Multicasting in Mobile Backbone Based Ad Hoc Wireless Networks

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Abstract – The synthesis of efficient and scalable multicasting schemes for mobile ad hoc networks is a challenging task. Multicast protocols typically construct a tree or mesh structure to distribute messages to multicast group members. Generally, these implementations impose scalability and efficiency limitations since they employ protocols that are based on a flat-topology networking architecture. We present three multicast algorithms that employ a dynamically synthesized Mobile Backbone Network (MBN) to achieve efficient message distribution among members of multicast groups. Using the synthesized Backbone Network (BNet), we have a hierarchical networking architecture that enables a multicast protocol to achieve low control overhead and high transmission efficiency. The multicast algorithms under investigation are: (1) BNet flooding multicast algorithm (BFMA); (2) Shared backbone multicast subnetwork (SBMS); (3) Hybrid multicast algorithm (HMA). Our simulation and mathematical analysis results demonstrate the enhanced performance achieved by these MBN-based multicast algorithms when compared to ODMRP, and provide performance comparisons for these algorithms.

I. INTRODUCTION

Multicasting is an operation that allows the distribution of a message to multiple recipients that are members of a designated group, and is useful to many ad hoc networking applications. Multicast protocols for MANETs typically construct a tree or mesh structure that is used to distribute messages to multicast group members. Generally, these implementations impose scalability and efficiency limitations for large networks since they employ protocols that are based on a flat-topology networking architecture. When nodal mobility and/or the number of multicast group members increase, traditional tree or mesh-based methods [3], [4], [5], [6] become inefficient due to the excessive number of control messages needed for the maintenance of the multicast structure. This packet control overhead will cause an increase in packet contention and collisions, resulting in network performance degradation. In order to address this scalability issue, it is essential to reduce the rate of the control messages. A number of studies attempting to reach such a reduction have been conducted. They can generally be classified into the following categories: overlay multicasting schemes [6], [8]; backbone-based multicasting mechanisms [9], [10]; and stateless multicasting algorithms [17], [18].

A comparison of the performance of different multicast protocols has been carried out in [7]. It is observed there that On-Demand Multicast Routing Protocol (ODMRP) [4] outperforms other examined protocols. ODMRP is a mesh-based multicast protocol that uses the forwarding group concept to select, for each multicast group a limited set of nodes for forwarding multicast messages. End-user group membership and multicast forwarding group membership are established and updated by each source on demand. A Join-Query packet is periodically broadcasted to refresh the end-user membership information and update the election of forwarding group members.

The objective of this paper is to present three backbone-based multicast algorithms that employ a dynamic Mobile Backbone Network (MBN) to achieve efficient message distribution among members of the multicast groups. The mobile backbone network architecture employed herein was presented in [1]. With the synthesized Backbone Network (BNet), we have a hierarchical networking architecture that enables a multicast protocol to achieve low control overhead and high transmission efficiency. The MBN-based multicast algorithms under investigation are: (1) BNet flooding multicast algorithm (BFMA); (2) Shared backbone multicast subnetwork (SBMS); (3) Hybrid multicast algorithm (HMA). Although performance comparison between intelligent broadcasting schemes and ODMRP for flat topology based MANETs has been studied in [11], BFMA is different in that it is based on a hierarchical backbone-based network layout.

Under the MBN protocol, nodes belong to one of these two classes: regular nodes (RN s) and backbone capable nodes (BCNs). A BNet is formed by dynamically electing BCNs to act as backbone nodes (BNs) and forming backbone links to interconnect neighboring BNs. Such a structure is illustrated in Fig. 1. The subnetwork that consists of thick solid lines connecting large solid circles interconnected by thick solid lines represents the BNet. In general, the MBN is designed so that it involves a sufficient but not excessive number of BNs, while providing high coverage. BCNs that are elected to convert into BNs will form the backbone network and the remaining nodes (unelected BCNs and RNs) will join the access net (ANet) of the BN that they are associated with. The ANets are represented as the dotted circles.

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The rest of the paper is organized as follows. Section II provides an overview of the MBN topology synthesis algorithm. Section III describes the three proposed MBN-based multicast algorithms. Section VI analyses the performance of the multicast algorithms. Section V shows the simulation environment. Section VI presents our simulation results and analysis. Finally, we conclude in section VII.

II. PRELIMINARY:
MBN TOPOLOGY SYNTHESIS ALGORITHM (MBN-TSA)

The MBN topology synthesis algorithm (TSA) employed herein has been proposed and presented in [2]. It is a fully distributed algorithm. There is no time synchronization between nodes; every node maintains its own time. Every node periodically sends Hello message to its direct neighbors. Note that in this design, nodes need to include only the BN neighbor list (instead of the full neighbor list) in their periodic Hello messages. In this manner, every node gains full 1-hop neighborhood and 2-hop BN neighborhood knowledge instead of full 2-hop neighborhood knowledge that is often required by other algorithms [12], [13] that construct a Connected Dominating Set (CDS).

A backbone network (BNet) is formed by dynamically electing backbone capable nodes (BCNs) to act as backbone nodes (BNs) and forming backbone links to interconnect neighboring BNs. Every BCN associates with one BN that is its direct neighbor. A BCN will convert to BN state if it needs to provide client coverage for its BCN neighbors or to enhance the local connectivity for its BN neighbors. A BN will convert back to BCN state if it finds that it is not needed for both client coverage and local connectivity purposes. For detailed description and performance analysis, please refer to [2].

III. BACKBONE-BASED MULTICAST ALGORITHMS

In the following subsections, we provide descriptions for the proposed backbone-based multicast algorithms. For all three algorithms, we use the distributed MBN topology synthesis algorithm to dynamically construct a backbone network that provides good coverage for all mobile nodes, i.e. each node is within a limited number of hops from a backbone node. This will ensure a level of backbone connectivity in response to communications link failures, nodal failures and nodal mobility.

A. BNet Flooding Multicast Algorithm (BFMA)

Under BFMA, multicast messages are flooded across the BNet. Each BN is responsible for copying the multicast packets of interest and distributing them to registered clients in its access net (ANet) that are recognized to be members of the message-designated multicast group. Since broadcast messages are relayed only by BNs, the rate of redundant packet transmissions in the network is reduced and the broadcast storm problem [14] is alleviated.

B. Shared Backbone Multicast Subnetwork (SBMS)

The SBMS protocol is a mesh-based multicast protocol. For each multicast group, every sender constructs a source-based tree connecting to all of its designated group members. The forwarding nodes included in these source-based trees (with the same multicast group) will join together to form a multicast subnetwork. The SBMS protocol differs from ODMRP in a number of aspects. Firstly, only the BNs are capable of becoming forwarding nodes in the multicast subnetwork. Secondly, the forwarding nodes know the identity of their corresponding 1-hop downstream nodes. Whenever a forwarding node (originator) discovers that one of its downstream nodes is missing (deduced by the non receipt of the corresponding Hello messages), a local reconstruction procedure is invoked to repair the link. Thirdly, the topology of the subnetwork is dynamically adjusted through the pruning and grafting of BNs as the latter lose and gain group members in their ANets. When a BN discovers that there is a new multicast member in its ANet, it will construct a link/branch to the closest forwarding node that is a member of the same multicast group. The multicast structure will eventually be “out of shape” due to nodal mobility. As a result, a periodic multicast route update is used to rebuild an optimized multicast subnetwork.

C. Hybrid Multicast Algorithm (HMA)

HMA is a hybrid BFMA/SBMS multicast algorithm whose multicast subnetwork structure dynamically adapts to the observed underlying network and multicast group membership conditions. HMA strives to achieve the better performance between BFMA and SBMS. The selection criteria include sender traffic load, number of multicast sources and number of multicast receivers. A sender-initiated periodic query is required for HMA to collect the necessary information to determine the best multicast structure to utilize for distributing the multicast packets. Since the query message is broadcasted, each sender is able to determine the number of multicast senders in the network. When the query reaches a multicast receiver, the receiver will respond with a reply message back to the originating sender with the amount of traffic load it received within a certain interval. The reply message also enables the sender to determine the number of multicast receivers in the network. The algorithm constructs a multicast subnetwork in the BNet when it discovers that the multicast group membership is small; alternatively it floods the multicast messages across the BNet when the multicast group membership is large and the network is heavily-loaded.
IV. PERFORMANCE ANALYSIS

The objective of this section is to present key performance measures for our proposed multicast algorithms. We are able to calculate the size of the multicast subnetwork and multicast efficiency for the algorithms under evaluation. Performance comparisons between BFMA and SBMS are presented in Section VI.

A. Backbone Network Size ($N_{BN}$)

The minimum-size BNet in a 2500m $\times$ 2500m operational area, with an effective radio transmission range of 300m is illustrated in Fig. 2. For analytical evaluations (that are used for system design, as well as to confirm and validate our simulation results), we use a disk covering approach to approximate the minimum size of the BNet. Such a lower bound estimate is obtained under the assumption that we can choose the optimum locations of the BNs to cover the whole area and form a connected BNet. The minimum BNet size for the underlying illustrative example is 56 BNs. Note that this lower bound is normally not achievable because under our MBN topology synthesis algorithm, BNs are selected among BCNs that randomly roam over the area of operations.

B. Multicast Subnetwork ($G_M$)

We assume nodes to employ omni-directional antennas. The transmission of a multicast packet by a sender BN is received by all of its direct neighbors, some receptions may be successful while others may not. When a multicast packet is transmitted across a designated multicast subnetwork $G_M$, only those directly-linked neighboring nodes that are also members of $G_M$ will retain and forward these packets. Thus, a multicast packet that is intended for $k_1$ multicast group members will be distributed through the subnetwork from the source BN to its $k_2$ destination BNs (whereby each of the latter manages an ANet that contains at least one single group receiver, such that $k_2 \leq k_1$). Note that the destination BNs will distribute the packet to their own ANets. For our MBN-based multicast schemes, since $G_M \subseteq BNet$, the upper bound for the number of BNs that can be selected to form the multicast subnetwork is $N(G_M) \leq N_{BN}$.

The data forwarding overhead ($D_{overhead}$) obtained from our simulation represents the ratio of the total number of multicast packets forwarded in $G_M$ to the total number of multicast packets successfully received by all receiving group members (not destination BNs). The total number of multicast packets forwarded in $G_M$ consists of 2 components:

1) When all group members receive the multicast packet, the number of BNs in $G_M$ that successfully forward the multicast packet is $N(G_M)$.

2) When a multicast packet is lost during the forwarding process in $G_M$, the fraction $\alpha$ of BNs in $G_M$ that successfully forward the multicast packets (averaged over all simulation runs) is $\alpha N(G_M)$, where $0 \leq \alpha \leq 1$.

Thus, using $PDR$ to represent the average value of realized packet delivery ratio across $G_M$ and $N_R$ as the total number of receiving multicast members, the data forwarding overhead for a multicasting scheme is defined as

$$D_{overhead} = \frac{N(G_M) PDR \cdot \left[ \alpha N(G_M) (1 - PDR) \right]}{N_R \times PDR}$$

$$= \frac{\beta N(G_M)}{N_R \times PDR}.$$  \hspace{2cm} (1)

From (1), the multiplication factor $\beta$ is expressed as

$$\beta = \left( 1 - \alpha \right) PDR + \alpha,$$  \hspace{2cm} (2)

where $0 \leq \beta \leq 1$. Note that when $PDR \approx 1$, $\beta \approx 1$. In this case, the size of the multicast subnetwork, $N(G_M)$ is reduced to

$$N(G_M) = D_{overhead} \times N_R.$$  \hspace{2cm} (3)

C. Multicasting Efficiency ($\eta$)

For each multicast scheme, the total data traffic/transport load applied over all BNs that are members of $G_M$ is given by

$$\lambda_{data} = \tilde{\lambda}_S \times N_S \times \beta N(G_M),$$  \hspace{2cm} (4)

where $\tilde{\lambda}_S$ represents the sender traffic load, $N_S$ denotes the number of sending nodes for the underlying multicast group and $\beta$ is the multiplication factor shown in (2). Note that for clarity of presentation we only consider a single multicast group; yet, the presented analysis applies in the same manner to each multicast group and to the combined total loading.

The overall internal traffic load is calculated as $\lambda = \lambda_{data} + \lambda_{control}$. Under the MBN-based multicast algorithms, the contribution of the control traffic load to the overall internal traffic load is insignificant when compared to that made by the data component. This is because the control packets in our schemes are relatively small, typically having a size that is less than 10% the size of a medium-size 512 bytes data packet. For example, under BFMA, the control overhead (consists only of the MBN-TSA’s 1-hop Hello messages) is

$$\lambda_{BFMA} = 250 \text{ nodes} \times (\text{control packet size} / \text{Hello message interval})$$

= 250 \text{ nodes} \times (400 \text{ bits} / 2 \text{ sec}) = 50 \text{ kbps},
while simulation runs for our illustrative network shows that the data rate, $\lambda_{data}$ for an efficiently-loaded network is in the order of Mbps. The effective overall internal BNet capacity, which is also identified as the network’s transport capacity is

$$C_i = SRF \times R,$$

(5)

where $SRF$ denotes the network’s spatial reuse factor and $R$ is the channel’s link layer data rate. The network’s normalized internal loading ratio is defined as

$$\tau = \frac{\lambda_i}{C_i},$$

(6)

with $\lambda_i \leq C_i$ to express the fraction of the overall internal transport capacity that is occupied by multicast traffic. The multicasting efficiency of the system is defined as the ratio between the total multicast throughput ($\lambda_{TH}$) measured at the multicast receivers and the total internal multicast traffic load:

$$\eta = \frac{\lambda_{TH}}{\lambda_i} = \frac{(\lambda_i \times N_{B} \times N_{R}) \times PDR}{\lambda_i}$$

(7)

V. PROTOCOL PARAMETERS AND SIMULATION MODELS

A. Simulation Environment

The simulation models of the proposed multicasting schemes were implemented in QualNet v 3.6.1. The Distributed Coordination Function (DCF) of IEEE 802.11 is used as the MAC layer protocol. The channel capacity is 2 Mbps and the effective radio transmission range is 300m. The multicast protocol parameter values can be found in Table I. Different refresh intervals were examined for ODMRP and SBMS, and the optimum value was selected to be 10 and 30 seconds for the respective protocols to achieve low overhead while maintaining a good packet delivery ratio. The general settings for conducting the simulation scenarios were listed in Table II. Network traffic load is calculated as (packet size $\times$ number of sender $\times$ number of packet/sec/sender). All nodes were placed randomly within the area. The inter-arrival time of data packets for each sender is exponentially distributed. The senders were chosen randomly with uniform probability among all the network nodes. The member nodes join the multicast session at the beginning of simulation and remain as members throughout the simulation. Note that all multicast senders and receivers belong to the same multicast group.

B. Simulation Metric

- Packet Delivery Ratio (PDR): The ratio of the number of data packets actually received by the receivers versus the expected number supposed to be received.
- Data Forwarding Overhead: Represents the number of data packets transmitted (including packet retransmissions) for each data packet that is successfully delivered to the receivers.
- Control Overhead: Represents the number of control packets transmitted for each data packet that is successfully delivered to the receivers. This metric measures how efficiently control packets are utilized for delivering data.

VI. SIMULATION RESULTS AND ANALYSIS

A. The Effects of Mobility

In this scenario, the simulation is run for two different sets of multicast receivers – groups of 10 and 50 receivers, each with 10 senders at a relatively high total sender traffic load of 70 kbps. Nodes move according to the random waypoint mobility model. Mobility speed was varied from 0 m/s to 20 m/s. Fig. 3(a) shows the PDR of the protocols under different mobility speeds. Our multicast algorithms achieve excellent PDR levels for both receiver sizes, as compared to ODMRP. BFMA achieve high throughput through flooding in the BNet, while SBMS maintains its robustness to mobility with redundant routes in the multicast subnetwork. It is noted from the plot that the PDR of HMA follows the better of the two basic schemes.

Fig. 3(b) shows the number of data packet transmissions performed for each successful data packet delivery. We observe that all of our multicast algorithms achieve excellent data forwarding overhead as compared to ODMRP due to the use of the backbone network to limit the number of packet forwarding nodes. Generally, the use of a simple flooding scheme would induce the highest level of forwarding overhead, barring the use of any intelligent flooding [15], [16]. However, hierarchical multicasting schemes such as BFMA restrict the flooding of messages to the smaller BNet. SBMS has the best data forwarding overhead because the algorithm uses a multicast subnetwork in the BNet that only allows a specially selected group of nodes to forward the multicast message. With a network that contains a small multicast group size of 10 multicast members, BFMA is not as efficient as SBMS, as is illustrated in Fig. 3(b). The multicast subnetwork constructed by SBMS limits the distribution scope of messages and thus exhibits improved performance. Again, we observed that HMA selects SBMS as its underlying multicast scheme to achieve a better data forwarding overhead.

Comparison of control overhead for the underlying protocols is shown in Fig. 3(c). For our backbone-based multicast algorithms, the key control overhead involves the employment of Hello messages, which are used to maintain the MBN layout and operation. The overhead traffic of ODMRP includes Join-Query and Join-Reply messages.

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BFMA does not incur any extra control overhead other than the MBN-TSA’s Hello messages. SBMS and HMA has higher control overhead than BFMA since these algorithms require the use of periodic updates. Note that the control overhead incurred for all algorithms remains relatively constant because the underlying periodic updates are not triggered by mobility. Increasing the updating frequency of ODMRP such that it shares similar control overhead with BFMA/SBMS/HMA will not improve the PDR of ODMRP since the refresh interval selected is considerably optimal.

**B. The Effects of Network Traffic Load**

In this scenario, the network traffic load was varied by changing the sender packet flow rates. Using a peer-to-peer multicasting model, a multicast sender simultaneously acts as a multicast receiver. For multicast group sizes of 10 and 50, both using a packet size of 512 bytes, the total sender traffic load of (20, 40, 80, 120, 160 kbps) is loaded into the network. The simulation is run with mobility speed of 10m/s.

Fig. 4(a) shows the PDR of the multicast protocols versus total sender traffic load. As the traffic load increases, the rate of collision and packet loss increases, causing the PDR of the multicast protocols to degrade. The advantage of using backbone-based multicasting is apparent in this case: our multicast algorithms perform much better than ODMRP in highly-loaded networks due to their excellent data forwarding overhead as shown in Fig. 4(b). For small multicast group size of 10, the per-source multicast subnetwork constructed by SBMS limits the distribution scope of the multicast messages, resulting in a better packet delivery performance. On the other hand, for large multicast group size of 50, both BFMA and SBMS have similar data forwarding overhead, i.e. the multicast subnetwork of SBMS almost consists of the entire BNet in order for the senders to connect to all of the intended multicast receivers. As a result, BFMA has a better PDR in this scenario because it utilizes less control overhead than SBMS, as shown in Fig. 4(c).

Under BFMA, for a small multicast group size of 10, simulation results in Fig. 4(b) show that $D_{\text{BFMA}}^{\text{overhead}} \approx 10$. Since multicast packets are flooded across the BNet, the size of the multicast subnetwork for BFMA, $N(G_{bfma}^{BFMA})$ equals to the size of the BNet. Assuming that no packet losses are incurred ($PDR = 1$), the average size of the BNet for our simulation runs can be determined using (3):

$$N_{BN} = N(G_{bfma}^{BFMA}) = 100$$

We select a total sender traffic load of 60kpbs for the subsequent calculations. From (4), the total data traffic load $\lambda_{data}^{BFMA} = 6$ Mbps. From Section IV, we obtained $\lambda_{control}^{BFMA} = 50$ kbps. Thus, the overall internal multicast traffic load is $\lambda_{j}^{BFMA} \approx 6$ Mbps. Approximate analysis using the relative size of the area dimensions with respect to the transmission range provides an estimated spatial reuse factor of 3.5. From (5), we have $C_j = 7$ Mbps. Thus, from (6), we obtain a network capacity consumption level $\tau$ of about 80%. For a
sender traffic load of 6 kbps and \( PDR = 1 \), the multicast efficiency for BFMA is calculated using (7):

\[
\eta = \frac{\lambda_{TH}}{\lambda_{BMFA}} = \frac{6\text{ kbps} \times 10 \times 10}{6\text{ Mbps}} = 10\%
\]

The realized multicast efficiency depends on the number of intended multicast receivers. If we increase the number of receivers to 50, the efficiency level will increase five fold.

Under the SBMS scheme, simulation results observed in Fig. 4(b) show that \( D_{\text{overhead}} \approx 8 \). Using our definition in (3), the average number of BNs required to form the SBMS multicast subnetwork is

\[
N(G_{\text{SBMS}}) = 80.
\]

The total data traffic load, \( \lambda_{\text{data}}^{\text{SBMS}} = 4.8 \text{ Mbps} \). The control traffic load induced by the SBMS scheme consists of Hello messages that are created and used by the topology synthesis algorithm and the periodic query and reply messages. To simplify our calculations, we assume that the reply messages created by the receivers are flooded in the BNet when traveling back to the originating sender. This yields a conservative worse-case calculation for control traffic load:

\[
\lambda_{\text{control}}^{\text{SBMS}} = \text{MBN-TSA} + \text{periodic queries and replies} \leq 50 \text{ kbps} + \left( N_g \times N_p \right) \times N_R \times \frac{\text{control packet size}}{\text{periodic query interval}} = 183 \text{ kbps}
\]

The overall internal multicast traffic load, \( \lambda_{i}^{\text{SBMS}} \approx 5 \text{ Mbps} \). Thus, we obtain the corresponding results for SBMS:

\[
\tau = 71\%, \quad \eta = 12\%
\]

The main parameter values obtained from the comparison of the BFMA and SBMS are listed in Table 3.

**VII. CONCLUSIONS**

In this paper, we propose three hierarchical multicast algorithms that employ a Mobile Backbone Network (MBN) to achieve efficient message distribution among members of multicast groups. Through a series of simulation based evaluations and analytical derivations, the performance characteristics of our MBN-based multicast algorithms are compared. Our results show that BFMA is highly scalable in terms of its performance sensitivity to variation in nodal mobility and network traffic loading levels, whereas the SBMS scheme is noted to be best suited for networks that are characterized by smaller multicast group sizes. HMA is a hybrid BFMA/SBMS multicast algorithm that strives to achieve the better performance between BFMA and SBMS. Simulation results have confirmed that the scheme's performance behavior follows the better of the two basic schemes, with control overhead that is similar to that induced by the SBMS scheme. Overall, our backbone-based multicast algorithms achieve excellent packet delivery ratios while requiring relatively low data forwarding overhead.

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**TABLE III**

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<tr>
<th>( D_{\text{overhead}} )</th>
<th>BFMA</th>
<th>SBMS</th>
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</thead>
<tbody>
<tr>
<td>( \lambda_{\text{data}} )</td>
<td>6 Mbps</td>
<td>4.8 Mbps</td>
</tr>
<tr>
<td>( \lambda_{\text{control}} )</td>
<td>50 kbps</td>
<td>( \leq 183 \text{ kbps} )</td>
</tr>
<tr>
<td>( G_{M} )</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>( \tau )</td>
<td>80%</td>
<td>71%</td>
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<tr>
<td>( \eta )</td>
<td>10%</td>
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**REFERENCES**


