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On the Problem of Wireless Scheduling With Linear Power Levels

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Abstract

In this work we consider the problem of communication scheduling in wireless networks with respect to the SINR(Signal to Interference plus Noise Ratio) constraint in metric spaces. For the powers of sender nodes we consider the *linear* power assignment, which is one of commonly considered power schemes. We give a constant factor deterministic approximation algorithm for scheduling in wireless networks, which are given in some special class of metric spaces, which contains the Euclidean spaces. To the best of our knowledge, this is the first constant factor approximation algorithm for this problem. Simultaneously we obtain the approximate value of the optimal schedule length with error at most a constant factor.

1 Introduction

A basic problem in wireless networks is the problem of finding the throughput capacity of a network and using the network close to its capacity. The solution of this problem is related to the maximum spatial reuse in the network. Given some set of transmission requests (sender-receiver node pairs in the network, which we will call also "links"), the goal is to schedule the transmissions so that all they can be done successfully in the minimum time. The main factor affecting the successful data transmissions in wireless networks is the signal interference of the concurrently transmitting nodes, which in general makes it impossible to do all the needed transmissions at the same time: there can be a receiver node, which cannot decode the data intended to it because of the "noise" made by other transmitions. So one needs to split the set of requests into subgroups, in each of which all sender nodes can transmit concurrently. Then all the data transmission can be done in a time proportional to the number of different groups in the schedule. The goal is to minimize the number of groups, which is called *complexity* or *length* of the schedule.

As the signal interference is the root of the scheduling problem, the solution depends crucially on the model of the interference exploited for the calculations. In the most part of the existing literature on this topic the interference in wireless networks has been described by *graph-based models*, or *protocol models*. Those models are based on the communication graph, in which two nodes are connected if they are in mutual transmission ranges, and if a node transmits some data, then no other node in its neighbourhood (graph neighbourhood) can transmit at the same time. Recent studies show that for the scheduling problem these models are not enough realistic. Particularly, problems of these models stem from the assumption that the affect of some node on others is constant in some disk around that node, and zero outside of that disck, whereas in reality the mechanism of the affect of a transmitting node on the others is essentially more sophisticated. An alternative to the graph-based models is the *physical model*, which is more realistic than graph-based models. It assumes that the affect of a transmitting node on other nodes decreases proportionally to a constant power of the distance from that node (if there are no obstacles). In this work we adopt the physical model of communication. Based on this model, the *SINR (Signal to Interference plus Noise Ratio)* constraint is considered for reflecting the possibility or impossibility of accepting the signal of some sender by the corresponding receiver.

The solution of the scheduling problem depends also on the power levels of the nodes in the network: each node can transmit the data with a specific power, so the more is the power of a node, the stronger is the signal received by the intended receiver (also the more is the "noise" made by that node to other transmissions). Our results are mainly for *linear* power assignments, which along with *uniform* power assignments are used in most of currently designed MAC (Medium Access Control) protocols for wireless networks, due to their simplicity and energy-efficiency. In the case of uniform power assignments the power level of all sender nodes is the same throughout the network, and in the case of linear power assignments the power of each sender node is proportional to a constant power of the distance from the reciever node. As the linear power assignment is the minimum power needed to deliver a unit signal strength to the receiver, it is considered a "good" power assignment from the point of view of energy consumption, wich is a crucial issue in sensor networks.

2 Related Work and Our Results

There is a solid amount of theoretical work on the topic of scheduling in wireless networks with graph-based models, as [7] and [11], which now are proven to be not as efficient for this task as physical models (see [9]). The initial work considering the physical model mainly consisted of different heuristics, which didn't have proven guarantees for their results, but instead were taking as a base some simulation results, which were mostly done on network models with nodes randomly distributed in some region of the Euclidean plane. The theoretical studies considering the physical model of communication started to appear in recent years. They were considering arbitrary topologies of networks (arbitrary placement of nodes) and providing algorithms with proven results. In [10] an algorithm is given, which for a network on the Euclidean plane and n transmission requests, sets appropriate power levels for the sender nodes, and produces a schedule of complexity $O(I_{in}\log^2 n)$, where n is the number of communication requests, and I_{in} is a "static" measure of interference, which can be calculated from the topology of the network. In that work there is no proven approximation ratio to the optimal schedule length.

In [8] it is shown that there are some instances of the scheduling problem with uniform or linear power levels, for which the optimal schedule complexity is $\Omega(n)$, while with other power assignments one could get a schedule of length $O(log^e(n))$ for some constant e. Moreover, in [1] they show that the same is true for all *oblivious power assignments*, i.e. when the power level of a sender node depends only on the distance between the sender and the receiver nodes.

For *uniform* power levels in [3] an approximation algorithm is given, which is proven to approximate the optimal schedule length within a factor of $O(\log(n))$ in Euclidean spaces.

In [5], improving the result of [3], an algorithm is given with a constant approximation ratio. In [4] an algorithm is designed, which approximates the optimal schedule length with uniform power levels within a constant factor, if the distances between the sender and the receiver nodes are "almost" the same for all communication requests. The algorithm works in so called "fading" metric spaces.

In [2] some measure of interference is introduced(let's denote it by I), which can be calculated by the topology of the network, and it is shown that with *linear* power assignment the optimal schedule complexity is $\Omega(I)$, when the nodes are located in an arbitrary metric space. In the same paper a randomized algorithm is given, which outputs a schedule of complexity $O(I + \log^2 n)$ with high probability (and works for an arbitrary metric space). Using this algorithm as a subroutine, also a randomized algorithm is given for the problem of so-called *multi-hop scheduling with fixed paths*, where the requests are lying on some given directed paths, and they must be scheduled taking into account also their sequence on the paths. This algorithm finds a multi-hop schedule of length $O(I + \log^2 nD)$ with high probability, where D is the length of the longest path.

In this work we improve the results of [2] for some specific metric spaces (including Euclidean spaces), and give a constant factor approximation algorithm for scheduling the requests in the case of linear power assignments. At the same time we show that the optimal schedule length for the case of linear powers is $\Theta(I)$. Note that taking this algorithm as a subroutine in the multi-hop scheduling algorithm of [2], one can get a slightly better performance guarantee of $O(I+\log nD)$ instead of $O(I+\log^2 nD)$, using the same(essentially) proof as in [2].

3 Notations and Formulation of the Problem

Throughout this work we assume the wireless network nodes to be statically located (i.e. the network is not mobile) in a metric measure space X with a distance function d and a measure μ.

The ball in X with center p and radius $r > 0$ is the set

$$B(p,r) = \{q \in X | d(p,q) < r\},$$

and the ring with center p, width $w > 0$ and outer radius $r > w$ is the set

$$R(p,r,w) = \{q \in X | r - w \leq d(p,q) < r\}.$$

For a ring $R = R(p,r,w)$ we denote $b(R) = B(p,r)$ and $B(R) = B(p,r-w)$.

We assume that the measure μ satisfies the following condition: for any two balls A and B with radii a and b respectively,

$$\frac{\mu(A)}{\mu(B)} \leq K \left(\frac{a}{b}\right)^m \tag{1}$$

holds for some constants $K \geq 1$ and $m \geq 1$, which are specific to the metric space. Given is a set of links $L = \{1,2,\ldots,n\}$, where each link v represents a communication request from a sender node s_v to a receiver node r_v. Following the notations of [5], we introduce the "asymmetric distance" from link v to link w as the distance from v's sender to w's receiver, denoted by $d_{vw} = d(s_v, r_w)$. We assume the distances d_{vw} to be non-zero for all v, w. The length of the link v is denoted by $d_{vv} = d(s_v, r_v)$. Each transmitter s_v is assigned a power level P_v, which does not change. We assume that the strength of the signal decreases with the distance from the transmitter, more specifically, the received signal strength from the sender of w at the receiver of v is $P_{wv} = \frac{P_w}{d_{wv}^\alpha}$, where $\alpha > 0$ denotes the *path-loss exponent*. For interference we adopt the *SINR* model, where for a link v the node r_v successfully receives a message from the sender s_v if and only if the following condition holds:

$$P_{vv} \geq \beta \left(\sum_{w \in S \setminus v} P_{wv} + N \right), \tag{2}$$

where $N \geq 0$ is the ambient noise, $\beta > 1$ denotes the minimum SINR required for message to be successfully received, and S is the set of concurrently scheduled links. We say that S is *SINR-feasible* if (2) is satisfied for each link $v \in S$. Throughout this work by saying that nodes are assigned linear power levels we mean that the power level of each sender s_v is $P_v = c_l d_{vv}^\alpha$, where c_l is a constant, and by saying that the nodes are assigned uniform power levels, we mean that all powers are equal to some constant P. The problem we are interested in is the following: we are given a set of links, and the goal is to partition that set into the minimum number of SINR-feasible subsets or *slots*.

4 Auxiliary Facts

Here we present some facts, which we will use in the subsequent sections.

The follwing is a known inequality:

$$\sum_{i=1}^{\infty} \frac{1}{i^s} \leq \frac{s}{s-1}, \text{ if } s > 1, \tag{3}$$

which can be proven by noticing that $\sum_{i=1}^{\infty} \frac{1}{i^s} \leq \int_1^{\infty} \frac{1}{x^s} dx + 1$.

A proof of the following lemma can be found, for example, in [6], page 28.

Lemma 1. *For reals $a_1, a_2, \ldots, a_m (a_i \geq 0, i = 1, 2, \ldots, m)$, and $r, s (0 < r < s)$,*

$$\left(\sum_{i=1}^{m} a_i^s \right)^{\frac{1}{s}} < \left(\sum_{i=1}^{m} a_i^r \right)^{\frac{1}{r}}$$

holds, unless all a_i but one are zero.

For the next lemma, consider any given real numbers $a \geq 1$ and $c > 0$, and the function $f(t) = (a+c)^t - a^t$. Note that $f(t)$ is a monotonically increasing function on $[1, \infty]$, as $f'(t) > 0$ for $t \geq 1$. So $f(t) \leq f(\lceil t \rceil)$ for $t \geq 1$. For an integer $k \geq 1$ we have

$$(a+c)^k - a^k = c \sum_{i=0}^{k-1} (a+c)^i a^{k-1-i} \leq kc(a+c)^{k-1},$$

so we have the following lemma:

Lemma 2. *For reals $a \geq 1, c > 0, t \geq 1$, holds $(a+c)^t - a^t \leq \lceil t \rceil c (a+c)^{\lceil t \rceil - 1}$.*

5 The Algorithm for the Linear Powers

In this section we consider the *linear* power assignment, and present a scheduling algorithm, which is very simple and approximates the optimal schedule length within a constant factor. Before stating the algorithm we define the *affectance* of a link, which is the analogue of the affectance for uniform power levels from [5].

Definition 1. *The affectance of a link v, caused by a set S of links, is the following sum of relative interferences of the links from S on v,*

$$a_S(v) = \sum_{w \in S \setminus v} \left(\frac{d_{wv}}{d_{wv}}\right)^{\alpha}.$$

With the affectance defined, SINR constraint for a set of links S and a link v in case of linear power levels can be written as

$$a_S(v) \leq \frac{1}{\beta} - \frac{N}{c_l}. \tag{4}$$

Note that linear power assignment with $c_l = \beta N$ is the minimal possible assignment for fulfilling the SINR ratio in case when there are no other nodes transmitting. So we assume c_l is greater than βN. Usually the related literature the ambient noise is assumed to be 0, but here we don't need to do so. For simplicity of formulas we replace the right side of (4) with $1/\beta$.

5.1 Formulation of the Algorithm

Below is the sequence of steps of the algorithm. The idea is to sort all the links in descending order of their lengths, and starting from the first one, consequently add them to the first slot, in which already scheduled links influence this one no more than a predefined constant. So it is a kind of a "first-fit" algorithm. The algorithm is similar to the algorithm designed for uniform power levels in [5], but the proof of the approximation ratio is basen on different arguments.

Algorithm 5.1

1. Input: the links $1, 2, \ldots, n$
2. sort the links in descending order of their lengths: $l_1, l_2, \ldots, l_n$
3. $S_i \leftarrow \emptyset, i = 1, 2, \ldots$
4. for $t \leftarrow 1$ to n do
    - 4.1 find the smallest i, such that $a_{S_i}(l_t) \leq \frac{1}{c^{\alpha}}$
    - 4.2 schdule l_t with S_i: $S_i := S_i \cup l_t$
5. output: $(S_1, S_2, \ldots)$

Here $c > 3$ is a constant, which will be defined in coming sections.

It is easy to see, that the algorithm is polynomial. In the next section we will give the proof of correctness of the algorithm.

5.2 Correctness of the Algorithm

We start with a simple lemma, which shows that if two links are scheduled in the same slot, then they can not be "too close" together. Let the links w and v be assigned to the same slot by the algorithm, and $d = \max\{d_{vv}, d_{ww}\}$.

Lemma 3. *For any two links w and v, which are as above, the following holds:*

$$d_{vw} \geq (c-2)d,\ d_{wv} \geq (c-2)d \text{ and } d(s_v, s_w) \geq (c-3)d.$$

Proof. Suppose $d = d_{vv} \geq d_{ww}$. Then from the definition of the algorithm it follows that $\left(\frac{d_{vv}}{d_{vw}}\right)^{\alpha} \leq \frac{1}{c^{\alpha}}$, so $d_{vw} \geq c \cdot d_{vv}$. On the other hand, by the triangle inequality $d_{wv} \geq d_{vw} - d_{vv} - d_{ww} \geq (c-2)d_{vv}$. The last inequality follows from the second one and the triangle inequality: $d(s_v, s_w) \geq d_{wv} - d_{vv} \geq (c-3)d_{vv}$. ■

Consider the set of links S assigned to the same slot by the algorithm, and $v \in S$. Let S^- denote the subset of S, which contains the links shorter than v.

Lemma 4. *There exists a constant c_0, depending only on m, K and α, such that for the link v and the set of links S^- as above,*

$$a_{S^-}(v) \leq \frac{c_0}{(c-3)^{\alpha}},$$

holds, if $\alpha > \frac{m}{m+1-\lceil m \rceil}$.

Proof. For simplicity, throughout this proof we denote $q = c-2$. Consider the partition of the metric space into concentric rings $R_i = R(r_v, (i+1)qd_{vv}, qd_{vv})$ for $i = 1, 2, \ldots$, and the ball $B(r_v, qd_{vv})$. From Lemma 3 and definition of S^- it follows that there are no senders from S^- inside $B(r_v, qd_{vv})$. Now for some $i > 0$ consider the links from S^- with senders inside R_i, and denote that set by S_i^-. Let's for each link w denote $\rho_w = \frac{(q-1)d_{ww}}{2}$. Then it follows from the last inequality of Lemma 3 that for each such link w the ball $B(s_w, \rho_w)$ doesn't intersect the corresponding ball of any other link. Further, all such balls are contained in the ring $R_i' = R(r_v, (i+1)qd_{vv} + \rho_v, qd_{vv} + 2\rho_v)$. So from the countable additivity of μ it follows that

$$\sum_{w \in S_i^-} \mu(B(s_w, \rho_w)) \leq \mu(R_i') = \mu(B(R_i')) - \mu(b(R_i')) \text{ or, as } K \geq 1,$$

$$\sum_{w \in S_i^-} \frac{\mu(B(s_w, \rho_w))}{\mu(B(R_i'))} \leq 1 - \frac{\mu(b(R_i'))}{\mu(B(R_i'))} \leq K - \frac{\mu(b(R_i'))}{\mu(B(R_i'))}. \tag{5}$$

From (1) we have the following inequalities for each link w:

$$\frac{\mu(b(R_i'))}{\mu(B(R_i'))} \leq K\left(\frac{iqd_{vv} - \rho_v}{(i+1)qd_{vv} + \rho_v}\right)^m \text{ and}$$

$$\frac{\mu(B(s_w, \rho_w))}{\mu(B(R_i'))} \geq \frac{1}{K}\left(\frac{\rho_w}{(i+1)qd_{vv} + \rho_v}\right)^m,$$

which combined with (5) leads to the following:

$$\sum_{w\in S_i^-} \rho_w^m \le K^2\left(((i+1)qd_{vv}+\rho_v)^m-(iqd_{vv}-\rho_v)^m\right)\le$$

$$K^2(qd_{vv})^m\left((i+2)^m-i^m\right)\le 2\lceil m\rceil K^2(qd_{vv})^m(i+2)^{\lceil m\rceil-1}, \tag{6}$$

where we used Lemma 2 and the fact, that $\rho_v < qd_{vv}$. Dividing both sides of (6) on $\left(\frac{q-1}{2}\right)^m$ and replacing $q-1$ by $q/2$ in denominator, we get

$$\sum_{w\in S_i^-} d_{ww}^m \le 2^{2m+1}\lceil m\rceil K^2 d_{vv}^m (i+2)^{\lceil m\rceil-1}. \tag{7}$$

Note that the affect of the senders from S_i^- on v is $a_{S_i^-}(v)=\sum_{w\in S_i^-}\left(\frac{d_{ww}}{d_{wv}}\right)^\alpha$. From the triangle inequality and the definition of ring R_i, the following holds: $d_{wv}\ge d(s_w,s_v)-d(s_v,r_v)\ge(q-1)d_{vv}i$, so

$$a_{S_i^-}(v)\le\frac{\sum_{w\in S_i^-} d_{ww}^\alpha}{((q-1)d_{vv}i)^\alpha} \tag{8}$$

Using Lemma 1, from (7) and (8) we get an upper bound on the affect of the senders from R_i:

$$a_{S_i^-}(v)<\frac{\left(\sum_{w\in S_i^-} d_{ww}^m\right)^{\alpha/m}}{((q-1)d_{vv}i)^\alpha}\le\frac{\left(2^{2m+1}\lceil m\rceil K^2 d_{vv}^m(i+2)^{\lceil m\rceil-1}\right)^{\alpha/m}}{((q-1)d_{vv}i)^\alpha}\le$$

$$\le\frac{8^\alpha\left(\lceil m\rceil K^2\right)^{\alpha/m}}{(q-1)^\alpha i^{\alpha\left(\frac{m+1-\lceil m\rceil}{m}\right)}}, i=1,2,\dots$$

By summing over i, and using (3), we complete the proof of the lemma (as we have $\alpha>\frac{m}{m+1-\lceil m\rceil}$):

$$a_{S^-}(v)\le\frac{8^\alpha\left(\lceil m\rceil K^2\right)^{\alpha/m}}{(q-1)^\alpha}\sum_{i=1}^{\infty}\frac{1}{i^{\alpha\left(\frac{m+1-\lceil m\rceil}{m}\right)}}\le$$

$$\frac{8^\alpha\left(\lceil m\rceil K^2\right)^{\alpha/m}}{(q-1)^\alpha}\cdot\frac{\alpha(m+1-\lceil m\rceil)}{\alpha(m+1-\lceil m\rceil)-m},$$

so we have $c_0=\frac{8^\alpha\left(\lceil m\rceil K^2\right)^{\alpha/m}\alpha(m+1-\lceil m\rceil)}{\alpha(m+1-\lceil m\rceil)-m}$. ■

Lemma 4 helps to prove the following theorem.

Theorem 1. *If* $c\ge\sqrt[\alpha]{\beta(c_0+1)}+3$ *and* $\alpha>\frac{m}{m+1-\lceil m\rceil}$, *then the output of the algorithm is a feasible schedule.*

Proof. Let v be any link, which is scheduled with a set of links S. Consider all the links in S, which are longer than v. From the definition of the algorithm it's clear, that those links affect v in total no more than $\frac{1}{c^\alpha}$. According to Lemma ??, the affectance of the links shorter than v is less than $\frac{c_0}{(c-3)^\alpha}$, so the overall affectance on the link v is $a_S(v)<\frac{1}{c^\alpha}+\frac{c_0}{(c-3)^\alpha}\le\frac{c_0+1}{(c-3)^\alpha}\le\frac{1}{\beta}$. ■

5.3 The Approximation Ratio

In this section we will show that the algorithm outputs a schedule, which is longer than the optimal one no more than by a constant factor.

The following definition is taken from [2].

Definition 2. *Let S be a set of transmission requests and p a node in the network, then we define*

$$I_p(S) = \sum_{w \in S} \min\left\{1, \left(\frac{d_{ww}}{d(s_w, p)}\right)^{\alpha}\right\}, \text{ and } I(S) = \max_p I_p(S).$$

When S is the set of all links (which we denoted by L), we use the notation $I(L) = I$. I is a measure of interference, which in [2] is shown to be a lower bound(with a constant factor) for optimal schedule length in case of linear power assignments: if T is the minimum schedule length, then $T = \Omega(I)$. More specifically, in [2] it is shown that if $R_1, R_2, \ldots, R_T$ is an optimal schedule of length T, then $I(R_i) \leq \frac{2 \cdot 3^{\alpha}}{\beta} + 1$ for $i = 1, 2, \ldots, T$. It's then easy to see, that if S is a set of links, and $S = \cup S_i$, where $S_i \cap S_j = \emptyset$ for $i \neq j$, then

$$I(S) \leq \sum_i I(S_i), \tag{9}$$

so it follows that

$$T \geq \frac{\beta}{2 \cdot 3^{\alpha} + \beta} I. \tag{10}$$

This bound is proven in case when $N = 0$, but it is easy to see that it holds also for the case of non zero ambient noise.

Theorem 2. *a) If $c > 3$ and the output of Algorithm 5.1 is a feasible schedule, then it is a constant factor approximation for scheduling with linear powers,*

b) the optimal schedule length in case of linear powers is $\Theta(I)$.

Proof. Suppose $A_1, A_2, \ldots, A_t$ is the output of Algorithm ??. Let v be a link from A_t. By the definition of the algorithm we have

$$a_{A_i}(v) > \frac{1}{c^{\alpha}}, \text{ if } i < t.$$

As much as $c > 1$, we have also

$$I_{r_v}(A_i) > \frac{1}{c^{\alpha}}, \text{ so } I_{r_v}(L) = \sum_{i=1}^{t} I_{r_v}(A_i) > (t-1)\frac{1}{c^{\alpha}}.$$

On the other hand we have

$$I_{r_v}(L) \leq I(L), \text{ so } t < c^{\alpha} I(L) + 1,$$

which together with (10) proves the theorem. ∎

6 Conclusion and open problems

In this work we tried to do a step towards finding some approximations for optimal schedule lengths for linear and other power assignments. For linear powers we found a constant factor approximation algorithm and the approximate value of the optimal schedule length with error at most a constant factor. These approximations can also be useful for future attemps to find and evaluate distributed algorithms for the scheduling task. Our results work for some special metric measure spaces, which include Euclidean spaces with standard Lebesgue measure (note that for k-dimensional Euclidean space $m = k$, and $K = 1$, so our results hold with $\alpha > k$).

An open problem is to extend the obtained results for this problem to more general metric spaces and for less constrained values of the path loss exponent α: the constant factor algorithms obtained so far are proven to work only for sufficiently "smooth" metric spaces, such as Euclidean spaces, and for sufficiently large α(except the algorithm from [4] for nearly equilength links, which still puts requirements on α).

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Առանց լարի ցանցերում գծային հզորություններով հերթագրման խնդրի մասին

Տ. Տոնոյան

Ամփոփում

Այս աշխատանքում դիտարկվում է առանց լարի ցանցերում հեռարձակումների հերթագրման խնդիրը մետրիկական տարածություններում՝ SINR(Signal to Interference plus Noise Ratio) սահմանափակումների նկատմամբ: Ցանցի հանգույցների հզորությունների համար դիտարկվում է գծային սխեման, որը հաճախ դիտարկվող հզորության սխեմաներից է: Մենք բերում ենք հաստատուն գործակցով մոտարկող ալգորիթմ հերթագրման խնդրի համար, դիտարկելով խնդիրը որոշակի տիպի մետրիկական տարածություններում, ներառյալ Էվկլիդյան տարածությունները: Ըստ մեր տեղեկությունների՝ սա առաջին հաստատուն գործակցով մոտարկող ալգորիթմն է այս խնդրի համար: Միևնույն ժամանակ մենք գտնում ենք օպտիմալ հերթի երկարության մոտավոր արժեքը, առավելագույնը հաստատուն գործակցի սխալանքով: