Multicost Energy-Aware Broadcasting in Wireless Networks with Distributed Considerations

Christos Papageorgiou*, Panagiotis Kokkinos, and Emmanouel Varvarigos

[1] University of Patras, Patras, Greece
[2] Research Academic Computer Technology Institute, Patras, Greece

Abstract. In this paper we propose an energy-aware broadcast algorithm for wireless networks. Our algorithm is based on the multicost approach and selects the set of nodes that by transmitting implement broadcasting in an optimally energy-efficient way. The energy-related parameters taken into account are the node transmission power and the node residual energy. The algorithm's complexity however is non-polynomial, and therefore, we propose a relaxation producing a near-optimal solution in polynomial time. We also consider a distributed information exchange scheme that can be coupled with the proposed algorithms and examine the overhead introduced by this integration. Using simulations we show that the proposed algorithms outperform other solutions in the literature in terms of energy efficiency. Moreover, it is shown that the near-optimal algorithm obtains most of the performance benefits of the optimal algorithm at a smaller computational overhead.

1 Introduction

Advances in battery lifetime during recent years have not kept in pace with the significant decline in computation and communication costs in ad hoc and sensor networks. Thus, considering the lack of any fixed infrastructure and the requirements for long operating lifetime, energy is a crucial resource limiting the performance and range of applicability of such networks. Furthermore, the cooperative nature of both ad hoc and sensor networks, makes broadcasting one of the most frequently performed primitive communication task. Being able to perform this communication task in an energy-efficient manner is an important priority for such networks.

In this paper we propose an optimal energy efficient broadcasting algorithm, called Optimal Total and Residual Energy Multicost Broadcast (abbreviated OTREMB) algorithm, for wireless networks consisting of nodes with preconfigured levels of transmission power. It is quite common that the nodes comprising wireless networks, either ad hoc or sensor, are not able to dynamically adjust

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their transmission power, since their processing capabilities are inherently minimal. Our algorithm is optimal, in the sense that it can optimize any desired function of the total power consumed by the broadcasting 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 broadcast, 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 Broadcast (abbreviated NOTREMB) algorithm, that produces a near-optimal solution to the energy-efficient broadcasting problem in polynomial time. The proposed algorithms try to jointly maximize the network lifetime and minimize its energy consumption, by following the multicost routing approach [6]. Multicost routing has been verified to perform better than single-cost routing in terms of energy-efficiency for the case of unicast routing in wireless networks [16]. In this work we show that multicost routing schemes can also be used for energy-efficient broadcast communication.

The routing process (unicasting, multicasting or broadcasting) involves two levels: the information exchange level and the routing algorithmic level. The proposed algorithms focuses on the routing level and thus assumes that all the necessary information for the optimal broadcast schedule to be computed is instantly available at each node. This is also the approach followed by the majority of related works. As far as the information exchange level is concerned, we examine a distributed information exchange protocol and discuss the emerging tradeoffs regarding the algorithm's performance and the induced overhead.

In the performance results we evaluate our broadcast algorithms assuming instant and costless knowledge of the network information, obtaining in this way a performance upper bound of the proposed solutions, and ignoring the information exchange overhead. We compare the optimal and near-optimal algorithms to other representative algorithms for energy-efficient broadcasting. Our results show that the proposed algorithms outperform the other algorithms 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 broadcasting. In Section 5 the simulations setting is outlined and the performance results are presented. Finally, in Section 6 we give the conclusions drawn from our work.

2 Related Work

Energy-efficiency in all types of communication tasks (unicast, multicast, broadcast) has been considered from the perspective of either minimizing the total energy consumption or maximizing the network lifetime. Most versions of both optimization problems are NP-hard [11,17,14]. Two surveys summarizing much of the related work in the field can be found in [5,1].

A major class of works in the field start with an empty solution which is gradually augmented to a broadcast tree. A seminal work presenting a series of basic energy-efficient broadcasting algorithms, like Minimum Spanning Tree, Shortest Path Tree and Broadcast Incremental Power (BIP), is [19]. 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. In Broadcast Average Incremental Power (BAIP) algorithm [18] many new nodes can be added at the same step with the average incremental cost defined as the ratio of the minimum additional power required by a node in the current tree to reach these new nodes to the number of new nodes reached. The Greedy Perimeter Broadcast Efficiency (GPBE) algorithm [8] uses another greedy decision metric, defined as the number of newly covered nodes reached per unit transmission power. In [3], the Minimum Longest Edge (MLE) and the Minimum Weight Incremental Arborescence (MWIA) algorithms are presented. The MLE first computes a minimum spanning tree using as link costs the required transmission powers and then removes redundant transmissions. 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. In [2], the Relative Neighborhood Graph (RNG) topology is used for broadcasting. In Local Minimum Spanning Tree (LMST) [13] each node builds a one-hop minimum spanning tree. A link is included in the final graph if it selected in the local MSTs of both its edge nodes. In [7] a localized version of the BIP algorithm is presented. All the aforementioned works assume adjustable node transmission power. One of the few papers that assumes preconfigured power levels for each node is [10], where two heuristics for the minimum energy broadcast problem are proposed.

Local search algorithms perform a walk on broadcast forwarding structures. The walk starts from an initial broadcast topology obtained by some algorithm and in each step, a local search algorithm moves to a new broadcast topology so that the necessary connectivity properties are maintained. The rule used at each step for selecting the next topology is energy-related and the algorithm terminates when no further improvement can be obtained. In [19], the Sweep heuristic algorithm was proposed to improve the performance of BIP by removing transmissions that are unnecessary, due to the wireless broadcast advantage. Iterative Maximum-Branch Minimization (IMBM) [12] 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 [17], 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 [4] is applied to every transmitting node and shrinks its transmission radius so that less than r nodes hear each transmission. The LESS heuristic [9] permits 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 Broadcast Algorithm

The objective of the Optimal Total and Residual Energy Multicost Broadcasting (OTREMB) algorithm is to find, for a given source node, an optimal sequence of nodes for transmitting, so as to implement broadcasting 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 broadcasting 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 OTREMB algorithm's operation consists of two phases, in accordance with the general multicost algorithm [6] on which it is based. In the first phase, the source node u calculates a set of candidate node transmission sequences $\mathcal{S}_u$, called set of non-dominated schedules, which can send to all nodes any packet originating at that source. In the second phase, the optimal sequence of nodes for broadcasting is selected based on the desired optimization function.

3.1 The Enumeration of the Candidate Broadcast Schedules

In the first phase of the OTREMB algorithm, every source node u maintains at each time a set of candidate broadcast schedules $\mathcal{S}_u$. A broadcast schedule $S \in \mathcal{S}_u$ is defined as $S = \{(u_1 = u, u_2, \ldots, u_h), V_S\}$, where $(u_1, u_2, \ldots, u_h)$ 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: the minimum residual energy R_S of the sequence of nodes $u_1, u_2, \ldots, u_h$, the total power consumption T_S caused when these nodes are used for transmission and the set P_S of network nodes covered when nodes $u_1, u_2, \ldots, u_h$ 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 omni-directional 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, 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. The assumption of omni-directional antennas is not necessary for the proposed algorithms to work, provided that we know the set of nodes $D(u_i)$ that can correctly decode a packet transmitted by node u_i; the performance results to be presented in Section 5, however, assume that omni-directional antennas are used.

Initially, each source node u has only one broadcast 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 broadcast schedules from source node u are calculated as follows:

1. Each broadcast 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 the final step.

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 broadcast 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 the first step 1, for all broadcast 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 the final step.
4. Among the schedules in $\mathcal{S}_u$ we form the subset of schedules S for which P_S includes all network nodes. This subset is called the *set of non-dominated schedules* for broadcasting from source node u, and is denoted by $\mathcal{S}_{u,\mathcal{B}}$.

3.2 The Selection of the Optimal Broadcast Schedule

In the second phase of the OTREMB algorithm, an optimization function $f(V_S)$ is applied to the cost vector V_S of every non-dominated schedule $S \in \mathcal{S}_{u,\mathcal{B}}$ 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 broadcasting. The schedule with the minimum cost is selected. In the performance results described in Section 5, the optimization function used is

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

which favors, among the schedules that cover all nodes, those that consume less total energy T_S and whose residual energy R_S is larger. Other optimization functions and parameters (with or without weights) could also be used, depending on the interests of the network. 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 OTREMB algorithm finds the optimal broadcast 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 OTREMB includes all the non-dominated schedules for broadcasting 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 OTREMB. 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 OTREMB, implies that S' was not produced by OTREMB either. Since S is a non-dominated schedule with minimal number of transmissions among those not produced by OTREMB, and S' was not produced by OTREMB 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.

4 The Near-Optimal Total and Residual Energy Multicost Broadcast Algorithm

The OTREMB 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 OTREMB algorithm, it results in more schedules being pruned (not considered further) and smaller algorithmic complexity. In fact, 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 OTREMB algorithm, as the Near-Optimal Total and Residual Energy Multicost Broadcast algorithm (abbreviated NOTREMB).

5 Information Exchange Protocols

The proposed algorithms require information that can be provided by information collection and dissemination mechanisms. An important categorization of the information protocols is whether they work in a centralized, decentralized or a distributed manner. In the centralized case, all the needed information is gathered by some central node that is accessible by all the other nodes of the network. In the decentralized scenario this information is gathered separately by each node. In the distributed case, only local information is available at each node and decisions are taken either based on this information, or by gathering on demand additional information, using an information protocol.

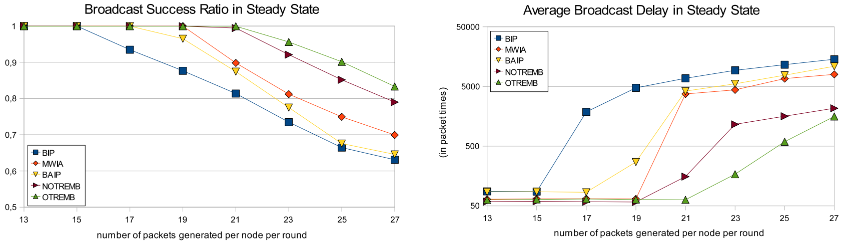
For our optimal and near-optimal broadcasting algorithms we can use a distributed information exchange mechanism. When a packet needs to be broadcasted, the source node broadcasts a control packet containing an empty schedule S. Every node u receiving this packet and not belonging to the set of covered nodes, updates the schedule S according to the way described in the first step of the enumeration of the broadcast sequences phase of the algorithms (Section 3.1). Then node u broadcasts the updated control packet to its neighbors. When all nodes are covered, the control packet is returned to the source node, using the information included in the sequence S. Before a newly received sequence S is added to the source node's set of schedules $\mathcal{S}_{u,\mathcal{B}}$, its domination relation with the other schedules in the set is checked. In the end, the optimization function is applied to the schedules in $\mathcal{S}_{u,\mathcal{B}}$ in order to select the best schedule. The algorithm's performance depends directly on the accuracy of the information at each node. The described information collection scheme can be used both in a periodic and an on-demand fashion. However, the tradeoff between the information accuracy and the induced overhead regarding network traffic and energy consumption needs to be considered.

In our performance results, we decided to focus only on the broadcast algorithm assuming instant and costless knowledge of the network information. Therefore, the results obtained there, can be viewed as an upper bound on the actual performance of the proposed solutions. This permits us to focus on the routing problem without having to deal with the implementation details of the information exchange protocol that could obscure the routing issues.

6 Performance Results

6.1 Simulation Setting

We implemented and evaluated the proposed algorithms, using the Network Simulator ns-2 [15]. 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. In our experiments the initial energy E_0 is taken to be equal for all nodes (5, 10 and 100 Joules). The proposed algorithms are compared against the fixed-power versions of the BIP [19], the MWIA [3] and the BAIP [18] algorithms.



(a) (b)

Fig. 1. The broadcast success ratio p and the average broadcast delay D in the steady-state of the algorithms evaluated, for a different number of broadcast packets N inserted in the network

We evaluate the proposed algorithms under the infinite time horizon model. In this model, the broadcasting strategies are evaluated assuming packets and energy are generated over an infinite time horizon, according to a round-based scenario. At the beginning of each round, the node energy reserves are restored to a certain level, and an equal number of packets N to be broadcasted is generated at every node. A round terminates when the residual energy of at least half of the network nodes falls below a certain safety limit. Packets that are not successfully broadcasted during a round, continue from the point they stopped (e.g., a node with residual energy levels below the safety limit) in the following round(s) until their broadcast is completed. The succession of rounds continues until the network reaches steady-state, or until it becomes inoperable (unstable). We use the following metrics:

- The average broadcast delay D of a packet is the time that elapses from the time instant it is generated at a source node, until the time it has reached all nodes of the network, possibly after several rounds.
- The broadcast success ratio p, defined as the ratio of the number of packets successfully broadcasted (reached all nodes of the network) over the total broadcast packets sent.

6.2 Simulation Results

Figure 1.a presents the broadcast success ratio p at steady state and the average broadcast delay D (in packet times), for a different number of broadcast packets N inserted at each node per round. We observe that even for relatively light traffic inserted in each round, the BIP, the MWIA and the BAIP algorithms are not able to successfully broadcast all the packets generated. The OTREMB and NOTREMB schemes have the maximum stability region (maximum broadcast throughput) and remain stable for up to $N = 21$ packets per node per round. By taking into account energy-related cost parameters and switching through multiple energy-efficient paths, both OTREMB and NOTREMB spread energy consumption more evenly and increase the volume of broadcast traffic that can

be successfully served. In Figure 1.b, where the delay versus traffic is depicted, the load curves of the BIP, MWIA and BAIP algorithms are above those of the OTREMB and the NOTREMB algorithms. Since packets whose broadcast is not completed during a round fill the node queues and congest the network, the average delay of the BIP, MWIA and BAIP algorithms quickly becomes very large. Naturally, when the traffic load inserted increases beyond each scheme's maximum stable throughput, the delays will also become unbounded, and the success ratio p will start falling. The OTREMB and the NOTREMB algorithms have smaller average delay D and remain stable for higher loads than the other schemes considered. In both figures we observe that the NOTREMB algorithm performs comparably to the OTREMB algorithm.

7 Conclusions

We studied energy-aware broadcasting in wireless networks, and proposed an optimal (OTREMB) and a near-optimal (NOTREMB) algorithm, based on the multicost concept. A distributed information collection mechanism was also introduced in order to make the proposed algorithms suitable for distributed operation. Our results show that the proposed multicost algorithms outperform the other algorithms considered, consuming less energy and successfully broadcasting more packets to their destination. Moreover, NOTREMB has similar performance to that of the OTREMB while having considerably smaller execution time.

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