Joint Optimization of Path Selection and Link Scheduling for Millimeter Wave Transport Networks

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***Abstract*—The future wireless transport networks are expected to carry traffic flows with different throughput and delay requirements due to the introduction of C-RAN and different functional splits that can be used. A promising wireless technology to support the high throughput requirements of C-RAN splits is Millimeter Wave (mmWave) band technologies being standardized by IEEE 802.11ad. Our target here is to derive the mathematical formulation of the path selection and link scheduling problem for mmWave transport networks by defining the constraints brought by different functional splits and the IEEE 802.11ad standard. We present two objective functions that can be used for this problem: load balancing and minimization of the use of air time. We implemented the derived formulations in an MILP solver and evaluated realistic scenarios of wireless fronthaul/backhaul networks assessing the splits defined by NGFI for LTE.**

***Index Terms*—C-RAN, Transport network, Millimeter Wave transport, LTE Fronthaul**

I. Introduction

In the future mobile networks, a significant increase in traffic load to be carried by transport network is expected, which comes with strict requirements defined by applications and splits defined by e.g. NGFI [1] and the need for differentiated services to be provided by a flexible transport network.

The envisioned transport network that will need to carry this diverse traffic thus needs to be able to provide flexibility and re-configurability depending on the requirements of the network. Optimized routing and scheduling of resources, and network re-configurability are some of the topics that acquire a greater deal of focus in future mobile transport networks in an SDN environment where a controller has a complete knowledge of the network and could enforce certain rules that network elements should follow to optimize overall functioning to meet traffic requirements [3]. One of the management functions that can be implemented in a SDN deployment is the forwarding rules (i.e., path selection) and scheduling of resources (e.g., time slot assignments) per traffic class. Millimeter Wave (mmWave) communication defines highly directive antennas, which translate in low interference between adjacent transmitting links, and a great amount of available bandwidth, which enables the high transmission rates required by certain functional splits.

In this work we study the joint path selection and link scheduling problem as a mathematical optimization problem. We assume the co-existence of backhaul and fronthaul traffic corresponding to different NGFI splits, each with a different set of data rate and delay requirements. In addition, we assess the IEEE 802.11ad standard for mmWave communication to define its related constraints. We present two objective functions that can be used for this problem: load balancing and minimization of the total time slots used for mmWave links. We propose a joint optimization for these two contradicting objectives, and evaluate it in an MILP solver for a scenario, where flows from small cells transported wirelessly to their fibre attachment points at macro cells. We quantitatively compare the results of this joint optimization solution to those of a two-stage optimization, where the two objectives are evaluated sequentially, and to those of a shortest-path-based heuristic for two types of splits defined by NGFI. In contrast to the works in the literature focusing mainly on the objective of maximizing the throughput [3]-[6], in this work we provide different optimization approaches to the path selection and link scheduling of resources in a mmWave transport network.

II. Path Selection and Link scheduling optimization

A. Overview

The basic network architecture that will be employed is the one exposed in IEEE 802.11ad standard in which the basic network element is known as the Personal Basic Service Set (PBSS) which consists of a controller and a set of nodes that can communicate with each other, as long as they are in the same PBSS. Following the standard we have that one particular station acts as the PBSS Control Point (PCP) and is the one in charge of scheduling the resources and sending control frames to all nodes. Usually one node acts as the PCP but in our case we assume that the network controller acts as the PCP.

In order to support communication between the transport nodes in mmWave bands using this highly directive antennas, the frame structure and allocation procedures defined have to be compliant with the IEEE 802.11ad standard, which defines MAC and PHY specifications for Very High Throughput communication in mmWave bands.

This frame structure is composed of two main subframes, the Beacon Header Interval (BHI) and Data Transmission

Interval. The Beacon header is used to exchange management information and network announcements to all nodes, as well as beamforming training frames to take advantage of the high throughput available when highly directional antennas are employed. The BHI is followed by a Data Transmission Interval (DTI) in which actual nodes exchange information. In this interval there are either Contention-Based access periods (CBAP) in which stations contend for the use of the air interface and service periods (SP) in which two nodes exchange either data or extended beamforming frames. The DTI is composed by any combination of SP and CBAP allocations.

The SP or CBAP scheduling procedures on each Beacon Interval are defined by the IEEE 802.11ad standard, each one different delay, latency and overhead restrictions. It is worth nothing that the scheduling of resources is done by the PCP or the network controller, which has the complete network state information and thus is capable of enforcing rules to nodes on how to communicate with their peers. Only the network coordinator is the one in charge of sending beacon frames so the nodes can know when they are allowed to transmit or receive traffic.

The 802.11ad standard defines three basic scheduling procedures to allow the communication of nodes in an orderly manner, which are: dynamic scheduling, pseudo-static allocation and announcement of management frames.

B. System Model and Assumptions

The system model assumptions that we took into account in order to define our network architecture and topology are the following:

- Following the 802.11ad standard, each transport node is composed of 4 STA, whereas each STA is composed of a 90 steerable antenna element, limiting number of possible links that can be scheduled on each transport node. This 4-STA based transport node model is based on standardized commercial products in the market.
- TDMA operation capabilities are assumed at the PCP, so this entity will issue Service Periods, each limited by a duration no more than one time slot in order for peer stations to send its frames. With this assumption, resource allocation is translated in time-slot allocation.
- Pseudo-static allocation for the air-interface allocation is assumed. Here each SP or CBAP allocated to each STA reoccur every Beacon Interval.
- A link based optimization is assumed. This is possible by allowing upper MAC layer to multiplex multiple MSDU's from different flows in the same air interface frame A-MPDU.

Our formulation, assumes that PCP has TDMA capabilities. That is, PCP is able to divide scheduling frame (DTI portion of BI) in time slots or transmission opportunities in which STA's can transmit frames to its peers. These time-slots are the basis for our time slot scheduling formulation. We assume that on each slot several different flows can be appended given as long as certain thresholds like maximum allowed MAC payload, maximum allowed traffic on each slot and maximum slot duration are met. This time slot allocation is done during the Service Periods of the DTI of each BI.

Given the amount of traffic demanded by each source and the traffic transmitted or sent by each transport node, allocated slots to each node are dynamic and adaptive, this means that air time is scheduled to each link if and only if it has data queued. If no data is queued on a link then no air time is going to be allocated.

C. Network Model

For the sake of simplicity for our mathematical formulation the complete network topology is characterized by a bipartite graph $G=(V,E)$ where $|V|=N$, and $|E|=M$ where V is the set of N transport nodes including source and destination nodes and the edges E are physical mmWave links between each pair of nodes. We denote $\mathscr{S}$ and $\mathscr{D}$ as the source and destination node set respectively and each flow per source-destination pair k as (s_k,d_k,w) where w denotes the flow number, s_k denotes the source node and d_k the destination node of pair k. For the sake of simplicity in network optimization, diverse traffic flows can be bundled on certain traffic classes depending on their source and their traffic specifications.

D. Problem Formulation

We define the path selection and time-slot scheduling problem as a optimization formulation in which two main objectives are defined. First we want to optimize load balancing, that is, distribute traffic flows optimally across the network by minimizing the traffic in the maximum utilized links. Given the limitations of the underlying transport technology used and the great amount of different traffic generated for example, in urban scenarios, balancing heavy and low flows could provide serious improvements on network performance while avoiding overloading of transmission links.

Second, we aim to minimize the number of timeslots needed to deliver each flow to each destination, taking into account delay and latency specifications. Each demand is characterized by its TSPEC (i.e. data rate, packet size, number of stream etc), origin and destination nodes. Due to the limitations on the values that the variables can take and the multiple constraints, a complex integer programming optimization problem is represented in which decision variables are determined for each problem. First we define the links that are going to be used on path between each source-destination pair and then a resource scheduling optimization is performed in order to assign time-slots to the different flows taking into account constraints regarding maximum capacity, SINR, timing constraints and node capabilities. For the path selection we define the following variable:

$$x_{ij}^{kw} = \begin{cases} 1, & \text{if link (i,j) transmits flow } w \text{ from pair k} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

The path selection problem finds the optimal path assignment for each demand, following a minimization of the maximum utilized link. The feasible solution is restricted by constraints of minimum flow demands, link delay and maximum capacity.

Next, timeslot scheduling optimization is in charge of allocating resources to the traffic that each node will handle. To accomplish this, a variable represented by u^t_{ij} states the following:

$$u^t_{ij} = \begin{cases} 1, \text{if link (i,j) is scheduled to transmit traffic in time t} \\ 0, \text{otherwise} \end{cases} \tag{2}$$

We aim to find the optimal allocation of available timeslots to each flow received and sent by each node. The solution for the timeslot scheduling depends on whether link (i,j) is part of the feasible solution of the path selection problem.

1) Path Selection Optimization: For the path selection problem we want to optimize the number of links and the demand that they will carry in order to achieve load balancing. To do this we define an optimization goal of minimizing the maximum link utilization in the network. The solution will find the links to be used for the paths between each source and destination pair.

The mathematical formulation is the following:

$$min\left(\max_{\forall(i,j)\in E}\left\{\frac{\sum_{k=1}^{||\mathscr{K}||}\sum_{w=1}^{W_k} f^w_k \cdot x^{kw}_{ij}}{c_{ij}}\right\}\right) \tag{3}$$

$$\sum_{k=1}^{||\mathscr{K}||}\sum_{w=1}^{W_k} f^w_k (x^{kw}_{ij} + x^{kw}_{ji}) \leq c_{ij}, \forall (i,j) \in E \tag{4}$$

$$\sum_{j:N(i)} f^w_k x^{kw}_{ij} - \sum_{j:N(i)} f^w_k x^{kw}_{ji} = \begin{cases} f^w_k, i = s_k \in \mathscr{S} \\ -f^w_k, i = d_k \in \mathscr{D}, \\ 0, otherwise \end{cases} \tag{5}$$

$$\forall i \in V, \forall k \in \mathscr{K}, \forall w \in W_k$$

$$\sum_{j\in N(i)} x^{kw}_{ij} \leq 1, \forall k \in \mathscr{K}, \forall i \in V, \forall w \in W_k \tag{6}$$

$$\sum_{(i,j)\in E} x^{kw}_{ij} \leq MH^w_k, \forall k \in \mathscr{K}, \forall w \in W_k \tag{7}$$

$$x^{kw}_{ij} \in [0,1]\ \forall (i,j) \in E,\ \forall w \in W_k, \forall k \in \mathscr{K}$$

Constraint (4) determines that for each link in the network, the summation of the flows that will be carried by the bidirectional link between two peer STA's must never be greater than the link capacity. Constraint (5) ensures that the minimum flow requirements are met and constraint (6) is defined in order to avoid having multiple paths per flow w of source destination pair k. Constraint (7) restricts the maximum number of hops that each flow will go through to reach its destination. This maximum number of hops MH^w_k are defined by each flow's TSPEC requirements.

2) Time Slot Scheduling: The main optimization goal that will be developed in this section is aimed to minimize the number of timeslots needed in order to send and receive all the traffic demand efficiently. The variable u^t_{ij}, as explained before, will be a binary variable that states if timeslot number t is used to send its scheduled traffic through link (i,j). The feasible solution that this optimization problem will give is the optimal assignment of resources available on each node, depending on outgoing and incoming traffic.

From the path selection problem we define a set of ordered links from each source-destination pair as a vector with elements that represent the number of hops. This set of ordered links is part of the solution of the path problem.

$$l^w_k = [l^w_k(1), l^w_k(2), ..., l^w_k(H^w_k)] = [(s_k, j), (j,p)...., (r, d_k)] \tag{8}$$

In (8) each h-th element of the vector is a link that is part of the path between source-destination pair k for flow w. Each hop is characterized by a pair (i,j).

The objective function for the time slot scheduling problem is then as follows:

$$min\sum_{i\in V}\sum_{t=1}^{T}\sum_{j:N(i)}\left(u^t_{ij} - \frac{u^t_{ij}u^t_{ji}}{2}\right) \tag{9}$$

s.t.

$$\sum_{k=1}^{||\mathscr{K}||}\sum_{w=1}^{||W_k||} f^w_k (x^k_{ij} + x^k_{ji}) \leq \sum_{t=1}^{T}\frac{c_{ij}}{T}(u^t_{ij} + u^t_{ji}), \forall (i,j) \in E \tag{10}$$

$$||H^w_k||((t_s + d_{tx} + t_{over})) + \sum_{h=1}^{H^w_k}\left(\max_{t\in[0,..,T]}(tu^t_{l^w_k(h+1)}) - \min_{t\in[0,..,T]}(tu^t_{l^w_k(h)})\right)d_t \tag{11}$$

$$\leq \beta_{f^w_k}, \forall k \in \mathscr{K}, \forall w \in W_k$$

$$\sum_{j\in N(i)} u^t_{ij} + u^t_{ji} \leq 1, \forall i \in V, \forall t \in T, \tag{12}$$

$$SINR_{ij} = \frac{\frac{P_{i,j}}{L_{ij}}}{No + \sum_{\substack{k\neq i \\ k\in N(j)}} P_{kj}u^t_{ij}} \geq \gamma_e, \forall i,j \in E, \forall t \in T \tag{13}$$

$$u^t_{ij} \in [0,1]\ \forall (i,j) \in E,\ \forall T$$

The objective function aims to minimize number of slots used by each one of the links in the network. The second term of the objective function is used to avoid counting one time slot twice if in the solution both uplink and downlink links are scheduled in the same time-slot.

Constraint (10) ensures that minimum throughput requirements for each one of the flows that go through each node are going to be met and that for each time slot, the scheduled flows cannot be greater than the maximum capacity of the link on a given time. In this constraints we allow flows to be scheduled on the same link providing that the duration is at most, the duration of one time slot.

The per flow timing constraint is represented in (11). Here H_k represents the number of hops that each flow from source and destination pair k will go through. Each element h represents an arc (i,j) of the path defined in the path selection problem.

The delay introduced by the slot assignment is calculated by taking the difference between the time in which flow is received and the time in which it is sent in the next hop. That way we can define how much time it takes to process each traffic on each node. The other terms include the switching delay, air transmission delay (d_{t_x}) and overhead time from upper and MAC layers. The total overhead can be approximated as:

$$t_{over} = 2 * t_{SIFS} + t_{guard} + t_{PHY} \tag{14}$$

In (14) we assume that the time needed to wait for a block ACK from receiver station is negligible. The second term depends on the timeslot allocation. The constant d_t represents the scheduled air interface time that each STA is allocated in order to deliver traffic flows. The sum of both terms must be kept beneath a maximum latency threshold β_{f_k} for each type of flow. SIFS values as well as guard time and PHY header time for each frame sent by each station on each SP are based are given by the IEEE 802.11ad standard. Constraint (12) exhibits the half-duplex limitations of each node. On any given time slot t, each node is only able to receive or send data through one of its links.

Finally equation (13) shows the SINR constraint in which depending on the SINR of the receiving node, link ij can be allocated on time slot t only if this SINR value is higher than a predefined threshold. The possible interferer links of pair (i,j) are predefined given the network topology and state. The path loss calculation is done based on the alpha-beta-gamma (ABG) path loss model [8].

E. Joint Optimization

In the last subsection we described both sub-problems in which we solve path selection first and then find a solution for the optimal time-slot allocation. This approach finds an optimal solution for the path selection formulation and with these results, it allocates time-slots to each one of the links.

In this section we will define the joint optimization in which both objective functions are solved at the same time and the problem is treated as a multi-objective optimization.

The main constraints for both sub-problems are defined in the same way, taking into account the relatio nship that relates the flows that are going to be scheduled on each link and the number of time slots each link will be allocated. For this matter, we combine both objective functions into a single scalar objective function that includes both path selection and timeslot allocation. Initially we include weights associated to each term of the single-objective function.

The joint problem is defined as follows:

$$\begin{aligned} min\ \gamma_1 \sum_{i\in V}\sum_{t=1}^{T}\sum_{j:N(i)} \left(u_{ij}^t - \frac{u_{ij}^t u_{ji}^t}{2} \right) \\ + \gamma_2 \left(\max_{\forall (i,j)\in E} \left\{ \frac{\sum_{k=1}^{||\mathscr{K}||}\sum_{w=1}^{||W_k||} f_k^w \cdot x_{ij}^{kw}}{c_{ij}} \right\} \right) \end{aligned} \tag{15}$$

where,

$$\gamma_1 + \gamma_2 = 1$$

$$\gamma_i \geq 0,\ i = 1,2$$

For the joint optimization formulation the constraints $(4) - (14)$ are still valid and represent the set of constraints for the multi-objective optimization. The values of the weights on each objective function in the single scalar multi-objective function determine the Pareto Optimal Solutions from the multi-objective optimization problem. A solution **b*** is said to be Pareto Optimal solution if and only if there does not exist a feasible solution **b** such that each objective function g_i follows the relation $g_i(b) \geq g_i(b^*)$ for all $i = 1,2$. The strength of finding a Pareto set is that every alternative in this set is optimal for at least one optimization function. Moreover, the values for each weight can be chosen by the user in order to obtain certain preferred solutions.

F. Shortest Path Heuristic Algorithm (SHPH)

In this section, we present a heuristic algorithm for the path selection and link scheduling problem. As a first step, the algorithm prioritizes each flow according to their latency and throughput requirements, this means that highly restrictive flows are going to be scheduled first in order to meet their requirements. For each one of these flows, a minimum hop count path is chosen (for which an optimization solver is required) and for each assigned link the remaining link capacity and a cost is determined, where the cost is the number of slots used at the link. This process is repeated until all high priority traffic has links allocated. For the remaining flows a least cost path to destination is calculated and the same process of link capacity and link cost calculation is carried out. After all traffic flows have scheduled links, minimization of used slots for every link is applied by allowing MAC aggregation when possible.

III. MILP Solver Evaluations

In this section, we describe the performance evaluation procedure for the three approaches explained in the past sections. We will make a comparison of the Two-stage optimization, Joint Optimization and SHPH approaches in order to asses and compare their performance on a particular scenario with a specific number of flows, source and destination pairs and transport nodes. The evaluated scenario is shown in Figure 1. Each transport node is equipped with mmWave wave capabilities and 4 STA's, each one with 90 steerable antenna.

The scenario is composed of 14 Transport nodes, 2 source nodes (ETN) and 3 destination nodes (IATN). Source nodes are represented by small cells, usually located on lampposts

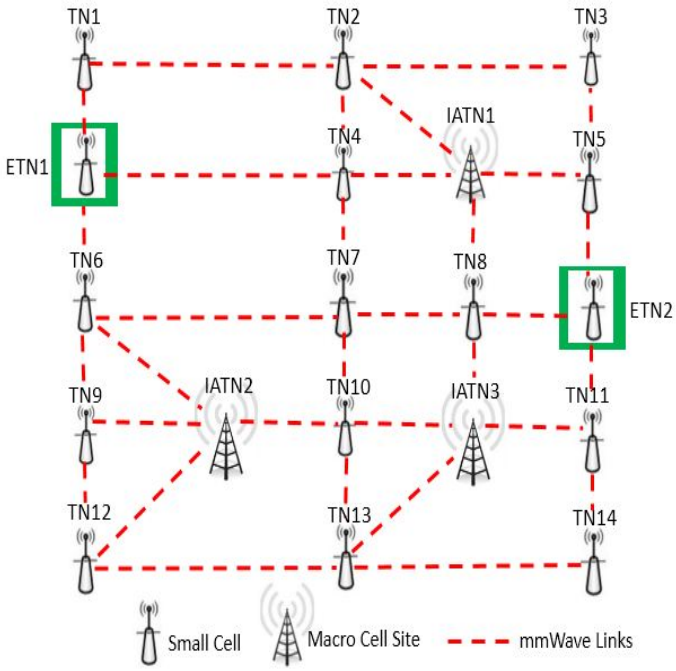

Fig. 1: Evaluation Scenario

and destination nodes represented by Macro cells. The traffic between each source and destination nodes are defined by the different functional splits based on a C-RAN deployment presented in [2], were different splits in the processing chain are defined.

For LTE traffic the data rate requirements data rates are based on the Next Generation Fronthaul Interface (NGFI) [1] and Next Generation Mobile Networks (NGMN) Alliance [9]. Its calculations are based on a single 20HMz LTE carrier with 8 antenna ports and the highest MCS attainable for DL (64QAM) and UL (16QAM). Depending on the functional split chosen, data rates can vary and also latency requirements will depend on the added functionality of Base Band Units. Functional splits 1 and 4 as stated in the NGFI White Paper [1] that account for an aggregated total of 0.247 *Gbps* and 3.2 *Gbps* respectively. Functional Split 4 is based on assuming functions like Channel Estimation and Layer Mapping to be done in the RRH, which resembles functional split B on [7]. Conversely, split 1 resembles Split C in [2] in that it leaves latency restrictive functions to RRH and leaves Higher MAC functionality to BBU. The physical and MAC layer parameters used in the optimization are shown in Table I.

We compared the three approaches, namely Joint Optimization (JO), Two-Stage Optimization (TSO) and Shortest Path Heuristic Algorithm (SHPH) presented earlier. The evaluation of our three approaches are done on Gurobi Optimization Solver, which is a powerful solver that supports a broad range of programming languages and optimization models such as Mixed Integer Programming and Quadratic Constrained Programming and also supports multiple objective problems with robust prioritization by finding solutions doing an exhaustive

TABLE I: Evaluation Parameter Values

Parameter	Value
t_{SIFS}	$3\mu s$
d_{tx}	$3\mu s$
t_s	$10\mu s$
t_{guard}	$3\mu s$
t_{PHY}	$4.79\mu s$
PHY Layer	OFDM
Link Capacity 4G	$4.69Gbps$
MAC aggregation	A-MSDU
Distance between TNs (d_n)	$100m$
Frequency Band	$60GHz$
EIRP	$40dBm$
Antenna Gain	$8.5dBi$
Rain Attenuation	$0.44dB$
Oxygen Absorbtion	$2.3dB$

search over possible solutions based on different methods and algorithms.

Each source node produces a total of 12 flows of both FH and BH traffic, which are evenly distributed to each one of the three destination nodes. The base load of each flow for 4G traffic scenarios is the NGFI aggregated total divided by 12 flows. On our analysis the load of each flow is varied according to a load profile from 10%-100% load. The values of the weights for the JO approach are 0.5 for both γ_1 and γ_2.

Figure 2 shows the maximum link utilization for the chosen scenario with 4G traffic flows present and Figure 3 shows the resource utilization in terms of the timeslots used to carry all the traffic to their destinations. On the other hand, Figure 4 shows the time to solve or computation time. This represents the time that the solver needs to find an optimal solution for each load demand.

The results obtained by the Joint Optimization approach leaves with overall better solutions at the expense of higher computation times. Given that the objective function for the first problem in the TSO approach is load balancing, maximum link utilization yields better performance on most of the cases.

Subsequently for the resource utilization, the Joint Optimization attains a better performance overall compared to the alternate approaches, which shows the advantage of defining a multiobjective optimization. Same results were obtained with 4G traffic although higher load balancing is obtained in the TSO approach. In this case we can see that number of slots needed to carry 4G traffic is low, even taking into account that a 4Gbps link capacity was used.

Thus, we can see that by finding first the optimal path selection for each flow on a load balancing scheme TSO approach does not fully exploit MAC aggregation, which has direct effect on resource utilization. When all flows have paths scheduled on the path selection, MAC aggregation acts on these predefined flows. This two step optimization limits the search for optimal solutions to both subproblems, which in turn reduces system performance overall and renders similar solutions to the SHPH algorithm.

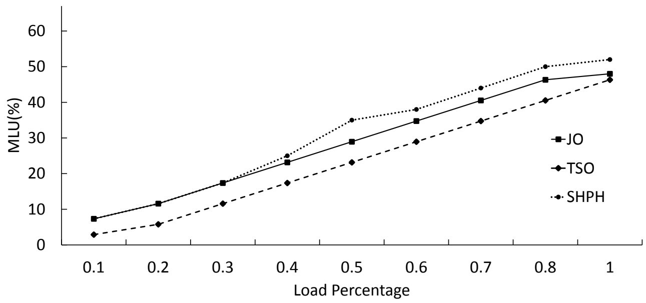

Fig. 2: Maximum Link Utilization

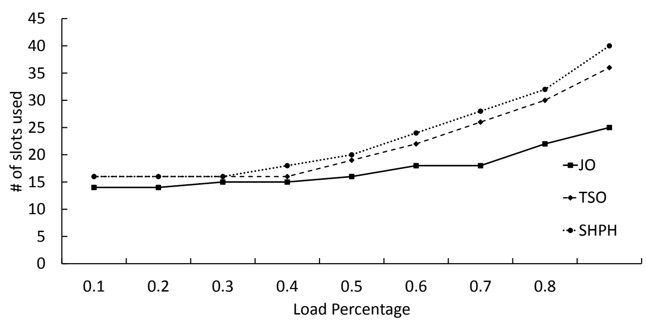

Fig. 3: Resource Utilization

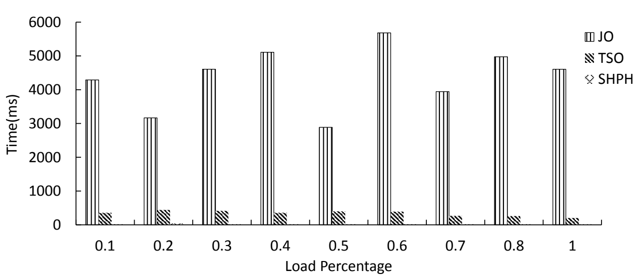

Fig. 4: Time to Solve

IV. Conclusions

Millimeter Wave technology, as a transport network physical layer technology, with projected enhancements in achievable data rates, is one technology that can provide flexibility in terms of network topology due to the reconfigurable nature of their links through the use of highly directive antennas. Although beam-forming delay and sector level sweeping was not taken into account in our problem formulation, the delay issued by beam-forming is negligible compared to scheduling delay, switching delay and per hop delay introduced by the network.

Link scheduling and resource scheduling as shown by the results, can be jointly optimized, achieving optimal results at the expense of utilizing higher computational time to find a solution to the MOP problem. However, given aggregation of flows to one timeslot with the use of flow aggregation on each transport node, further increase in performance is attained. However on a more realistic network, synchronization is a main issue that has to be taken into account when flow aggregation is addressed and where multiple paths are defined.

The use of multiobjective schemes with highly exhaustive searches could pose a problem due to the high volatility of future mobile networks and their need to be quickly adaptable and highly reliable. However having multiple objectives functions allows to have flexibility on how the search for the optimal point is made depending on certain controllers criteria or optimization performance requirements. On a pure mathematical basis, these criteria can be changed by modifying the weights on the joint optimization formulation or the parameters for the exhaustive searches on the optimization solver.

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