH_2 &= \text{Location request overhead} + \text{Location reply overhead} \\ &= O(C) + O(C) = O(C) \end{aligned} \quad (19)$$

Therefore, the total communication overhead of location service (OH_{LS}) for each multicast source is as follows:

$$\begin{aligned} OH_{\mathrm{LS}} &= \text{communication inside the source cell} + \text{communication among other cells} \\ &= OH_1 + OH_2 \\ &= O(1) + O(C) = O(C) \end{aligned} \quad (20)$$

It is obvious that the number of location request packets is greatly reduced and each network cell receives only one packet. This enables the execution of a scalable location discovery service utilizing the network virtual structure.

Table 3 summarizes the number of packets generated in each forwarding zone. It also shows the efficiency of the proposed forwarding strategy by comparing it with the traditional packet flooding; where packets are sent to all neighboring cells except the one that the packet already received from. In addition, **Fig. 4** highlights the large gap between the proposed strategy and the traditional packet flooding especially as the level number increases.

Table 3. Summary of different forwarding strategies of location service packets

Level number	# packets for our forwarding strategy	# packets for flooding strategy
Level 1	1×6 = 6	1 × 6 = 6
Level 2	2 × 6 = 12	6 × 5 = 30
Level 3	3 × 6 = 18	12 × 5 = 60
Level 4	4 × 6 = 24	18 × 5 = 90
Level 5	5 × 6 = 30	24 × 5 = 120
	⋮	
Level *i*	*i* × 6	((*i*-1)×6) × 5

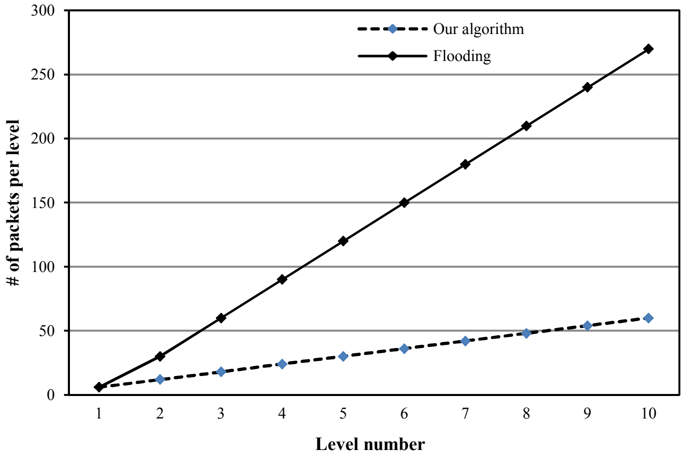


Fig. 4. Comparison between different forwarding strategies of location service packets.

It is clear that the proposed packet forwarding strategy between the network cells can effectively reduce the number of nodes which participate in forwarding the location service packets. It is worth mentioning that utilizing hexagon shape reduces the number of cells in the network compared to other shapes, which reduces the resulting overhead.

3.2.4 Route Discovery Overhead

The route discovery process starts by finding a route between the source and the coordinators; and later between the coordinators and the other destinations in the same sub-group (using the same mechanism). In other words, the source builds a sparse multicast tree with the coordinators and each coordinator builds a lower multicast tree with the local members in each sub-group.

Since restricted directional flooding (*RDF*) is used for forwarding route discovery packets, the number of nodes that participate in forwarding these packets depends on the euclidean distance between the sending node and the intended destination. In other words, upon receiving the route discovery packets, a node with lower euclidean distance (towards the destination) will be considered as forwarding node. This strategy helps in reducing the resulted overhead compared to broadcast strategy (in which all nodes existing in the network participate in forwarding the route discovery packets).

The following numerical example shown in **Fig. 5** illustrates the efficiency of *RDF* forwarding strategy. Assume that a particular source (*S*) needs to discover a route to a particular destination (*D*). Also, assume that a network area with dimensions 3km×3km is given and the number of nodes in this network is N=540 (considering node density as 60/km^2). For simplicity, it is assumed that the distance between *S* and *D* represents the diagonal of a square ($h \times w$) in which only the nodes within this square are considered as forwarding nodes. The number of nodes (m) in this flooding area is defined as follows:

$$m = \frac{\textit{Flooding area}}{\textit{Network area}} \times N = \frac{a}{A} \times N = \frac{h \times w}{H \times W} \times N \tag{21}$$

Where a is the flooding area, A is the network area, (h, w) are the dimensions of the flooding area and (H, W) are the dimensions of the entire network area.

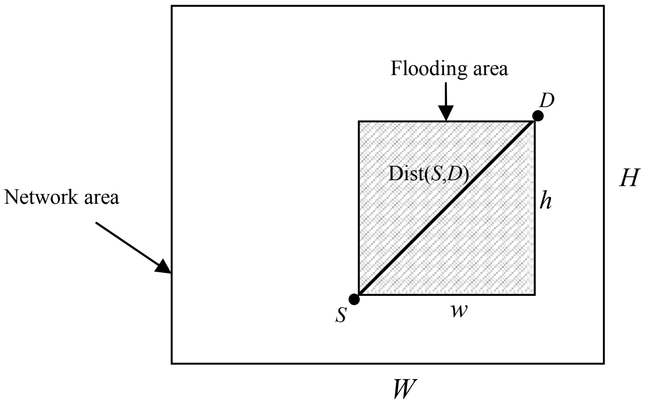


Fig. 5. Example of *RDF* flooding mechanism.

Fig. 6 shows the number of nodes that participate in forwarding the route discovery packets vs. the distance (in meters) between *S* and *D*. The figure considers both *RDF* strategy and blind flooding strategy.

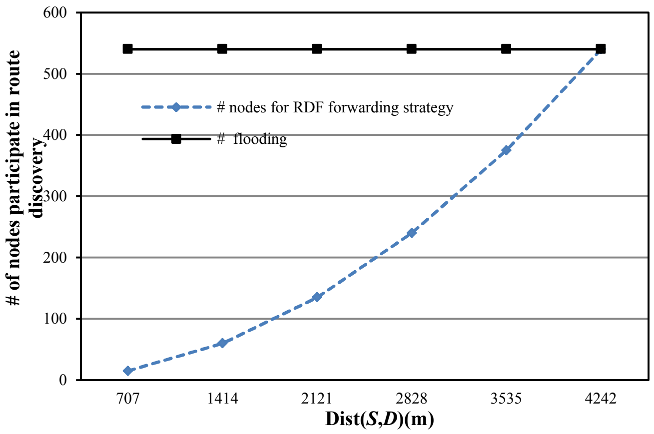


Fig. 6. Comparison between different flooding strategies of route discovery packets.

The resulting overhead for *RDF* strategy is $O(m)$ while in flooding scenario the overhead is $O(N)$. This overhead is generated between the source and each destination. Considering the number of destinations (d_{num}), then the overhead for route discovery using *RDF* (OH_{RDF}) is:

$$OH_{RDF} = O\left(\sum_{i=1}^{d_{num}} m_i\right) \tag{22}$$

The overhead of using *RDF* in the proposed protocol is much less than that of network flooding (OH_{FLD}) which is defined as:

$$OH_{FLD} = O(N \times d_{num}) = O(N) \tag{23}$$

The reply packets are forwarded through the reverse paths until they reach the original source node. The overhead of these reply packets is $O(1)$. Thus the total overhead of route discovery process (OH_{RD}) is:

$$OH_{RD} = O\left(\sum_{i=1}^{d_{num}} m_i\right) + O(1) = O\left(\sum_{i=1}^{d_{num}} m_i\right) \tag{24}$$

3.2.5 Route Maintenance Overhead

Since MANET topology is dynamic, the established routing path may be broken due to movement of one or more nodes along the route. Therefore, to recover the broken link, the affected node initiates a notification packet to the upstream nodes to update their routing table and inform the source to reinitiate new route discovery packet. In the proposed protocol, broken link affects only the nodes that are part of the routing path and does not have global effect. Thus the overhead of route maintenance phase is limited to the upstream and downstream nodes in the effected routing path, which is $O(1)$.

3.2.6 Summary of Control Overhead Analysis

As mentioned in section 3.2, the total control overhead of the proposed protocol is:

$$T_{\mathrm{OH}} = OH_{\mathrm{NC}} + OH_{\mathrm{NM}} + OH_{\mathrm{LS}} + OH_{\mathrm{RD}} + OH_{\mathrm{RM}} \tag{11}$$

Table 4 summarizes the packet overhead analysis of different phases of the proposed protocol.

Table 4. Control overhead cost in different protocol phases

Protocol working phase	**Total overhead**
Network construction (OH_{NC})	$O(N)$
Network maintenance (OH_{NM})	$O(C \times n))$
Location service algorithm (OH_{LS})	$O(\mathrm{C})$
Route discovery (OH_{RD})	$O\left(\sum_{i=1}^{d_{num}} m_i\right)$
Route maintenance (OH_{RM})	$O(1)$

From **Table 4**, it can be seen that the control overhead resulted from network creation and maintenance is limited to the number of nodes in local cells and the number of cells in the network. Also, the location discovery process is related to the number of cells which is not affected by the number of nodes in the network. The table also shows that the route discovery is restricted to the area towards destinations rather than the entire network area.

4. Performance Evaluation

In this section, we evaluate the effectiveness of the proposed protocol using GloMoSim [13]. The performance of this protocol has been compared with that of ODMRP [15], the best-studied on-demand multicast protocol for MANETs.

4.1 Simulation Environment and Parameters

The simulations were run with 240 nodes moving over network area of 2km × 2km, unless otherwise specified. Node mobility is simulated according to the random waypoint mobility model, since it is considered as one of the most utilized models in the literature [22]. Each simulation is executed for 600s. To study the behavior of the routing protocol without considering the environmental factors such as fading, shadowing and noise, the radio transmission range (250m) was assumed to be fixed and cannot dynamically controlled. The used MAC layer was IEEE 802.11 with a maximum channel capacity of 2Mb/s and the bandwidth requirement was set to 0.2Mb/s. A single multicast group with a single source and 48 receivers are used. The multicast source generates traffic of 128Kbps using Constant Bit Rate (CBR) traffic generator. The multicast groups' members are chosen randomly and join the multicast groups at the beginning of the simulation and remain as members throughout the simulation. For the following figures, each data point represents an average of ten runs with identical configuration but different seed values.

4.2 Simulation Results

We are mainly interested in the protocol's scalability and efficiency under several circumstances. We compare the performance of ODMRP and PBQMRP with the change of network size and mobility speed. The commonly used performance metrics that we are also intrested in are:

1. **Packet Delivery Ratio (PDR):** The ratio between the number of multicast data packets delivered to all multicast receivers and the number of multicast data packets supposed to be delivered to multicast receivers. This ratio represents the effectiveness of the multicast routing protocol.
2. **Normalized Packet Overhead (NPO):** The ratio of control packets transmitted to data packets delivered. This ratio investigates the efficiency of utilizing the control packets in delivering data packets. The counted routing packets include those sent during route initialization and maintenance phases for both protocols. In PBQMRP, all packets sent during the location service phase are also included in calculating this metric. Sending a control packet over one link is counted as one packet. For example, if a control packet traverses a route of *N* hops, *N* packets are counted.
3. **Cluster Overhead:** It is calculated as the summation of all packets sent during the setup and maintenance phases. The transmission at each hop along the paths is counted in the calculation of this metric.

4.2.1 Effect of Network Size

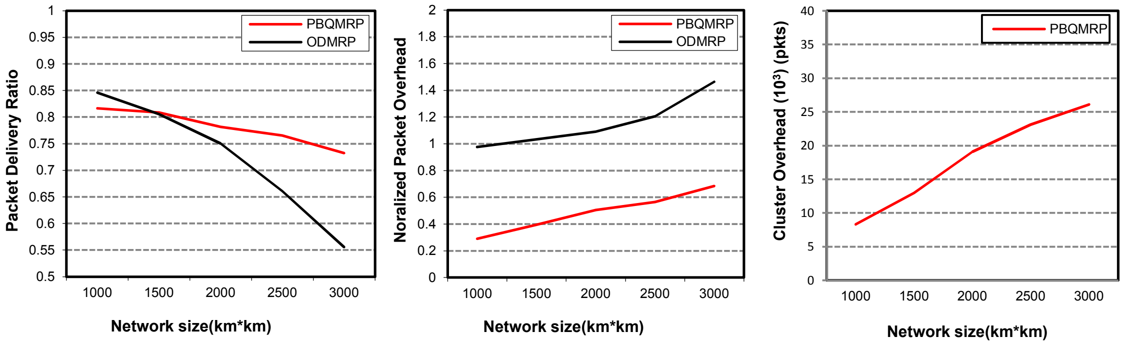
In this scenario, the performance of PBQMRP and ODMRP with different network sizes is evaluated. The mobility speed is fixed to 5m/s with 30s pause time. The number of nodes increases when the physical network size increases such that the density of nodes is maintained. The node density is set as 60 nodes/km^2. Hence, the number of nodes under various physical network sizes is set to 60 nodes in 1km × 1km, 135 nodes in 1.5m × 1.5km, 240 nodes in 2km × 2km, 375 nodes in 2.5km × 2.5km, and 540 nodes in 3km × 3km respectively.

Fig. 7(a) shows that PBQMRP is more scalable for large network sizes. As expected, the PDR for both protocols decreases as the network size increases. This is because increasing the dimension of the network increases the length of the discovered routes. This increases the probability of dropping some packets. However, in ODMRP, the decrease of PDR drops faster compared to PBQMRP. PBQMRP has higher PDR compared to ODMRP (7.9%). When the network size reaches 3km × 3km, the difference in PDR between both protocols reaches 18%. This gap results from the fact that PBQMRP uses only the routes that satisfy the requested QoS constrains which reduces the probability of packet drop.

In **Fig. 7(b)**, the normalized packet overhead of both PBQMRP and ODMRP increases as the network size increases. When the network size increases, the probability of having link break in the selected routes increases accordingly. This leads to reinitiating the route discovery process, thus increasing the number of control packets.

In PBQMRP, only the nodes closer to the destination participate in forwarding route request packets, which contribute to having reduced overhead. PBQMRP reduces NPO by 57.7% compared to ODMRP. Thus, ODMRP incurs larger overhead to forward the data packets and its NPO dramatically increases. The reason is that increasing the network size and keeping the node density lead to larger number of nodes participating in routing process, which provokes considerable redundant broadcast packets (*Join_Query* and *Join_Reply*). These results match the analytical results, which ensures that PBQMRP effectively reduces the control overhead.

Fig. 7(c). shows that cluster overhead increases when the network size increases. Increasing the network size results in increasing the number of control packets generated to maintain the network construction stable. Also, in position-based routing, it is expected to increase the number of position update packets as the number of nodes increases. Moreover, increasing the size of the network while fixing the cell size results in having larger number of cells which accordingly increases the overhead resulted from CLs election and CL-CLB backup.



(a) PDF vs. network size (b) NPO vs. network size (c)Cluster overhead vs. network size

Fig. 7. Effect of network size

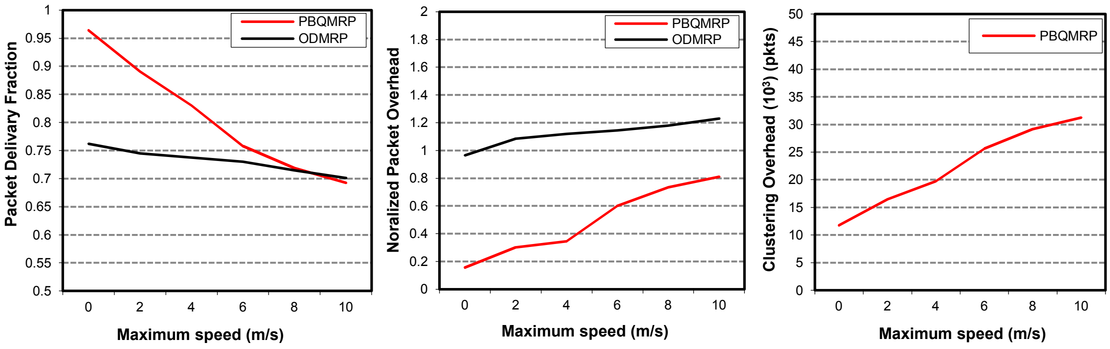
4.2.2 Effect of Node Mobility Speed

Fig. 8(a) shows the PDR for both protocols under various mobility speeds. As expected, PDR for the two protocols is very sensitive to mobility and as the node mobility increases the delivery ratio decreases. This is expected, since fast movement of the nodes increases the probability of link failure and topology change which leads to higher packets' dropout. In both protocols, multicast construction is likely to be stable under low mobility; therefore, the delivery rate is high. It is noticed that PBQMRP has a higher PDR at low to moderate mobility due to the efficient use of the network resources via using *RDF* during route discovery and the fact that only the routes that satisfy the bandwidth requirements are accepted. These two features effectively reduce the contention and increase the opportunity to deliver more data packets. Compared to ODMPR, PBQMRP increases the PDR by 10.6% on average. This makes PBQMRP more suitable in applications that are characterized with moderate mobility like confernces, shopping malls and exhibitions.

On the other hand, ODMRP shows lower but steadier packet delivery ratio and its performance drops only slightly as mobility speed increases. This is due to the mesh structure of ODMRP which provides multiple paths. As node mobility speed increases further, there are more frequent disconnections in the network and hence PDR is expected to decrease for both ODMRP and PBQMRP. PBQMRP is efficient in data forwarding but it is less robust to mobility and its performance degrades faster as the mobility increases due to its multicast tree design. In PBQMRP, as mobility increases, link breakage occurs more frequently and data cannot be forwarded until the route reconstruction process is completed. On the other hand, ODMRP performance is expected to decrease when the node mobility speed exceeds 10m/s. However, ODMRP shows more robustness to node mobility by utilizing the redundant paths in its forwarding group. The trade off is ODMRP's significant increase in control overhead because nodes participating in multicast sessions need to generate control packets periodically regardless of whether the route is stable or not.

Fig. 8(b) shows the normalized packets overhead for different mobility speed for PBQMRP and ODMRP. It can be seen that the normalized packet overhead of PBQMRP is lower than that of ODMRP for the different mobility speeds. PBQMRP improves the NPO by an average of 56.1% compared with ODMRP.

In PBQMRP, smaller number of nodes participates in routing the packets. This is because forwarding the packets is limited to the nodes that are in the way to the destination without the need of flooding. This is due to the use of RDF in forwarding the request packets. This result is also highlighted in the analytical analysis (refer to subsection 3.2.4). Also, during the route discovery of PBQMRP, the route request packet is dropped if the required bandwidth cannot be met, this reduces the control overhead. On the contrary, NPO of ODMRP slightly increases when the mobility speed increases. This is because the periodic *Join_Query* packets are flooded out at the same rate for different mobility speeds. When the nodes move faster, the next hop is more likely to move away, which makes the reverse routes learned through *Join_Query* are not reliable. So, if the *Join_Reply* is sent to the next hop that is no longer available, it gets dropped. That causes the *Join_Reply* to be sent several times without finding the next hop. Then, the node broadcasts another *Join_Query* packet to search for a route to the source node. All neighbor nodes receiving such packet need to generate their own *Join_Reply* packets, which causes the increase in normalized packet overhead when the mobility is increased.



(a) PDF vs. Max. mobility speed

(b)NPO vs. Max. mobility speed

(c)Cluster overhead vs. Max. mobility speed

Fig. 8. Effect of node mobility

In **Fig. 8(c),** the cluster overhead increases as node mobility increases. This increase is expected since increasing mobility speed generates more control packets to maintain the network structure and handle nodes movement in the network. From the simulated performance evaluation, it is observed that the cluster formation has direct impact on the protocol performance. So, our proposed protocol is designed in an appropriate way to ensure that the benefits from clustering could outweight the costs.

5. Discussion

From the analytical results presented in section 3, many points can be highlighted. First, in the network construction phase, the resulting message overhead is $O(N)$ as all nodes are involved in constructing the network structure. However, network construction occurs only once during network setup. The analysis also shows that selecting the cluster shape has direct impact on the control overhead of cluster-based routing protocols. Using hexagonal clustering, the number of clusters is minimized. This effectively reduces the overhead of the cluster head communications. Also, from the analysis, it is obvious that network maintenance operations are performed locally to reduce the computation and communication overhead.

The analytical results also indicate that the message overhead of performing the location service algorithm is $O(C)$. This means that the overhead depends on the number of cells in the network and is not affected with increasing the number of nodes in the network. Hence, our location service is able to support large networks with large number of destinations. This is a result of the efficient packets forwarding strategy between clusters, which eliminates duplicate packets.

The illustrations of performing position-based routing show that restricting the search for QoS paths in small regions reduces the number of request packets compared to blindly searching the entire network. This effectively reduces the traffic of route request packets and the probability of collision in the network. At the same time, this mechanism assures high probability of finding multiple paths between the source and the destinations. In the simulated scenarios, it is shown that PBQMRP outperforms ODMRP and delivers more packets with reduced control overhead. Hence, our simulation performance analysis assist the analytical approach results that also ensures the reduced control overehead of our protocol.

6. Conclusion

This paper has presented PBQMRP, a novel clustering scheme that supports multicast routing in MANETs. PBQMRP exploits the geographic information to construct a virtual cluster backbone to handle the dynamic topology network. This cluster is utilized to perform a location service algorithm without duplicate packets. Then an on-demand multicast tree is constructed between the source and all destinations using the location information of the mobile nodes.

We conducted a performance study of the proposed protocol using both analytical and simulation approaches. The results of both approaches demonstrate the efficiency of the proposed protocol in supporting large-scale networks and maintaining a stable routing topology. The analysis also highlights the impact of selecting the cluster shape on performing efficient routing.

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