Link Scheduling in Wireless Cooperative Communication Networks

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***Abstract*—In this paper, we study the *link scheduling* problem in wireless cooperative communication networks, in which receivers are allowed to combine copies of a message from different senders to combat fading. We formulate a problem called *cooperative link scheduling problem (CLS)*, which aims to find a schedule of links that uses the minimum number of time slots to inform all the receivers. As a solution, we propose an algorithm for CLS with $g(\mathcal{K})$ approximation ratio, where $g(\mathcal{K})$ is so called *diversity of key links*. Simulation results indicate that our cooperative link scheduling approaches outperform non-cooperative ones.**

***Index Terms*—cooperative communication; link scheduling; approximation algorithm**

I. Introduction

In wireless networks, the problem of scheduling link transmissions, or the *scheduling problem*, has been a subject of much interest over the past years. In the scheduling problem, given a set of links, we need to determine *which links* should be active at *what times* and at *what power levels* should communication take place. The goal of the problem is to optimize one or more of performance objectives, such as *network throughput*, *delay* or *energy consumption*. Though the scheduling problem has been well studied based on various network models [1]–[9], to the best of our knowledge, none of the previous works takes into account cooperative communication (CC) for this problem, where receivers are allowed to cooperatively combine the received messages to combat transmission errors.

In wireless communication networks, before a message reaches the receiver, it may have several copies stored by other nodes. For example, the sender's neighboring nodes can store the unintended message from the sender due to the broadcast nature of wireless transmission; also, in multi-hop transmission, relay nodes can store the copies of the original message. In CC, the nodes storing the copies (including the original message) are allowed to send the copies to the receiver simultaneously, and the receiver can combine the signal power of the received copies in an additive fashion using a cooperative diversity technique (*e.g.*, maximal ratio combining (MRC)) [10] to recover the message.

The objective of this paper is to study the link scheduling problem in wireless cooperative communication networks, namely the *cooperative link scheduling* problem. Similar to the works in [7]–[9], we consider the problem separately from the routing problem and the power control problem, each of which constitutes a topic of their own. Therefore, we concentrate our attention on scheduling single-hop links, assuming all senders transmit at a fixed power level. In summary, our problem is different from the previous link scheduling problems since the received signal power of cooperative links can be combined in an additive fashion at the receiver in our work. Notice that the second difference implies that a link will not transmit message once its destination has been informed.

In this paper, we study the link scheduling problem based on the signal to interference plus noise ratio (SINR) model [11], [12], which allows us to account for CC. The objective of this work is to optimize *delay* of the network. To achieve this goal, we formulate a problem, namely the *cooperative link scheduling problem (CLS)*, of which the goal is to find a schedule of links to inform all the receivers using the minimum number of time slots. As a solution, we propose a *link length diversity (LLD)* based algorithm to solve CLS, called LLD-CLS, respectively. The basic idea of LLD-CLS is to partition all the links into several classes based on their length (*i.e.*, distance between the link's sender and receiver) and schedule the links in each class separately. We prove that LLD-CLS has $g(\mathcal{K})$ approximation ratio, where $g(\mathcal{K})$ denotes the diversity of key links, i.e., the magnitudes of link length. Finally, the experimental results indicate that our cooperative link scheduling algorithms outperform the previous non-cooperative algorithm [7].

II. Design Details

A. Problem Formulation

In this part, we first describe the CLS problem: In the CLS problem, we are given a set of nodes in a geometric plane, a set of requests, where each request is composed of a set of links and a receiver, and the

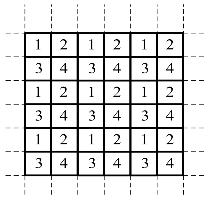

Fig. 1. LLD-CLS.

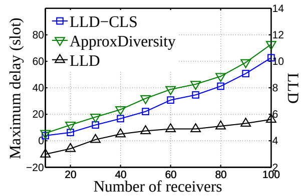

Fig. 2. Throughput.

decoding threshold, and we need to determine the set of active links at each time slot to minimize the maximum delay of all the requests. Hence, a CLS schedule can be represented by a link set sequence $\mathcal{I}_{\text{cls}} = \{\mathcal{I}^1, ..., \mathcal{I}^T\}$, where $\mathcal{I}^t$ is the set of active links at time slot t and T is the number of time slots the schedule takes. We say a CLS schedule is *feasible* iff this schedule enables every intended receiver to be informed. The objective of the CLS problem is to find a feasible CLS schedule that takes the minimum number of time slots. Then, the CLS problem can be formally formulated as

Instance: A finite set of nodes in a geometric plane V, a set of requests $F = \{f_1, ..., f_N\}$ (each request $f_i \in F$ has a set of links $\mathcal{I}_i$ and a receiver r_i), and constants decoding threshold γ_{th} and time constraint T.

Question: Existence of a CLS schedule $\mathcal{I}_{\text{cls}}$ *s.t.*

- $\mathcal{I}^t \cap \mathcal{I}^{t'} = \phi \quad \forall 1 \leq t < t' \leq T$;
- each r_i can be informed by time slot T.

B. Algorithm Design

The CLS problem is NP-hard since it can be reduced from the knapsack problem [13]. Due to the hardness of the problem, we cannot find the optimal solution in polynomial time. Hence, we proposed a link length diversity (LLD) based algorithm (or LLD-CLS for short) for CLS. LLD-CLS consists of three steps:

1) Find the link with the shortest length for each receiver;

2) Build $g(\mathcal{K})$ disjoint link classes L_1, ..., $L_{g(\mathcal{K})}$ according to the links' length:

$$L_k = \{l \in L | 2^{h_k} \cdot \sigma \leq d(l) < 2^{h_k+1} \cdot \sigma\} \tag{1}$$

3) For each link class L_k, construct a feasible schedule using a greedy strategy. When scheduling L_k, the whole region is partitioned into a set of squares with size $\beta_k = 2^{k+1} \cdot \sigma\beta$, where σ denotes the minimum link length and $\beta = \left(\frac{8\Delta(\alpha-1)\gamma_{\text{th}}}{\alpha-2}\right)^{\frac{1}{\alpha}}$, and all the squares are colored regularly with 4 colors (see Fig. 1). Links whose receivers belong to different cells of the same color are scheduled simultaneously. Then, the distances between the links activated simultaneously are large enough, and hence the interference is overcome. The approximation ratio of LLD-CLS is $O(g(\mathcal{K}))$ (due to the limited space, we will not describe the detail proof here).

III. Experimental Results

Finally, we compare the delay of LLD-CLS with a smart non-cooperative link scheduling algorithm, called ApproxDiversity [7]. We set the number of senders by 200, and vary the number of receivers from 10 to 100 with 10 increase in each step, where all the nodes were distributed uniformly at random on a plane field of size 100×100.

Fig. 2 shows the experimental results. As expected, LLD-CLS outperforms ApproxDiversity and Approx-LogN in maximum delay. This is because that LLD-CLS allows receivers to combine weak signal powers from senders, which helps increase the opportunities for receivers to recover their messages. In addition, we have two observations from the figures: (1) the maximum delay increases as the LLD increases, and (2) the maximum delay increases as the number of receivers increases. These two observations are caused by the LLD-based algorithms' mechanism, which first partitions the link set into disjoint link classes, and then separately schedules the links in each class in squares. For (1), higher LLD always generates more link classes, leading to more time slots to schedule the whole link set. As for (2), higher receiver density causes more nodes to be in each square, and hence more time slots to schedule each link class.

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