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Joint Stream Control and Scheduling in Multihop Wireless Networks with MIMO Links

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***Abstract*—MIMO links can significantly improve network throughput by supporting multiple concurrent data streams between a pair of nodes and suppressing wireless interference. In this paper, we formally define a new cross-layer optimization problem for MIMO-based multihop wireless networks, which is referred to as the joint Stream Control and Scheduling Problem (SCSP). We first present a constant factor approximation algorithm to solve the SCSP. In addition, we present a heuristic algorithm to improve the performance further, which is shown to be efficient in practice by our numerical results.**

***Index Terms*– Smart antenna, MIMO, scheduling, stream control, cross-layer design.**

I. Introduction

Future multihop wireless networks such as wireless mesh networks [1] are expected to support various data and multimedia applications which all involve a large volume of data traffic. For the past few years, different kinds of smart antenna technologies have been proposed to reduce interference and improve network throughput [5]. The Multiple-Input Multiple-Output (MIMO) antenna is one of them, which employs multiple antenna elements to offer multiple Degrees of Freedom (DOFs) for communications in a node. A transmitting node can divide the incoming data flow into multiple independent data streams and transmit them simultaneously over multiple antenna elements (DOFs), and the intended receiving node is able to separate and decode the received data streams based on their spatial signatures. This special feature is referred to as spatial multiplexing [10]. In addition, one or more antenna elements (DOFs) in a receiving node can also be used to suppress the interference from other links in a common neighborhood. Due to spatial multiplexing and interference suppression, MIMO links can significantly improve network throughput. Therefore, they are especially desirable for multihop wireless networks with heavy traffic demands, such as wireless mesh networks. However, they pose new challenges for the physical and MAC layer designers: how should the DOFs of each node be arranged (transmit, receive or suppress interference) at certain times such that space utilization can be maximized? This is referred to as the *stream control* problem in [2], [10]. Therefore, new resource allocation schemes need to be proposed to exploit the benefits of using MIMO links. This is the focus of this paper.

Even though MIMO antennas have been extensively studied in the literature, research on networking with MIMO links is still in its early stage. In [4], Hu and Zhang devised a MIMO-based MAC protocol, developed analytical methods to characterize the corresponding saturation throughput and studied the impact of MIMO MAC on routing. In [10], the authors discussed key optimization considerations, such as spatial multiplexing, for MAC layer design in ad hoc networks with MIMO links. They presented a centralized algorithm as well as a distributed protocol for stream control and medium access with those key optimization considerations incorporated. A unified representation of the physical layer capabilities of different types of smart antennas including MIMO, and unified medium access algorithms were presented in [11]. Cross-layer optimization for MIMO-based wireless networks has also been studied in [2], [6] recently. In [2], Bhatia and Li presented a centralized algorithm to solve the joint routing, scheduling and stream control problem subject to fairness constraints. A distributed link scheduling, power control and routing algorithm was proposed in [6].

In this paper, we focus on cross-layer optimization in TDMA-based multihop wireless networks with MIMO links. Specifically, we formally define a new fundamental problem in such networks, the joint Stream Control and Scheduling Problem (SCSP), which seeks a stream control solution along with an interference-free transmission schedule with minimum frame length to fully satisfy the given traffic demands of the links. We first present an algorithm to solve the SCSP and prove its performance is bounded by a constant factor of the optimal solution. Furthermore, we present a heuristic algorithm to improve the performance further, whose efficiency is justified by our numerical results. To our best knowledge, this paper provides the first formal definition of the SCSP, and proposes both theoretically well-founded and practically useful algorithms to solve it.

The rest of this paper is organized as follows. We describe the system model and formulate the SCSP in Section II. Two algorithms are presented to solve the SCSP in Section III. We present numerical results in Section IV and conclude the paper in Section V.

II. Problem Formulation

We consider a multihop wireless network, in which each node v is stationary and has a MIMO antenna with K_v DOFs. All nodes transmit at the same fixed power level in a single common channel. Moreover, spatial diversity for range extension is not considered here, as [2]. Therefore, each node has a uniform transmission range R_T and a uniform interference range $R_I \geq R_T$. In addition, the network has a TDMA-based MAC layer, where the time domain is divided into time slots with equal constant durations. A routing solution is assumed to be given by an existing routing protocol and the traffic demand on each link d_e is assumed to be known *a priori*. Finding a routing solution is outside the scope of this paper.

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A directed graph $G(V, E)$, referred to as the *communication graph*, is used to model the network, in which each vertex $v \in V$ corresponds to a wireless node, and there is a directed link $e = (u, v)$ from node u to node v if $||u - v|| \leq R_T$ and $d_e > 0$. Note that we are only interested in those links with traffic demands ($d_e > 0$) as well as their end nodes.

Wireless interference is modeled by the protocol model [3] here. If u_i, v_i, u_j, v_j are distinct nodes and $||u_i - v_j|| \leq R_I$, then we say link $e_i = (u_i, v_i)$ *interferes* with node v_j and link $e_j = (u_j, u_j)$. A node may *transmit*, or *receive* and *suppress interference* at a certain time. However, it cannot transmit and receive simultaneously due to the half-duplexing constraint. With MIMO links, a node v can transmit multiple, but no more than K_v, independent data streams along one or multiple outgoing links at the same time. A node v can also receive up to K_v independent streams from one or multiple incoming links simultaneously. Hence, there can be no more than $K_e = \min\{K_u, K_v\}$ concurrent streams over a MIMO link $e = (u, v)$ in a time slot. If a node is in the receiving mode, it can also suppress interference from concurrent transmitting nodes within the interference range using the same number of DOFs as the interfering streams. A node is *saturated* if it uses all of its DOFs, and is *idle* if it does not use any of its DOFs (i.e., it is not a transmitting node or a receiving node). We use T, R and I to represent the set of transmitting, receiving and idle nodes, respectively. Let $c_{e,k}$ denote the volume of traffic that can be successfully delivered over link e using k active data streams in a time slot. Due to multipath or rich scattering, different streams in a link may have different data rates [2]. We are interested in the marginal capacity increase achieved by adding an additional stream for the link in a given time slot. We define the marginal capacities for a link as $r_{e,k} = c_{e,k} - c_{e,k-1}$ for $k = 1, \ldots, K_e$ ($c_{e,0} = 0$). We further assume that the streams have been sorted for each link so that $r_{e,1} \geq r_{e,2} \geq \ldots \geq r_{e,K_e}$.

Suppose that we are given a set E of MIMO links, and a traffic demand $d_e > 0$ for each link $e \in E$. We define a *stream usage vector* $X = \{x_1, x_2, \ldots, x_e, \ldots, x_{|E|}\}$ to specify the number of active streams x_e on each link e. Since d_e can be an arbitrary number, there may not exist an integer $k \leq K$ such that $c_{e,k} = d_e$. Typically in a TDMA-based wireless system, we may need to allocate multiple time slots for a link in order to fully satisfy the traffic demands. A *feasible transmission schedule* $S = \{s_1, \ldots, s_t, \ldots, s_L\}$ can be viewed as a collection of feasible stream control solutions (R_t, T_t, I_t, X_t), each of which can be used to control transmissions of data streams in a time slot t. We summarize the constraints for a feasible transmission schedule below.

$$\sum_{t=1}^{L} c_{e,x_{t,e}} \geq d_e \quad \forall e \in E \tag{1}$$

$$\sum_{e \in E_v^{out}} x_{t,e} \leq K_v, \ \sum_{e \in E_v^{in}} x_{t,e} = 0, \quad \forall v \in T_t; \tag{2}$$

$$\sum_{e \in E_v^{in} \cup E_v^{inf}} x_{t,e} \leq K_v, \ \sum_{e \in E_v^{out}} x_{t,e} = 0, \quad \forall v \in R_t; \tag{3}$$

$$\sum_{e \in E_v^{out} \cup E_v^{in}} x_{t,e} = 0, \quad \forall v \in I_t \tag{4}$$

In the above formulation, the optimization variables are the 3-way partitions (T_t, R_t, I_t), the stream usage variables $x_{t,e} \geq 0$ for each time slot t and the number of time slots (frame length) L. E_v^{in}, E_v^{out} stand for the set of links going into and out of node v respectively. $E_v^{inf} = \{e = (x, y) | ||x - v|| \leq R_I, x \neq v, y \neq v\}$ represents the set of links that interfere with node v. Constraint (1) ensures that the link traffic demands are satisfied. Constraint (2) makes sure that the number of outgoing streams from every transmitting node is no more than its number of DOFs and it will not receive any streams from a neighbor because of half-duplexing. Similarly, in a receiving node, its number of DOFs must be large enough to receive intended streams and suppress interference from other concurrent transmissions, and moreover, it cannot transmit any streams, which is guaranteed by constraint (3).

Definition 1 (SCSP): The **Stream Control and Scheduling Problem (SCSP)** seeks a feasible transmission schedule $S = \{s_1, \ldots, s_t, \ldots, s_L\}$, such that the frame length L is minimized.

III. The Proposed Algorithms

In this section, we present two algorithms, SCSP-1 and SCSP-2 to solve the SCSP. We prove that SCSP-1 is a constant factor approximation algorithm, whose approximation ratio depends on a simple structural property of the network. SCSP-2 is based on SCSP-1 and can achieve better performance in practice. But it does not have the same performance guarantee.

Link scheduling in wireless networks with omni-directional antennas can be done by finding a valid coloring for the *contention graph* [7] where each vertex corresponds to a link in the communication graph and there is an edge between a pair of vertices if they interfere with each other. A greedy algorithm can solve the coloring problem by first sorting the vertices in the contention graph by decreasing vertex degrees and then coloring them one by one using a first-fit greedy approach [8], [12]. The colored vertex and the incident links are removed from the contention graph after each pass and vertices will be re-ordered based on their new degrees. This type of greedy coloring algorithm is guaranteed to return a coloring for a contention graph G_C using at most $\Delta(G_C) + 1$ colors, where $\Delta(G_C)$ is the maximum vertex degree in G_C.

The contention graph described before is not suitable for a network with MIMO links and the greedy algorithm mentioned above can not be directly applied here because interfering links may still be arranged in the same time slot as long as the enough DOFs can be used to suppress interference (see constraint (3)). We divide link contention (interference) into two types: *strong* and *weak*. Strong contention arises when two links cannot be scheduled in the same time slot under any circumstances. An incoming link into a node has a strong contention with any outgoing link from the same node, since a node cannot simultaneously transmit and receive due to the half-duplexing constraint. Formally, links $e_i = (u_i, v_i)$ and $e_j = (u_j, v_j)$ strongly contend with each other if and only if $u_j = v_i$ or $u_i = v_j$. We define the *strong contention graph* $G_{strong}(V_E, E_{strong})$, where each vertex $v_e \in V_E$ corresponds to a link $e \in E$ and there is an edge between a pair of vertices if their corresponding links strongly contend with each other. For each link $e = (u, v)$ in the communication graph G, we can compute $\xi(e) = \delta_{in}(u)+\delta_{out}(v)$, the number of links that e has a strong contention with, where $\delta_{in}(v)$ and $\delta_{out}(v)$ refer to in and out degree of the node v respectively. Let $\xi = \max_e \xi(e)$ and note that $\xi = \Delta(G_{strong})$.

A pair of links that contend for resources but that can be scheduled in the same time slot (e.g. a set of outgoing links from v) if related DOFs are arranged properly, are said to have weak contention. There are exactly three situations where weak contention can arise between $e_i = (u_i, v_i)$ and $e_j = (u_j, v_j)$: 1) $u_i = u_j$; 2) $v_i = v_j$; 3) $\exists e_k = (u_k, v_k)$ (possibly $k = i$ or $k = j$) such that $||v_k - u_i|| \le R_I$ and $||v_k - u_j|| \le R_I$. The third case occurs when two transmitting nodes (u_i and u_j) interfere with a third receiving node (v_k); thus e_i and e_j contend for the interference suppression ability (available DOFs) in v_k that is trying to receive data on link e_k. This defines the *weak contention graph*, $G_{weak}(V_C, E_{weak})$. Fig. 1 illustrates strong and weak contentions in a simple example. In the figure, panel A shows a simple network with 9 nodes and 6 links. In panel B, we show the corresponding strong and weak contention graphs together due to the space limit. Solid and dotted lines indicate strong and weak contention respectively.

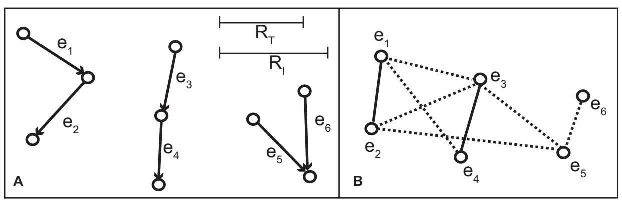

Fig. 1. An example of weak and strong contentions.

Recall that if multiple independent streams are concurrently transmitted over a link in a time slot, the marginal capacity added by these additional streams diminishes with the number of active streams. Thus, the total number of streams needed to satisfy the traffic demand of a link depend on whether those streams appear in separate time slots, or in shared time slots. Let b_e be the best case number of streams required in a schedule to satisfy link e's traffic demand, which can be obtained by scheduling at most one stream for e in each time slot. Similarly, let w_e be the worst case number of streams required, which can be obtained by packing K streams per time slot for link e's traffic demand, until fewer than K streams are needed to fulfill the requirement and then packing these in an additional time slot. We also define $\rho(e) = \lceil w_e/b_e \rceil$ and let $\rho = \max_e \rho(e)$. Let $\Lambda = \max_{e_i=(u_i,v_i)} |\{e_k = (u_k, v_k)|\exists e_j = (u_j, v_j), ||v_j - u_i|| \le R_I, ||v_j - u_k|| \le R_I\}|$ (possibly $j = i$). Observe that the degree of a vertex in G_{weak} is bounded by Λ since the above expression accounts for each of the three ways that a link e_k can be connected to e_i via an edge in the weak contention graph. We present the following algorithm to solve the SCSP.

The central idea of the algorithm SCSP-1 is to first divide the links into components ($\{C_i\}$), containing only weak contentions and then color these components (after first duplicating each link enough times so that its traffic demand will be satisfied by the schedule). These colorings are then used to assign streams to time slots. For example, for a link e, if its color set $s(e)$ contains two colors that were selected to form some W_j then e will appear twice in W_j and in the corresponding time slot j, i.e., e will carry 2 streams in time slot j. Schedules are constructed for each component C_i and then merged together to form a single schedule S.

Algorithm 1 SCSP-1

Step 1	Color G_{strong} using a greedy coloring algorithm. This yields a partition of V_E into p classes $C_1, \ldots, C_p$, where $p \le \Delta(G_{strong}) + 1 = \xi + 1$.
Step 2	Construct $G_i = (V_i, E_i)$ from C_i as follows: For each $e \in C_i$, create a clique Q_e containing w_e nodes and add it to V_i. If $e_j, e_k \in C_i$ and $(e_j, e_k) \in E_{weak}$, then add $Q_{e_j} \times Q_{e_k}$ to E_i.
Step 3	Color each G_i using a greedy coloring algorithm. Assume the total number of colors used for G_i is d_i and let $f_i = \lceil d_i/K \rceil$.
Step 4	For each G_i: Let $s(e)$ denote the set of colors given to edges in Q_e. For each color c, let $U_c = \{e \| c \in s(e)\}$ denote the set of edges given color c. Form multisets $W_{j+1} = U_{jK+1} \cup U_{jK+2} \cup \cdots \cup U_{jK+K}$ for $j = 0, \ldots, f_i - 2$. Let $W_{f_i} = U_{(f_i-1)K+1} \cup \cdots \cup U_{d_i}$. Create a sub-schedule S_i for G_i consisting of f_i time slots. Time slot j is constructed by allocating each link e a number of streams equal to the multiplicity of e within W_j.
Step 5	Merge the sub-schedules together to form a single schedule $S = (S_1, \ldots, S_p)$ that solves the input instance of SCSP. Truncate the tail of S as much possible such that all link traffic demands remain satisfied. Return S.

Lemma 1: Algorithm SCSP-1 produces a feasible transmission schedule S that satisfies all link traffic demands.

Proof: We first argue that all the time slot assignments are feasible in the sense that no strong contention constraints are violated and that each node uses no more than K DOFs. Since each sub-schedule S_i contains only links from C_i, it follows that no strong link contentions will be violated. This ensures that there is an implicit assignment of nodes to a (T, R, I) partition for each time slot. Next, we argue that no constraints of type (2) will be violated as all of the outgoing links from a node u that belong to C_i have weak contentions with one another and so will be assigned different colors (including links that receive multiple colors). The number of different colors present in any multiset W_j is at most K. This implies that in the time slot associated with W_j, there are at most K streams transmitted from u, so u has sufficient DOFs. Receiving nodes v must allocate DOFs to receive streams and suppress interference from any links in their interference range. By construction, all such links and any concurrent incoming links into v will form a clique in G_i so they must receive different colors. In any time slot, there will be at most K streams allocated among any of these links, so v will have enough DOFs to receive its incoming streams and suppress interference.

Next we argue that all link demands are met by S. This follows from the fact that we create w_e copies of every link before coloring and place them in a clique so each copy must be given a distinct color. Hence, within the final schedule S, there will be w_e streams scheduled for link e. Thus, even in the worst case, i.e. if e is given K streams in each time slot that it is scheduled, it will still be given enough streams to satisfy its demand. ∎

Theorem 1: Algorithm SCSP-1 provides a schedule whose length is within a factor $(\xi+1)(\Lambda+1)\rho$ of optimal.

Proof: Suppose that we are given an optimal schedule $S = (s_1, \ldots, s_{t^*})$ for a given SCSP instance, where t^* is the minimum possible frame length. We can create a new schedule S' that is p times longer by creating p new time slots $s'_{i,1}, s'_{i,2}, \ldots, s'_{i,p}$ for each original time slot s_i, where $s'_{i,j}$ contains all of the links from s_i that belong to C_j. Then we collect the time slots for each C_j into sub-schedules: $S' = (S'_1, \ldots, S'_p)$, where $S'_j = (s'_{1,j}, \ldots, s'_{t^*,j})$. Thus S'_i is a valid schedule for the links in C_i. Next, we use these sub-schedules to create a valid coloring for each G_i. This can be done by expanding each time slot $s'_{i,j}$ into K distinct colors. Let the links in C_j be ordered $e_{j,1}, \ldots, e_{j,|C_j|}$. Considering the links in this order we assign them the same number of colors as streams they are allocated in $s'_{i,j}$. If the link currently being considered contends with any previous links, we give it distinct colors. This is possible since $s'_{i,j}$ is a feasible schedule for all transmitting and receiving nodes involved. So if two links have a weak contention, they must be assigned non-intersecting sets of colors. Let G'_i be a graph that is constructed identically to G_i in algorithm SCSP-1 above, except the cliques corresponding to each link e will contain exactly the number of streams assigned to e in S (this will be at least b_e). Then, the above procedure colors G'_i using at most Kt^* colors. Next, we construct a new graph G''_i by replacing each vertex v in G'_i with a clique Q'_v of size ρ. If $(u, v) \in E(G'_i)$ then we will add $Q'_u \times Q'_v$ to $E(G''_i)$. By making ρ distinct copies of each color used for G'_i, we can color G''_i using at most $\rho K t^*$ colors. Next, observe that G_i is a subgraph of G''_i. Thus,

$$\chi(G_i) \le \rho K t^*. \tag{5}$$

The coloring algorithm is guaranteed to produce a coloring of G_i using at most $\Delta(G_i) + 1$ colors. Let κ be the size of the largest Q_e clique in G_i. By the construction of G_i, $\Delta(G_i) + 1 \le (\Lambda + 1)\kappa$. On the other hand, $\kappa \le \chi(G_i)$, by the property that a valid coloring of a graph containing a clique of size c must use at least c colors. Thus, Step 3 of the SCSP-1 algorithm colors G_i using at most $(\Lambda + 1)\chi(G_i) \le (\Lambda + 1)\rho K t^*$ colors, where the inequality follows from (5). Thus, the subschedule for each C_i produced in Step 4, uses at most $(\Lambda+1)\rho t^*$ colors, as K colors are packed into each time slot. Combining these schedules yields a valid schedule for the SCSP instance that is within a factor of $(\xi+1)(\Lambda+1)\rho$ of optimal. ∎

Next, we describe an alternative version of this algorithm, SCSP-2. The main difference is that we will only duplicate each link in C_i K times when forming the graph G_i. When using the resulting coloring of G_i, we will allow colors to be reused i.e., the same color can appear in multiple time slots and can also occur more than once in a single time slot. The idea behind SCSP-2 is that it may be possible to pack more than K colors into a time slot, provided that no DOF constraints are violated. The algorithm attempts to do this opportunistically to maximize the total capacity of all streams selected in the time slot. We also allow individual colors to be reselected if they are useful a second or third time. We limit the size of the cliques in G_i to be of size K in order to improve the efficiency of the graph coloring step. It is still possible that the algorithm can choose to allocate K streams for a particular link in a given time slot, if that appears to be the most effective choice.

Algorithm 2 SCSP-2

Step 1 Color G_{strong} using a greedy coloring algorithm. This yields a partition of V_E into p classes $C_1, \ldots, C_p$, where $p \le \xi + 1$.

Step 2 Construct $G_i = (V_i, E_i)$ from C_i as follows: For each $e \in C_i$, create a clique Q_e containing K nodes and add it to V_i. If $e_j, e_k \in C_i$ and $(e_j, e_k) \in E_{weak}$, then add $Q_{e_j} \times Q_{e_k}$ to E_i.

Step 3 Color each G_i using a greedy coloring algorithm.

Step 4 **for** $i = 1$ **to** p
  $S_i = \emptyset$
  while $\exists$ an unsatisfied link in C_i, construct
   a new time slot s' as follows:
   while all DOF constraints are slack:
    Select the color from the G_i-coloring that
    maximizes the total marginal stream capacity
    added to unsatisfied links; add this color to s'.
   endwhile
   $S_i = S_i \cup \{s'\}$.
  endwhile
 endfor

Step 5 Return a single schedule $S = (S_1, \ldots, S_p)$.

Both SCSP-1 and SCSP-2 have time complexity $O(D \cdot (|E| \lg |E|))$, where D depends on the numeric value of the traffic demand relative to the stream capacities. Specifically, we can take $D = \max_e w_e$, a bound on the maximum number of streams necessary to satisfy the traffic demand of any link.

IV. Numerical Results

In this section, we illustrate the performance of the proposed algorithms via numerical results. In the simulations, we randomly place n nodes in a $1100m \times 1100m$ region. Each node has a fixed transmission range of $250m$ and a fixed interference range of $500m$ [9]. The capacity of a stream on a link e is normalized to $\alpha(1.0 - 0.1 * (j - 1))$, where j is an integer number in $[1, 6]$ and α is a small random number uniformly distributed in $[0.5, 1.0]$. For example, the capacity of the largest capacity stream is $\alpha * 1.0$, the capacity of the second largest capacity stream is $\alpha * 0.9$, and the capacity of a link with two streams is $\alpha * 1.9$. The number of time slots (frame length) is used as the performance metric. Each number presented in the figures is the average over 10 runs. In each run, a network is randomly generated.

In all of the scenarios, we randomly choose m links from the network in each run. For the first three scenarios, n is set to 35. In the first scenario, the traffic demand on each link is set to a random number uniformly distributed in $[3.50, 7.00]$. Each node has 4 DOFs. m varies from 30 to 105. In the second scenario, $m = 75$ and the traffic demand is generated in the same way as the first scenario. The number of DOFs in each node is changed from 1 to 6. In the third scenario, the number of links is set to 75 and the number of DOFs in each node is set to 4. The link traffic demand is set to a random number uniformly distributed in $[3.50, 7.00]$, multiplied by a *demand factor* changing from 0.333 to 2.00. In the last scenario, we test larger networks with 70 nodes, each of which has 4 DOFs. The traffic demand generation is the same as the first scenario. m varies from 60 to 135. The corresponding results are presented in Fig. 2 – Fig. 5.

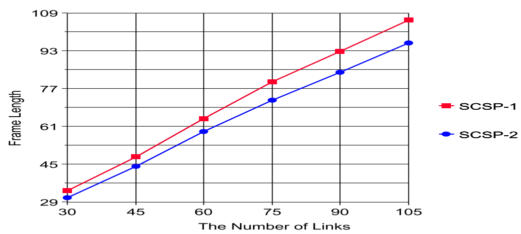

Fig. 2. Scenario 1: frame length VS. the number of links

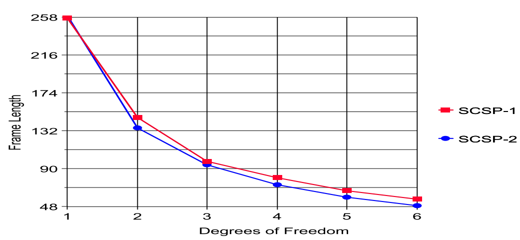

Fig. 3. Scenario 2: frame length VS. DOF

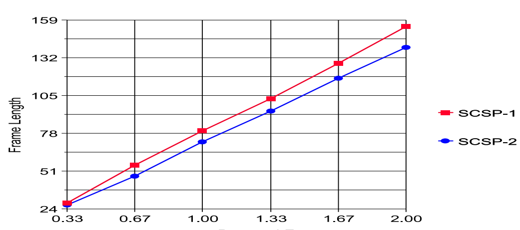

Fig. 4. Scenario 3: frame length VS. traffic demand

The performance given by the two proposed algorithm are fairly close. However, SCSP-2 consistently outperforms SCSP-1 in all of the cases as expected. An average of 8.6% improvement is achieved. The number of DOFs seriously impact the performance. As you can see from Fig. 3, the frame length drops sharply with the increasing number of DOFs

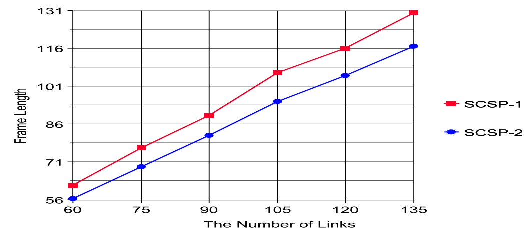

Fig. 5. Scenario 4: performance in denser networks

since more DOFs lead to more active streams in a time slot. In addition, you can see from Fig. 4 that the frame length increases sharply with the increase of traffic demands (which are adjusted by increasing the demand factor) as expected. From Figs. 2 and 5, we can see that in relatively denser networks, the frame lengths are larger due to the stronger interference in a common neighborhood.

V. Conclusions

In this paper, we presented two algorithms to solve a new optimization problem, the joint Stream Control and Scheduling Problem (SCSP), in multihop wireless networks with MIMO links. The first algorithm was proved to be a constant factor approximation algorithm and the second one was shown to be more efficient in practice by the numerical results.

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