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What is the Optimum Length of a Wireless Link?

M. Ufuk Çaglayan, Fikret Sivrikaya, and Bülent Yener

In multi-hop wireless networks, the choice of transmit power at a station determines its coverage area and therefore its neighbours. Higher power levels result in 'longer' links and reduce the number of hops for a packet. On the other hand, high transmission powers decrease the capacity of neighbouring wireless links due to the interference generated, and may have an adverse effect on overall network capacity. In this paper, we consider networks of identical wireless stations, where each station has the same set of power levels available for transmission. We focus on the case of static power assignment, i.e. the power assignment to each station is made permanently and remains the same for all packets transmitted from the station. The power assignment to nodes has to be performed in such a way as to minimize 'potential interference' across the network while maintaining connectivity. We present first an optimal Integer Programming (IP) formulation, then a more efficient and near-optimal IP for this problem. Since IP formulations are NP-hard (Nondeterministic Polynomial) we present heuristics based on randomized rounding of Linear Programming (LP) relaxations. All solutions provide for a power assignment to nodes ensuring connectivity in the network, while at the same time aiming to minimise total interference. We compare the quality of results against the optimal solutions, and analyse the efficiency of each model.

Keywords: Ad-hoc, Minimum Interference, Static Power Assignment.

1 Introduction

Wireless ad hoc networks are becoming increasingly more widespread since they allow a number of nodes to communicate without the need for an infrastructure or any prior configuration. As an example of ad hoc networks, imagine a group of people meeting in a room with their laptops and spontaneously forming a network, without the need for an infrastructure or a central access point. This manner of communication is said to be multi-hop: a node wanting to communicate with another node may not be within the transmission range of its intended receiver, and needs to send its data through other intermediate nodes hop-by-hop. Most recent wireless devices provide a set of power levels available for use in transmission. The choice of transmit power at a station determines its coverage area and therefore its neighbours. Higher power levels result in 'longer' links and reduce the number of hops for a packet. On the other hand, high transmission powers decrease the capacity of neighbouring wireless links due to the generated interference, and may have an adverse effect on overall network capacity.

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Previously, algorithms and techniques were proposed to find an optimal transmission power setting to ensure connectivity [6][2][7][5]. The pioneering work described in [3] provided the first, albeit asymptotic, results regarding power level and connectivity. In [6] the authors propose an algorithm to adjust the power level in order to ensure a minimum degree constraint on each node. In [2] a similar degree constraint is enforced to ensure a bound on the end-to-end throughput. In [5] low power levels are reported to result in planar graphs in which the links are only established between nearby nodes to give power optimal routes. However, transmitting with small power levels increases the number of hops for a packet to reach its destination, which in turn may cause higher total (over the entire network) power consumption. Thus, the problem of inducing a network graph for routing, the power control problem and the routing problem are closely interlinked. None of the prior work considers the joint problem with the exception of [1] which considers the joint power control and optimal routing problem for a given SIR (Signal to Interference Ratio) bound. This present article differs from [1] in several ways. Firstly, we formulate the power assignment problem as a minimization of maximum interference while ensuring strong connectivity. Since max-min optimization problems are in general harder than minimization problems, we transform the max-min problem to a *cost* minimization problem. The routing problem is solved by computing the shortest paths on the induced network graph with link costs being the distance metric.

In this work, we study generic ad hoc networks with no prior traffic information. Instead we assume that each node pair in the network is equally likely to talk to each other, and that the load on each communication link is identical in the steady state. To statically assign power levels to nodes in such a scenario, we consider the 'potential interference' on each link (i.e. on the receiver of each link). We define 'potential interference' on a link as the total amount of interference observed on the link when all neighbouring links are active (being used for transmission). Thus, for a given power assignment, the potential interference is the maximum interference a link can actually suffer at any specific time. In the rest of this paper, we will usually omit the term 'potential' and simply refer to 'interference' with no change to the meaning.

We present two different integer programming formulations for the optimal solution of the integrated problem of connectivity and interference. The objective is to minimize overall interference in the network while ensuring connectivity. The first integer programming is called the *SIR model*, as we consider the interference created on each link by other communications, and try to satisfy the SIR constraint on each link. This is a well known approach to the problem, but we extend this model in two ways: firstly we generalize the problem by defining two sets, representing the *coverage area* and *interference area* for each node, and secondly we modify the problem so that the SIR bound is not given as an input; instead we set the objective to find the optimal (maximum) SIR bound such that SIR constraints are not violated. These extensions yield a more generic formulation for the problem. Our second integer programming formulation is a novel approach, called the *cost model*. In this case, we consider the interference a link creates on other links (note the difference with the SIR model, where we consider the interference on a link created by other links). By pre-processing, we assign a cost to each link as the amount of interference it incurs on neighbouring links. The objective, therefore, is to assign power levels to nodes such that the network is strongly connected and the total link cost is minimized. We argue that the two programming formulations produce very similar results, but the cost model is far more efficient than the SIR model, and should therefore be preferred in order to obtain optimal/near optimal results. We also present two heuristics based on LP (Linear Programming) relaxations of IP (Integer Programming) formulationss and randomized rounding. We call these models LP SIR and LP Cost, each denoting the heuristic obtained by the LP relaxation of corresponding IP formulation.

The rest of this paper is organized as follows. Section 2 describes the SIR model and presents the IP formulation corresponding to this model. Then the Cost model and related IP are described in section 3, while section 4 explains the heuristics obtained by relaxing the binary variables in IP formulations and then randomly rounding the results to obtain feasible approximations. Section 5 is devoted to the presentation of experimental results and a comparison between the models in terms of efficiency and quality of solutions. Section 6 concludes the paper.

2 SIR Min-Max Optimization

Given a set R of nodes (stations) and discrete power levels $p = 1, \cdots ,L$ we present a linear integer programming formulation that combines the problem of covering with disks with a multicommodity flow problem. We assume that each power level p of a node v induces two circles representing the coverage area and the noise area for v. Both circles are centred at origin node v and have radii r_p and R_p, respectively. We call these cycles *primary* and *secondary* disks of v at power level p. We assume that for power level p, node v can establish a direct link to each node in the primary disk. Let $\delta^1_{p,v}$ be the set of nodes covered by the primary disk of v with radius r_p. We also assume that power level p is not sufficient to communicate with the nodes that reside outside the primary disk but inside the secondary disk. These nodes receive some useless energy, or noise, from v. Let $\delta^2_{p,v}$ be the set of nodes covered by the secondary disk of v with radius R_p. Note that $\delta^1_{p,v} \subseteq \delta^2_{p,v}$. Similarly, let $\Delta^1_{p,v}$ and $\Delta^2_{p,v}$ denote the set of nodes that v is covered by their primary and secondary disks, respectively at power level p.

At any point T in time, node v can communicate with a node u in $\delta^1_{p,v}$ directly. This transmission will cause interference on all nodes except u in $\delta^2_{p,v}$. Thus we assume that, at time T, sets $\delta^1_{p,v}$ and $\delta^2_{p,v}$ define all outgoing (outbound) links of v such that one of the links carry data and the rest carry only noise or interference. When a signal is emitted by node u with power level p, the amount of signal or interference received at node v will be determined by the physical layer aspects, called the link gain $g_p(u, v)$. We assume that link gains are given as input, and they reflect the received signal strength at the receiver. Similarly the sets $\Delta^1_{p,v}$ and $\Delta^2_{p,v}$ define the inbound links of node *v*. Total interference on receiver *v*, while communicating with transmitter *u*, is the sum of the interference from all nodes except *u* in $\Delta^2_{p,v}$.

The problem is to assign a power level to each node such that the network is strongly connected with regard to the primary disks, and that the signal-to-interference ratio (SIR) constraint is not violated for any receiver with regard to the secondary disks.

Let X^p_u be a binary decision variable indicating whether node *u* is assigned power level *p*. Then, each node must be assigned exactly one power level:

$$\sum_p X^p_u = 1 \qquad \forall u \in R \tag{1}$$

We need to ensure that the induced directed graph is strongly connected. To achieve this, we embed a multicommodity flow problem into our formulation where variable $f^{s,d}_{u,v,p}$ is the amount of flow on directed link $< u, v >$ established with power level *p* for commodity from source *s* to destination *d*. We assume that each node has a unit commodity to send to any other node in the system, in order to ensure strong connectivity.

$$\sum_{p \in L} \sum_{v \in \delta^1_{p,u}} f^{s,d}_{u,v,p} - \sum_{p \in L} \sum_{v \in \Delta^1_{p,u}} f^{s,d}_{v,u,p} = t \tag{2}$$

for all *u*, where $t = +1$ if $u = s$, $t = -1$ if $u = d$, and $t = 0$ otherwise. We must further ensure that the flow can only be pushed over existing edges:

$$0 \le f^{s,d}_{u,v,p} \le X^p_u \qquad \forall u, v, s, d \in R, p \in L \tag{3}$$

Next we consider the SIR bound at a receiver *v* while communicating with transmitter *u*. Let $G(u, v, p) = X^p_u \cdot g_p(u, v)$ be the signal strength at power level *p* for such transmission. Total interference on *v* is computed for $a \neq u$ as follows:

$$I(u, v) = \sum_p \sum_{a \in \Delta^2_{p,v}} X^p_a \cdot g_p(a, v) \tag{4}$$

To ensure that SIR is at least of a given QoS bound θ at receiver node *v*, we must have

$$\frac{G(u, v, p)}{I(u, v)} \ge \theta \quad \forall u, v \in R, p \in L \quad \text{s.t.} X^p_u = 1$$

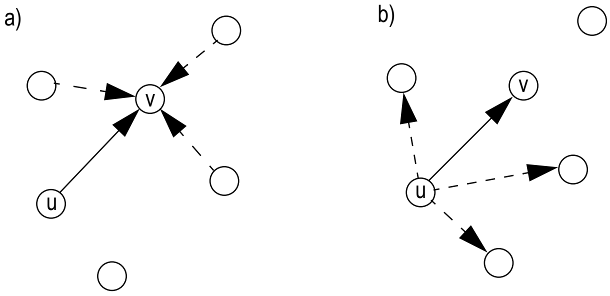

Figure 1: The Difference between the Two Models, a) SIR Model, b) Cost Model. (The *cost* of the link between *u* and *v* is determined by the dashed links in each model.)

We linearly formulate the SIR constraints as

$$G(u, v, p) - \theta \cdot I(u, v) + \left(1 - X^p_u\right) \cdot \beta \ge 0 \tag{5}$$

where β is a large positive constant. Note that if node *u* is assigned power level *p*, then the last term is zero and has no effect. Otherwise, the last term dominates and the constraint is trivially satisfied. In this paper, instead of studying networks with a given SIR bound, we consider a more generic case. We convert the model such that the SIR bound is not a part of the input, but instead the objective is to maximize the SIR bound θ that satisfies all constraints. Obviously, this makes the problem nonlinear, since the term $I(u, v, p)$ includes variable X^p_u and its product with variable θ makes the constraint nonlinear. However, by a simple modification in SIR constraints, we can get a new linear formulation. Note that if we divide the equation (5) by θ, we eliminate the nonlinearity caused by the product of two variables in the second term. However, this time we get a product of $G(u, v, p)$ and $1/\theta$ which is still nonlinear. We finally observe that the variable X^p_u can be omitted when calculating $G(u, v, p)$ since for any u, p such that $X^p_u = 0$, the SIR constraint is trivially satisfied, and thus the value of X^p_u is effectively always 1 for the SIR constraints. Therefore, we can rewrite the SIR constraint as

$$\alpha \cdot G(u, v, p) - I(u, v) + \left(1 - X^p_u\right) \cdot \beta \ge 0 \tag{6}$$

where α is a new variable that we introduce, and stands for $1/\theta$. Then the optimization problem is to minimize α subject to constraints (1), (2), (3), (4) and (6).

3 Interference (Cost) Minimization

In this section, we present a different approach to the same problem. Recall that in the SIR model we consider the interference on a link *caused by other links*, and try to minimize that interference network-wide. In the 'cost model' of this section, we define a cost for each link as the amount of interference it incurs *on other links*, and try to minimize the total cost across the network (see Figure 1). Intuitively the two approaches should yield similar results, and we justify this intuition by experimental results in section 5. We also show by experimental results that the 'cost model' is much more efficient than 'SIR model' in terms of running time.

In the cost model, we represent the network as a directed multigraph G in which there is a link (edge) from node u to node v for each power level that u can communicate to v. If an edge corresponds to a transmission from node u to node v with power level p (i.e. if $v \in \delta^1_{p,u}$), then we label that edge with the three-tuple (u, v, p). Let E denote the set of edges in graph G, corresponding to all such communication links. We assign a weight to each link as the amount of interference it incurs on other links. The problem is then to select a set of outgoing edges (by choosing a power level) for each node with minimum total weight, such that the graph is strongly connected. The cost of edge (u, v, p) is calculated as follows (for $a \neq v$):

$$c(u, v, p) = \sum_{\alpha \in \delta^2_{p,u}} g_p(u, a) \forall (u, v, p) \in E \qquad (7)$$

The optimization problem is to

$$\text{Minimize} \sum_{(u, v, p) \in E} X^p_u \cdot c(u, v, p)$$

subject to constraints (1), (2), (3) and (7). The cost model constitutes an integer programming, whose solution yields results close to the optimal solution with much smaller running times. This is mainly because the integer programming of the SIR model has the objective function of type *minimizing the maximum cost*, while the cost model has the objective of *minimizing the total cost*. The former type of integer programs is usually much harder to solve than the latter. Moreover, in the SIR model the total interference on a link is caused by neighbouring transmissions and its amount depends on the power level selected at a distant station. Since the power assignments are made as a solution to the problem, we can not calculate the interferences on each link by pre-processing. Note that each $I(u, v)$ value depends on X^p_a, for all $a \in \Delta^2_{p,v}$. This makes the integer programming formulation more complicated. On the other hand, in the cost model, the amount of interference incurred by any link l on other nodes is just a function of the power level chosen at the transmitter of link l. Therefore, in the cost model, by representing the network as a multigraph, we can calculate and assign costs to each edge by pre-processing. Note that the value of $c(u, v, p)$ does not depend on any variable of the linear programming. These issues create a significant difference between the running times of the two formulations.

4 Heuristics Using LP Relaxations and Randomized Rounding

Since the integer programming formulations are NP-hard (Nondeterministic Polynomial) we can only solve them for small networks (of sizes up to 20 nodes) in reasonable amount of time. Hence we relax each integer programming formulation to a linear program (LP) and then apply randomized rounding [4] to the fractional values obtained, in order to obtain the integer (binary) values as an approximation to the optimal solution. To obtain the LP relaxations, we simply convert binary variables X^p_u into real values between 0 and 1:

$$0 \le X^p_u \le 1 \qquad \forall u \in R, p \in L$$

Thus the solutions to the LP relaxations constitute a probability distribution of power levels for each node. In other words, the fractional values for the power levels at a node all take values between 0 and 1, and they add up to 1 as dictated by constraint (1). Therefore we can directly use the LP relaxation solution as probabilities for randomized rounding. For example, assume that there are $L = 3$ power levels available at a node and the LP results for node u is $X^0_u = 0.2$, $X^1_u = 0.7$, $X^2_u = 0.1$. We can then randomly choose p_0 (the minimum power level) with probability 0.2, p_1 with probability 0.7, and p_2 with probability 0.1 as the power level for node u. In general, the solution obtained after randomized rounding may violate some constraints in the original integer programming. In our case, the network may not be connected for the power levels obtained after rounding. Therefore after randomized rounding, we check the resulting graph for strong connectivity and if not connected repeat the randomized rounding process until a strongly connected graph is obtained. Instead of independent repetitions, we increase the probabilities of higher power levels at each step of the algorithm, to ensure convergence to a feasible result. We define a small constant γ, which is a parameter and can be adjusted. At each step of the algorithm, we add $(p-1)\gamma$ for each node u, then normalize the resulting values such that $\sum_p X^p_u = 1$, where p is the index of power levels sorted in increasing order. Hence we add higher values to the higher power levels. Note that a large value of γ provides a faster convergence to a feasible result, but the result obtained may be poor in quality since the probabilities of higher power levels increase very rapidly and the solution is more likely to assign high transmission powers to most of the nodes. On the other hand, a small value of γ may result in longer running times, but the quality of results may be higher. In the extreme case of setting $\gamma = 0$, each step of the algorithm is an independent

Model	Min. Intf.	Max. Intf.	Avg. Intf.	Time
SIR	0	1.045	**0.597**	6 sec
COST	0	1.241	**0.650**	2 sec
LP_SIR	0.113	2.128	**0.687**	2 sec
LP_COST	0.165	1.756	**0.693**	1 sec
NAIVE	0.856	4.237	**2.550**	–

Table 1: Results and Running Times for 10-node Network.

Model	Min. Intf.	Max. Intf.	Avg. Intf.	Time
SIR	0.195	1.849	**1.074**	197 sec
COST	0.253	2.117	**1.107**	11 sec
LP_SIR	0.253	3.951	**1.766**	16 sec
LP_COST	0.253	3.633	**1.384**	5 sec
NAIVE	0.688	4.630	**3.179**	–

Table 2: Results and Running Times for 15-node Network.

Model	Min. Intf.	Max. Intf.	Avg. Intf.	Time
SIR	0.814	3.443	**2.231**	1408 sec
COST	0.706	4.147	**2.253**	146 sec
LP_SIR	1.102	5.441	**3.245**	141 sec
LP_COST	1.257	5.450	**3.285**	42 sec
NAIVE	1.625	10.403	**5.630**	–

Table 3: Results and Running Times for 20-node Network.

repetition of randomized rounding with initial probabilities, but in that case one can not guarantee termination (with a feasible result) of the algorithm. In our experiments, which we present next, we set $\gamma = 0.01$.

5 Experimental Results

We use AMPL (A Mathematical Programming Language) to formulate the integer programs and LP relaxations, and solve them by CPLEX Optimizer v.8.1. For the integer programming formulations, we use networks of sizes 10, 15 and 20. For the LP relaxations we also present results for 30-node networks. In this section we present the quality of results as well as running times for each model in order to compare their performance and efficiency.

For all networks studied, there are three power levels available at each node, indexed with integers 0, 1 and 2. We set these power levels as p_0 = 1 mW, p_1 = 2 mW and p_2 = 5 mW. We analyse all four models described; SIR, COST, LP SIR (heuristic based on LP relaxation of the SIR model), and LP COST (heuristic based on LP relaxation of the cost model). Since the objective functions of SIR and cost models are different, we cannot directly compare the objective values returned by the models to test their performance. Therefore in order to compare all four models with a common metric, we developed a separate module in C++ which takes as its input the solution of a model, i.e. power assignments, and returns the minimum, maximum and *average interference* values observed on any link in the network. We can use the average interference as a metric to evaluate the performance of each model: the lower this value, the better the performance. All values for the randomized heuristics are selected as the values corresponding to the best solution over 100 independent runs, in order to minimize the randomization effect on the performance comparisons.

Model	Min. Intf.	Max. Intf.	Avg. Intf.	Time
LP_SIR	0.130	3.815	**1.637**	2826 sec
LP_COST	0.302	5.103	**1.966**	179 sec
NAIVE	0.302	7.391	**2.781**	–

Table 4: Results and Running Times for 30-node Network.

The results are presented in Tables 1 through 4 for all four network sizes. We were only able to solve the IP models in a reasonable amount of time for networks of sizes up to 20. The last column of each table shows the time it takes for each model to generate a solution. Note that the performance of the cost model is quite close to that of the optimal SIR model, but cost model returns solutions much faster than the SIR model. Also note that the running times of the heuristics, LP COST and LP SIR, are, as expected, much lower than those of IP models. However their performance worsens relative to the IP based models as the network size increases. SIR, being the optimal model, has the minimum average interference values for all networks. The minimum and maximum interference values provide information about deviation from the mean value, and can be used as an extra measurement. We rescale all interference values by multiplying by a large constant for clarity of presentation. In order to obtain a better understanding of the relativity between values in the tables, we introduce the *naive algorithm* which simply chooses the highest power level for each node in the network. This obviously yields upper bounds on observed interferences and may help us to better understand the goodness of approximation results. On the bottom lines of Tables 1–4 we present the results obtained for this *naive algorithm*.

6 Conclusion

We have presented two integer programming formulations and two heuristics based on randomized rounding of LP relaxations for static power assignment problem in multi-hop wireless networks, where the objective is to minimize interference throughout the network while ensuring end-to-end connectivity. When comparing the SIR model and the cost model there is a trade-off between the optimality of results and the running times of algorithms. However, we argue that the loss in optimality is low compared to the gain in efficiency, especially with regard to the IP formulations. Moreover, heuristics based on LP relaxations perform quite well for small networks, but we have observed that the gap between the results of IPs and their relaxations increases as the network grows.

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