Energy-Efficient Communication in Multi-interface Wireless Networks*

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Abstract. We study communication problems in wireless networks supporting multiple interfaces. In such networks, two nodes can communicate if they are close and share a common interface. The activation of each interface has a cost reflecting the energy consumed when a node uses this interface. We distinguish between the symmetric and non-symmetric case, depending on whether all nodes have the same activation cost for each interface or not. For the symmetric case, we present a $(3/2 + \epsilon)$–approximation algorithm for the problem of achieving connectivity with minimum activation cost, improving a previous bound of 2. For the non-symmetric case, we show that the connectivity problem is not approximable within a sublogarithmic factor in the number of nodes and present a logarithmic approximation algorithm for a more general problem that models group communication.

1 Introduction

Wireless networks have received significant attention during the recent years. They support a wide range of popular applications and usually constitute parts of larger, global networks, and the Internet. Wireless networks are in general heterogeneous in the sense that they are composed of wireless devices of different characteristics like computational power, energy consumption, radio interfaces, supported communication protocols, etc. Modern wireless devices are equipped with multiple radio interfaces (like most commonly wireless interfaces in use today such as Bluetooth, WiFi and GPRS) and can switch between different communication networks according to connectivity requirements and quality of service constraints (see Fig. 1). Selecting the best radio interfaces for specific connections depends on several factors, like for example, availability of an interface at a particular device, interference constraints, the necessary communication bandwidth, the energy consumed by an active interface and its lifetime, the interfaces available in some neighborhood, topological properties of the network, etc.

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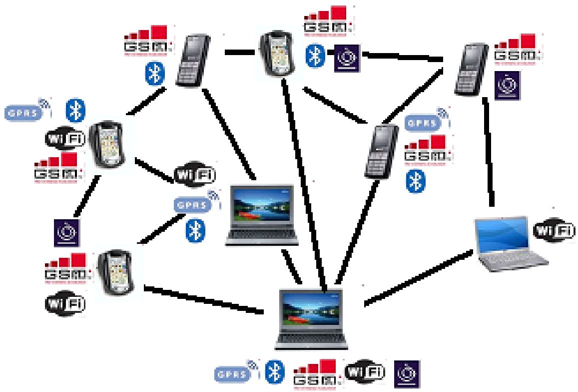

Fig. 1. Modern wireless devices are equipped with multiple radio interfaces and can switch between different communication networks

We study communication problems in wireless networks supporting multiple interfaces. The nodes of such networks are wireless devices equipped with some wireless interfaces. Communication between two such nodes can be established if (i) they are sufficiently close to each other and (ii) both share a common interface. If these requirements are met, then communication is established at a cost equal to the cost of activating a particular interface which is common in both nodes. The activation cost of an interface reflects the energy consumed when a node uses this interface. Our objective is to activate interfaces at the network nodes so that some connectivity property is preserved and the total cost of activated interfaces is minimized. Depending on the required connectivity property, several communication problems in multi-interface wireless networks arise. We consider two such problems: ConMI and GroupMI. In ConMI, we require that the communication is established among all network nodes. In GroupMI, communication must be established among groups of nodes (that do not necessarily include all nodes of the network). ConMI is a special case of GroupMI. We distinguish between two cases. The more general one is when the activation cost for some interface is not the same at all network nodes; this is the non-symmetric case. In the symmetric case of the problem, the cost of activating a particular interface is the same at all network nodes.

Related work. Multi-interface wireless networks have recently attracted research interest since they have emerged as a de facto communication infrastructure and can support a wide range of important and popular applications. In this setting, many basic problems already studied for "traditional" wired and wireless networks have been restated [2], especially those related to network connectivity [5,8] and routing [6] issues. However, the energy efficiency requirements increase the complexity of these problems and pose new challenges.

A combinatorial problem that falls within the general class of communication problems in multi-interface wireless networks has been studied in [11]. In that paper, a graph with desired connections between network nodes is given and the objective is to activate interfaces of minimum total cost at the network nodes so that all the edges in this graph are established. Several variations of the problem are considered depending on the topology of the input graph (e.g., complete graphs, trees, planar graphs, bounded-degree graphs, general graphs) and on whether the number of interfaces is part of the input or a fixed constant. The paper considers both unit-cost interfaces and more general symmetric instances.

ConMI has been introduced in [12] which studies symmetric instances of the problem. ConMI is proved to be APX-hard even when the graph modeling the network has a very special structure and the number of available interfaces is small (e.g., 2). On the positive side, [12] presents a 2-approximation algorithm by exploiting the relation of ConMI on symmetric instances with the minimum spanning tree on an appropriately defined edge-weighted graph. Better approximation bounds are obtained for special cases of ConMI such as the case of unit-cost interfaces.

Our results. We distinguish between the symmetric and non-symmetric case, depending on whether all nodes have the same activation cost for an interface or not. For the symmetric case, we present a $(3/2+\epsilon)$–approximation algorithm for ConMI, improving the previously best known bound of 2 from [12]. The main idea of the algorithm is to use an almost minimum spanning tree (MST) in an appropriately defined hypergraph and transform it to an efficient solution for ConMI. We also consider GroupMI for symmetric instances where we obtain a 4-approximation algorithm; here, we transform instances of the problem to instances of Steiner Forest in a similar way [12] transforms ConMI to MST. For the non-symmetric case, we show that the connectivity problem is not approximable within a sublogarithmic factor in the number of nodes through a reduction from Set Cover, and present a logarithmic approximation algorithm for the more general GroupMI problem. Here, we transform instances of the problem to instance of Node-Weighted Steiner Forest and exploit approximation algorithms of Guha and Khuller [10] (see also [1]) for Node-Weighted Steiner Forest. We remark that techniques for the Node-Weighted Steiner Forest have also been applied either implicitly [3] or explicitly [4] to minimum energy communication problems in ad hoc wireless networks. To the best of our knowledge, neither GroupMI nor non-symmetric instances of multi-interface wireless networks have been studied before.

The rest of the paper is structured as follows. We present some preliminary technical definitions and our notation in Section 2. The upper bound for symmetric instances of ConMI appears in Section 3. The algorithm for GroupMI is presented in Section 4. The results for non-symmetric instances of GroupMI are presented in Section 5.

2 Definitions and Notation

The wireless network is modelled by a graph G in which nodes correspond to network nodes and edges represent potential direct connections between pairs of network nodes. We denote by I the set of available interfaces. Each node u supports a set $I_u \subseteq I$ of interfaces. Two nodes u and v can communicate when they have the same interface activated provided that there exists an edge between them in G. Given a set of activated interfaces $S_u \subseteq I_u$ at each node u, we define the communication graph G_S that has the same set of nodes with G and an edge $e = (u, v)$ of G belongs to G_S if $S_u \cap S_v \neq \emptyset$. Activating interface g at node u has a non-negative cost $c_{u,g}$. Our objective is to activate interfaces at the nodes of G so that the induced communication graph has some connectivity property and the total cost of activated interfaces is minimized. Depending on the required connectivity property, several communication problems in multi-interface wireless networks arise. We consider two such problems: ConMI and GroupMI. In ConMI, we require that the communication graph is connected and spans all nodes of G. In GroupMI, we are additionally given a set of terminal nodes $D \subseteq V$ partitioned into p disjoint subsets $D_1, D_2, ..., D_p$. Here, for $i = 1, ..., p$, we require the communication graph to connect the terminal nodes of D_i. Clearly, ConMI is a special case of GroupMI. We distinguish between two cases. The more general one described above is the non-symmetric case. In the symmetric case of the problem, the cost of activating interface g at each node is the same and equal to c_g.

In the following we usually refer to well-known combinatorial optimization problems such as the Steiner Forest and the Node-Weighted Steiner Forest. In both problems, the input consists of a graph $G = (V, E)$ and a set of terminals $D \subseteq V$ partitioned in p disjoint subsets as in GroupMI, and the objective is to compute a forest of minimum total cost (weight) so that the terminals in the subset D_i belong to the same tree of the forest. In Steiner Forest, each edge e of G has an associated non-negative weight w_e; in Node-Weighted Steiner Forest, the edges are unweighted and each node u has a weight w_u.

3 A ConMI Algorithm for the Symmetric Case

We present a $(3/2+\epsilon)$–approximation algorithm for the symmetric case of ConMI improving the previously known upper bound of 2.

Our algorithm works as follows. Consider an input instance J, a set of available interfaces I and sets I_u of interfaces supported at each node u. First, we transform the graph G into an instance of the problem of computing a minimum spanning tree (MST) in an appropriately defined hypergraph H. Then, we solve almost exactly the MST problem in H using a polynomial-time approximation scheme of Prömel and Steger [13]. We use the resulting tree to determine the interfaces to activate in the nodes of G so that the corresponding communication graph is a connected spanning subgraph of G. This is the output of our algorithm. We show that the algorithm obtains an approximation guarantee of $3/2 + \epsilon$, where ϵ is the approximation guarantee of the MST algorithm in the hypergraph H.

The hypergraph $H = (V, F)$ has the same set of nodes as the graph G. We define the set of edges F of H as follows. We consider all triplets of nodes

v_i, v_j, v_k so that $I_{v_i} \cap I_{v_j} \cap I_{v_k} \neq \emptyset$ which are connected with at least two edges among them in G. We insert the triplet (v_i, v_j, v_k) as a hyperedge f of F. We denote by $s(f)$ the interface in $I_{v_i} \cap I_{v_j} \cap I_{v_k}$ of minimum cost; we call $s(f)$ the interface associated with hyperedge f. We assign to f a weight of $3c_{s(f)}$. This corresponds to the fact that by activating interface $s(f)$ at nodes v_i, v_j, v_k, the edges connecting them are contained in the corresponding communication graph at a cost of $3c_{s(f)}$.

We consider all pairs of nodes v_i, v_j so that $I_{v_i} \cap I_{v_j} \neq \emptyset$ which are connected with an edge in G. We insert the pair (v_i, v_j) as a hyperedge f of F. Again, we denote by $s(f)$ the interface in $I_{v_i} \cap I_{v_j}$ of minimum cost. We assign to f a weight of $2c_{s(f)}$. This corresponds to the fact that by activating $s(f)$ at nodes v_i, v_j, the edge connecting them is contained in the corresponding communication graph at a cost of $2c_{s(f)}$.

Since the edges of the hypergraph H consist of at most 3 nodes, we use the polynomial-time approximation scheme of [13] to obtain a spanning tree T of H. For each edge f of T, we activate interface $s(f)$ at the nodes of G that belong to f. In this way, in the corresponding communication graph the nodes belonging to the same hyperedge of T are connected and since T is connected and spans all nodes of V, the whole communication graph is a spanning subgraph of G, as well.

We denote by *cost*(J) the total cost of the solution obtained by our algorithm, by *opt*(J) the cost of the optimal solution, by $mst(H)$ the cost of the minimum spanning tree of H and by *st*(H) the cost of the spanning tree T. We prove the following two lemmas.

Lemma 1. *cost*$(J) \leq$ *st*(H).

Proof. Since the set S_u of interfaces activated at each node u consists of interfaces associated with the hyperedges of T that contain u, it holds:

$$\mathit{cost}(J) = \sum_{u \in V} \sum_{g \in S_u} c_g \leq \sum_{u \in V} \sum_{f \in T : u \in f} c_{s(f)} = \sum_{f \in T} w(f) = \mathit{st}(H). \qquad \square$$

Lemma 2. $mst(H) \leq \frac{3}{2}$*opt*(J).

Proof. Consider an optimal solution to ConMI for instance J that consists of sets of interfaces S_u activated at each node u of G. We denote by S the set of all activated interfaces and by G_S the corresponding communication graph. We decompose G_S into different subgraphs; there is one such subgraph for each interface of S. We denote by G_g the subgraph of G consisting of the set of nodes V_g which have interface g activated in the optimal solution and of the set of edges E_g connecting nodes of V_g in G. Clearly, $\mathit{opt}(J) = \sum_{g \in S} c_g |V_g|$. For each $g \in S$, we compute a minimum spanning tree on each connected component of G_g; the minimum spanning trees on the connected components of G_g form a forest T_g.

We decompose the edges of T_g into special substructures that we call *forks*; a fork is either a set of two edges incident to the same node or a single edge. In each connected component of T_g with m nodes, the procedure that decomposes its edges into forks is the following. If there are two leaves u and v with a common parent, we include the edges incident to u and v in a fork. We remove u, v, and their incident edges from the tree. If no two leaves have a common parent, then some leaf u has a node v of degree 2 as a parent or there is only one remaining edge between two nodes u and v. In the first case, we include the edges incident to u and v in a fork and remove u, v, and their incident edges from the tree. In the second case, we simply include the edge between u and v in a fork and remove it from the tree. We repeat the procedure above until all edges of the tree are included in forks. In each step (possibly besides the last one), 2 among the at most $m-1$ edges of the tree are included in a fork. Hence, the number of forks is at most $m/2$. By repeating this decomposition for each connected component of T_g, we obtain a decomposition of the edges of T_g into at most $|V_g|/2$ forks. The endpoints of each fork of T_g correspond to a hyperedge in H with weight at most $3c_g$. The union of all these hyperedges is a connected spanning subgraph of H (since the union of the T_g's yields G_S). The cost of the minimum spanning tree of H is upper-bounded by the total cost of the hyperedges in this spanning subgraph, i.e.,

$$mst(H) \leq \sum_{g \in S} 3c_g \frac{|V_g|}{2} = \frac{3}{2} opt(J). \qquad \square$$

By Lemmas 1 and 2 and since $st(H) \leq (1+\epsilon) mst(H)$, we obtain the following:

Theorem 1. *For any constant $\epsilon > 0$, there exists a polynomial-time $(3/2+\epsilon)$–approximation algorithm for ConMI.*

4 Group Communication in the Symmetric Case

In this section, we present an algorithm for symmetric instances of GroupMI that has a constant approximation ratio. The main idea of the algorithm is similar to the algorithm of Kosowski et al. [12] for ConMI but instead of using a polynomial-time algorithm for MST, we use the 2-approximation algorithm of Goemans and Williamson [9] for the Steiner Forest problem.

Consider an instance J of GroupMI with a graph $G = (V, E)$ with n nodes, a set of terminal nodes $D \subseteq V$ partitioned into p disjoint subsets $D_1, ..., D_p$ and sets I_u of interfaces supported by each node $u \in V$. We construct an instance J_{SF} of Steiner Forest consisting of a graph $H = (V, A)$ and the set of terminals D partitioned into the same p disjoint subsets of terminals. The set of edges A contains all edges (u, v) of E such that $I_u \cap I_v \neq \emptyset$. Consider an edge $e = (u, v)$ of A and let $s(e)$ be the interface of minimum cost in $I_u \cap I_v$. Then, the weight w_e of e is equal to $2c_{s(e)}$.

We use the algorithm of [9] to solve Steiner Forest for the instance J_{SF} and obtain a forest F which preserves connectivity among the nodes of each terminal set D_i. We obtain the solution to the original instance J as follows. For each interface edge e in F, we activate interface $s(e)$ at the endpoints of e. Clearly, in this way the edges of G that correspond to F are contained in the corresponding communication graph and the required connectivity requirements for instance J are satisfied.

The upper bound on the approximation ratio of the algorithm is given in the following statement. The proof is obtained by extending the arguments used in [12].

Theorem 2. *There exist a 4-approximation algorithm for symmetric instances of GroupMI.*

Proof. Omitted. □

5 Group Communication in the Non-symmetric Case

In this section, we consider the problem GroupMI for non-symmetric instances. In this case, even the simpler problem ConMI does not have constant approximation algorithms as the following statement indicates.

Theorem 3. *Non-symmetric ConMI in networks with n nodes is hard to approximate within $o(\ln n)$.*

Proof. We use a simple reduction from Set Cover. Consider an instance of Set Cover with a ground set U of m elements and a collection $\mathcal{T}$ of subsets of U. The size of the collection $\mathcal{T}$ is polynomial in m. We construct an instance of ConMI as follows. The set of interfaces I has two interfaces 0 and 1. The graph G has a root node r, nodes $u_1, ..., u_{|\mathcal{T}|}$ corresponding to the sets of $\mathcal{T}$, and nodes $v_1, ..., v_m$ corresponding to the elements of U. Node r supports only interface 0 (i.e., $I_r = \{0\}$) with an activation cost 0. Nodes $u_1, ..., u_{|\mathcal{T}|}$ support interfaces 0 and 1 (i.e., $I_{u_i} = \{0, 1\}$) with activation costs 0 for interface 0 and 1 for interface 1. For $i = 1, ..., m$, node v_i supports only interface 1 ($I_{v_i} = \{1\}$) with an activation cost 0. For each set T_i of $\mathcal{T}$, node u_i is connected through an edge with each node v_j so that element j belongs to the set T_i. The root node r has edges to each node u_i, for $i = 1, ..., |\mathcal{T}|$.

We can easily show that any cover of U with C sets from $\mathcal{T}$ yields a solution to ConMI with cost at most C and vice versa. Indeed, consider a solution to the Set Cover instance that consists of a subset of $\mathcal{T}'$ of $\mathcal{T}$. By activating interface 0 at nodes $r, u_1, ..., u_{\mathcal{T}}$ and interface 1 at nodes $v_1, ..., v_m$ and nodes u_i, such that $i \in \mathcal{T}'$, we obtain a solution to the ConMI instance of cost $|\mathcal{T}'|$. Also, given a solution to the ConMI instance, we obtain a cover of U of the same cost by picking the sets of $\mathcal{T}$ that correspond to the nodes u_i which have interface 1 activated. Using well-known inapproximability results for Set Cover [7,14], we obtain an inapproximability bound of $\tau \ln m$. Since the number of nodes n in the instance of ConMI is polynomial in m, we obtain the desired result. □

Next, we present an $O(\ln n)$–approximation algorithm for non-symmetric GroupMI by reducing the problem to instances of Node-Weighted Steiner Forest. The reduction is similar to reductions for minimum energy communication problems in ad hoc wireless networks [4].

Consider an instance J of GroupMI with a graph $G = (V, E)$ with n nodes, a set of terminal nodes $D \subseteq V$ partitioned into p disjoint subsets $D_1, ..., D_p$ and sets I_u of interfaces supported by each node $u \in V$. We construct an instance of Node-Weighted Steiner Forest consisting of a graph $H = (U, A)$ and a set of terminals $D' \subseteq U$ partitioned into p disjoint subsets $D'_1, ..., D'_p$. The graph H is defined as follows. The set of nodes U consists of n disjoint sets of nodes called supernodes. Each supernode corresponds to a node of V. The supernode Z_u corresponding to node $u \in V$ has the following $|I_u| + 1$ nodes: a hub node $Z_{u,0}$ and $|I_u|$ bridge nodes $Z_{u,g}$ for each interface $g \in I_u$. For each pair of nodes $u, v \in V$ and each interface $g \in I_u \cap I_v$, the set A of edges contains an edge between the bridge nodes $Z_{u,g}$ and $Z_{v,g}$. Also, for each node $u \in V$, A contains an edge between the hub node $Z_{u,0}$ and each bridge node $Z_{u,g}$, for $g \in I_u$. Each hub node has weight 0. A bridge node $Z_{u,g}$ corresponding to node $u \in V$ and interface $g \in I_u$ has weight equal to the activation cost $c_{u,g}$ of interface g at node u. The set of terminals D' consists of all the hub nodes. For $i = 1, ..., p$, the set D'_i in the partition of D' consists of the hub nodes $Z_{u,0}$ for each node $u \in D_i$.

We denote by J_{NWSF} the resulting instance of Node-Weighted Steiner Forest. We use a known algorithm for solving Node-Weighted Steiner Forest for the instance J_{NWSF} and obtain a forest F which is a subgraph of H without isolated nodes and which preserves connectivity among the nodes of each terminal set D_i. We obtain the solution S to the original instance J as follows. For each interface g in I_u, we include g in S_u iff $Z_{u,g}$ is a node of F.

The next lemma captures the main property of the reduction.

Lemma 3. *If F is a ρ–approximate solution to J_{NWSF}, then S is a ρ–approximate solution to J.*

Proof. Let u, v be nodes belonging to the same terminal set D_i. Then, the hub nodes $Z_{u,0}$ and $Z_{v,0}$ belong to the set D'_i and there exists a path q from $Z_{u,0}$ to $Z_{v,0}$ in F. The edges of q are either edges connecting a hub node with a bridge node in the same supernode or bridge nodes between different supernodes. Consider the edges of q that connect bridge nodes of different supernodes in the order we visit them by following path q from $Z_{u,0}$ to $Z_{v,0}$. For each such edge $(Z_{x,g}, Z_{y,g})$ the edge (x, y) belongs to G and all of them define a path q' from u to v in G. Since $Z_{x,g}$ and $Z_{y,g}$ belong to F, nodes x and y have interface g activated and hence the edges of q' belong to the induced communication graph.

In the following we show that the total activation cost $cost(J)$ of our solution equals the cost $cost(J_{NWSF})$ of F and that the optimal activation cost $opt(J)$ is lower-bounded by the cost $opt(J_{NWSF})$ of the optimal solution for J_{NWSF}. In this way, we obtain that

$$cost(J) = cost(J_{NWSF}) \leq \rho \cdot opt(J_{NWSF}) \leq \rho \cdot opt(J).$$

Indeed, interface g is activated at node u only if the bridge node $Z_{u,g}$ belongs to F. Since, $w(Z_{u,g}) = c_{u,g}$, we have that the total activation cost of our solution for J is equal to the cost of F.

Now, consider an optimal solution to J consisting of sets S_u of activated interfaces at each node u of G. We construct a subgraph F' of H as follows.

For each edge (u, v) in the communication graph G_S, and for each interface g belonging to $S_u \cap S_v$, we add edge $(Z_{u,g}, Z_{v,g})$ to F'. For each node u and each interface $g \in S_u$, we add edge $(Z_{u,0}, Z_{u,g})$ to F'. Using similar reasoning as above, we obtain that F' maintains the connectivity requirement between nodes of the same terminal set D'_i and the total weight of its nodes equals the total activation cost in the optimal solution of J. Hence, the cost of the optimal solution of J_{NWSF} is not higher than the cost of F'. □

In [10], Guha and Khuller present a $1.61 \ln k$–approximation algorithm for Node-Weighted Steiner Forest, where k is the number of terminals in the graph. We use this algorithm to solve J_{NWSF}, and following the discussion above we obtain a solution of J which is within $1.61 \ln |D|$ of optimal. Thus, we have:

Theorem 4. *There exists a $1.61 \ln |D|$–approximation algorithm for non-symmetric GroupMI, where D is the set of terminals.*

Moreover, if J is an instance of ConMI, then $p = 1$ and the instance J_{NWSF} is actually an instance of Node-Weighted Steiner Tree which can be approximated within $1.35 \ln k$.

Theorem 5. *There exists a $1.35 \ln n$–approximation algorithm for non-symmetric ConMI with n network nodes.*

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