Multicasting in Energy Aware Mobile Backbone Based Wireless Ad Hoc Networks
(Invited Paper)

Choo-Chin Tan and Izhak Rubin
Electrical Engineering Department
University of California, Los Angeles (UCLA)
Los Angeles, CA 90095
{choo, rubin}@ee.ucla.edu

Abstract – The synthesis of efficient and scalable multicasting schemes for wireless ad hoc networks is a challenging task. In this paper, we present three multicast algorithms that employ a dynamically synthesized Energy-Aware Mobile Backbone Network (E-MBN) to achieve efficient message distribution among members of the multicast groups. E-MBN incorporates a power saving mechanism that allows inactive nodes to transition into sleep state to conserve energy, and elects nodes with higher energy reserves as backbone nodes (BNs) to extend network lifetime. 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); and (3) dynamically adaptive hybrid multicast algorithm (HMA). We study the throughput (per-watt) performance efficiency of the E-MBN based multicast protocols through analytical and simulation evaluations. For fair comparison, we defined and implemented an extended version of ODMRP with power saving mechanism (ODMRP-PS). Our results demonstrate the enhanced performance achieved by the E-MBN based multicast algorithms when compared to ODMRP-PS, 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 multicast group, and is useful in many ad hoc networking applications such as tactical battlefield communications. Many wireless ad hoc/sensor networks include nodes that are highly energy limited. To preserve acceptable operational lifetimes for these nodes, it is essential to employ multicast protocols that minimize nodal energy consumption while providing reliable network transmissions. Existing energy conservation mechanisms for ad hoc networks can be classified into two categories: active and passive.

Active energy conservation schemes reduce energy consumption of a node based on operation optimization instead of turning off its radio module. Various energy-efficient multicasting schemes [1], [2] have been introduced to find a minimum-energy multicast tree such that the total energy cost is minimized by adaptively adjusting the radio transmission power levels, whereas maximum lifetime multicast schemes [3], [4] rely on balancing the energy dissipation among nodes to maximize the operational lifetime of the network.

Passive energy conservation schemes reduce energy consumption of a node by turning off its radio module when it has no communication activity. The radio module can be modeled to dynamically operate in four key states: sleep, idle, receive, and transmit states. Table 1 illustrates the energy consumption rates of the Lucent WaveLAN 802.11b network interface card, as measured by L. Feeney et al. [5]. The energy consumption of a nodal entity when it resides in idle state is only slightly lower than that observed when it resides in receive state. Thus, it is crucial from the energy-saving perspective to switch the radio module to sleep state when a node is not in use, rather than only depending on plain active energy conservation schemes.

Multicast protocols for wireless ad hoc networks 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 [6], [7], [8], [9] become inefficient due to the excessive number of control messages needed for the maintenance of the multicast forwarding structure. This packet control overhead will cause an increase in packet contention and collisions, resulting in network performance degradation. In [10], we have introduced mobile backbone based multicast algorithms to solve this scalability issue. Using a dynamically synthesized backbone network, we have a hierarchical networking architecture that enables a multicast protocol to achieve low overhead and high transmission efficiency.

The objective of this paper is to present three multicast algorithms that employ a dynamically synthesized Energy-Aware Mobile Backbone Network (E-MBN) to achieve
efficient message distribution among members of the multicast groups. E-MBN is an extension of the MBN architecture which incorporates a power saving mechanism that allows inactive nodes to transition into sleep state to conserve energy, and elects nodes with higher energy reserves to act as forwarding nodes to extend the lifetime of the network. The E-MBN based multicast algorithms under investigation are: (1) Bnet flooding multicast algorithm (BFMA); (2) shared backbone multicast subnetwork (SBMS); and (3) dynamically adaptive hybrid multicast algorithm (HMA). We study the throughput efficiency performance of the E-MBN based multicast algorithms through analytical and simulation evaluations. For fair comparison, we have defined and implemented an extended version of ODMRP with power saving mechanism (ODMRP-PS). The specifications and detailed description of ODMRP-PS can be found in the Appendix.

The rest of the paper is organized as follows. In Section II, we provide an overview of the energy-aware mobile backbone network architecture and its topology synthesis algorithm. In Section III, we present the three proposed E-MBN based multicast algorithms. In Section IV, we analytically study the performance of the multicast algorithms. In Section V, we briefly describe our simulation scenario and settings. In Section VI, we present our simulation results and analysis. Finally, we conclude in Section VII.

II. ENERGY-AWARE MOBILE BACKBONE NETWORK (E-MBN)

Under the original Mobile Backbone Network (MBN) architecture [11], nodes belong to one of these two classes: regular nodes (RNs) and backbone capable nodes (BCNs). The backbone network (Bnet) is constructed 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 large solid circles interconnected by thick solid lines represents the Bnet. In general, the Bnet is designed so that it involves a sufficient but not excessive number of BNs while providing high topological coverage. Assuming a connected network layout, each BCN is a single hop away from at least one BN, and each RN can reach at least a single BN by traversing a path that consists solely of RNS. We note that for the special case under which all nodes are BCNs, the Bnet serves as a Connected Dominating Set (CDS) of the network graph. Each BCN or RN is required to associate with a single BN. A BN and its associated BCNs and RNs will form an access network (Anet). The Anets are represented by the dotted circles in the figure.

The Energy-Aware Mobile Backbone Network (E-MBN) is introduced to achieve two objectives: firstly, we want conserve energy by allowing inactive nodes that are not involved in multicasting operation to transition into sleep state; and secondly, we want to extend the lifetime of the network by balancing the energy dissipation of the nodes. The first objective can be achieved by incorporating a MAC layer power saving mechanism into MBN, which design is in accordance to the operation of IEEE 802.11 power saving mode. Under the MBN power saving scheme, which was first introduced in [12], BNs are kept awake all the time to coordinate the sleeping/suspending schedules among its local non-backbone nodes (the non-elected BCNs and RNs) located in their corresponding Anets. All nodes wake up periodically at the beginning of each super frame and stay awake during this control and management (C&M) period.

Under the E-MBN architecture, BNs are selected among BCNs in a network based on selection rules that strive to meet certain criterion. For example, under passive energy conservation schemes, it is desirable to form a small backbone to save more energy. However, constructing a minimum size Bnet without energy awareness will lead to quick energy exhaustion to this small subset of nodes that forms the Bnet, risking a disconnection of the entire network. Thus, to extend the lifetime of a network, we require an energy-aware topology synthesis algorithm that allows the relatively energy-deficient BNs to be converted back to BCNs and elect energy-abundant BCNs to act as BNs.

The Topology Synthesis Algorithm (TSA) employed herein is a modified version of the one presented in [13]. It is a fully distributed algorithm. Every node periodically sends hello messages to its direct neighbors. A backbone network (Bnet) is formed by dynamically electing backbone capable nodes (BCNs) to act as backbone nodes (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 a BCN if it finds that it is not needed for both client coverage and local connectivity purposes. These conversion decisions are based
on the weight of the nodes. The weight of a node can be calculated based on its node ID, degree, capability or some stability measures. Please refer to [13] for a detailed description of the conversion algorithm.

In order to extend the lifetime of a network, we require an energy aware conversion algorithm that allows the relatively energy-deficient BNs to be converted back to BCNs (so that they can fall asleep) and elect BCNs with higher residual energy to act as BNs. In order words, we want to reduce the variance of the energy consumption among the nodes. The hello messages in TSA are modified to include nodal residual energy information. Thus, the average 1-hop neighbors’ residual energy for node \( u \) is defined as:

\[
E_{\text{avg}}(u) = \sum_{v : \text{deg}(u)} E_r(v) / \text{deg}(u),
\]

where \( E_r(u) \) is the residual energy of node \( u \), and \( \text{deg}(u) \) is the degree of node \( u \), where \( \text{deg}(u) = |N_B(u) \cup N_{BCN}(u)| \). \( N_B(u) \) and \( N_{BCN}(u) \) represent the set of 1-hop BN and BCN neighbors of node \( u \) respectively. RN neighbors are not included in this definition since they are not involved in the Bnet construction. The energy threshold is then found to be:

\[
E_{\text{TH}}(u) = \alpha \times E_{\text{avg}}(u),
\]

where \( 0 \leq \alpha \leq 1 \) is a multiplicative factor. A BN \( u \) will be forced to convert into a BCN when \( E_r(u) \leq E_{\text{TH}}(u) \). Under this residual energy constraint, the weight of node \( u \), \( wt(u) \) is modified to ensure it will have a lower possibility to become a BN under the TSA conversion criteria. However, in order to maintain Bnet connectivity, node \( u \) will remain as a BN until a neighboring BCN is elected to be the new BN. This conversion process is performed under the condition that Bnet must maintain good topological coverage, i.e. a BN will remain as a BN if there is no neighboring BCNs that can act as its replacement, until all its energy is depleted.

### III. E-MBN Based Multicast Algorithms

In the following subsections, we provide descriptions for the proposed E-MBN based multicast algorithms. For all three algorithms, we use the distributed E-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 ensures a level of backbone connectivity in response to communications link failures, nodal failures and 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-subnet-based multicast protocol. For each multicast group, every sender constructs a source-based Bnet Shortest Path Tree (BSPT) connecting to all of its designated group members. The superposition of the BSPTs (of the same multicast group) will form the multicast subnetwork for SBMS. For multiple sources attached to the same source BN, only a single BSPT is constructed. The SBMS protocol differs from ODMRP in a number of aspects. Firstly, only 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 movement. As a result, periodic multicast route updates are required 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 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 messages are 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.

### IV. Performance Analysis

The objective of this section is to present key performance measures for our proposed multicast algorithms. We are able to mathematically characterize the multicast efficiency and bit-per-joule performance for the algorithms under evaluation. Our analysis proceeds as follows: we first
examine the backbone network size and multicast subnetwork to obtain an expression for multicast efficiency. Then, we evaluate the number of active nodes and energy consumption level for different multicast algorithms to obtain an expression for bit-per-joule throughput efficiency.

A. Backbone Network Size

The minimum-size Bnet for a 1500m × 1500m operational region with an effective radio transmission range of 300m is illustrated in Fig. 2. Kershner [15] showed that no arrangement of circles could cover an area more efficiently than the hexagonal lattice arrangement. The effective radio transmission range of a node, \( r \), determines the length of a hexagon’s side. For analytical and simulation evaluations, we use a unit disk covering approach to approximate the minimum size of the Bnet. Such a lower bound estimate is obtained under the assumption that we could choose the optimum locations of the BNs to cover the entire area, i.e. the BNs are located at the vertices of the hexagons. The Bnet forms a Connected Dominating Set (CDS) since any node located inside a hexagon is reachable from at least one of the vertex nodes of the hexagon. Since each hexagons is completely covered, this pattern guarantees connected-coverage to the entire area. Using this arrangement, the minimum number of BNs required to form a Bnet to cover the entire \( D \times D \) square region \( (D > r) \) is approximated to be

\[
\frac{4}{3\sqrt{3}} \approx 0.769 \frac{D^2}{r^2} \quad [16].
\]

Thus, the minimum Bnet size for the underlying illustrative example is approximated to be 19 BNs. Note that this lower bound is not normally achievable in real scenario because BNs are selected among BCNs that randomly roam over the area of operation.

B. Multicast Subnetwork \((G_M)\)

An ad hoc network can be represented as an undirected graph \( G = (V_G, E_G) \), where \( V_G \) is the node set and \( E_G \) is the set of links between nodes. 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, though some receptions may be successful while others may not. Let \( G_M = (V_M, E_M) \subseteq G \) be the multicast subnetwork. When a multicast packet is transmitted across a designated \( G_M \), only those directly-linked neighboring nodes \( v \in V_M \) will retain and forward these packets. Thus, a multicast packet that is intended for \( k_2 \) 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 destination BNs will distribute the packet to their own Anets. For our E-MBN based multicast schemes, let \( G_{Bnet} = (V_{Bnet}, E_{Bnet}) \) be the backbone network graph, where \( V_{Bnet} \) consists of all BNs and \( N(G_{Bnet}) = |V_{Bnet}| \) be the number of BNs in the Bnet. \( E_{Bnet} \) is the set of links that interconnect the nodes \( v \in V_{Bnet} \). Since \( G_M \subseteq G_{Bnet} \), the upper bound for the number of BNs that can be selected to form the multicast subnetwork is \( N(G_M) \leq N(G_{Bnet}) \).

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:

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

(ii) 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 \( N_S \) as the total number of receiving multicast members, the data forwarding overhead for a multicasting scheme is defined as:

\[
D_{overhead} = \frac{N(G_M) \cdot PDR + \alpha N(G_M) (1 - PDR)}{N_S \times PDR} \quad (3)
\]

The multiplication factor \( \beta \) can be expressed as:

\[
\beta = \left(1 - \alpha\right) PDR + \alpha \quad (4)
\]

where \( 0 \leq \beta \leq 1 \). Note that when \( PDR \approx 1 \), then \( \beta \approx 1 \).

C. Multicast 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:

\[
f_{data} = \lambda_S \times L_P \times N_S \times N(G_M) \quad (5)
\]

where \( \lambda_S \) represents the average packet arrival rate, \( L_P \) is the average data packet size, and \( N_S \) denotes the number of source nodes for the underlying multicast group. 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 \( f_I = f_{\text{data}} + f_{\text{control}} \). Under the E-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 TSA’s 1-hop hello messages) for a network with 100 nodes is:

\[
\begin{align*}
    f_{\text{BFMA}}^{\text{control}} &= N \times \left( \frac{L_c}{\text{update interval}} \right) \\
    &= 100 \times (400 \text{ bits} / 1 \text{ sec}) \\
    &= 40 \text{ kbps},
\end{align*}
\]

where \( N \) is the total number of nodes in the network and \( L_c \) is the average control packet size. Simulation runs for our illustrative network shows that the data rate, \( f_{\text{data}} \), 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:

\[
C_i = \text{SRF} \times R,
\]

where \( \text{SRF} \) denotes the network’s spatial reuse factor and \( R \) is the channel’s link layer data rate. The upper bound for SRF for a \( D \times D \) square region can be approximated to be \( D^2/\pi r^2 \).

The network’s normalized internal loading ratio is defined as:

\[
\tau = \frac{f_I}{C_i}
\]

(7)

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 \( (f_{\text{mul}}) \) measured at the multicast receivers and the total internal multicast traffic load

\[
\eta = \frac{f_{\text{mul}}}{f_I} = \frac{\lambda_s \times L_p \times N_s \times N_g}{f_I}.
\]

(8)

D. Number of Active Nodes \( (N_a) \)

For E-MBN based multicasting, all BNs must be active all the time, regardless of whether they are selected to be in \( G_M \) under different multicast schemes. The rest of the nodes (BCNs and RNs) will be in sleep state unless they are the source or receiver nodes. A BCN can be appointed to be a source or receiver, resulting in the possibility that some of these nodes could be converted into BNs under the TSA conversion criteria. Thus, the average number of active nodes for E-MBN based multicasting is:

\[
N(G_{\text{burst}}) \leq N_a \leq \max \left( N(G_{\text{burst}}) + \gamma (N_G + N_s), N \right),
\]

(9)

where \( \gamma \) is the probability that a sender or a receiver is not a BN, and \( N \) is the total number of nodes in the network. For ODMRP-PS, we obtained:

\[
N(G_s) \leq N_a \leq \max \left( N(G_M) + \gamma^* N_G, N \right),
\]

(10)

where \( \gamma^* \) is the probability that a receiver is not a forwarding node.

E. Energy Consumption Rate \( (W) \)

For our approximate analysis, we assume the energy consumption rates for a node that is in the receive state is the same as that incurred when it is in the active idle state. Also, we neglect the energy consumption rate when a node is in sleep state, since it is significantly smaller than the energy consumption rates incurred when a node is in other states.

The energy consumption rate for a node that is in the active non-transmission state is \( W_i \) watts, while the energy consumption rate in the transmission state is \( W_T \) watts. The energy consumption rate consists of three components:

(i) Contributed by nodes during periods that are transmitting packets.

(ii) Contributed by nodes that are active (either in idle or receive state) but are not in the transmission state.

(iii) Contributed by nodes during the control and management (C&M) period.

With \( N_s \) and \( \lambda_s \) denoting the number of sender and average packet arrival rate respectively, the average energy consumption rate \( W \) is given as:

\[
W = (1 - \epsilon) \left[ \left( \frac{N(G_s) \lambda_s L_p N_s}{R} \right) W_G + N_s (1 - \rho) W_N \right] + \epsilon \left( N_N \lambda_s W_T + (1 - \epsilon) N N \right),
\]

where \( \rho = \frac{N(G_s) \lambda_s L_p N_s}{N_s R} \) is the fraction of time an active node stays in the transmission state, \( \epsilon \) represents the fraction of time a node stays in the C&M state, and \( \zeta \) denotes the fraction of time a node is transmitting control messages during the C&M period. In our simulation, when a node has 20 neighbors, the size of its hello message is determined to be 110 bytes. Thus, the transmission time of a hello message is equal to 0.44 ms, under a data rate of 2 Mbps. We have adopted in our simulation a hello period duration of 50 ms and this has proven to be sufficiently long for accommodating the hello message traffic load generated in our simulations under a prescribed nodal density. Since \( \zeta \) is a very small number, the average energy consumption rate can be simplified to be:

\[
W = (1 - \epsilon) \left[ N_s W_G + N_s \rho (W_T - W_N) \right] + \epsilon \left( N N \right).
\]

(11)

F. Bit-Per-Joule Throughput Performance

The bit-per-joule throughput efficiency performance for ODMRP-PS and E-MBN based multicast algorithms is concluded as the ratio between the total multicast throughput \( (f_{\text{mul}}) \) measured at the multicast receivers and the average energy consumption level from (11):

\[
\chi = \frac{f_{\text{mul}}}{W} = \frac{\lambda_s L_p N_s N_g}{(1 - \epsilon) \left[ N_s W_G + \rho (W_T - W_N) \right] + \epsilon \left( N N \right)}.
\]

(12)

This analytical expression is used to compare with the bit-per-joule simulation result in Section VI.
V. PROTOCOL PARAMETERS AND SIMULATION MODELS

A. Simulation Environment

The simulation models of the proposed multicasting schemes were implemented in QualNet. 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 2. Different refresh intervals were examined for ODMRP and SBMS, and the optimum value was selected to be 3s and 10s for the respective protocols to achieve low overhead while maintaining a good packet delivery ratio. The general settings for conducting different simulation scenarios were listed in Table 3. All nodes were placed randomly within the area. The inter-arrival time of data packets for each sender is exponentially distributed, with an average of 0.5s. The radio power levels are selected to be $W_r = 900$ mW and $W_t = 1300$ mW. The multicast senders were chosen randomly with uniform probability among all the nodes. The member nodes join the multicast session at the beginning of simulation and remain as members throughout the simulation. Note that for clarity of presentation, all multicast senders and receivers are selected to be in 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 successfully delivered to the receivers.
• Control Overhead: Represents the number of control packets transmitted for each data packet successfully delivered to the receivers.
• Bit-Per-Joule Performance: Represents the energy throughput efficiency performance of a multicast algorithm.

VI. SIMULATION RESULTS AND ANALYSIS

A. Multicast Algorithm Comparisons

In this scenario, the simulation is run with 10 receivers and a mobility speed of 10 m/s. Nodes move according to the random waypoint mobility model. The multicast senders represent incoming network flows, each with an average flow rate of 8.2 kbps. Fig. 3(a) shows the packet delivery ratio (PDR) of the multicast algorithms under different number of senders. All multicast algorithms under our investigation achieve excellent PDR under the prescribed network scenario.

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 over ODMRP-PS due to the use of backbone network to limit the number of forwarding nodes.

TABLE II
MAJOR PROTOCOL PARAMETER VALUES

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>ODMRP</td>
<td>Join-Query Refresh Interval</td>
<td>3 seconds</td>
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<tr>
<td>MBN-TSA</td>
<td>Hello Message Interval</td>
<td>1 second</td>
</tr>
<tr>
<td>SBMS</td>
<td>Subnetwork Refresh Interval</td>
<td>10 seconds</td>
</tr>
<tr>
<td>HMA</td>
<td>Query Refresh Interval</td>
<td>10 seconds</td>
</tr>
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TABLE III
SIMULATION ENVIRONMENT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Simulation Duration</td>
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<tr>
<td>Network Dimension</td>
<td>1500m x 1500m</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>100</td>
</tr>
<tr>
<td>Average Data Packet Size</td>
<td>512 bytes</td>
</tr>
</tbody>
</table>
Comparison of control overhead for the underlying protocols is shown in Fig. 3(c). For our E-MBN based multicast algorithms, the key control overhead involves the employment of hello messages, which are used to maintain the Bnet. The overhead of ODMRP-PS consists of control messages utilized for its Query-and-Reply phase. BFMA does not incur any extra control overhead other than the TSA’s hello messages. SBMS and HMA have higher control overhead than BFMA since these algorithms require the use of periodic updates similar to ODMRP. However, we observed that our multicast algorithms still achieve excellent control overhead over ODMRP since the control messages for our multicast algorithms are only distributed in the Bnet.

A comparison of the multicast algorithms can be performed by taking the simulation results obtained above and using them in (3) – (8). For example, under BFMA, simulation results from Fig. 3(b) show that \( D_{\text{overhead}}^{\text{BFMA}} \approx 2.1 \).

Since multicast packets are flooded across the Bnet, the size of the multicast subnetwork for BFMA, \( N(G^{\text{BFMA}}_M) \) equals to the size of the Bnet. Assuming that no packet losses are incurred (\( PDR \approx 1 \)), the average size of the Bnet for our simulation runs can be determined using (3):

\[
N(G_{\text{Bnet}}) = N(G^{\text{BFMA}}_M) \approx 21,
\]

which is close to the theoretical minimum Bnet size of 19 BNs. For our subsequent calculations, we select the case with 5 multicast senders (for a total sender traffic load of 41kbps). From (5), the total data traffic load \( f_{\text{data}}^{\text{BFMA}} \) = 860 kbps. From Section IV, we obtained \( f_{\text{control}}^{\text{BFMA}} \) = 40 kbps. Thus, the overall internal multicast traffic load is \( f_{\text{data}}^{\text{BFMA}} = 900 \) kbps.

Approximate analysis using the relative size of the area dimensions with respect to the transmission range provides an estimated spatial reuse factor of 4. The multicast efficiency for BFMA can be calculated using (8):

\[
\eta = \frac{f_{\text{data}}^{\text{BFMA}}}{f_{\text{data}}^{\text{BFMA}}} = \frac{8.2 \text{ kbps} \times 5 \times 10}{900 \text{ kbps}} = 45%.
\]

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. By repeating the process above, we are able to find the multicast efficiencies for SBMS and ODMRP-PS. The main parameter values obtained for the comparison of the three multicast algorithms are listed in Table 4.

### B. Bit-Per-Joule Performance

The bit-per-joule throughput efficiency performance achieved under different number of senders is plotted in Fig. 4, showing results obtained by simulation as well as from our mathematical expression shown in (12). Both our E-MBN based multicast algorithms are better than ODMRP-PS because they employ a backbone network to limit the number of forwarding nodes, leading to a smaller number of active nodes as compared to that incurred by ODMRP-PS.

Since SBMS has a better data forwarding overhead than BFMA (as observed from Fig 3(b)), it is commonly assumed that SBMS should have a better bit-per-joule performance because less nodes are required to retransmit the multicast messages. However, in terms of energy consumption, we observed from Fig. 4 that both simulation and analytical results show that SBMS has similar performance as BFMA. This observation has lead to the conclusion that transmit power \( W_t \) is not a major contributing factor to the bit-per-joule calculation (under a 2 Mbps wireless channel). The number of active nodes \( \bar{N}_a \) for a multicast algorithm is the major contributor since both of our E-MBN based multicast algorithms have similar number of active nodes, i.e. the BNs that form the Bnet, resulting in similar bit-per-joule performance. In addition to that, it is noted that SBMS has a slightly longer average C&M period (where every node is
awake to perform the exchange of hello message under E-MBN) than BFMA since SBMS uses periodic multicast route updates to maintain an optimized multicast subnetwork.

ODMRP-PS has a longer $C&M$ period than SBMS and BFMA due to its Query-and-Reply phase. For fair comparison, we force BFMA to have the same average $C&M$ interval as ODMRP-PS (in this case, the $C&M$ period consists of 10% of the overall simulation run time). We observed from Fig. 5 that BFMA (suboptimal) still outperforms ODMRP-PS, proving that our hierarchical based algorithm is better in terms of bit-per-joule throughput efficiency. The energy efficiency improvement achieved by BFMA when using an optimal $C&M$ period (which is determined to be 5% of the overall simulation run time, and represented as BFMA (optimal) in the plot) has further emphasize the importance of minimizing number of active nodes to achieve the best bit-per-joule throughput efficiency for a multicast algorithm. For further improvement, we allow the topology synthesis algorithm to select nodes that are members of the multicast group (senders and receivers) to be part of the Bnet since in our simulation we assume the multicast senders and receivers are always active in order to transmit and receive multicast messages, and the result for this case is represented as BFMA (improved) in the plot. When BFMA is run under E-MBN (represented as BFMA (energy aware) in the plot), we observed that it has the best bit-per-joule performance since the algorithm comprise all the optimization advantages discussed previously.

C. Network Lifetime Extension

Energy conservation is only meaningful when it helps to extend the lifetime of a network with energy-limited nodes. It is desirable to balance the energy dissipation of the nodes so that they would not run out of energy early in some area, resulting in a disconnection of the entire network. In this scenario, each forwarding node is given a limited energy of 40J. The simulation continues to run until nodes run out of energy or packet delivery ratio (PDR) of the multicast algorithms drop below a certain threshold, which we consider as the sign that the surviving nodes can no longer connect the network effectively. The packet delivery ratio and the number of alive nodes are measured every 10 seconds. Although different definitions of network lifetime have been used in previous publications, we assume network lifetime to be represented by a PDR threshold of 0.7, i.e. we consider a network is ‘dead’ or deemed ‘useless’ when its PDR falls below 70%. From Fig. 6, we observed that BFMA extends the lifetime of a network by approximately 70% beyond that of ODMRP-PS. From Fig. 7, we observed that BFMA has a significantly higher number of alive nodes as compared to ODMRP-PS. This is important since a higher number of alive nodes will achieve better area coverage (in a sensor network). In addition to that, in a dynamic scenario, nodes with energy could possibly move into an area to replace other nodes that run out of energy to maintain network connectivity.

![Packet Delivery Ratio versus Simulation Time](image1)

**Figure 6. Packet Delivery Ratio versus Simulation Time**

![Number of Alive Nodes versus Simulation Time](image2)

**Figure 7. Number of Alive Nodes versus Simulation Time**

VII. CONCLUSION

In this paper, we propose three hierarchical multicast algorithms that employ a mobile backbone network to achieve efficient message distribution among members of multicast groups. Through a series of analytical derivations and simulation based evaluations, the performance characteristics of these algorithms are compared. Our results show that E-MBN based multicast algorithms achieve better multicast efficiencies and bit-per-joule performances than ODMRP-PS. The use of an energy-aware mobile backbone by our multicast algorithms enables them to achieve excellent packet delivery ratios while requiring relatively low data forwarding overhead. This leads to the construction of smaller multicast subnetworks that allow more nodes to sleep, resulting in better energy conservation. In order to extend the lifetime of the network, an energy-aware topology synthesis algorithm is implemented to balance the energy dissipation of the nodes that form the mobile backbone. Our results show that BFMA extends the lifetime of a network by 70% beyond that of ODMRP-PS (which uses a power saving mechanism similar to the operation of IEEE 802.11 power saving mode).
APPENDIX

A. E-MBN Power Saving Scheme

In this appendix we provide a detailed description of the E-MBN power saving scheme. The specifications for this scheme build on top of the operation of the IEEE 802.11 power saving mode and the hello message exchange process used by our topology synthesis algorithm (TSA). Under TSA, each node periodically issues hello messages to learn its link-layer neighbors. In our scheme, a node includes wake up notification (corresponding to that included in an IEEE 802.11 ATIM message) in its hello messages. Nodes wake up periodically and stay awake during a specified period of time, which is identified as the control and management (C&M) period. This period is selected in a manner that allows nodes to successfully send their most current hello message to their neighbors during the underlying period interval. Thus, any node that has a message to forward to a neighbor is able to notify and wake up this neighbor. Nodes that do not transmit or receive any wake up notification during the C&M period will sleep to conserve energy.

Nodes are synchronized to wake up at the beginning of each super frame. The time duration of a super frame is determined by the underlying multicast protocol. For our E-MBN power saving scheme, this is set to be 1 second. A frame synchronization mechanism is employed by the nodes. Accurate synchronization may be hard to achieve between nodes that are multi-hop away. However, we note that accurate frame synchronization acquisition is only required for the interaction between neighboring nodes. A number of synchronization mechanisms have been proposed and studied for the operation in multi-hop networks [19], [20], [21]. In [21], the frequency at which synchronization beacons are generated is significantly reduced by requiring only nodes that are members of a minimum connected dominating set (MCDS) to send synchronization beacons. This approach is readily incorporated into our E-MBN power saving scheme.

Our E-MBN power saving scheme is specified in accordance with the finite state machine whose state transition diagram is shown in Fig. 8. A control and management (C&M) period is established at the start of each super frame, and it is equivalent to the ATIM interval in IEEE 802.11 power saving mode. While in this state, each node broadcasts a hello message to its neighboring nodes. A C&M timer is used for controlling the interval during which a node stays in its C&M state. In our simulation, when a node has 20 neighbors, the size of its hello message is determined to be equal to 110 bytes. Thus, the transmission time of a hello message is equal to 0.44 ms, under a data rate of 2 Mbps. When the wireless link is not overloaded, our simulations have shown the overall MAC access delay to be (at the 99-percentile) lower than 1 ms. We have adopted in our simulation a hello period duration of 50 ms and this has proven to be sufficiently long for accommodating the hello message traffic load generated in our simulations under the prescribed nodal density.

Given that a node is in the C&M state, it will transition into the active state if any of following conditions is satisfied:

(i) The node has received wakeup notification(s).
(ii) The node is scheduled to send a data message.
(iii) The node is elected to act as a backbone node (BN).

While in active state, a node can transmit and receive data messages. An active state timer is used for controlling the length of time that a node stays in active state. In our implementation, this active state duration is set to be 900 ms. Note that a packet transmission that is not completed within an active state is continued during the subsequent C&M state.

A node transitions into sleep state to conserve energy when it is not engaged in any packet transmission or reception activity (to avoid the overhearing issue when the radio module of a node is in idle state). The duration in which a node stays in sleep state can be selected individually by each node. At the end of its sleep state duration, the node waits until the start of the subsequent C&M period and then transitions into C&M state. In our simulations, this sleep state duration is set to be 900 ms.

Under our E-MBN power saving scheme, a node maintains a list of its neighboring nodes to which it needs to forward packets currently residing in its queue. A node uses this list to include wakeup notifications in its next hello message for the designated neighbors, and to ensure the availability of these neighbors. If any one of these ‘downstream’ nodes is missing, a local reconstruction procedure is performed (as performed by the SBMS scheme).

B. ODMRP Power Saving Protocol (ODMRP-PS)

On-Demand Multicast Routing Protocol (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. A Join-Query packet is periodically broadcasted to update the election of forwarding group members and refresh the end-user group membership information. For each multicast group, every source will construct a source-based shortest path tree (SPT) connecting to all of its designated group members. The superposition of these SPTs (of the same multicast group) will form the multicast forwarding mesh for ODMRP.
We modified the original ODMRP scheme to include a power saving mechanism for fair comparison with our E-MBN based multicast algorithms. The state transition diagram of the finite state machine for ODMRP with power saving mechanism (ODMRP-PS) is shown in Fig. 9.

Although the exchange of hello messages is not required for ODMRP-PS, nodes are still required to synchronize to wake up at the beginning of each super frame. Note that the period of the super frame is equivalent to the refresh interval of ODMRP. Again, frame synchronization mechanism is employed by the nodes, with accurate frame synchronization acquisition only required for the interaction between neighboring nodes as specified for the E-MBN power saving scheme. In the original protocol, Join Query messages are piggybacked in data packets and flooded across the whole network as part of the operation that constructs the multicast forwarding mesh. In our implementation, we decoupled the control and data forwarding mechanism of ODMRP to make the protocol more scalable, since the flooding of a relatively big data packets is undesirable. The decoupling also ensures a shorter interval for the sources to obtain Join Replies back and conditions, whereas the sleep and active state durations are both set to be 2.7 seconds.

REFERENCES


Figure 9. Finite State Machine for the ODMRP-PS Scheme