A Novel Link Scheduling Algorithm for Wireless Networks using Directional Antenna

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***Abstract*—For a given set of communication links whose senders transmit at a fixed power level, it is a hot problem to select a maximum set of links that can be transmitted simultaneously, which is known to be NP-hard. The existing algorithm only apply to the condition of omnidirectional transmission. This paper addresses the problem in a plane wireless network where the nodes use directional antennas under physical interference model. We develop a directional interference model applicable to such networks, and first propose the approximation algorithm to solve scheduling problem under this model. We proved the correctness of the algorithm by mathematical analysis. We have also proved the great advantages of using directional antenna by extensive simulations.**

***Index Terms*—Link Scheduling, Directional Antennas, Physical Interference Model**

I. Introduction

This paper mainly studies a typical question in wireless networking which transmit node equip with directional antennas. One of key problem in a given wireless network is to improve the throughput capacity. In the case of shared only one channel, a plurality of communication links transmission at the same time will lead to signal interference. In wireless network, link scheduling problem is to reduce the maximum interference when the links transmit simultaneously, and ensure the message can be successfully accepted by the receiving node. The main objective is to achieve efficient spatial reuse and increase network capacity, considering wireless interference among concurrently transmitting nodes.

By concentrating the energy in specific direction, opposed to omni-directional transmission, Directional antennas can provide the benefits of increased range, reduced interference and increased spatial reuse of bandwidth. Due to the benefits from the directional antennas, the scheduling scheme need to take into account the nature of the antenna beam direction at each node.

The problem One-slot Maximum Set of Links (OSML) is to seek a largest set of solution links from a given set A that can be transmitted simultaneously. This optimization problem is NP-hard proved by Gussevskaia [1]. Plenty of research to this problem, some approximation scheduling algorithms was be proposed [1], [2], which is performance good.

Nowadays, various ways to solve the problem of OSML under physical interference model was present. The author of [1] designed the first non-trivial approximation algorithm with approximation bound $O(log\frac{max_{l\in A}d(l)}{min_{l\in A}d(l)})$. Goussevskaia made huge efforts on developing a constant approximation bound in the literature [2], which proposed a $O(logn)$ approximation for the problem of maximizing the number of links scheduled in one time-slot. Then, Peng-Jun Wan $at\ al$ [3] given a further analysis to the OSML problem under physical interference model. Besides, they summarize the method to solve this kind of problem in [4]. Recently, more influential elements has been take into account in the experiment, like power control [5], throughput capacity and communication latency [6]. Pei, Guanhong [7] developed the first rigorous distributed algorithm for link scheduling in the SINR model. It uses physical carrier sensing and the distributed decisions are made based on the Received Signal Strength Indication (RSSI).

However, mostly research of link scheduling based on omnidirectional transmission. Ramamurthi [8] proposed a generalized physical interference model apply to the directional antennas, both take into account the main lobes and the side lobe of antennas. But the problem they focus is different from our research. The benefits of directional antennas to improve network capacity has been deep analysed in [9]. Although directional antennas have been studied for cellular networks and has been deployed for cell-sectoring, rarely used for OSML problem.

In this paper, we design a directional interference model applicable to directional antennas. Then we propose an approximation algorithm for the problem of OSML based on directional interference model. We giving the correctness analysis, performance analysis and provides a sound mathematical proof to some special case. Finally, we also present the performance of the algorithm by simulation, which compared with a omnidirectional algorithm.

The rest of the paper is organized as followed. Section II describes our directional interference model. In section III, we formulate the scheduling algorithm for the problem, and provide mathematical analysis of the OSML algorithm. In section IV, we present simulation results to illustrate the performance of our scheduling algorithm, and section V concludes the paper.

II. The Directional Interference Model

An essential issue to link scheduling problem in wireless networks is the interference model. Here is a list of some notation meaning. All the networking nodes V lie in plane and transmit at a fixed power P. The Euclidean distance between any pair of nodes is denoted by d_{uv}. The antenna gain of the node u is G_u. The path loss model is then determined by the path-loss exponent α, which is a constant greater than 2 but less than 6 typically. Specifically, when a node u transmit a signal at power P, the power of this signal is captured by another node v is $Pd_{uv}^{-\alpha}G_uG_v$. The signal quality perceived by receiver is measured by the SINR (signal to interference and noise ratio), which is the quotient between the power of the wanted signal and the total power of unwanted signals and the ambient noise (both internal and external).

Here is a brief introduce to independent set. It is a set of disjoint links that can be scheduled at a same time slot, formulated as follows. A set of links $S = \{(u_1, v_1), (u_2, v_2), ..., (u_k, v_k)\}$ are said to be independent if:

(1) all links in S are disjoint;

(2) for each $1 \leq i \leq k$, the SINR of the link u_i, v_i with respect to $u_j : 1 \leq j \leq k, j \neq i$ is at least β.

1) physical interference model [10]: In this model, the transmission from sending node s_v is successfully received by receiver r_v if and only if

$$SINR = \frac{Pd_{vv}^{-\alpha}}{N + \sum_{l_w \in S} Pd_{wv}^{-\alpha}} \geq \beta, \tag{1}$$

where $\alpha > 2$ is the path-loss exponent, $\beta > 1$ is the minimum SINR required for successful reception and determined by the hardware conditions, N is the ambient noise around receiving node (note that α, β, N are all constants). This models a situation where the SINR must be no less than certain threshold β, in order to correctly interpret the wanted signal. It is a very effective model for omnidirectional transmission, takes the total interference into account due to all transmissions.

In our search, each nodes sending by directional antenna but received by omni-directional antenna. The problem of OSML can be formulated as follows. Given a set of links $L = \{l_1, l_2, ...l_n\}$, where each link l_i represents a communication request from a sender node s_i to a receiver r_i, and our object is to seek a maximum independent set in one time-slot, that means each links in the independent set can be scheduled simultaneously.

We assume the length of link l_v is denoted by d_{vv}, and simplify directional antennas as only have one main beam, fixing the direction of the antenna. Which the interference range only in a particular angle generated by sending node.

2) direcional interference model [10]: The link $l_v = (s_v, r_v)$ successfully transmitted under the following conditions:
(1) In the absence of other links:

$$SNR = \frac{PG_{s_v}G_{r_v}d_{vv}^{-\alpha}}{N} \geq \beta. \tag{2}$$

(2) Presence of interference from other links:

$$SINR = \frac{PG_{s_v}G_{r_v}d_{vv}^{-\alpha}}{N + \sum_{l_w \in S} PG_{s_w}G_{r_v}d_{wv}^{-\alpha}\varphi_{wv}} \geq \beta, \tag{3}$$

where P is transmission power of the transmit node, link $l_w \in S$ scheduled concurrently with l_v, G_{s_v} and G_{r_v} is the antenna

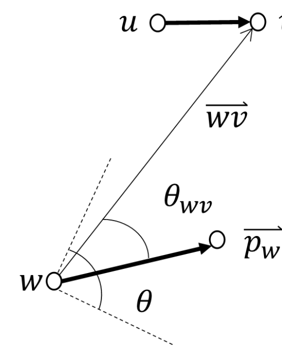

Fig. 1. Angle Judge.

gain of sending node and receiving node, it is a constant which deceive by hardware conditions.

The model was proposed to narrow the interference angle by using directional antenna, so we need to determine whether exist interference between the links that transmission in the same time. Here we use φ_{wv} to solve this problem, where vector $\vec{p_w}$ present the send direction of node w, the send angle of directional antennas is θ_w. Definition as follows:

$$\varphi = \begin{cases} 0, \theta_{wv} > \theta_w/2, \\ 1, \theta_{wv} \leq \theta_w/2, \end{cases}$$

where θ_{wv} is the angle between antenna direction $\vec{p_w}$ of sender node w with the vector $\vec{wv}$ that the direction of sender node w to receiver node v. We use this angle to judge whether the receiving node is in the send range of the sender node. As shown in Fig. 1. We can use the following formulate to get the angle θ_{wv}, and decide the interference between links.

$$\theta_{wv} = arccos(\frac{\vec{p_w}\vec{wv}}{|\vec{p_w}||\vec{wv}|}).$$

In this research, we assume that all nodes transmit with the same power level P. There are some definition, use $P_{vv} = PG_sG_r/d_{vv}^{\alpha}$ represent the signal receive power of r_v send by s_v, and $I_{wv} = PG_{s_w}G_{r_v}\varphi_{wv}/d_{wv}^{\alpha}$ denote the signal interference received by node r_v from a sender s_v that transmit at the same time.

III. The Scheduling Algorithm

In order to solve the scheduling problem of OSML (One-slot Maximum Set of Links), we present the follow OSML algorithm. Start with some definitions, the $relative\ interference$ (RI) of a link l_u on link l_v, namely $RI_u(v) = I_{uv}/P_{vv}$. The $affectedness$ (proposed in [2]) of link l_v, caused by a set of links S, is the sum of the relative interferences of the links in S on l_v, as well as the effect of noise, scale by β, or

$$\begin{aligned} A_S(l_v) &= \beta\left(\frac{N}{P_{vv}} + \sum_{l_u \in S} RI_u(v)\right) \\ &= \beta\frac{\sum_{l_u \in S} I_{uv} + N}{P_{vv}}. \end{aligned} \tag{4}$$

The formula of $affectedness$ was got from $SINR \geq \beta$. Observe that the $affectednsee$ of link l_v satisfy $A_S(l_v) \leq 1$, equivalent to the $SINR \geq \beta$, means link l_v can successful transmission.

Algorithm 1 OSML Algorithm

Require: Set of links in the increasing order of length $L = l_1, l_2, ..., l_n$; $S \leftarrow \emptyset$, $I \leftarrow \emptyset$, $L_1 \leftarrow \emptyset$.
Ensure: OMSL schedule S.
1: Set c according to formula 5.
2: **repeat**
3: $l_v = (s_v, r_v) \leftarrow$ the first link in L.
4: $L \leftarrow L \backslash l_v$, $S \leftarrow S \cup l_v$.
5: $L_1 \leftarrow l_u \in L : d(s_u, r_v) \leq c \cdot d_{vv}$, $\varphi_{uv} = 1$.
6: $L \leftarrow L \backslash L_1$.
7: **repeat**
8: $l_w \in L \leftarrow$ satisfy $\varphi_{wv} = 1$.
9: $I \leftarrow I \cup l_w$.
10: **until** L is traversal end.
11: **repeat**
12: $l_a = (s_a, r_a) \leftarrow$ the first link in I.
13: $I \leftarrow I \backslash l_a$.
14: **repeat**
15: $I_a \leftarrow l_u \in I : d_{ua} = d(s_u, s_a) \leq d_{aa}/2$.
16: $I \leftarrow I \backslash I_a$.
17: $L_v \leftarrow I_a \cup L_2$.
18: **until** I is traversal end.
19: **until** $I = \emptyset$.
20: $L \leftarrow L \backslash L_v$.
21: Set $I \leftarrow \emptyset$.
22: $L_2 \leftarrow l_u \in L : A_S(l_u) \geq 2/3$.
23: $L \leftarrow L \backslash L_2$.
24: **until** $L = \emptyset$.
25: **return** S.

Our approximation algorithm for OSML is outlined above. We can simplify the algorithm as a brute-force method. Let L be the set of given communication links, we assume that each link $l_v \in L$ can success communication, added to the solution, its safety ($SINR \geq \beta$) is guaranteed in the step of select. Set L is a sequence which sorted in the increasing order of length of links. Depend on the definition of SINR, we can get the feature that the shorter the length, the more stable of the link. S stores the link in one of independent set, and I is the set of links have interference with the select link l_v in each iterative. In every iteration of the algorithm, there have three step to select the legal and remove illegal link. The first link l_v in L is moved from L to S, and use this link as the begin of the first round of selection. The first step (line 6) we need discards all links $l \in I$ whose sender are close to the receiver of l_v, meaning $d(r_v, s_w) \leq c \cdot d_{vv}$ (c is a constant bigger than 2, and explained in next part).

$$c = max\left(2, (2 \cdot 3^3 \cdot \beta \cdot \frac{\alpha - 1}{\alpha - 2})^{\frac{1}{\alpha-2}}\right).$$

Then make sure the distance between any two links from set I is bigger than d_{vv}, remove the illegal links from L (line 16). The last step (line 23), all links $l_u \in L$, whose affectedness $A_s(l_u)$ rose to or above a threshold of $2/3$, are removed from L (the number of $2/3$ will explain in next part). This iterative is repeated until all links in L have been select or deleted. In the end, we will get the scheduling set S from OSML algorithm. Next we prove that the obtained schedule is both correct and competitive.

A. Correctness of OSML Algorithm

In this section we prove that the solution S obtained in OSML Algorithm is correct, all selected links can be scheduled concurrently without collisions, $\forall l_v \in S$, $A_S(l_v) \leq 1$.

There some definitions need to be used in the proof. For link $l_v \in S$, let S_v^- be the set of links that length shorts than l_v, and S_v^+ be the links longer than l_v, there have some interference between l_v and any link l_w from S_v^- or S_v^+ ($\varphi_{wv} = 1$).

We can get from third part in iteration of the algorithm (line 22), each link in the scheduling set S satisfy that the $affectedness$, $A_{S_v^-}(l_v) \leq 2/3$, means that for each links $l_v \in S$, when the link is add to the set S, the $affectedness$ of l_v get by S_v^- is less than $2/3$, since it has not been deleted by in the previous step. In order to ensure that each links in S can be successful communication at the same time slot, the SINR of each link should be satisfy $SINR \geq \beta$. It show that we just need to ensure $\forall l_v \in S$, $A_{S_v^+}(l_v) \leq 1/3$.

In order to give a clear analyse, here are some geometric definition now. We used D_w present the discs of radius $d_{ww}/2$ around receiver node $s_w \in S_v^+$. From the first elimination criterion, we know the discs D_w do not contain any sender $s_z \neq s_w$ and $s_z \in S_v^+$. Focus on the links set I which have interference on link l_v. At the first, division the sender set in I into concentric rings $Ring_k$ which have evenly spaced of cd_{vv} around the receiver r_v. Each ring $Ring_k$ contains all senders $s_w \in S_v^+$, for which $k(cd_{vv}) \leq d_{wv} \leq (k+1)(cd_{vv})$. Because of $d_{wv} \geq c \cdot d_{vv}$, so that the first ring $Ring_0$ does not contain any sender from S_v^+. Consider all senders $s_w \in Ring_k$, for the concentric rings $Ring_k$, $k > 0$. All discs D_w of radius $d_{vv}/2$ around node s_w which located in $Ring_k$ must be completely contained in an extended ring $EXRing_k$, and the area is calculated by the fellow formula:

$$\begin{aligned} A(EXRing_k) &= [(d_{vv}(k+1)c + d_{vv}/2)^2 \\ &\quad - (d_{vv}kc - d_{vv}/2)^2]\pi \\ &= c(2k+1)(c+1)d_{vv}^2\pi. \end{aligned}$$

Since that each around discs D_w of area $A(D_w) \leq d_{vv}^2\pi/4$ around senders $s_w \in I$ do not intersect, and the minimum distance between r_v and s_w is $k \cdot c \cdot d_{vv}$, $s_w \in Ring_k$, $k > 0$. The total interference coming from ring $Ring_k$, $k > 1$ is bounded by

$$\begin{aligned}
I_{Ring_k}(l_v) &\leq \sum_{s_w \in Ring_k} I_{s_w}(l_v) \\
&\leq \frac{A(EXRing_k)}{A(D_w)} \cdot \frac{PG_{s_w}G_{r_v}\varphi_{wv}}{(kcd_{vv})^\alpha} \\
&\leq \frac{4(2k+1)(c+1)c}{k^\alpha c^\alpha} \cdot \frac{PG_{s_w}G_{r_v}\varphi_{wv}}{(d_{vv})^\alpha} \\
&\leq \frac{1}{k^{\alpha-1}} \cdot \frac{1}{c^{\alpha-2}} \cdot \frac{PG_{s_w}G_{r_v}\varphi_{wv}}{d_{vv}^\alpha} \cdot 3^2 \cdot 2.
\end{aligned}$$

The value of $PG_{s_w}G_{r_v}\varphi_{wv}$ is fixed in above deduce. $A(EXRing_k)/A(D_w)$ represent the maximum number of links have interference to link l_v in the ring $Ring_k$, and we choose $d(s_w, r_v) = k(cd_{vv})$ ensure the interference to l_v is the maximum. The last inequality holds since $k \geq 1$ and $c \geq 2$, obtain $2k+1 \leq 3k$ and $c+1 \leq 3c/2$. Summing up the interferences over all rings yields

$$\begin{aligned}
I_{S_v^+}(l_v) &< \sum_{k=1,\dots n} I_{Ring_k}(l_v) \\
&\leq \sum_{k-1,\dots n} \frac{1}{k^{\alpha-1}} \cdot \frac{1}{c^{\alpha-2}} \cdot \frac{PG_{s_w}G_{r_v}\varphi_{wv}}{d^\alpha vv} \cdot 2 \cdot 3^2 \\
&< \frac{\alpha-1}{\alpha-2} \cdot \frac{1}{c^{\alpha-2}} \cdot \frac{PG_{s_w}G_{r_v}\varphi_{wv}}{d_{vv}^\alpha} \cdot 2 \cdot 3^2,
\end{aligned}$$

where the last inequality holds since $\alpha > 2$. This results in affectedness

$$\begin{aligned}
A_{S_v^+}(l_v) &= \beta \cdot \frac{\sum_{l_u \in S_v^+} RI_u(v) + N}{P_{vv}} \\
&= \beta \cdot \frac{I_{S_v^+}(l_v) + N}{P_{vv}} \\
&< \frac{\alpha-1}{\alpha-2} \cdot \frac{2 \cdot 3^2}{c^{\alpha-2}} \cdot \frac{1}{P_{vv}} \cdot \frac{PG_{s_w}G_{r_v}\varphi_{wv}}{d_{vv}^\alpha} \\
&+ \frac{N \cdot \beta}{P_{vv}}
\end{aligned}$$

In order to simplify the analysis, assume that there have no ambient noise $N = 0$, antennas gain and the sending power of each nodes were fixed value.

$$\begin{aligned}
&A_{S_v^+}(l_v) = \frac{\alpha-1}{\alpha-2} \cdot \frac{2 \cdot 3^2}{c^{\alpha-2}} \cdot \beta \leq 1/3 \Rightarrow \\
&c = max\left(2, (2 \cdot 3^3 \cdot \beta \cdot \frac{\alpha-1}{\alpha-2})^{\frac{1}{\alpha-2}}\right).
\end{aligned} \tag{5}$$

We have shown that each $l_v \in S$, satisfy $A_S(l_v) = A_{S_v^-}(l_v) + A_{S_v^+}(l_v) \leq 2/3 + 1/3 = 1$, which means that $SINR \geq \beta$ for each link in scheduling set S. From above mathematical analysis, the value of c was depend on design of third elimination part in algorithm. The judgement of $A_{S_v^-}(l_v) \leq 2/3$ just personal sense, and we proved the correctly.

B. Performance Analysis of OSML Algorithm

To analyze the performance of algorithm, we compared the solution ALG of OSML algorithm to an optimal solution, say OPT. Considering the complexity of directional transmission, we set some special case, and analyse the performance under those case. At first, give some lemma that satisfy the condition of omnidirectional antennas $\theta = 360°$.

$lemma$ 1: Let X be a feasible solution and let l_v be a link in X. The number of sender nodes in X within distance $k \cdot d_{vv}$, $k \geq 1$ of the receiver r_v is at most k^α.

$Proof$: The relative interference of each sender $l_u \in X \backslash l_v$, where $d_{uv} \leq k \cdot d_{vv}$

$$RI_u(v) = \frac{I_{uv}}{P_{vv}} = \frac{P/d_{uv}^\alpha}{P/d_{vv}^\alpha} = (\frac{d_{vv}}{d_{uv}})^\alpha \geq \frac{1}{k^\alpha},$$

which means the maximum number is k^α, otherwise the $\sum_{l_u \in X} RI_u(v) > 1$. Thus the lemma was been proved.

Then, we set other spacial case that communication angle is $\theta = 180°$ of each nodes, and have the same orientation angle. Along with the direction of the orientation angle, the length of links getting shorter and shorter. In this case, the shortest link have no influence to the transmission of other links, which means the last elimination step (line 23) of algorithm have no effect, but get the interference from the larger length of links. ALG_{180} represent the solution of OSML algorithm, and OPT_{180} is the optimal solution in the same condition.

$lemma$ 2: In kth iteration of the algorithm, we got one link to the solution ALG_{180} and $|OPT_k| \leq (c + (k-1)/2)^\alpha$, OPT_k was the optimal solution in kth iteration.

$Proof$: Due to the special condition, we just need analyse the first and second elimination part in the algorithm. Consider the set $X_v \subseteq OPT_{180}$ eliminated in the first part of algorithm (line 6), in the iteration when link $l_v \in ALG_{180}$ was added to the scheduling solution. Each link $l_w \in X_v$ is of length at least d_{vv}, and the distance of its sender at most $c \cdot d_{vv}$ from receiver r_v. By $Lemma$ 2, there can be at most c^α in the set X_v.

For the second part of the proof, which equivalent to a pretreatment for the next iteration of the algorithm. Consider the set $L_v \subseteq L$ that the length of each links bigger than the link $l_v \in ALG_{180}$. In this part of eliminated, ensure the distance of each sender of links at least $d_{vv}/2$. We used the Y_k represent the links which exist in second part of elimination at kth iteration, and the d_k is the distance of the kth iteration when link $l_k \in ALG_{180}$ added to the scheduling solution, $d_k = d(l_k)/2$.

Combine the result of the last iteration. In the kth iteration, it is possible that the links in the discs around $l_w \in Y_k$ was been delete with the radius at most R_k. In the first iteration, the radius $R_1 = d_1 = d(l_1)/2 \leq d_k$. If $k = 2$, $R_2 = R_1 + d_2 \leq 2d_k$. From the induction result, in the kth iteration, which l_v added to the solution. At worst, maybe delete all the links in the discs of radius $R_k = R_{k-1} + d_{vv}/2 \leq k \cdot d_{vv}/2$ around each sender $s_w \in Y_k$.

In general, during the process of kth iteration, $l_v \in ALG_{180}$ was the legal link. Combine the first part and second part of elimination. Each link $l_w \in X_v$ is of length at least d_{vv} and has its sender of distance at most $c \cdot d_{vv} + (k-1) \cdot d_{vv}/2$ from receiver r_v. Therefore, can be at most $(c + (k-1)/2)^\alpha$ senders in X_v.

Due to the complexity of the directional antennas, we can not offered generally demonstration for the algorithm. But the number of non-intersect links is the least number of scheduling links. In other words, all of the non-intersect links can be scheduling at the same time.

In next section, we will shown the performance of the OSML algorithm.

IV. Evaluations

In this section, we validate OSML's performance through simulation analysis. We compared the performance with One-slot scheduling algorithm (proposed in [2]). We present the performance of algorithm under the influence of links number, directional antennas interference range and antennas gains.

To simplify the analysis of experiment result. We list the following conditions: (1) All of the links random distributed on a plane field of size $1000*1000$ units (see Fig. 2). (2) All of the links transmit in the same power. (3) In the experimental, we ignore the influence by ambient noise $N = 0$.

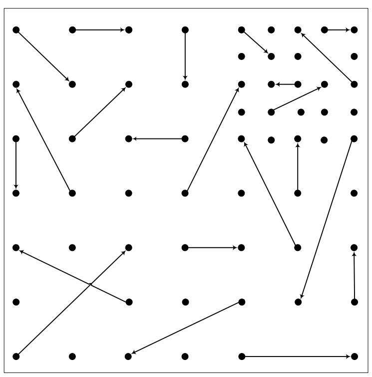

Fig. 2. Simulated Topologies.

In OSML scheduling algorithm, The size of the independent set present the performance of the algorithm. In our experiment, we using the number of links of the independent set as the performance standard.

We give some parameter values used in experiment. Path-loss exponent $\alpha = 3$, minimum SINR required for a message to be successfully received $\beta = 1.2$, ambient noise $N = 0$. Maximum of the link length $l_{max} = 20$ and the minimum $l_{min} = 10$. General condition, the directional angle of the antennas $\theta = 60°$, and the antenna gain $Gain = 20$.

A. Experimental Results and Analysis

The results are shown in Fig. 3, we analyze affect by the length of the input scheduling set to the algorithm, and set $n \in \{100, 200, 400, 800, 1600, 3200, 6400, 12800, 25600\}$. The simulation present that the size of the maximum independent set grows along with the increase of the number of the request link, but due to the limitations of the space, growth rate becomes slower and tends to balance.

We have a general impression of the performance of the algorithm from above results. Now we give some results from other aspect to the algorithm. First, the influence

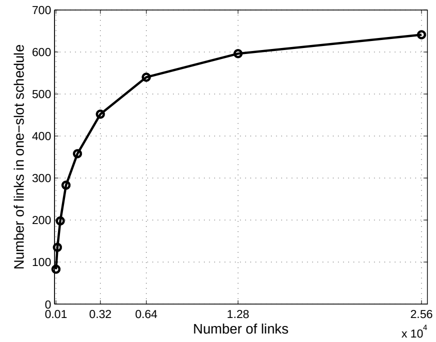

Fig. 3. OSML Scheduling Algorithm. Nodes random distribution and $\theta = 60°$ or $\theta = 120°$, the number of links in one-slot schedule show the perform of the algorithm.

by the directional angle, the range of the angle satisfied $\theta \in \{30°, 60°, 90°, ..., 360°\}$, and we make a comparison experiment $n = 100$ and $n = 3200$. In Fig. 4. We known that the angle make a great influence to the performance of the OSML scheduling algorithm, when other parameters were fixed. The smaller the angle, the better performance of the algorithm. In the case of maximum angle $\theta = 360°$, the algorithm has a worst performance.

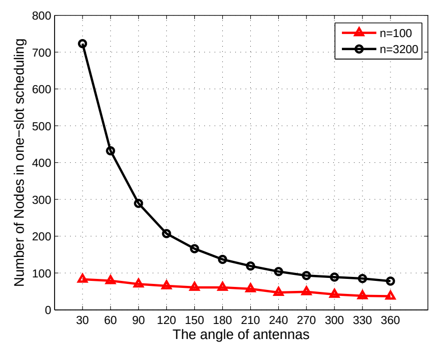

Fig. 4. Influence of Directional Angle. Change the angle of the directional antennas, compared the performance in high density with low density.

Figure 5 show the results of the influence to the algorithm by the antenna gain. We set up a fixed directional angle $\theta = 60°$, antenna gain $G \in \{5, 10, 15, 20, 25, 30, 35, 40\}$, adopt double groups $n = 100$, $n = 3200$. According to the formula of SINR, we known that the changes of the antennas gain have a small effect to the result of algorithm. The simulation results shown that even if there have some fluctuation, the antennas gain have limited impact to the algorithm.

The above results were just get by separate analyzed of the OSML algorithm. Now we do some comparison between OSML algorithm and the one-slot scheduling algorithm. Parameter settings: $Gain = 20$, $\theta = 60°$, and the number of links $n \in \{100, 200, 400, 800, 1600, 3200, 6400, 12800, 25600\}$. Shown in Fig. 6, in random network topology, the performance of the OSML algorithm is batter than the one-slot algorithm. This is advantage of directional antennas, reduce the interfer-

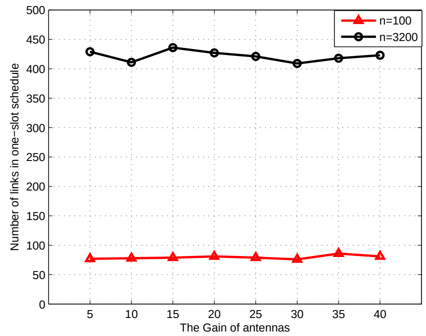

Fig. 5. Influence of Antenna Gain. Change the gain of the directional antennas, compared the performance in high density with low density.

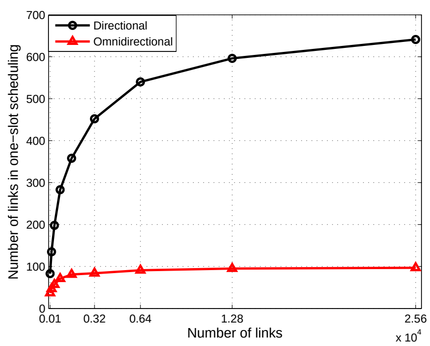

Fig. 6. Comparison between OSML and One-slot Algorithm. Use the same simulation data which generated at randomly by computer, but add the parameter of directional angle $\theta = 60°$ or $\theta = 120°$ when use to running OSML algorithm.

ence range by every nodes. In a fixed range of scene, more link can be allow for transmit together. In Fig. 7, we change the angle of the antenna $\theta = 360°$, two curves of the algorithm are very similar in the condition of lower density, but slightly worse than one-slot algorithm in high density network. This performance is the comparison of the algorithm. OSML was designed to adapt the situation of direction. So OSML can't performed as well as other omnidirectional algorithm.

To sum up, in random distribution wireless network, it has get an obvious effect to reduce the interference when multiple links transmission simultaneously by using directional antennas. The OSML scheduling algorithm have better performance than this omnidirectional algorithm, and we also obtain that the antenna gain have a limited effect to the algorithm, but seriously influence by directional angle.

V. Conclusions

In this paper, we developed a directional interference model for wireless network where the nodes using directional antennas. We first proposed a OSML approximation algorithm based on the directional interference model, and show the performance by simulation and mathematical analysis. The results of experiments proved that the performance of OSML was greatly affected by antenna interference angle, but not

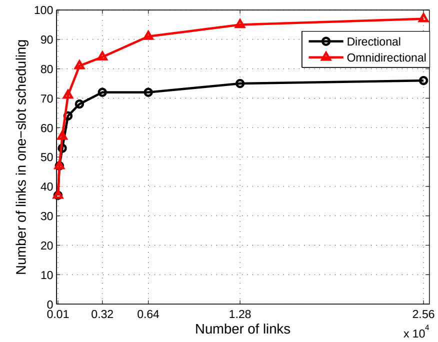

Fig. 7. Comparison between OSML and One-slot Algorithm. Set the directional angle $\theta = 360°$, which means use same random data running in different algorithm, compared the performance of two algorithm.

sensitive to antenna gains. Compared with the omni-directional antennas algorithm, OSML bring better result due to the nature of directional antennas. However, there are several challenges to OSML. The radiation beam of directional antenna is more complicated than we thought. From the OSML algorithm, we show the advantage of directional antenna to the problem of link scheduling, and hope that will be a significant step to solve this problem.

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