Energy-efficient Multicasting in Wireless Networks with Fixed Node Transmission Power

Christos Papageorgiou
University of Patras, Greece
xpapageo@ceid.upatras.gr

Panagiotis Kokkinos
Research Academic Computer Technology Institute, Greece
kokkinop@ceid.upatras.gr

Emmanouel Varvarigos
Research Academic Computer Technology Institute, Greece
manos@ceid.upatras.gr

ABSTRACT

In this work, we propose an energy-efficient multicasting algorithm for wireless networks for the case where the transmission powers of the nodes are fixed. Our algorithm is based on the multicost approach and selects an optimal energy-efficient set of nodes for multicasting, taking into account: i) the node residual energies, ii) the transmission powers used by the nodes, and iii) the set of nodes covered. Our algorithm is optimal, in the sense that it can optimize any desired function of the total power consumed by the multicasting task and the minimum of the current residual energies of the nodes, provided that the optimization function is monotonic in each of these parameters. Our optimal algorithm has non-polynomial complexity, thus, we propose a relaxation producing a near-optimal solution in polynomial time. The performance results obtained show that the proposed algorithms outperform established solutions for energy-aware multicasting, with respect to both energy consumption and network lifetime. Moreover, it is shown that the near-optimal multicost algorithm obtains most of the performance benefits of the optimal multicost algorithm at a smaller computational overhead.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Comm.; C.2.2 [**Network Protocols**]: Routing Protocols

General Terms

Algorithms, Experimentation, Measurement, Performance

Keywords

wireless networks, multicasting, multicost, energy, optimal

1. INTRODUCTION

In this paper we propose an optimal energy efficient multicasting algorithm, called Optimal Total and Residual Energy Multicost Multicast (abbreviated OTREMM) algorithm, for wireless networks consisting of nodes with preconfigured levels of transmission power. Our algorithm is optimal, in the sense that it can optimize any desired function of the total power consumed by the multicasting task and the minimum of the current residual energies of the nodes, provided that the optimization function is monotonic in each of these parameters. The proposed algorithm takes into account these two energy-related parameters in selecting the optimal sequence of nodes for performing the multicast, but it has non-polynomial complexity. We also present a relaxation of the optimal algorithm, to be referred to as the Near-Optimal Total and Residual Energy Multicost Multicast (abbreviated NOTREMM) algorithm that produces a near-optimal solution to the energy-efficient multicasting problem in polynomial time.

Our proposed algorithms try to jointly maximize the network's lifetime and minimize its energy consumption, by following the multicost routing approach [5]. In contrast to single-cost routing, where each network link is characterized by a single scalar cost parameter, in multicost routing a vector of cost parameters is assigned to each link. The cost vectors of the constituent links of a path are combined according to an associativity operator, which is different for each cost parameter, in order to produce the cost vector of the path. Multicost routing has been verified to perform well in terms of energy-efficiency for the case of unicast routing in wireless networks [12].

We compare, through simulations, the optimal (OTREMM) and near-optimal (NOTREMM) algorithms to other representative algorithms for energy-efficient multicasting. Our results show that the proposed algorithms outperform the other algorithms considered under the assumption of fixed node transmission powers with respect to both energy consumption and network lifetime, by making better use of the network energy reserves. Another important result is that the near-optimal algorithm performs comparably to the optimal algorithm, at a significantly lower computation cost.

The remainder of the paper is organized as follows. In Section 2 we discuss prior related work. In Sections 3 and 4 we present the optimal and near-optimal algorithms introduced in this paper for energy-efficient multicasting. In Section 5 the simulations setting is outlined and the performance results are presented. Finally, conclusions are presented in Section 6.

2. RELATED WORK

Energy-efficiency in unicasting, multicasting and broadcasting has been considered from the perspective of either

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minimizing the total energy consumption or maximizing the network lifetime. Most versions of both optimization problems are NP-hard [9, 13], and have been mainly studied in their simplest form, the broadcasting case. A broadcasting algorithm can always be used for multicasting, by pruning the unnecessary transmissions to leaf nodes of the broadcast tree that do not belong to the multicast group, but this may not always result in an efficient algorithm. Two surveys summarizing much of the related work in the field can be found in [4, 1]. To the best of our knowledge is the first time that an optimal multi-cost algorithm is presented for the multicast problem in wireless networks.

A seminal work is [15], which presents a series of basic energy-efficient broadcasting algorithms, like Minimum Spanning Tree (MST), Shortest Path Tree (SPT) and Broadcast Incremental Power (BIP). The MST algorithm constructs a minimum energy spanning tree for broadcasting, while the SPT algorithm uses Dijkstra's algorithm in order to obtain a tree consisting of the minimum energy unicast paths to a destination. The BIP algorithm maintains a single tree rooted at the source node, and new nodes are added to the tree, one by one, on a minimum incremental cost basis. A variation of BIP is the Broadcast Average Incremental Power (BAIP) algorithm [14] where many new nodes can be added at the same step. The Greedy Perimeter Broadcast Efficiency (GPBE) algorithm [6] applies the same tree formation procedure as the BIP algorithm, but it is based on another greedy decision metric, defined as the number of newly covered nodes reached per unit transmission power. In [2] the Minimum Longest Edge (MLE) and the Minimum Weight Incremental Arborescence (MWIA) algorithms are proposed. The MLE first computes a minimum spanning tree using as link costs the required transmission powers and then removes redundant transmissions based on the nature of the wireless broadcast. In MWIA a broadcast tree is constructed using as criterion a weighted cost that combines the residual energy and the transmission power of each node. Afterwards, the unnecessary edges are removed in a way similar to the MLE algorithm. All the aforementioned works assume adjustable node transmission power. One of the few papers that assumes preconfigured power levels for each node is [8], where two heuristics for the minimum energy broadcast problem are proposed: a greedy one that uses as criterion for adding a new node in the tree, the ratio of the expended power over the number of the nodes covered by the transmission, and a node-weighted Steiner tree based algorithm. Multicasting is also considered in [9] where an algorithm based on the directed Steiner tree and two heuristic algorithms for the energy-efficient multicasting problem are proposed.

In [15], the Sweep heuristic algorithm is proposed to improve the performance of BIP by removing transmissions that are unnecessary. Iterative Maximum-Branch Minimization (IMBM) [10] starts with a trivial broadcast tree where the source transmits directly to all other nodes and at each step replaces the longest link with a two-hop path that consumes less energy. In [13], EWMA is proposed that modifies a minimum spanning tree by checking whether increasing a node's power so as to cover a child of one of its children, would lead to power savings. The r-Shrink heuristic [3] is applied to every transmitting node and shrinks its transmission radius so that less than r nodes hear each transmission. One node is examined at each step and the new tree formation is kept if there are savings in energy consumption. The LESS heuristic [7] extends the EWMA algorithm by permitting a slight increase in the transmission power of a node so that multiple other nodes can stop transmitting or reduce their transmission power.

3. THE OPTIMAL TOTAL AND RESIDUAL ENERGY MULTICOST MULTICAST ALGORITHM

The objective of the Optimal Total and Residual Energy Multicost Multicasting (OTREMM) algorithm is to find, for a given source node and desired multicast group $\mathcal{M}$, an optimal sequence of nodes for transmitting, so as to implement multicasting in an energy-efficient way. In particular, it selects a transmission schedule that optimizes any desired function of the total power T consumed by the multicasting task and the minimum R of the residual energies of the nodes, provided that the optimization function used is monotonic in each of these parameters, T and R. The OTREMM algorithm's operation consists of two phases, in accordance with the general multicost algorithm [5] on which it is based. In the first phase, the source node u calculates a set of candidate node transmission sequences $\mathcal{S}_{u,\mathcal{M}}$, called set of non-dominated schedules, which can send to all nodes in the multicast group $\mathcal{M}$ any packet originating at that source. In the second phase, the optimal sequence of nodes for multicasting is selected based on the desired optimization function.

In general, the multicasting process involves two levels: the information exchange level and the multicasting algorithm level. Information protocols deal with collecting and disseminating network state information, while multicast algorithms compute the optimal-best multicast trees using this information. Our focus is on the multicasting algorithmic level and thus assume that each node has global knowledge of the network topology and all other information it needs for making multicast decisions.

3.1 The enumeration of the candidate multicast schedules

In the first phase of the OTREMM algorithm, every source node u maintains at each time a set of candidate multicast schedules $\mathcal{S}_u$. (The schedules in $\mathcal{S}_u$ are not only for multicasting to the desired multicast group $\mathcal{M}$, but to any set of nodes.) A multicast schedule $S \in \mathcal{S}_u$ is defined as

$$S = ((u_1 = u, u_2, \dots, u_h), V_S)$$

where $(u_1, u_2, \dots, u_h)$ is the ordered sequence of nodes used for transmission and $V_S = (R_S, T_S, P_S)$ is the cost vector of the schedule, consisting of: (i) the minimum residual energy R_S of the sequence of nodes $u_1, u_2, \dots, u_h$, (ii) the total power consumption T_S caused when these nodes are used for transmission and (iii) the set P_S of network nodes covered when nodes $u_1, u_2, \dots, u_h$ transmit a packet.

When node u_i transmits a packet at distance r_i, the energy expended is taken to be proportional to r_i^a, where a is a parameter that takes values between 2 and 4. Because of the broadcast nature of the medium and assuming omnidirectional antennas, a packet being sent or forwarded by a node can be correctly received by any node within range r_i of the transmitting node u_i. Therefore, multicast and broadcast communication tasks in these networks correspond to finding a sequence of transmitting nodes, instead of a sequence of links as it is common in the wireline world.

Initially, each source node u has only one multicast schedule $\{\emptyset, (\infty, 0, u)\}$, with no nodes, infinite node residual energy, zero total power consumption, while the set of covered nodes contains only the source. The candidate multicast schedules from source node u are calculated as follows:

1. Each multicast schedule

   $$S = ((u_1, u_2, \ldots, u_{i-1}), (R_S, T_S, P_S))$$

   in the set of non-dominated schedules $\mathcal{S}_u$ is extended, by adding to its sequence of transmitting nodes a node $u_i \in P_S$ that can transmit to some node u_j not contained in P_S. If no such nodes u_i and u_j exist, we proceed to step 4.

   Then the schedule S is used to obtain an extended schedule S' as follows:

   - node u_i is added to the sequence $u_1, u_2, \ldots, u_{i-1}$ of transmitting nodes
   - $R_{S'} = \min(R_i, R_S)$, where R_i is the residual energy of node u_i
   - $T_{S'} = T_S + T_i$, where T_i is the (fixed) transmission power of node u_i
   - the set of nodes $D(u_i)$ that are within transmission range from u_i are added to the set P_S.
   - the extended schedule

     $$S' = ((u_1, \ldots, u_{i-1}, u_i),$$

     $$(\min(R_S, R_i), T_S + T_i, P_S \cup D(u_i)))$$

     obtained in the way described above is added to the set $\mathcal{S}_u$ of candidate schedules.

2. Next, a *domination relation* between the various multicast schedules of source node u is applied, and the schedules found to be dominated are discarded. In particular, a schedule S_1 is said to *dominate* a schedule S_2 when $T_1 < T_2$, $R_1 > R_2$ and $P_1 \supset P_2$. In other words schedule S_1 dominates schedule S_2 if it covers a superset of nodes than the one covered by S_2, using less total transmission power and with larger minimum residual energy on the nodes it uses. All the schedules found to be dominated by another schedule are discarded from the set $\mathcal{S}_u$.

3. The procedure is repeated, starting from step 1, for all multicast schedules in $\mathcal{S}_u$ that meet the above conditions. If no schedule $S \in \mathcal{S}_u$ can be extended further, we go to step 4.

4. Among the schedules in $\mathcal{S}_u$ we form the subset of schedules S for which $P_S \supset \mathcal{M}$. This subset is called the *set of non-dominated schedules* for transmitting from source node u to multicast group $\mathcal{M}$, and is denoted by $\mathcal{S}_{u,\mathcal{M}}$.

3.2 The selection of the optimal multicast schedule

In the second phase of the OTREMM algorithm, an optimization function $f(V_S)$ is applied to the cost vector V_S of every non-dominated schedule $S \in \mathcal{S}_{u,\mathcal{M}}$ of source node u, produced in the first phase. The optimization function combines the cost vector parameters to produce a scalar metric representing the cost of using the corresponding sequence of nodes for multicasting. The schedule with the minimum cost is selected. In the performance results described in Section V, the optimization function used is

$$f(S) = \frac{T_S}{R_S}, \text{for } S \in \mathcal{S}_{u,\mathcal{M}},$$

which favors, among the schedules that cover all nodes in the multicast group $\mathcal{M}$, those that consume less total energy T_S and whose residual energy R_S is larger. This way our algorithm jointly and in an optimal manner maximizes the network's lifetime and minimizes its total energy consumption. Other optimization functions could also be used, depending on the interests of the network, and different functions could be used for different multicast groups. The only requirement is that the optimization function has to be monotonic in each of its parameters.

THEOREM 1. *If the optimization function $f(V_S)$ is monotonic in each of the parameters involved, the OTREMM algorithm finds the optimal multicast schedule.*

PROOF. Since $f(V_S)$ is monotonic in each of its parameters, the optimal schedule has to belong to the set of non-dominated schedules (a schedule S_1 that is dominated by a schedule S_2, meaning that it is worse than S_2 with respect to all the parameters, cannot optimize f). Therefore, it is enough to show that the set $\mathcal{S}_u$ computed in Steps 1-3 of OTREMM includes all the non-dominated schedules for multicasting from node u.

We let $S = ((u_1, u_2, \ldots, u_h), (R_S, T_S, P_S))$ be a non-dominated schedule that has minimal number of transmissions h among the schedules not produced by OTREMM. Then for the schedule $S' = ((u_1, u_2, \ldots, u_{h-1}), (R_{S'}, T_{S'}, P_{S'}))$ we have that $R_S = \min(R_{S'}, R_h)$, $T_S = T_{S'} + T_h$, and $P_S = P_{S'} \cup D(u_h)$. The fact that S is non-dominated and was not produced by OTREMM, implies that S' was not produced by OTREMM either. Since S is a non-dominated schedule with minimal number of transmissions among those not produced by OTREMM, and S' was not produced by OTREMM and uses less transmissions, this means that S' is dominated. However, since S is non-dominated, this means that S' is also non-dominated (otherwise, the schedule S'' that dominates S', in the sense that it has $T_{S''} < T_{S'}$, $R_{S''} > R_{S'}$ and $P_{S''} \supset P_{S'}$, extended by the transmission from node u_h would dominate S), which is a contradiction. $\square$

4. THE NEAR-OPTIMAL TOTAL AND RESIDUAL ENERGY MULTICOST MULTICAST ALGORITHM

The OTREMM algorithm finds the schedule that optimizes the desired optimization function $f(V_S)$, but it has non-polynomial complexity, since the number of non-dominated schedules generated by the first phase of the algorithm can be exponential. In order to obtain a polynomial time algorithm, we relax the domination condition so as to obtain a smaller number of candidate schedules. In particular, we define a *pseudo-domination* relation among schedules, according to which a schedule S_1 *pseudo-dominates* schedule S_2, if $T_1 < T_2$, $R_1 > R_2$, and $|P_1| > |P_2|$, where T_i, R_i, $|P_i|$ are the total transmission power, the residual energy of the broadcast nodes and the cardinality of the set of nodes covered by schedule S_i, $i = 1, 2$, respectively. When this pseudo-domination relationship is used in step 2 of the OTREMM algorithm, it results in more schedules being pruned (not considered further) and smaller algorithmic complexity. Actually, by weakening the definition of the domination relationship the complexity of the algorithm becomes polynomial (this can easily be shown by arguing that T_i, R_i and $|P_i|$ can take a finite number of values, namely, at most as many as the number of nodes). The decrease in time complexity, however, comes at the price of losing the optimality of the solution. We will refer to this this near-optimal variation of the OTREMM algorithm, as the Near-Optimal Total and Residual Energy Multicost Multicast algorithm (abbreviated NOTREMM).

5. PERFORMANCE RESULTS

The performance of the OTREMM and NOTREMM algorithms is evaluated in comparison to established solutions for energy-efficient multicasting. However, since most of the algorithms proposed in the literature assume adjustable node transmission power, we have included their fixed-transmission power versions in our evaluation. The proposed algorithms are compared against the multicast version of the BIP algorithm [15], to be referred to as MIP algorithm [15], the MWIA algorithm [2], and the NJT algorithm [9].

We implemented and evaluated the algorithms, using the Network Simulator ns-2 [11]. We use a 4×4 two-dimensional grid network topology of 16 stationary nodes with distance of 50 meters between neighboring nodes. Each node's transmission radius is fixed at a value uniformly distributed between 50 and 100 meters. The multicasting strategies are evaluated under the packet evacuation model, where each node starts with a certain amount of initial energy and a given number of packets to be multicasted to a multicast group $\mathcal{M}$. The objective is to serve as many of them as possible before the energy is depleted. In our experiments the initial energy E_0 is taken to be equal for all nodes (5, 10 and 100 Joules). Each node multicasts 200-1000 packets (at steps of 200). A node belongs to the multicast group $\mathcal{M}$ with a probability q.

Figure 1 illustrates the average number of transmissions h undertaken by a packet in order to reach all destinations in its multicast group $\mathcal{M}$, for different values of the number of packets multicasted per source. It can be seen that the MIP and MWIA algorithms result in the worst performance. This can be explained by the fact that both algorithms select a multicast schedule based on the nodes transmission power and its combination with the nodes residual energy, respectively, resulting in more transmissions required per packet in order to reach all destinations in its multicast group $\mathcal{M}$.

In Figure 2 we illustrate the average node residual energy R at the end of an evacuation period. The best performance is achieved by the OTREMM algorithm, and is closely followed by that of NOTREMM, while the MIP, MWIA and NJT algorithms significantly underperform the OTREMM and NOTREMM algorithms. It is important to note that the NOTREMM algorithm performs comparably to the optimal algorithm, but has considerably smaller computational overhead. The MIP and MWIA algorithms are the worst performers; due to the large number of transmissions h they require, even though they both use transmissions that are less energy-consuming.

The proposed OTREMM algorithm outperforms all other strategies with respect to the multicast success ratio p (defined as the ratio of the number of packets successfully multicasted over the total multicast packets sent) as shown in Figure 3. The success ratio p of MIP and NJT starts falling, compared to that of OTREMM and NOTREMM, even for relatively light inserted traffic. The MWIA algorithm performs significantly better than MIP and NJT due to the fact that it takes into account both the node transmission powers and residual energies in selecting the multicast schedule. The MIP algorithm completes considerably less multicasts than OTREMM and NOTREMM since it consumes more energy, as already seen in Figure 2. The reason NJT completes less multicasts than OTREMM and NOTREMM can be explained by the distribution of energy consumption in the network, described next. Again, NOTREMM achieves very good performance that is only marginally inferior to that of OTREMM.

Figure 4 illustrates the current number of nodes L with depleted energy reserves as a function of time. We can see that the OTREMM and NOTREMM algorithms do not only result in fewer nodes running out of energy, but also these node energy depletions occur later in the experiment in comparison to the MIP, MWIA and NJT algorithms. The MWIA algorithm outperforms both MIP and NJT since under the MWIA algorithm the first energy depletions are posterior to the ones under MIP and NJT. This explains the higher multicast success ratio p of MWIA in comparison to MIP and NJT. If at least one node of the multicast group $\mathcal{M}$ runs out of energy no more successful multicast can be com-

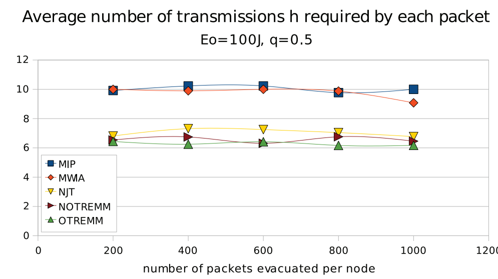

Figure 1: The average number of transmissions h required by each packet, for the case q=0.5, and node initial energy E_0 equal to 100 Joules.

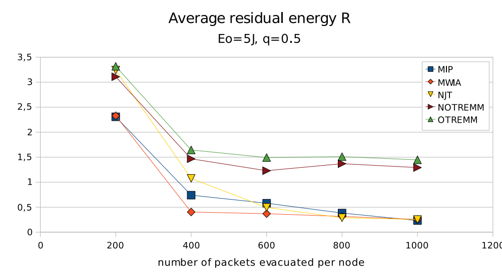

Figure 2: The average node residual energy R at the end of the evacuation, for the case q=0.5, and node initial energy E_0 equal to 5 Joules.

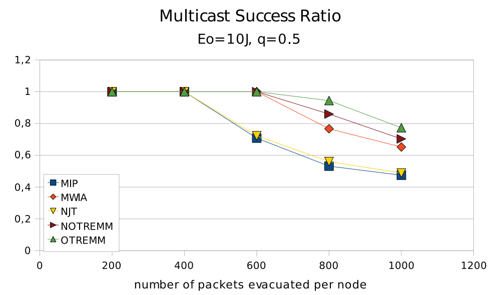

Figure 3: The multicast success ratio p, for the case q=0.5, and node initial energy E_0 equal to 10 Joules.

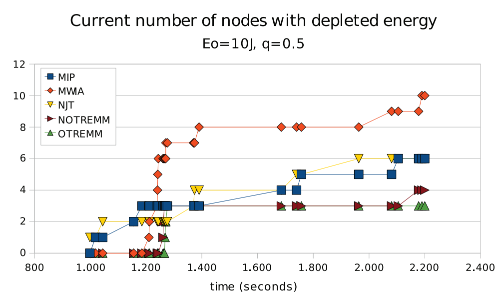

Figure 4: The current number of nodes L with depleted energy reserves, for the case q=0.5, and node initial energy E_0 equal to 10 Joules.

pleted. Even though NJT consumes on the average similar energy with that of OTREMM and NOTREMM, it spreads energy consumption less uniformly, with many nodes running out of energy rather soon while other nodes still having plenty of energy. This explains its inferior multicast success ratio p mentioned earlier (Figure 3). The performance of the NOTREMM algorithm is again almost identical to that of the optimal OTREMM algorithm.

6. CONCLUSIONS

We studied energy-efficient multicasting in wireless networks, and proposed an optimal (OTREMM) and a near-optimal (NOTREMM) algorithm, based on the multicost concept. The OTREMM algorithm is optimal in the sense that it can optimize any desired function of the total power consumed by the multicasting task and the minimum of the current residual energy of the nodes, provided that the optimization function is monotonic in each of these parameters. Our performance results show that the proposed multicost algorithms outperform the other established heuristic algorithms considered, consuming less energy and successfully multicasting more packets to their destination, under the packet evacuation model. An interesting conclusion drawn from our simulations is that the near-optimal multicost algorithm, NOTREMM, has similar performance to that of the optimal multicost algorithm, OTREMM, while having considerably smaller execution time, indicating that the computation overhead of the optimal algorithm is not justified by its performance superiority.

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