Multi-path Routing and Stream Scheduling with Spatial Multiplexing and Interference Cancellation in MIMO Networks

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***Abstract*—In MIMO networks, there are two transmission strategies, SM (spatial multiplexing) and IC (interference cancellation). The use of SM and IC brings additional complexity for routing and transmission scheduling of the links. Almost all existing works on throughput optimization for MIMO systems are based on the assumption that traffic routing is given and they focus only on stream scheduling, where the performance of the system is limited. In this work, we study the joint optimization problem of routing and stream scheduling for MIMO networks, where the traffic is allowed to be routed through multiple paths to take benefit from concurrent transmissions. The problem is first formulated as an Integer Linear Programming (ILP) problem, and solved optimally by using the column generation approach. An efficient online heuristic algorithm for multi-path routing and stream scheduling with dynamic traffic load is then proposed based on the column generation approach. Extensive simulation results have been conducted to demonstrate the efficiency of the proposed algorithms.**

***Index Terms*—MIMO, stream scheduling, stream control, multi-path routing.**

I. Introduction

Multiple-Input Multiple-Output (MIMO) is a powerful physical layer technology that provides significant link capacity improvements over the conventional technologies [1], [2]. There are two transmission strategies, Spatial Multiplexing (SM) and Interference Cancellation (IC) [3], [4]. SM allows multiple independent data streams to be transmitted over the same link simultaneously by multiple pair of transmitting / receiving antenna elements. IC enables a receiving node to use its antenna elements to separate and suppress the signals from interfering sources.

The utilization of both SM and IC can help to increase the performance of MIMO systems significantly [5]–[8]. However, It brings additional complexity for joint routing and transmission scheduling: the routing scheme should consider to route the data into multiple interfering MIMO links to take the advantage of IC; while the transmission scheduling scheme, which is referred as the *stream scheduling* scheme, should not only schedule the transmissions on links, but also make decisions on MIMO transmission strategies. Almost all existing works on throughput optimization for MIMO systems assume the routing of the system is given and they focus only on stream scheduling, where the performance of the system is limited.

There are some works that study joint routing and scheduling problem in traditional networks [9], [10]. These works usually formulate the problem as an integer linear optimization problem, and use the mathematical tools to find the solution. Due to their high complexity and the static nature, this type of methods are not suitable for the situation of online real-time scheduling with dynamic traffic demands. To our best knowledge, there is no online method that considers joint routing and stream scheduling in MIMO systems.

In this paper, we study the Multi-path Routing and stream Scheduling (MRS) problem in multi-hop wireless networks with MIMO links. That is, given a multi-hop network topology and the traffic demands on wireless node pairs. We route the traffics to the destinations through multiple available paths, and schedule the transmissions to take full advantage of SM and IC. Our aim is to maximize the system throughput by employing joint method for multi-path routing and stream scheduling. We first present a Column-generation based Multi-path Routing and stream Scheduling (C-MRS) method to solve the MRS problem optimally in static situation. This method is based on an Integer Linear Programming (ILP) formulation of the problem, where the traffic demand of the nodes are given in prior. Then we propose an Online Multi-path Routing and stream Scheduling (O-MRS) method that addresses the MRS problem with dynamic traffic demands using an iterative updating procedure.

The rest of this paper is organized as follows. We describe the system model and formulate the MRS problem in Section II. The C-MRS method that solves the MRS problem in static situations is presented in Section III. The O-MRS method that can be used for the dynamic situations of MRS problem is proposed in Section IV. Extensive simulation results are presented in Section V. We conclude the paper in Section VII.

II. Problem Formulation

A. System Model

The multi-hop wireless network consists of n wireless nodes, denoted as $v_1, v_2, ..., v_n$. We assume all nodes use fixed transmit power, and operate on the same frequency band. Each node v_i is equipped with a_i antennas, which are also called Degrees of Freedoms (DoFs). The number of DoFs may be different from node to node.

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We assume the system works in TDMA mode. All communication links are directional and have the same data rate. We define a *data stream* as the data that can be transmitted in a timeslot by a pair of antennas over a link. The data stream is the basic unit of traffic in this paper. The network is modeled as a directed graph $G(V, L)$, where V is the set of all nodes, and L is the set of available directed communication links. For a directed link $l_{ij} = (v_i, v_j) \in L$, we call v_i as the source node, and v_j as the destination node.

The traffic demands in the system are given. Let d_{ij} denote the traffic demand of a source-destination pair (v_i, v_j), which is the number of data streams that requires to be delivered to v_j within a TDMA scheduling frame. Note that v_i and v_j may or may not have a direct communication link.

We adopt the protocol interference model in this paper. The interferences can be described by a directed graph $G_I(V, E_I)$, where the vertices are the nodes in the system, and the set of directed edges E_I denotes the interferences between the nodes. For a directed edge $e_{ij} = (v_i, v_j) \in E_I$, we say, v_j is interfered by v_i.

In TDMA, the time frame is divided into a sequence of equal-length timeslots. In each timeslot, there is a *slot scheduling* that schedules the transmission of data streams on the links. In this work, our aim is to optimize the throughput on all source-destination pairs with traffic demands. We propose a method to find a sequence of slot scheduling for every timeslot in a TDMA scheduling frame, such that the MIMO constraints on all timeslots and the traffic demands on all source-destination pairs are satisfied, and the length of the scheduling frame is minimized.

B. MIMO Constraints

For each timeslot in the TDMA scheduling frame, there are some MIMO constraints that govern the slot scheduling. Since the matrix-based MIMO constraints in physical layer are too complex to be adopted in the optimizations in network layer, we use the DoF-based MIMO constraints based on the model proposed by Shi et al. [11] as follows.

When a node transmits signals in a timeslot, its antennas can be used for SM transmission strategy to transmit multiple independent data streams simultaneously. One DoF is required to transmit each of the data stream. Thus, the total number of streams that can be simultaneously transmitted by this node is constrained by the number of its DoFs.

When a node receives signals in the timeslot, some of its antenna will be used for SM strategy to decode the intended-to-receive data streams, and some other antennas can be used for IC strategy to suppress interference signals. The combined use of SM and IC enables a node to receive data streams even in the presence of interferences. One DoF is required to decode each of the intended-to-receive stream, or cancel each of the interference stream. Thus, the number of intended-to-receive streams plus the number of interference streams at the node is constrained by the number of its DoFs.

Let z denote a slot scheduling within a timeslot. Let u_{ij}^z denote the utilization of link l_{ij} in the slot scheduling z, which refers to the number of streams scheduled to transmit on that link. Let V_{RX}^z denote the set of nodes that are scheduled to receive some intended data streams in slot scheduling z. We can formally define the MIMO constraints for a slot scheduling z as follows.

TX constraint. The total number of scheduled streams originating from v_i (i.e. transmitted by v_i) shall never exceed its number of DoFs:

$$\forall v_i \in V : \sum_{l_{ij} \in L} u_{ij}^z \leq a_i. \tag{1}$$

As for DoF constraint at the receiving nodes, we need to consider interference at those nodes. The *sensible streams* for v_i in slot scheduling z denote the scheduled streams that will interfere v_i. It includes both intended data streams and interfering streams for v_i. According to the interference model, any node v_k interferes node v_i has an edge $e_{ki} \in E_I$. Thus, the number of sensible streams of v_i in slot scheduling z can be calculated as:

$$\sum_{l_{kj} \in L : e_{ki} \in E_I} u_{kj}^z.$$

RX constraint. The total number of sensible streams for $v_i \in V_{RX}^z$ shall never exceed the number of its DoFs:

$$\forall v_i \in V_{RX}^z : \sum_{l_{kj} \in L : e_{ki} \in E_I} u_{kj}^z \leq a_i. \tag{2}$$

Half-duplex constraint. No node can transmit and receive data simultaneously. That is, for a node $v_i \in V_{RX}^z$, the total number of streams transmitted by it should always be 0.

$$\forall v_i \in V_{RX}^z : \sum_{l_{ij} \in L} u_{ij}^z \equiv 0. \tag{3}$$

In the above MIMO constrains, the set of nodes in RX state V_{RX}^z can be calculated as follows.

$$V_{RX}^z = \{v_j | v_j \in V, \sum_{l_{ij} \in L} u_{ij}^z > 0\}.$$

For a slot scheduling z, if all the three MIMO constraints are satisfied, it is a *feasible slot scheduling*.

C. Routing Constraint

In the multi-hop wireless network, a data stream at a node may experience several hops of transmissions via some intermediate nodes before it is delivered to the final destination node. We assign the streams into n concurrent transmission *sessions* according to the final destination of the stream. That is, all streams destined to node v_i belong to the i^{th} session. We can generate a routing graph for each session, where all streams are sinked to the same destination node in a session. Let λ_{ij}^k denote the traffic demand on communication link l_{ij} on the routing graph of the k^{th} transmission session, we have the following routing constraint for a TDMA scheduling frame as follows.

Routing constraint. In any transmission session, say the k^{th} session, the incoming traffic plus the original traffic of any node $v_i, (i \neq k)$, must equal to the outgoing traffic of this node.

$$\forall v_i, v_k \in V, (i \neq k) : \sum_{l_{ji} \in L} \lambda_{ji}^k + d_{ik} = \sum_{l_{ij} \in L} \lambda_{ij}^k. \quad (4)$$

D. Traffic Constraint

A TDMA scheduling frame f consists of a sequence of timeslots. In each timeslot, there is a slot scheduling z that schedules transmissions on links. Note that a slot scheduling z may be used multiple times in the scheduling frame. Let u_z^f denote the utilization of slot scheduling z in frame f, which refers to the number of appearance of slot scheduling z in frame f. Let Z denote the set of all slot schedulings used in this TDMA scheduling frame. To verify whether the TDMA scheduling frame satisfies all traffic demands, we have the following traffic constraint:

Traffic constraint. The total amount of traffic scheduled on any link in a TDMA scheduling frame f, shall never be less than the total traffic demand on this link.

$$\forall l_{ij} \in L : \sum_{z \in Z} u_{ij}^z u_z^f \geq \sum_{v_k \in V} \lambda_{ij}^k. \quad (5)$$

III. Column Generation based Routing and Scheduling in MIMO Networks

Suppose the set of all feasible slot schedulings is given as Z^*. The procedure of finding an TDMA scheduling frame f is to find the number of appearance of each feasible slot scheduling $z \in Z^*$, such that the cost (in terms of the total number of timeslots in f) is minimized, and the routing constraint (4) and traffic constraint (5) are satisfied. The MRS problem can be formulated as follows.

Minimize:

$$c_f = \sum_{z \in Z^*} u_z^f. \quad (6)$$

Subject to:

$$\begin{aligned}
\sum_{l_{ji} \in L} \lambda_{ji}^k + d_{ik} &= \sum_{l_{ij} \in L} \lambda_{ij}^k, && \forall v_k, v_i \in V, (i \neq k), \\
\sum_{z \in Z^*} u_{ij}^z u_z^f &\geq \sum_{v_k \in V} \lambda_{ij}^k, && \forall l_{ij} \in L, \quad (7) \\
\lambda_{ij}^k &\geq 0, && \forall v_k \in V, l_{ij} \in L, \\
u_z^f &\geq 0, && \forall z \in Z, \\
u_z^f &\in \mathbb{Z}, && \forall z \in Z. \quad (8)
\end{aligned}$$

The MRS problem is formulated as an integer linear programming (ILP) problem with routing and traffic constraints. However, due to the huge size of Z^*, it is practically impossible to use the above method to solve the MRS problem. Since the optimal TDMA scheduling frame usually only uses a limited number of feasible slot schedulings, the column generation approach [12], [13] could be adopted to reduce the size of the search space greatly.

We will present a Column-generation based Multi-path Routing and stream Scheduling (C-MRS) method to solve the MRS problem. The ILP problem is decomposed into a master problem and a subproblem in C-MRS. The master problem is effectively the same as the original ILP optimization problem shown above, but only use a limited number of known feasible slot schedulings Z. The subproblem is an optimization problem that tries to find a new feasible slot scheduling z which can potentially improve the solution of the master problem. A solution of the TDMA scheduling frame can be obtained iteratively. Each iteration has 3 steps: 1) solve the master problem using only the currently known feasible slot schedulings Z to get the current best solution with dual variables; 2) solve the subproblem according to the dual variables obtained from the master problem to get a new feasible slot scheduling z that can potentially improve the solution of the master problem; 3) add the new feasible slot scheduling z into the set Z. The iteration is repeated until no new feasible slot scheduling z can be found in step 2.

In this paper, the initial set of Z is simply the set of singleton links. That is, for each communication link in the system, we add a slot scheduling to set Z that only schedules one data stream on this link.

When the master problem is solved, the dual variables of every link in (7) can be obtained. Let c_{ij} denote the dual variable of link l_{ij} obtained from the master problem, which represents the marginal cost (in terms of number of timeslots required) to transmit a stream on l_{ij}. The reduced cost c_z^Δ of a feasible slot scheduling z can be calculated as follows.

$$c_z^\Delta = 1 - \sum_{l_{ij} \in L} u_{ij}^z c_{ij}, \quad (9)$$

where $\sum_{l_{ij} \in L} u_{ij}^z c_{ij}$ denotes the expected cost of scheduling all scheduled streams in z before z is added into Z, and integer 1 denotes that cost after z is added into Z.

If a new slot scheduling with negative reduced cost is found, it indicates that adding this scheduling to Z can potentially improve the result of the master problem. If no slot scheduling with negative reduced cost can be found, the solution of the master problem will be optimal. The subproblem of finding a feasible slot scheduling z with minimal reduced cost is defined as a minimizing problem as follows.

Minimize:

$$c_z^\Delta = 1 - \sum_{l_{ij} \in L} u_{ij}^z c_{ij},$$

Subject to:

$$\begin{aligned}
\sum_{l_{ij} \in L} u_{ij}^z &\leq a_i, && \forall v_i \in V, \\
\sum_{l_{kj} \in L : e_{ki} \in E_I} u_{kj}^z &\leq a_i, && \forall v_i \in V_{RX}^z, \\
\sum_{l_{ij} \in L} u_{ij}^z &\equiv 0, && \forall v_i \in V_{RX}^z, \\
u_{ij}^z &\geq 0, && \forall l_{ij} \in L, \\
u_{ij}^z &\in \mathbb{Z}, && \forall l_{ij} \in L.
\end{aligned}$$

IV. Online Routing and Scheduling in MIMO Networks

The column generation approach can help to reduce the complexity greatly in solving the MRS problem. However, this solution is still very time consuming, and is thus not suitable for the situation of online scheduling. Moreover, this solution does not take the transmission ordering into consideration. That is, an intermediate node may be scheduled to transmit some relay traffic before the traffic is delivered to this node. This is fine for a static system because this issue only appears in the first few TDMA frames. However, for the system with changing traffic demands, it affects the performance a lot.

We propose a new online scheduling approach, called the Online Multi-path Routing and stream Scheduling (O-MRS) method, to solve the MRS problem with dynamic traffic demands in MIMO networks. Corresponding to the dual variable (i.e., the marginal cost) in C-MRS method, the cost c_{ij} of a link l_{ij} in O-MRS method is defined as the average number of timeslots used for transmitting a single stream on this link. Basically, the total cost of all scheduled streams transmitted in one timeslot should be 1. However, since the transmission situation of different timeslots could be significantly different, this characteristic does not hold strictly for every timeslot. Nevertheless, for a period of time that contains many timeslots, this characteristic will be hold statistically. That is, the total cost of the streams transmitted should be around the number of timeslots in this period.

Inspired by the C-MRS method, the O-MRS method iteratively determines the stream scheduling of the next timeslot. Each iteration has 3 steps: 1) find a multi-path routing graph and the corresponding costs for each session of traffic on each node based on the estimation of the average cost on each link in the near future; 2) schedule the data streams on links in the next timeslot with the minimal reduced cost; 3) update the estimation of the cost on each link according to the performance of previous scheduled timeslots.

A. Multi-path Routing and Scheduling

Let p_{ij} denote a source-destination pair (v_i, v_j). Note that v_i and v_j may or may not have a direct communication link. We define a stream on p_{ij} as a data stream that is currently in the transmission queue of node v_i, and final destined to node v_j. Suppose there is already an accurate estimation of the cost on each link. For a stream on p_{ij}, there is a path with minimal total cost for delivering it. This cost is denoted by c^p_{ij}, which denotes the total expected cost in terms of number of timeslots used for delivering this stream on the most economic path.

In a timeslot, suppose there is a stream on p_{ik} scheduled to transmit over the link l_{ij}, $i \neq k$. After this stream is transmitted, this stream leaves from p_{ik} and goes to p_{jk} (i.e., d_{ik} is decremented by 1, and d_{jk} is incremented by 1). If $c^p_{jk} < c^p_{ik}$, we say, the route through l_{ij} is an *acceptable route* for the stream on p_{ik}. There is a value associated with the transmission on this route, $v_{ijk} = c^p_{ik} - c^p_{jk}$, which represent the expected delivery cost that is reduced if this stream goes from p_{ik} to p_{jk}. If $c_{ij} = v_{ijk}$, the route through l_{ij} is called the *master route* of this stream, because the cost on l_{ij} determines the cost of c^p_{ik}.

After transmitting a stream on p_{ik} through an acceptable route via link l_{ij}, this stream becomes "closer" to its destination in the view of the expected delivery cost. v_{ijk} represents the worth of this transmission. Since the cost of transmitting the links at a timeslot is fixed - always 1, we will try to maximize the worth of the transmissions in a single timeslot. Note that for a stream, there could be multiple acceptable routes with positive worths. As the transmission situation of different timeslots could be significantly different, the streams on the same source-destination pair may be scheduled to different routes at different timeslots. We define the *reduced cost* for the slot scheduling z in O-MRS method as follows.

$$c^{\Delta}_z = 1 - \sum_{l_{ij}, v_k} u^z_{ijk} v_{ijk}, \tag{10}$$

where u^z_{ijk} denote the number of streams on p_{ik} and scheduled on the route through l_{ij}.

The routing and scheduling procedure of O-MRS method becomes a slot scheduling problem. The aim of the problem is to find a feasible slot scheduling z that has minimal reduced cost c^{Δ}_z and schedule it. The TX, RX, and Half-duplex constraints are presented in (11), (12) and (13).

Minimize:

$$c^{\Delta}_z = 1 - \sum_{l_{ij}, v_k} u^z_{ijk} v_{ijk}.$$

Subject to:

$$\sum_{l_{ij}, v_k} u^z_{ijk} \leq a_i, \quad \forall v_i \in V, \tag{11}$$

$$\sum_{v_k, l_{xj}: e_{xi} \in E_I} u^z_{xjk} \leq a_i, \quad \forall v_i \in V^z_{RX}, \tag{12}$$

$$\sum_{l_{ij}, v_k} u^z_{ijk} \equiv 0, \quad \forall v_i \in V^z_{RX}, \tag{13}$$

$$0 \leq u^z_{ijk} \leq \lambda^p_{ik}, \quad \forall l_{ij} \in L, v_k \in V,$$

$$u^z_{ijk} \in \mathbb{Z}, \quad \forall l_{ij} \in L.$$

The set of nodes that receives some data V^z_{RX} in the above optimization formulation can be calculated as follows.

$$V^z_{RX} = \{v_j | v_j \in V, \sum_{l_{ij} \in L, v_k \in V} u^z_{ijk} > 0\}. \tag{14}$$

This slot scheduling problem can be transformed into a general stream scheduling problem (i.e., the scheduling problem in C-MRS) easily, and solved optimally by using the mathematical tools, such as CPLEX. There are also several heuristic solutions [5]–[8] that address this stream scheduling problem.

B. Cost Estimation

The above routing and scheduling method is based on the assumption that an accurate estimation of the cost on each link is known. In practice, these costs can be initialized by some simple methods and updated iteratively. The initial value of the estimated cost on a link l_{ij} could be calculated as follows.

$$c_{ij} = \frac{1}{\min\{a_i, a_j\}}, \tag{15}$$

where it is the cost on the case that link l_{ij} is the only scheduled link in a timeslot.

During the procedure of online routing and scheduling, we keep monitoring the queuing time of all streams in the system. If the streams queued at v_i have dramatically longer average queuing time than the streams queued at other nodes, there are two possible cases. 1) Enqueue issue: too many data streams are routed to node v_i, while v_i do not have sufficient bandwidth to deliver these data streams timely. Suppose there are many queued streams final destined to v_k. The estimated cost c^p_{ik} must be too low. 2) Dequeue issue: there has been a long time that no stream is dequeued. Suppose the stream at the head of the queue is final destined to v_k. The value v_{ijk} of all available routes through links $l_{ij} \in L$ must be too low, such that the scheduling of this stream on any route can hardly help to minimize the total reduced cost.

To address the above issues, we will adjust the estimated cost on the corresponding link. Suppose the master route of a stream on p_{ik} is through link l_{ij}. We will adjust the estimated cost of l_{ij} as follows.

$$\text{NEW}[c_{ij}] = (1+\delta)c_{ij}, \tag{16}$$

where δ is an update parameter with a value higher than 0. After updating the estimated cost, the cost on the master route is increased, which result in a increased c^p_{ik}, and sequentially the increased v_{ijk} of all available links l_{ij}. Thus, both the enqueue and dequeue issues are addressed.

Although the above updating scheme only increase the costs, we will normalize the costs of all links periodically. That is, the costs on the links will be updated up and down in the iterations, and the total expected cost of the streams transmitted in a time period is always around the number of timeslots used.

V. Performance Evaluation

To evaluate the performance of different routing and scheduling methods, a simulator for the Online Multi-path Routing and stream Scheduling (O-MRS) method for dynamic traffic demands in MIMO networks is implemented using C++ language. A solver that solves the MRS problem with static traffic by using the Column-generation based Multi-path Routing and stream Scheduling (C-MRS) method is developed using the IBM ILOG CPLEX library. We drop the integer requirement (8) in the master problem to accelerate the process of C-MRS solver. Thus, the solution obtained from the C-MRS solver can be only regarded as the upper bound of the optimization problem. A simulator for the Fixed Single-path Routing and stream Scheduling (F-SRS) method is also implemented. This method use a fixed routing, and schedules the data streams using a heuristic solution proposed in [8].

We generate multiple cases of system topologies. In each case, the wireless nodes are randomly placed in an area of 1300×1300 meters. The communication and interference ranges of a node is 300 and 500 meters respectively. One gateway node with 4 antennas is placed at the center of the area. For client node v_i, the number of its antennas a_i is randomly selected between 1 and 4.

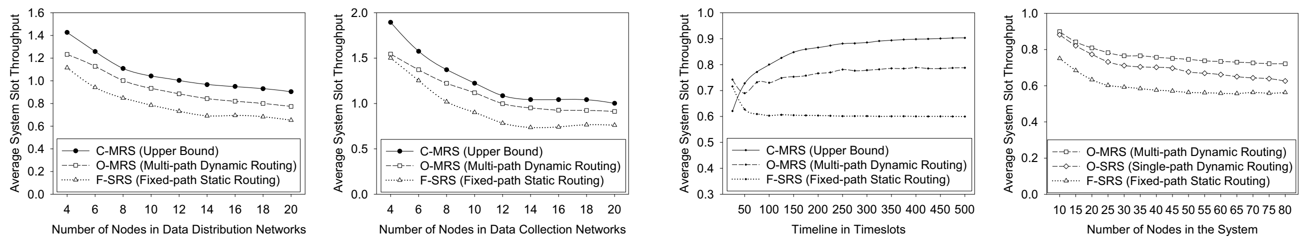
The C-MRS method will find a TDMA scheduling frame with minimal number of timeslots, such that the traffic demand of every source-destination pair is satisfied. The system throughput of the solution obtained from the C-MRS solver is defined as the average number of streams of demand that is satisfied (i.e. delivered) in one timeslot in the TDMA scheduling frame.

The online simulators for O-MRS and F-SRS methods schedule the traffic in the real time. For each source-destination pair p_{ij}, we initially generate d_{ij} streams of traffic that is destined to v_j on node v_i, and a new stream on this pair is generated periodically. The frequency of generating new traffics is adjusted automatically to make the total number of streams queued in the system stable. This setting is an abstraction of the automatic congestion control behavior in TCP/IP protocols. The system throughput is defined as the average number of data streams that are delivered to the final destinations in a timeslot. As the data streams might be transmitted over several hops before it is finally delivered, the defined throughput is naturally lower than the RAW system throughput.

A. Performance in Small Scale Networks

The C-MRS and O-MRS methods, as well as the F-SRS method that uses the fixed routing, are evaluated in the small scale data distribution networks. $4-20$ nodes are placed in the system (i.e., $3-19$ client nodes and one gateway). The traffic demand from the gateway to any client node is set to 1 stream. As shown in Fig.1(a), the O-MRS method achieves about 90% of the upper bound throughput calculated using the C-MRS method, and is 20% better than the fixed routing method F-SRS. It can be seen that the system with higher number of nodes tends to have lower performance. The reason is that when generating the source-destination pairs, a system with fewer nodes tends to have fewer hops for the pairs. Its system throughput thus becomes better than the system with more nodes.

We also evaluated these three methods in small scale data collection networks. The system throughputs of the three methods are shown in Fig.1(b). It is noticeable that the average system throughput in the data collection networks is higher than the data distribution networks. There are two reasons: 1) all antennas on the gateway node can be fully used in data collection networks by using IC strategy; while they cannot be fully utilized by SM on data distribution networks if the receiving client has lower number of antennas installed; 2) the clients located at the edge of the system usually have lower interferences to the other nodes; while in data distribution networks, these nodes have less opportunities to relay data.



(a) Data Distribution (b) Data Collection (c) Data Collection (Timeline) (d) Data Collection (Large Scale)

Fig. 1. System throughput in multi-hop MIMO networks.

Fig.1(c) shows the average throughput of the three different methods at different timeslots in a timeline in the data collection network with 20 nodes. The upper bound result is noticeable higher than the online methods. However, since this solution do not take the transmission ordering into consideration, in the first several scheduling frames, the actual throughput is affected.

The performance of F-SRS and O-MRS fluctuates at the first several timeslots. This is because some nodes are adjacent to the gateway node with 4 antennas, and the traffic on it are scheduled in priority and delivered with in a short period, which results in a high system throughput. However, since new traffic demands do not arrive at these nodes so quickly, the scheduling method can no longer take advantage in the following timeslots.

B. Large Scale Networks

The solver of C-MRS method is unable to solve the problem in large scale networks. We generate an extra simulator that using the similar idea to optimize the total reduced cost on the scheduling of each timeslot in O-MRS method, but only route the traffics on the master routes. We call it the Online Single-path Routing and stream Scheduling (O-SRS) method.

We generate a multi-hop wireless network with $10 - 80$ wireless nodes, and randomly generate 5 source-destination pairs with the traffic demand of 2. This is the case of a network with limited traffic. As shown in Fig.Fig.1(d), compared with O-SRS, the performance of a O-MRS becomes better when the network scales larger. The reason is that the limited traffic in the large scale network is usually unbalanced, and the multi-path routing scheme helps to balance the traffic and thus get more opportunities of simultaneous transmissions. For the cases with more balanced traffic, there would be no significant benefit from multi-path routing because the traffic are already quite balanced. However, in our simulation, the dynamic routing methods (O-MRS and O-SRS) always outperform the fixed routing method F-SRS significantly.

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VII. Conclusion

In this paper, we address the throughput optimization problem of joint routing and stream scheduling in MIMO networks, where the traffic is allowed to be routed through multiple paths to take more advantage from concurrent transmissions. The optimization problem is formulated as an ILP problem that takes the MIMO constraints for SM and IC into consideration, and solved optimally by using the iterative column generation approach. Inspired from the column generation approach, we propose a heuristic online method that routes the traffic and schedules the streams through the MIMO links dynamically using an iterative updating procedure. Extensive simulations have been done by a simulator developed in C++. The simulation results show the efficiency of the proposed algorithm, especially when the traffic in the network is not balanced.

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