Joint Routing and Scheduling for NOMA-Enabled Wireless Networks

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***Abstract*—This work studies scheduling and multi-path routing for maximum throughput in wireless networks. Unlike the literature, our model assumes that nodes are capable of multiplexing in the power domain (Non-orthogonal Multiple Access - NOMA) at the transmitters and successive interference cancellation (SIC) at the receivers. We assume that transmit powers of nodes are fixed. We form three-node composite links that perform either NOMA (one transmitter and two receivers) or SIC (two transmitters and one receiver), in addition to single links (one transmitter and receiver). These links are scheduled in time in a non-conflicting manner in order to maximize the weighted sum of end to end flow rates. This problem is formulated as a mixed-integer linear program (MILP). We separately tested the performance improvement by adding NOMA and SIC capabilities. Numerical results reveal that NOMA and SIC provide an almost equal and significant improvement ((25-30%)) in the weighted sum-rate. Lastly considered a specific case, where the sources of all flows are the same. In that case NOMA resulted in a 65-70% improvement, while SIC did not have any effect.**

***Index Terms*—Routing, Scheduling, NOMA, SIC, Integer Programming**

I. INTRODUCTION

Wireless data usage is growing faster than ever before [1] since as the number of users in a network has increased, the resources and services that wireless networks need to provide have become more demanding as well. Achieving higher system throughput and transmissions with lower delay have become neccessities. In order to attend the increasing demand for wireless services and considering the frequency spectrum is scarce and expensive resource, modern wireless networks are required to operate as efficiently as possible [1]. For this reason, the application of mathematical optimization methods in the study and design of key functionalities of wireless systems has acquired great relevance [1].

A wireless ad hoc network is a multihop network where communication between nodes is established over a common wireless channel without a fixed infrastructure. One of the main characteristics of wireless ad hoc networks is their node-centric broadcast nature of communication where nodes communicate with each other over multiple hops. Communication links exist between pairs of nodes that are within the transmission range of each other [2]. For pairs of nodes that are out of range, a connection could be established using multiple hops.

One of the problems of wireless ad hoc networks is node scheduling. In link scheduling algorithms, a node can transmit to only one node or receive from only one node at a given time and considers all other transmissions as interference [3]. So, when transmissions overlap in time, link collision occurs and signal reception is not successful [3]. The scheduling algorithms that avoid collision in time and space limit the capacity of wireless ad hoc networks [3]. Routing is another significant problem in wireless ad hoc networks since in an ad hoc network, a node can communicate only with the nodes in its range. For communication with nodes out of range, routing is necessary to determine which route results in the highest throughput.

Successive Interference Cancellation (SIC) is a technique that can decode multiple signals at the receiver. SIC uses the differences in the received user signals channel gains to order the received signals and decodes them successively according to this order, if the signals received are above a specific signal-to-interference plus noise ratio (SINR) threshold. When a node receives two signals, the signal with the lower channel gain is decoded first. After one signal is decoded, it is subtracted from the combined signal before the other signal is decoded. When one users signal is being decoded, the user signal with lower channel gain is assumed as interference and the user signal with higher channel gain is treated as noise. In a multihop network, the network performance is limited by interference and capability of nodes [4]. SIC, which directly encounters some of the effects of interference and allows multiple decodings [4]. has been shown to increase the throughput performance of the wireless ad hoc network [5].

In [5], both direct and indirect interference are considered in the scheduling of an ad hoc network with SIC. In SIC, the extraction of the desired signal depends on the successful detection of the stronger interfering signals and these interfering signals create indirect interference. Indirect interference has an effect on the detection of the desired signal. According to the paper, using SIC to cancel indirect interference resulted in the average throughput to increase 40%. In [6], a throughput maximization problem with a cross-layer solution for multi-hop wireless networks is developed using an iterative framework where after the time slot assignment is determined, the rest of the problem is formulated as a linear program. The algorithm was shown to achieve about 300% throughput performance improvement with SIC than the optimal solution using interference avoidance. [7] investigates the tradeoff between the SIC decoding capabilites and the achievable link data rates in a multirate multihop wireless network. In the study, joint interference management approach is used where interference avoidance and interference exploiting are applied together. A joint routing and scheduling problem with rate control is formulated as a mixed integer linear program to maximize the minimum flow throughput. Results of the study show that the improvement provided by SIC depends strongly on the strength of the received signals and large networks with SIC can have throughput gains over 20% when only SIC is used. It was also shown that SIC with rate control achieves better performance than only with SIC or rate control. In [8], a cross-layered joint optimization framework using SIC is proposed for a multihop wireless network. Since SIC can decode a limited number of signals due to the SINR constraints for the received signal powers, SIC needs to be considered with scheduling and routing for optimal throughput performance. A set of constraints for the physical, link and network layers are determined. The resulting framework is applied to a network throughput optimization problem. It is shown that in a 20 node network, 47% increase in throughput is achieved when SIC is used. In [9], joint effect of cooperative transmission and SIC on maximizing the number of links that can be active at the same time is investigated. In cooperative transmission, multiple transmitters transmit to a common receiver where these transmitted signals are combined. According to the paper, simulation results show that cooperative transmission and SIC have a complementary effect on improving the number of links that can be activated at the same time.

Non-orthogonal Multiple Access (NOMA) is a multiple access method where multiple users can occupy the same frequency channel. Compared to Orthogonal Multiple Access (OMA), where only one user occupies a frequency channel at a given time to avoid user interference, NOMA can accommodate several users to share time and frequency resources in the same spatial layer via power domain or code domain multiplexing [10]. By transmitting to multiple nodes at the same time, it provides massive connectivity, improved throughput and low transmission latency compared to OMA, where the total number of users are limited by the availability of orthogonal resources. In power domain NOMA, multiple users are multiplexed in the power domain at the transmitters using superposition coding (SC) . A fraction of the total transmit power is allocated to transmitting users based on the differences in users channel gains. At the receiveing users, multi-user signal separation is done using SIC. It has been shown that NOMA increases the throughput of a system by 30% compared to the throughput achieved by OMA [11]. Due to the properties that NOMA provides, using NOMA in ad hoc networks could increase the number of transmissions made from a single node in the same time slot, increasing the number of connected nodes and providing more link options for routing a transmission. Signals will be accumulated in a node and instead of using all transmit power for transmitting one signal at one time, same amount of power can be used to transmit multiple signals at the same time.

In the link scheduling algorithms designed in the mentioned papers above, one node can transmit to only one different node in a time slot. Using NOMA can enable the same nodes to transmit to different nodes in the same time slot. This way, transmissions will be completed in less time due to more links being scheduled in a time slot and with more routing options, routes resulting in higher throughput can be found for each transmission. In this work our contribution is consideration of routing and scheduling in a NOMA-enabled multihop wireless network. Routing and scheduling of nodes are optimized for system throughput maximization and the optimization problem is formulated as a mixed integer problem (MIP). A comparison to the performances of NOMA, SIC and single link scenarios are made to understand the effect of NOMA on the system throughput.

II. SYSTEM MODEL

N nodes are distributed uniformly random. There a number of communication sessions, which are routed in a multihop, multipath manner. Time is slotted and at each slot a number of links are scheduled to transmit simultaneously. We assume that the node locations are fixed and channel gains are constant throughout the sessions. Each node has a fixed transmit power P. Let $g_{ij} = d_{ij}^{-\gamma}$ be the channel gain between nodes i and j. Let d_{ij} be the distance between nodes i and j. Let σ^2 be the power of additive white gaussian noise.

A transmission is successful if the resulting SINR is greater than β. As a result a rate $R = \log_2 \beta$ bps/Hz is obtained. In classical wireless scheduling each node is allowed to either transmit to or receive from a single node.

A. SIC-Based Transmission

Recently the authors in [8] included the Successive Interference Cancellation (SIC), which enables reception from multiple concurrent transmission and improve throughput. In SIC a receiver can first decode, subtract and eliminate the strong interference and then decode the weaker signals. Even if the initial SINR is less than β, this threshold can be exceeded after applying SIC.

Let us assume that node i and j are transmitting concurrently to receiver k. Without loss of generality assume that channels are ordered as $g_{ik} \geq g_{jk}$. Receiver k first decodes message from user i and treats user j's signal as noise. Its SINR becomes $\frac{Pg_{ik}}{Pg_{jk}+\sigma^2}$. If $\frac{Pg_{ik}}{Pg_{jk}+\sigma^2} \geq \beta$ then message from user i is successfully decoded and subtracted from the total signal. Then receiver k decodes transmitter j's signal with SINR $\frac{Pg_{jk}}{\sigma^2}$. If this SNR is greater than β than user k successfully decodes its message, which completes the transmission.

B. NOMA-Based Transmission

In this work we assume nodes are also NOMA-enabled. In NOMA (Non-Orthogonal Multiple Access) a node can simultaneously transmit to more than one nodes. A transmitter shares its transmit power among more than one transmissions. Links with higher gain get lower power. The individual signals to be transmitted are added transmitted together. Each node in the receiver list first decodes and eliminates the signals in the order of decreasing transmit power and finally decodes its own signal.

Let us assume that node i is transmitting concurrently to receivers j, k. Let P_{ij} and P_{ik} be the transmit power allocated for receivers j and k. Without loss of generality assume that channels are ordered as $g_{ij} \geq g_{ik}$. We assume interference cancellation in the order of channel gains and transmit power is allocated as $P_{ij} \leq P_{ik}$. Receiver k first decodes message for user j and treats its signal as noise. Its SINR becomes $\frac{P_{ij}g_{ik}}{g_{ik}P_{ik}+\sigma^2}$. If $\frac{P_{ij}g_{ik}}{g_{ik}P_{ik}+\sigma^2} \geq \beta$ then message for user j is successfully decoded and subtracted from the total signal. Then user k decodes its signal with SINR $\frac{P_{ik}g_{ik}}{\sigma^2}$. If this SNR is greater than β than user k successfully decodes its message. Meanwhile user j treats signal for user k as noise and decodes its signal with SINR $\frac{P_{ij}g_{ij}}{g_{ij}P_{ik}+\sigma^2}$. If this SINR is greater than β then user j successfully decodes its signal, which completes the transmission.

In this work for simplicity we assume that in NOMA (SIC)-based transmission there are a two receivers (transmitters) and a single transmitter (receiver).

C. *Composite Links*

In [8] assumed SIC-enabled receivers and assumed that the transmitters have fixed power. This way, the SINR constraints can be written only with respect to binary decision variables for scheduling. However, as explained above, transmit power cannot be taken fixed for NOMA. In NOMA total power of a transmitter has to be shared between intended receiver nodes. This makes the problem more complicated. In this preliminary work, for simplicity, we take a different approach. We first determine the set of composite NOMA links and SIC links. Each composite links consists of three nodes. In the above scenario, a NOMA link (i, j, k) is considered feasible (both receivers j, k are able to decode their intended transmissions) if there exists P_{ij} and P_{ik} such that the following constraints are satisfied,

$$P_{ik} \geq \frac{\beta\sigma^2}{g_{ik}} \tag{1}$$

$$P_{ij} \geq \beta P_{ik} + \frac{\beta\sigma^2}{g_{ik}} \tag{2}$$

$$P_{ij} + P_{ik} \leq P \tag{3}$$

For a feasible NOMA link, first the transmit powers are set as $P_{ik} = \frac{\beta\sigma^2}{g_{ik}}$ and $P_{ij} = \beta P_{ik} + \frac{\beta\sigma^2}{g_{ik}}$ and then P_{ij} and P_{ik} are increased in the same proportions so that the full power $P_{ij} + P_{ik} = P$ is used.

A composite SIC link (i, j, k) is considered feasible (receiver k decodes both transmissions successfully) if channel gains satisfy the following inequalities,

$$\frac{Pg_{ik}}{\sigma^2} \geq \beta \tag{4}$$

$$\frac{Pg_{ik}}{Pg_{jk}+\sigma^2} \geq \beta \tag{5}$$

Let $\mathcal{L}$ be the set of composite links (including the single links).

D. *Conflicts*

Any two links (whether they are composite (NOMA/SIC) or single) are non-conflicting if they satisfy both conditions below

- They should not have any common nodes,
- They should be sufficiently apart from each other.

The first condition is obvious. Second condition is added in order to avoid significant interference. Here, we introduce a guard distance $\Gamma > 1$. Suppose there are two composite NOMA links (i, j, k) and (x, y, z). The following conditions have to be satisfied,

1) $d_{iy} > \Gamma \times d_{xy}$ and $d_{iz} > \Gamma \times d_{xz}$
2) $d_{xj} > \Gamma \times d_{ij}$ and $d_{xk} > \Gamma \times d_{ik}$,

that is, in order to schedule two composite links together, the distance from transmitter of any composite link to the receivers of any second link should be greater than the link distances of the second composite link, by some margin. If guard distance is increased (decreased), less (more) composite links can be packed in a time slot. Guard distance concept is a simplistic concept in order to take into account the interference between links. Exact formulation of interference is a subject of future work. Normally, if the above-mentioned distance is too close, interference cancellation can be done so that the two composite links can coexist. Values of Γ used in this paper are chosen by trial and error. A more robust interference management technique is a subject of future work.

III. PROBLEM FORMULATION

Let $a_{l,l'}, l, l' \in \mathcal{L_C}$ be the non-conflict matrix, where $a_{l,l'} = 1$ if composite links l and l' are not conflicting. Let $b_{i,j,l}$ be the matrix that defines the relation of link (i, j) with the composite link l. If the composite link l contains the link (i, j), then -$b_{i,j,l} = 1$. For example the composite NOMA link (i, j, k), or the single link (i, j) contain the link (i, j). The decision variables are as follows. Binary variable $\mathbf{y} = y_l[t], l \in \mathcal{L}, t = 1, \ldots, T$ takes value 1 if the composite link l is scheduled in time slot t. Binary variable $x_{i,j}[t]$ takes value one if link (i, j) (that is, any composite link containing link (i, j)) is scheduled in time slot t. Continuous non-negative variable r_f is the supported rate for flow $f \in \mathcal{F}$, where $\mathcal{F}$ is the set of flows in the network.

The problem of jointly optimal routing and link scheduling is defined as follows,

$$\max_{\mathbf{x},\mathbf{y}} \left\{ \sum_{f\in\mathcal{F}} w_f r_f \right\} \tag{6}$$

subject to

$$y_l[t] + y_{l'}[t] \leq a_{l,l'} + 1, \forall l, l' \in \mathcal{L}_{\mathcal{C}}, \forall t = 1, \ldots, T \tag{7}$$

$$\sum_{j \neq i} r_{i,j,f} = r_f, \forall f \in \mathcal{F}, i = s_f \tag{8}$$

$$\sum_{i \neq j} r_{i,j,f} = r_f \forall f \in \mathcal{F}, j = d_f \tag{9}$$

$$\sum_{k \in \mathcal{N}/i} r_{k,i,f} = \sum_{j \in \mathcal{N}/i} r_{i,j,f} \forall f \in \mathcal{F}, \forall i \in \mathcal{N}/\{s_f, d_f\} \tag{10}$$

$$x_{i,j}[t] = \sum_{l \in \mathcal{L}_{\mathcal{C}}} y_l[t] b_{i,j,l} \tag{11}$$

$$\sum_{f \in \mathcal{F}} r_{i,j,f} \leq \frac{R}{T} \sum_{t=1}^{T} x_{i,j}[t], \forall i \neq j \in \mathcal{N} \tag{12}$$

$$r_{i,j,f} \geq 0, \forall i, j \in \mathcal{N}, f \in \mathcal{F} \tag{13}$$

$$x_{i,j}[t], y_l[t] \in \{0, 1\}, \forall i, j \in \mathcal{N}, t = 1, \ldots, T, l \in \mathcal{L}_{\mathcal{C}} \tag{14}$$

The objective in (6) is maximizing the weighted sum rate of session flows. Parameter $w_f, f \in \mathcal{F}$ is the weight (importance) of flow f. Constraint (7) enforces that two conflicting composite links cannot be scheduled together in the same time slot. Constraint (8),(9) and (10) are the flow balance equations for the source, destination and intermediate nodes for each flow. Equality (11) means that link (i, j) is considered as scheduled if any composite link containing that link is scheduled. Constraint (12) enforces that total rate of flows passing through a link can not be greater than the number of scheduled instances of that link multiplied by $\frac{R}{T}$. Finally, constraints (13) and (14) enforce the nonnegativity of flows and binary nature of the decision variables $x_{i,j}[t]$, $y_l[t]$.

The objective and all constraints are linear in the decision variables. Therefore the problem is a mixed integer-linear programming (MILP) problem. It can be solved with standard solvers such as CPLEX.

IV. SIMULATION RESULTS

We perform simulations for a $N = 20$-node topology. Simulation parameters are listed in Table I.

TABLE I: Simulation Paramaters

Parameter	Definition	Value
N	Number of nodes	20
F	Number of Flows	3
w	Flow weights	$[5, 5, 5]$
T	Number of time slots	10
D_{max}	Network area radius	100 meters
γ	Pathloss exponent	3
σ^2	AWGN Noise Power	10^{-6} W
P	Node transmit power	1 W
β	SNR threshold	1
R	Scheduled Link Rate	1 bps/Hz
Γ	Guard Parameters	1.5 and 2

In the first set of simulations there are three flows. Sources are nodes $1, 2, 3$ and corresponding destinations are nodes $18, 19, 20$, respectively. We put sources and corresponding destinations on the edge of the circular area at maximum distance in order to observe multihop routing. Table II shows results for 10 different random topologies and interference guard parameter $\Gamma = 1.5$. It is seen that using NOMA or SIC does not differ much in terms of performance, but when compared with single links, they provide significant $(25-30\%)$ improvement in terms of weighted sum rate.

TABLE II: Performance of three different schemes for 10 different topologies. Guard parameter is $\Gamma = 1.5$

Trial #	**Set of Available Links**		
	Single Links	***Single + NOMA***	***Single + SIC***
1	3.5	4.5	4.5
2	4.0	4.5	4.5
3	3.5	5.0	5.0
4	4.0	4.5	4.5
5	4.0	4.5	4.5
6	3.5	4.5	4.0
7	4.0	5.0	5.0
8	3.5	5.0	5.0
9	3.5	4.5	4.0
10	3.0	4.0	4.0

In Table III we increased the interference guard parameter from $\Gamma = 1.5$ to 2. This means that it becomes harder to schedule links together. As expected the weighted sum rate decreases. Here also NOMA and SIC-enabled cases perform similarly. They both provide $25 - 30\%$ improvement with respect to the case, where only single links are used.

TABLE III: Performance of three different schemes for 10 different topologies. Guard parameter is $\Gamma = 2$.

Trial #	**Set of Available Links**		
	Single Links	***Single + NOMA***	***Single + SIC***
1	2.5	3.0	3.0
2	2.5	3.5	3.5
3	2.5	3.5	3.5
4	2.5	3.5	3.5
5	2.5	3.5	3.0
6	2.5	3.5	3.5
7	2.5	3.5	3.5
8	3.0	3.5	3.0
9	2.5	3.0	3.0
10	2.5	3.0	3.5

A. Single Source at the Center

In this part we show a case, where NOMA provides significant improvement. There are still 3 flows, however, the source of all flows is node 1, which is at the center. Destinations of flows (nodes $18, 19, 20$) are located at the edge of the circular area, 120 degrees apart. This reflects a case , where the base station distributes information to nodes. A sample topology is shown in Figure 1. As the information is spread form the center to the edges, there are many NOMA opportunities. As seen in Table IV NOMA-enabled case significantly increases the weighted sum rate ($65 - 70\%$). Using SIC links results in no improvement.

For the topology in Figure xxxx, Table V shows the scheduled single and NOMA links scheduled at each time slot. Results show that many NOMA opportunities are exploited and

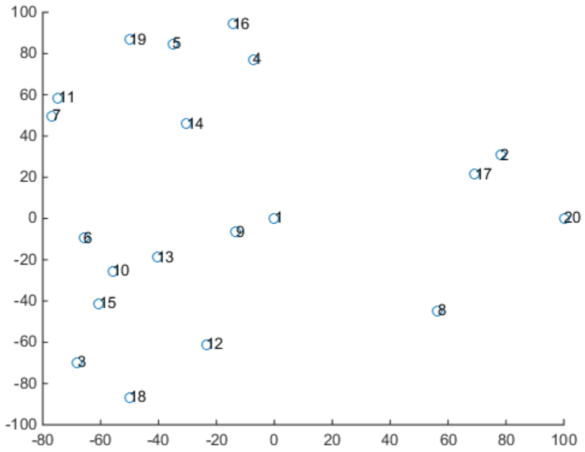

Fig. 1: A topology, where the source of all flows is at the center, and the destinations are at the edge.

TABLE IV: Single source at the center. Performance of three different schemes for 10 different topologies. Interference guard parameter is $\Gamma = 1.5$.

Trial #	**Set of Available Links**		
	Single Links	***Single + NOMA***	***Single + SIC***
1	5.0	8.5	5.0
2	5.0	8.5	5.0
3	5.0	8.5	5.0
4	5.0	7.5	5.0
5	5.0	8.5	5.0
6	5.0	8.0	5.0
7	5.0	8.0	5.0
8	5.0	8.5	5.0
9	5.0	8.5	5.0
10	5.0	9.0	5.0

nodes $2, 4, 5, 8, 9, 10, 11, 12, 14, 15, 17$ are used as intermediate (relay) nodes. We do not give the results for single-only link case, but in that case the nodes $2, 4, 5, 7, 8, 10, 12, 14, 15$ are used as relays (nodes 7 and 9 are not used).

Time Slot	Scheduled Links
1	(11,19), (15,18), (1,9,2)
2	(14,19), (9,10,18), (17,2,20)
3	(1,12,8), (4,5,19)
4	(1,17), (5,19), (10,18)
5	(8,20), (12,18), (1,14,4)
6	(2,20), (1,12,15), (4,16,19)
7	(3,18), (14,19), (1,9,8)
8	(8,20), (12,18), (1,14,4)
9	(8,20), (12,18), (1,14,4)
10	(14,11), (1,12,8)

TABLE V: Scheduled composite links in a 3-flow network where the source of all flows is node 1. 3-node composite links are all NOMA links

V. CONCLUSIONS

In this work we considered scheduling of links in a wireless network, jointly with multihop and multipath routing. In order to schedule more concurrent transmissions, we considered the use of Non-Orthogonal-Multiple-Access (NOMA). We formed NOMA-based 3-node composite links and solved the joint link scheduling and routing problem as a mixed integer linear program. For an arbitrary network NOMA provides $25-30\%$ improvement in weighted sum rate. For a specific network with source at the center and destinations at the edge, average performance gain reaches to $65-70\%$. For this specific case NOMA is also significantly better than Successive Interference Cancellation based transmissions recently proposed in the literature.

In this work we made simplistic assumption in treating interference. In order to find the exact optimal solution, transit power should also be an optimization parameter. In the near future we will try to effectively formulate such a joint scheduling, routing and power control algorithm. We will also investigate a near-optimal algorithm of polynomial complexity. Distributed implementation also deserves investigation.

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