Predictive Energy-Efficient Multicast for Large-Scale Mobile Ad Hoc Networks

Jung-Chun Kao and Radu Marculescu
Carnegie Mellon University
Pittsburgh, PA 15213-3890, USA

***Abstract*—Energy-efficient multicast routing is of primary concern for mobile ad hoc networks (MANET). However, *none* of existing energy-efficient multicast algorithms is applicable to large-scale MANETs, either due to their complexity (which is either NP-hard or polynomial with respect to the *network size*), or due to the huge overhead caused by frequent exchanges of location information. To solve the scalability and overhead issues, we propose the *P*redictive *E*nergy-efficient *M*ulticast *A*lgorithm (PEMA) which exploits statistical properties of the network, as opposed to relying on route details or network topology. The running time of PEMA depends on the *multicast group size*, not *network size*; this makes PEMA fast enough even for MANETs consisting of 1000 or more nodes. Simulation results show that PEMA not only results in significant energy savings compared to other existing algorithms, but also attains good packet delivery ratio in *mobile* environments.**

***Keywords*—Energy efficiency, multicast, mobile ad hoc network**

I. INTRODUCTION

A mobile ad-hoc network (MANET) consists of a set of autonomous mobile nodes, all capable of transmitting and receiving user packets. Such a network can either operate in a standalone fashion with the ability of self-configuration, or it can connect to the Internet. Minimal configuration and fast deployment make MANETs suitable for emergency situations like natural or human-induced disasters, military conflicts, emergency medical situations, etc.

Multicast applications running over MANETs (*e.g.*, video conferencing) are becoming of wide interest. As such, a crucial issue in MANETs is how to find the route(s) with minimum total energy consumption in order to ensure a communication session among a given set of group members. This problem is referred to as the *minimum-energy multicast routing*.

Even the minimum-energy broadcast routing (which is a special case of the minimum-energy multicast routing) turns out to be an NP-complete problem ([1] and [2]). Therefore, heuristics that exploit multi-hop routing and the "wireless multicast advantage" [3] were proposed for reducing the total energy involved in multicast routing. Given the locations of *all* network nodes, such heuristics seek to construct a multicast tree which can help to reduce the total energy consumption.

Representative energy-efficient multicast routing algorithms include the *M*ulticast *L*east-*U*nicast algorithm (MLU) [3], the *M*ulticast *Li*nk-Based *M*inimum *S*panning *T*ree algorithm (MLiMST) [3], the *M*ulticast *I*ncremental *P*ower algorithm (MIP) [3], and the *M*ixed *I*nteger *L*inear *P*rogramming (MILP) method [4]. MLU constructs the multicast tree as a superposition of all shortest unicast routes. Therefore, its complexity is $O(n^2)$. MLiMST first constructs a minimum-energy spanning tree consisting of *all* network nodes and then prunes all unnecessary nodes and links. The complexity of MLiMST is $O(n^2)$ or $O(n^3)$, depending on the implementation details. Along the same lines, MIP is a variation of MLiMST. MIP adds new nodes (one at a time) to the multicast tree based on the incremental increase of link energy at nodes in the tree. The complexity MIP is $O(n^3)$. The approximation ratio of the above three algorithms is analyzed in [11]. (The approximation ratio of an algorithm is defined as the result generated by the algorithm divided by the optimal solution.) Guo and Yang propose in [4] a mixed integer linear programming (MILP) method to solve the minimum-energy multicast problem. Although MILP gives an optimal solution, it is *not* scalable due to its *NP-hard* complexity and state explosion problem.

All the above energy-efficient multicast algorithms are too slow to be used in large-scale MANETs consisting of 1000 or more nodes. Moreover, due to the requirement of exchanging the entire network topology frequently, they are incompatible to existing routing protocols like AODV [5]-[6] and ODMRP [7]. In contrast to previous work, we propose the *P*redictive *E*nergy-efficient *M*ulticast *A*lgorithm (PEMA) to improve energy-efficiency in *large-scale* MANETs [1]. Because the complexity of PEMA *does not* depend on network size at all, PEMA is very scalable.

As such, PEMA can run easily on top of any unicast routing protocol to improve the energy savings, by serving as either a multicast extension at network layer or an application-layer multicast. To be able to work at both network and application layers, PEMA takes the routing decision based *only* on information about *member nodes* and *average node density* in the network; that is, there is no need for relying on explicit information about the route details or non-member nodes. Whereas other multicast algorithms like [10] construct

[*] This work is supported by CMU CyLab Army Research Office (ARO) under grant 9097.74.9, by Gigascale Systems Research Focus Center, one of the five research centers funded under the FCRP, a SRC program, under grant 10913.2, and by a Frank J. Marshall Graduate Fellowship for Jung-Chun Kao.

[1] Our proposed algorithm targets realistic scenarios, i.e., a wireless network consisting of 1000 or more nodes. At the same time, the group size varies and typically is much smaller than the network size.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE CCNC 2008 proceedings.

multicast trees based on the tracked-down information (*e.g.*, location, residual energy and link length of global or regional nodes), PEMA *completely* eliminates the overhead and requirement of tracking and exchanging such information.

To accurately predict the communication energy consumption without knowing the network topology and route details, we first derive *lower* and *upper bounds* on energy consumption; later, the predicted energy values become weighted averages of these two bounds. Based on these predicted energy values, PEMA determines how to send packets to group members in an energy efficient way, without relying on any global information about the network.

PEMA takes several iterations before completion. Each iteration decides *where* to send packets—determining the subset of group members to receive the packets in this iteration—and *how* to send packets—via a few multihop unicasts, or a one-hop multicast, or a combination thereof. Since there is no need to wait for the entire algorithm to complete, as soon as one iteration finishes, packets can be sent out immediately without any performance penalty. PEMA is *very scalable*; indeed, the worst-case complexity of one iteration and the entire algorithm is $O(g^2 \log g)$ and $O(g^3 \log g)$, respectively, where the *group size* g is the number of nodes (including the source node) within the same group.

The rest of this paper is organized as follows. Section 2 introduces the network and energy models. Section 3 presents the theoretical analysis and the newly derived bounds. Section 4 describes the energy-efficient multicast algorithm we propose, while the simulation results are shown in Section 5. Finally, Section 6 presents our concluding remarks.

II. The Network and Energy Models

Similar to [9], we consider an ad-hoc wireless network consisting of a set of nodes deployed randomly according to a planar Poisson distribution with an average density of ρ; that is, the number of nodes located within any region of area A is characterized by a Poisson random variable with mean ρA. Also, the number of nodes in an arbitrary region is independent of the number of nodes in any disjoint region. We note that if the number of nodes in the network is fixed, a planar Poisson distribution degenerates into a 2D uniform distribution.

Further, we use the energy model described in [3]. More precisely, if the sender sends a signal at transmission power level P_0, then the received signal power is $P_0 x^{-\alpha}$, where α is the propagation loss (or attenuation) exponent and x is the distance between the sender and receiver nodes. Typically, the propagation loss exponent takes values between 2 and 4, depending on the propagation characteristics of the wireless environment. In such an environment, a successful signal reception must have a signal-to-noise ratio (*SNR*) greater than a specified threshold. Without loss of generality, we normalize to 1 the actual transmission energy required for a successful transmission of a unit-size packet while traversing a unit distance. Therefore, the minimum transmission energy required for a unit-size packet to traverse a distance of x units, denoted by $E_L(x)$, can be represented as $E_L(x) = x^{\alpha}$. This normalized minimum transmission energy is referred to as the *link energy*.

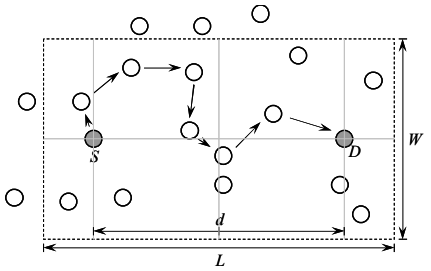

Fig. 1. An example of a rectangular forwarding area of length L and width W. Packets are forwarded from node S to node D within the forwarding area. Without losing generality, we assume that any node outside the forwarding area simply drops the received packets. The arrows depict the minimum-energy path from source to destination.

The *path energy* of a given path is defined as the sum of all link energy values along the path. Given a source-destination pair, the *minimum path energy* is defined as the smallest path energy value, over *all* possible paths which connect the given source-destination pair.

The path-loss energy model above does not consider the energy consumed by retransmissions due to the *dynamic* condition such as interference and packet collision. Because such dynamic information is rarely provided to upper layers by underlying protocols, it is neglected in the analysis in Section III. However, the simulation results in this paper (*e.g.*, Fig. 3) consider the extra energy consumption due to retransmissions.

III. Expected Minimum Path Energy

This section presents the lower and upper bounds that we derived for the expected minimum path energy between any given source-destination pair. The derivation is based on the statistical properties of the network. The key idea is to separate the link/path energy into two orthogonal components, namely an x- and a y-component. Then, using our derived lower and upper bounds, PEMA can predict the path energy values accurately without knowing the actual positions of the intermediate nodes and the actual length of links/paths.

Similar to [8], for any communication session, we constrain the packets to be routed within a *forwarding area* (rather than considering the entire network). The packets within the forwarding area can be routed *arbitrarily*, but any node outside the forwarding area is assumed to simply discard the received packets. The forwarding area is a rectangular region of length L and width W, containing the source and destination nodes as shown in Fig. 1. So we have $L \geq d$. However, we note that our analysis is *not* limited to any specific routing protocol based on a rectangular forwarding area.

In the following, we present the formulae derived for the lower and upper bounds. The derivation of the lower bound follows the fact that sending packets along the projection of any route on the x-axis, instead of the route, does *not* increase the energy consumption. The upper bound is derived by using the fact that a detour never decreases energy consumption. Due to page limitations, the detailed proof is omitted.

Theorem 1: Given the average node density ρ, a source-destination pair at distance d, and a forwarding area of length $L \geq d$ and width W, the expected minimum path energy

between the source-destination pair ($\overline{E}$) is greater than or equal to the lower bound:

$$\overline{E} \geq d^{\alpha} \sum_{n=0}^{\infty} \frac{e^{-\lambda} \lambda^{n} (n+1)}{(\alpha+1)(\alpha+2)\cdots(\alpha+n)} \quad (1)$$

where $\lambda = \rho dW$ and $\alpha > 1$ is the propagation loss exponent.

When α is an integer, (1) reduces to:

$$\overline{E} \geq d^{\alpha} \left[\frac{\alpha!}{\lambda^{\alpha}} (\lambda - \alpha + 1) - \frac{\alpha! e^{-\lambda}}{\lambda^{\alpha}} \left((\lambda - \alpha + 1) \sum_{i=0}^{\alpha-2} \frac{\lambda^{i}}{i!} - \frac{\lambda^{\alpha-1}}{(\alpha-2)!} \right) \right] \quad (2)$$

This lower bound in Theorem 1 is of practical use. Typically, α is an integer equal to 2, 3, or 4; therefore, the lower bound (2) has few terms. Even if α is not an integer, the lower bound (1) converges *quickly* because the number of nodes in the forwarding area (λ) is usually small.

Theorem 2: Given a node density ρ, a source-destination pair at distance d, and the forwarding area of length L and width W, the expected minimum path energy ($\overline{E}$) satisfies:

$$\overline{E} \leq 2^{\alpha/2-1} \left(\left[\mathrm{LB} + 2 \left(\frac{L-d}{2} \right)^{\alpha} \right] + \left[\frac{2(\rho LW - 1)}{(\alpha+1)(\alpha+2)} + \frac{2}{\alpha+1} \right] W^{\alpha} \right) \quad (3)$$

where α is the propagation loss exponent and **LB** is the lower bound given in (1) or (2) with $\lambda = \rho LW$ (rather than $\lambda = \rho dW$).

IV. New Energy-Efficient Multicast Algorithm

In this section, we describe the *P*redictive *E*nergy-efficient *M*ulticast *A*lgorithm (PEMA) in detail. To be able to run on top of any existing routing protocol and to minimize the algorithm overhead, only three types of information are provided to PEMA, namely, the *average node density* in the network, the *location of group members*, and the individual *unicast routes* from the source node to the group members (which are established during join process and maintained by the underlying routing protocol). However, we note that route details like the intermediate nodes, the path energy values along any routes, location of non-member nodes, etc. are assumed to be unknown; this makes perfect sense because in practice, underlying routing protocols rarely provide such information.

Under such conditions, PEMA makes decisions based on the *predicted* path energy values: Given a source-destination pair, the predicted path energy value is a *weighted average* of the lower bound (in Theorem 1), **LB**, and the upper bound (in Theorem 2), **UB**. That is, the predicted path energy value is w**LB** + (1 - w)**UB**, where $w \in [0, 1]$ is the assigned weight.

As shown in Fig. 2, PEMA takes a variable number of iterations before completion. Initially, the *remaining set*, denoted by $\underline{R}$, contains all the g group members including the source node. (The remaining set is defined as the set of the group members which have not yet received packets.) Each iteration (*i.e.,* lines 3-13 in Fig. 2) determines a *transfer hub*, denoted by H, and the set of *corresponding receivers*, denoted by $\underline{M}_H$. (The corresponding receivers are the nodes to which the transfer hub can multicast packets in an energy-efficient manner.) If the number of corresponding receivers is zero (*i.e.,* $\underline{M}_H$ is empty), PEMA finishes right after the source node sends packets individually (via the given unicast routes) to all the nodes in the remaining set $\underline{R}$. Otherwise, the source node S first sends packets via the given unicast route to the transfer hub which further forwards the packets to all the corresponding receivers in one transmission. Following that, the transfer hub and corresponding receivers are removed from the remaining set $\underline{R}$. PEMA continues the next iteration until the remaining set becomes empty.

```
1  R ← the set of all the group members including the source S
2  While R is not empty
3      For each node X in R
4          [M_X, U_X] ← PARTITION(R, X)
5          E_m(X) ← the maximum link energy between X and any node in M_X
       // Select the transfer hub H to be the node which minimizes E_m(X)/|M_X|
6      H ← arg min_{X∈R} E_m(X) / |M_X|
7      If M_H is not empty
8          Source S unicasts packet(s) via the given route to H.
9          H multicasts the packet(s) once, at energy E_m(H), to all nodes in M_H.
10         Remove H and all the nodes in M_H from R
11     Else
12         S unicasts packets individually via given routes to all nodes in R.
13         Remove all nodes from R.

PARTITION(R, X)
// Divides R into a multicast partition M and a unicast partition U
1  Q ← the ordered sequence after sorting R in order of the distance from X
2  E_m(|Q|) ← the link energy between X and the last (i.e. |Q|th) element of Q
3  For j ← |Q| down to 0
4      E_u(j) ← Σ_{i=j+1}^{|Q|} w LB(X, ith element of Q) + (1-w) UB(X, ith element of Q)
5      E_m(j) ← the link energy between X and the jth element of Q
       // Divides Q into two partitions, M and U, such that E_u + E_m is minimized.
6  n ← arg min_{0≤j≤|Q|} E_u(j) + E_m(j)
7  M_X ← the first n elements of Q
8  U_X ← all the elements that are in Q but not in M_X
9  Return [M_X, U_X]
```

Fig. 2. The pseudo code of PEMA. In the pseudo code, w is the assigned weight while **LB**(·,·) and **UB**(·,·) are the lower and upper bounds given in theorems 1 and 2. For better readability, the notations "arg min" and "Σ" are used; $\underline{M}_X$, $\underline{U}_X$, $E_m(j)$, and $E_u(j)$ are indexed by X or j. With small modification, such indexing and notations can be removed to achieve better efficiency.

During each iteration, the node with the smallest multicast energy per corresponding receiver is selected as the transfer hub. To calculate the multicast energy per corresponding receiver value, the PARTITION function is called for each node X in the remaining set $\underline{R}$. Assuming that the two assumptions[2] hold true, PARTITION($\underline{R}$, X) essentially gives the multicast partition $\underline{M}_X$ and unicast partition $\underline{U}_X$ that correspond to the most energy-efficient way of sending packets from X to all nodes in $\underline{R}$. More precisely, sending packets individually to all nodes in $\underline{U}_X$ through the unicast routes and multicasting packets to all nodes in $\underline{M}_X$ by one transmission is optimal, because this minimizes the corresponding total energy consumption, *i.e.*, $E_u + E_m$. The multicast energy per receiver associated with node X is $E_m(X) / |\underline{M}_X|$, where the multicast energy $E_m(X)$ equals the link energy between node X and the farthest node in $\underline{M}_X$. After calculating the multicast energy per corresponding receiver values for all nodes in $\underline{R}$, PEMA selects the node with the smallest multicast energy per corresponding receiver value as the transfer hub; then packets are sent from source to the

[2] The two assumptions are *i)* any other way of sending packets to all nodes in $\underline{R}$ from X, besides sending packets by direct transmissions or through the given unicast routes, is not allowed and *ii)* the actual path energy of all unicast routes connecting pairs is equal to the predicted path energy.

Table I.
THE AVERAGE NORMALIZED ENERGY FOR 1000-NODE NETWORKS AND FOR PROPAGATION LOSS EXPONENT $\alpha = 2$:

Group size g	MLU	MLi-MST	MIP	PEMA
10	1	0.99	0.90	0.36
25	1	0.90	0.84	0.65
50	1	0.84	0.78	0.71
75	1	0.82	0.76	0.73
100	1	0.81	0.76	0.72

Table II.
THE AVERAGE NORMALIZED ENERGY FOR 1000-NODE NETWORKS AND FOR PROPAGATION LOSS EXPONENT $\alpha = 3$:

Group size g	MLU	MLi-MST	MIP	PEMA
10	1	1.01	0.95	0.04
25	1	0.93	0.89	0.12
50	1	0.87	0.84	0.30
75	1	0.84	0.81	0.49
100	1	0.84	0.81	0.72

Table III.
THE AVERAGE NORMALIZED ENERGY FOR 1000-NODE NETWORKS AND FOR PROPAGATION LOSS EXPONENT $\alpha = 4$:

Group size g	MLU	MLi-MST	MIP	PEMA
10	1	0.97	0.95	0.004
25	1	0.92	0.90	0.02
50	1	0.89	0.88	0.07
75	1	0.87	0.85	0.15
100	1	0.87	0.85	0.23

transfer hub and corresponding receivers as explained previously.

The *worst-case* complexity of the algorithm in Fig. 2 is as follows. An iteration corresponds to an execution *inside* the while loop (*i.e.*, lines 3-13) in Fig. 2. Initially, $|\underline{R}| = g$ where g is the group size. Because each iteration decreases the size of $\underline{R}$ by at least 2, the number of iterations cannot exceed $\lceil g/2 \rceil$. The algorithm has one *for* loop, which calls the PARTITION function $|\underline{R}|$ times. The complexity of the PARTITION function is $O(|\underline{R}| \log|\underline{R}|)$ because the complexity of advanced sorting algorithms like quick sort is typically $O(|\underline{R}| \log|\underline{R}|)$ and the complexity of the *for* loop inside the PARTITION function is $O(|\underline{R}|)$. Since $|\underline{R}| \le g$, the worst-case complexity of an iteration is $O(g \cdot g \log g) = O(g^2 \log g)$. As such, the worst-case complexity of PEMA is $O(g/2 \cdot g^2 \log g) = O(g^3 \log g)$.

V. SIMULATION RESULTS

A. PEMA Improves Energy Efficiency

The goal of this subsection is to evaluate the energy efficiency of PEMA for several configurations against three well-known multicast algorithms. The important parameters for these configurations include the average number of nodes, the propagation loss exponent α, and the group size g. For each configuration, we ran simulations over 100 network instances and then average the results. In all simulations, W is set to $3/\sqrt{\rho}$. L for any pair is set to the pair distance. w is set to 0.5.

In this set of simulations, a number of nodes are randomly allocated within a 1000m×1000m region following a planar Poisson distribution; that is, a Poisson random number generator with a specified average is used to generate the actual number of nodes in the network and then these nodes are randomly deployed across the network. The group members are randomly selected from the network nodes.

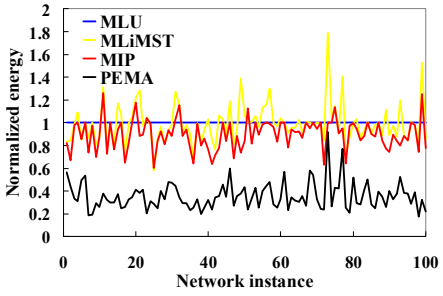

Fig. 3. The normalized energy for 1000-node network instances with $\alpha = 2$ and $g = 10$. This figure shows that PEMA is robust to variation in node density (±25%) from the estimated value.

The three algorithms we compare PEMA against are MLU, MLiMST, and MIP. Similar to [3], we use *normalized multicast energy* as a means to report the energy efficiency. Given a specific network instance, the normalized multicast energy of a multicast algorithm is defined as the multicast energy value under that multicast algorithm divided by the multicast energy value under MLU. Consequently, the smaller the average normalized multicast energy is, the better energy efficiency the multicast algorithm can provide.

For a fair comparison, the location of group members is available to all algorithms, but the location of non-member nodes is not. The routes established during the join process are given to all algorithms. However, their details (*e.g.*, the path energy values or intermediate nodes) are unknown.

Tables 1, 2 and 3 summarize the performance of each algorithm for large-scale networks with an average number of 1000 nodes. We simulate several cases with various propagation loss exponent ($\alpha = 2, 3, 4$) and various group size (ranging between 10 and 100). It is clear that PEMA outperforms all three well-known multicast algorithms for the entire range of parameter variation.

To better present the detail of the relative performance of these algorithms, we plot the normalized energy for all network instances in Fig. 3. The horizontal axis represents the instance ID (ranging from 1 to 100). As shown, PEMA outperforms all other algorithms for most network instances. Also, we can see the robustness of PEMA to variation in node density (a difference of ±25%, from the value used by PEMA).

B. PEMA Applicability to Mobile Environments

The goal of this subsection is to investigate the applicability of PEMA to *mobile* networks. In particular, an important metric reflecting the applicability of PEMA to mobile ad hoc networks is the packet delivery ratio.

To simulate the impact of interference due to varying transmission power and the impact of node mobility on this important metric, we ran PEMA on top of an AODV-like routing protocol using four levels of transmission power, namely, 30.48m, 91.44m, 365.76m, and 6437.376m. The first three values are typical for 802.11b/g transmission range in office, 802.11b/g range in outdoors, and 802.11a range in outdoors, respectively, while the last value is the typical 802.16 transmission range. All the paramters are fed into our in-house simulator.

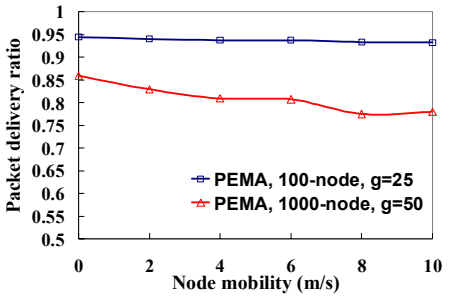

Fig. 4. As the speed of mobile nodes increases, the packet delivery ratio under PEMA decreases slowly.

Two *media access control* mechanisms are used by this routing protocol to improve the packet delivery ratio, namely, IEEE 802.11 DCF and CSMA/CA. Packets are sent using the IEEE 802.11 DCF if corresponding routes have been established and they remain valid. Otherwise, the packets are broadcasted using CSMA/CA to establish a new route, initiate a join process, or multicast packets.

Other simulation parameters are as follows. The network covers an area of 1000m×1000m. A fixed number of nodes (either 100 nodes or 1000 nodes) are placed randomly over the network region. Data packets of size 512 bytes are injected into each group at a rate of 4 packets per second. These data packets are multicasted to group members from source nodes using PEMA. The data rate in a wireless channel is 1 Mb/sec. The total number of multicast groups is set to one. All multicast groups live for 1 minute. After the 1-minute lifetime is up, a new multicast group is created to replace the old group.

Nodes mobility is modeled as a random waypoint process, which is widely used in performance analysis of ad hoc networks [12]. The node mobility speed varies between 0 to 10m/s. The pause time is fixed to 30 secs. The total simulation time is set to 900 secs. Results are averaged over multiple runs with different seeds for the random number generator.

As node mobility varies from 0 to 10m/s, Fig. 4 shows the packet delivery ratio under PEMA. (Packet delivery ratio is computed as the ratio of the total number of packets received by destination nodes to the number of packets that will be received in the case without any packet loss.) This figure confirms the applicability of PEMA to such mobile networks because *i)* the packet delivery ratio is high and *ii*) increasing the node mobility speed *does not* degrade the packet delivery ratio significantly.

Note that because the multicast group size is set to 25 in a 100-node network (or 50 in a 1000-node network), the communication involved within a single multicast group is analogous to the communication between 24 unicast source-destination pairs in a 100-node network (or 99 pairs in a 1000-node network). The difference in the total traffic volume is one major reason that causes the gap between the two curves in Fig. 4, although the numbers of multicast groups and traffic injection rates are the same.

VI. Conclusion

In this paper, we have proposed a *predictive* multicast routing algorithm, called PEMA, for energy savings in large-scale MANETs. The features that make PEMA distinct from other energy-efficient multicast algorithms proposed to date are twofold. First, PEMA is extremely fast because its running time is *independent of the network size*. Indeed, while previous algorithms result in very long execution times, PEMA is fast enough to run in large-scale MANETs composed of more than 1000 nodes. Second, the routing decision of PEMA does not rely on the information about network topology or route details.

The key technique for all these benefits despite apparently contrasting goals—low complexity, high energy efficiency and no need for information about any non-member node and link length—is energy *prediction*. Indeed, instead of relying on the actual values, PEMA makes the routing decisions based on its *predicted* energy values. For accurate predictions, we have derived lower and upper bounds and so, the predicted energy is calculated as a weighted average of these two bounds.

Finally, our simulation results show that, in terms of energy efficiency, PEMA outperforms three well-known algorithms. This is particularly significant as PEMA also provides good packet delivery ratio in mobile environments.

References

[1] M. Cagalj, J.-P. Hubaux, and C. Enz, "Minimum-energy broadcast in all-wireless networks: NP-completeness and distribution issues," in Proc. ACM Intl. Conf. on Mobile Computing and Networking (MobiCom), Atlanta, USA, Sep. 2002.

[2] D. Li, X. Jia, and H. Liu, "Energy efficient broadcast routing in static ad hoc wireless networks," IEEE Trans. on Mobile Computing, vol.3, no. 2, pp. 144-151, Apr.-June 2004.

[3] J. E. Wieselthier, G. D. Nguyen and A. Ephremides, "On the construction of energy-efficient broadcast and multicast trees in wireless networks," in Proc. IEEE INFOCOM, Tel-Aviv, Israel, Mar. 2000.

[4] S. Guo and O. W. Yang, "Minimum-energy multicast routing in static wireless ad hoc networks," in Proc. Vehicular Technology Conference (VTC), Los Angeles, USA, Sep. 2004.

[5] C. E. Perkins and E. M. Royer, "Ad hoc on-demand distance vector routing," IEEE Workshop on Mobile Computing Systems and Applications (WMCSA), New Orleans, USA, Feb. 1999.

[6] E. M. Royer and C. E. Perkins, "Multicast operation of the ad-hoc on-demand distance vector routing protocol," in Proc. ACM Intl. Conf. on Mobile Computing and Networking (MobiCom), Seattle, USA, Aug. 1999.

[7] S.-J. Lee, M. Gerla, and C.-C. Chiang, "On-demand multicast routing protocol," in Proc. IEEE Wireless Communications and Networking Conf. (WCNC), New Orleans, USA, Sep. 1999.

[8] Y. Ko and N. H. Vaidya, "Geocasting in mobile ad hoc networks: Location-based multicast algorithms," IEEE Workshop on Mobile Computing Systems and Applications (WMCSA), New Orleans, USA, Feb. 1999.

[9] P. Hall, *Introduction to the Theory of Coverage Processes*. John Wiley & Sons Inc., 1988.

[10] D. Pompili and M. Vittucci, "A probabilistic predictive multicast algorithm in ad hoc networks (PPMA)," Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), Bodrum, Turkey, June 2004.

[11] P.-J. Wan, G. Calinescu, and C.-W. Yi, "Minimum-power multicast routing in static ad hoc wireless networks," IEEE/ACM Trans. on Networking, vol. 12, no. 3, pp. 507-514, June 2004.

[12] E. Hyytia, P. Lassila, and J. Virtamo, "Spatial node distribution of the random waypoint mobility model with applications," IEEE Trans. on Mobile Computing, vol.5, no. 6, pp. 680-694, June 2006.