Slice-tailored Joint Path Selection & Scheduling in mm-Wave Small Cell Dense Networks

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***Abstract*— Network slicing allows the support of logical autonomous networks on top of a common infrastructure, offering a customized networking experience addressing distinct business demands. 5G networks are expected to support a plethora of applications and multi-tenant services, often with conflicting performance requirements. By enabling network slicing, 5G networks can assure the desired performance, but the limitation of radio spectrum brings new challenges in resource allocation and scheduling, especially for achieving the desired flexibility in resource sharing. In this context, this paper analyzes the joint path selection and backhaul link scheduling problem in a dense small cell network, assuming mm-Wave multi-hop backhaul. For supporting efficiently multiple slices with diverse Key Performance Indicators (KPIs), a slice-tailored resource allocation, scheduling, and selection of backhaul links and redundant paths is proposed. Such resource allocation process is complemented with adaptive routing and other flexible small cell related operations with particular focus on delay critical and throughput oriented slices.**

***Index Terms*—5G, Network Slicing, Wireless Backhauling, millimeter-wave, Radio Access Networks**

I. INTRODUCTION

The emerging 5G mobile networks are facing the challenge of supporting a plethora of applications and networking services, e.g., enhanced massive broadband (eMBB), ultra-reliable low latency communications (URLLC), massive Internet of Things (IoT) connectivity, etc., with diverse and often conflicting performance requirements. Whilst enhancing the network infrastructure is a straight forward solution, it can significantly increase the operational and capital expenditures for mobile operators. At the same time, the infrastructure enhancement may limit the potential opportunities for innovation and new business creation, since the service deployment cycles are still lengthy and the network behaves like a "black box", offering only over the top access to third parties.

In light of these, the concept of 5G network slicing was introduced into the mobile communication industry by NGMN [1] and currently studied and specified in terms of the radio aspects, architecture and management by 3GPP [2][3]. Network slicing refers to the creation of logical self-contained networks on top of a shared infrastructure considering networking and cloud resources, offering programmability and customization for third players and vertical segments, supporting multi-tenancy. An overview of network slicing enabler and interfaces enhancements considering the 3GPP architecture is provided in [4], while the notion of slicing in emerging 5G network of capabilities is elaborated in [5]. One of the pillar technologies for enabling the desired resource flexibility in allocating and managing network slicing is Software Defined Network (SDN). SDN supports the separation of the control-plane from the user-plane offering a global network view and resource programmability to third parties via open Application Programming Interfaces (APIs).

In ultra dense Heterogeneous Networks (HetNets) millimeter-wave radio (mm-Wave) multi-hop backhaul is perceived as an efficient solution to provide connectivity to access nodes, i.e. macro-cells and small cells. Several GHz-wide chunks of spectrum are available for mm-Wave, resulting in multiple Gbps even with low-order modulation schemes. Besides such high-data rates, mm-Wave radio can offer excellent immunity to interference, high security and an efficient frequency reuse [6]. However, mm-Wave radio requires a clear Line-of-Sight (LoS) propagation with its range possibly restricted by the oxygen absorption which strongly attenuates ≥60GHz signals over distances. To combat this, high gain directional antennas are used in order to compensate for the large free space propagation losses, while data can be transferred via multiple low-distanced hops to ensure a good backhaul link channel quality. To this end, one of the major challenges that should be addressed is the path selection or routing in coordination with scheduling for backhaul links considering the current channel conditions and service requirement.

Prior literature [7] [8], focuses on the aforementioned problem, however without considering network slicing and third party's service requirements, which can diversify the path selection and scheduling policies. In the state-of-the art literature, multiple routing and scheduling schemes were proposed and grouped in [7] considering different implementation options (e.g. whether routing and scheduling is separated or jointly performed in distributed or centralized manner). To this end, the authors in [8] investigated the joint routing and scheduling problem, which was formulated as a capacitated vehicle routing problem, where a central depot allocates passengers to vehicles and assigns paths that reach their destinations within the minimum time duration [9].

In the context of network slicing different slice requests can introduce distinct KPIs in terms of throughput, latency or reliability, which can impact the allocation and operation of Radio Access Network (RAN) resources. Without the loss of generality, this paper focuses on two slice types: (i) eMBB that requires ultra-high user throughput and (ii) URLLC, which restricts latency to 1ms requiring 99.999% service availability. In a shared ultra dense HetNets infrastructure with mm-Wave backhauling, routing and scheduling policies should be aligned with the slice specific requirements. This involves the resource allocation in backhaul links, the consideration of the number of hops in routing and the scheduling operation of small cells.

The objective of this paper is to exploit network virtualization and the notion of SDN programmability to facilitate flexibility into the user plane considering the aforementioned criteria. In particular, the contributions of this paper include: (i) the logic to dynamically identify backhaul links and hence paths per given time window, considering the target KPIs of a particular slice request, i.e. in terms of capacity, latency and resiliency, and (ii) the queuing and forwarding logic related to the traffic of incoming flows based on the link selections in the previous step and per slice target KPIs.

The remainder of this paper is organized as follows: Section II presents the network architecture. Section III describes the system model and joint path selection and scheduling problem. Following, section IV discusses the solution framework and Section V describes the simulation set-up and the results analysis. Finally, Section VI summarizes our findings.

II. Network Architecture

The network architecture which was adopted in this paper is based on the SDN paradigm [10][14], wherein a centralized controller abstracts the network infrastructure enabling programmable path selection, resource allocation and RAN control plane functionalities, e.g. the wireless scheduler, to third parties.

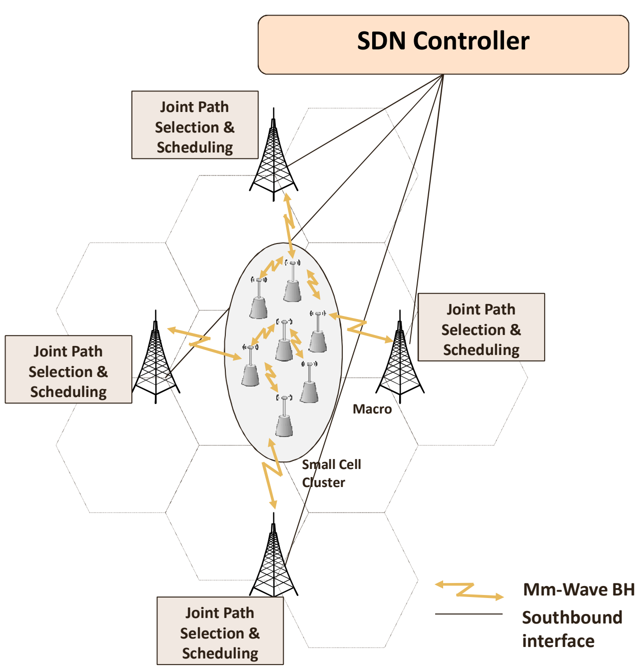

Fig.1: Physical deployment and functionality placement

The proposed SDN architecture consists of a centralized SDN controller that coordinates the path selection and resource allocation policies based on the KPIs of incoming network slice requests. The SDN controller programs a local coordinator function residing on each macro-cell traffic aggregator with the appropriate RAN control plane, which allows tenants to use different wireless schedulers on their allocated slice. Each local coordinator is responsible for the path allocation and wireless scheduling within a multi-hop environment considering direct traffic relay among neighboring small cells via an in-band backhauling. A simple example that illustrates the proposed SDN architecture pointing out the main functional entities is illustrated in Fig.1.

It is worth noting that the control intelligence related with the multi-hop small cell infrastructure is divided and organized into a set of local coordinators. This allows fast scheduling and rapid reaction to re-calculate paths in order to meet the stringent latency and reliability KPIs without the direct involvement of the SDN controller. Such network architecture can improve significantly the scalability of SDN controller, especially in highly dynamic environments, e.g. mm-Wave backhaul networks, in where determining, installing and reconfiguring data paths can potentially be frequent. The resulting hierarchical two level scheduling allow less granular scheduling to be performed by the SDN controller, which manages underlying set of local coordinators.

A significant parameter to consider when arranging the propose SDN architecture is the formation of HetNet clusters, and their association with particular SDN controllers. Considerations regarding path computation and configuration response time, monitoring of the network status and response to topology alternations should be taken into account when forming clusters and in placing an SDN controller.

III. Problem Formulation

In this study, one or more macro-cell sites (i.e. local traffic aggregators) are placed on top of an underlay of small cells and are responsible to forward traffic to/from residing small cell users, as well as coordinate the backhaul /access resource management. In this scenario, multiple paths originating from different macro-cells towards the same set of small cells are used to accommodate the slice-tailored KPIs by enabling backhaul link diversity. The physical establishment of a path resembles a tunnel, enclosing a set of small cells which may relay traffic flows with a given order and a variable number of hops in mm-Wave shared spectrum. Each path can encapsulate multiple traffic flows with different characteristics and towards distinct destinations.

The system consists of multiple macro cells (or local aggregators), $n=1,2,..,N$, which reside on top of a cluster of small cells. The small cell cluster network encloses $l=1,2,..,L$ Small Cell-Access Points (SC-APs) and all nodes are equipped with antennas for the access, as well as directional antennas for the macro / small cell backhaul, which operate in higher frequencies.

Let $G(V,E)$ be the graph consisting of a set of V nodes (Backhaul (BH) and access nodes) and a set of E edges. An edge $e \in E$ is a connection between two nodes $1, v2 \in V$.

The presence of an edge e indicates that data can be exchanged between $v1$ and $v2$. We assume m links in the network, where the links are considered un-directional. Here, we also introduce a set of $\boldsymbol{S}$ slices where slice $\boldsymbol{s}$ specific traffic originates from one or more sources (macro-cells) and terminates to one or more destination SC-AP(s) with the desired rate R_s and maximum delay, resiliency, etc. T_s (as defined by slice related KPIs and conveyed by the SDN controller to the macro-cells). We define the potential load of link e due to demand from slice s as $l(e,s)$, to identify the potential load per link. Each link e has a capacity, defined as $c_e, \forall e \in E$, and a desired data rate which corresponds to the summation of all the slice traffic traversing it. Here, high directional antennas can be used to compensate for the high path attenuation. In this case, interference by other links is assumed to be negligible due to the high directivity of the antennas and the half duplex constraint (nodes only transmit or receive per time-instance). Using the definitions of the link capacity and the link load, a new parameter which captures the number of time-slots required for a link to satisfy its demand is shown:

$$f_e = \left\lceil \frac{\sum_{s \in S} l(e,s)}{c_e} \right\rceil \tag{1}$$

where $\lceil \cdot \rceil$ accounts for the ceiling function, i.e. the least integer that is greater than or equal to x. In other words, f_e which is interpreted as a cost function for each link, captures how many timeslots are required for the traffic to be carried on each link, so as to meet the data rate requirements. The worse the channel conditions, the higher the number of timeslots needed to reserve one BH link.

Another key parameter, which is going to be used for the scheduling part formulation, is the set of all bi-partite sub-graphs of the graph $G(V,E)$, denoted as $\boldsymbol{G'}$. Each of these G'_i sub-graphs represents a combination of link activations (one set of the bi-partite graph is the transmitter nodes and the other set is the receiver nodes). Each of these sub-graphs is associated with a weighting factor $w_{G'i}$ which represents the fraction of time that this combination of active links endures.

The objective is how to select the best links and paths to be used from each macro-cell towards particular small cells, in order to satisfy its data rate demand and delay constraints. The joint path selection and scheduling problem has two main parts. The path selection part, which performs the selection of links forming multi-hop paths, is based on the average backhaul channel conditions and the slice KPI requirements. In addition, per traffic flow scheduling is also supported dynamically to allocate resources at the backhaul links, in a way that the service-oriented KPIs can be met.

The maximization of total BH throughput is equivalent to the minimization of the total number of timeslots, defining the ratio of the demand over the backhaul link capacity towards a small cell, which is equivalent to finding a path per traffic flow that minimizes the total cost under certain constraints. .In other words, the objective is to find paths the traffic should follow and links to be activated per slice and macro-cell so as to maximize the system performance, i.e.

$$\min \sum_{s \in S} \sum_{n \in N} \sum_{e \in E} f_e(s,n)\, x_e(s,n) \tag{2}$$

Subject to:

$$\sum_{e=\{n,j\} \in E} x_e(s,n) = k(s), \forall s \in S \tag{3}$$

$$\sum_{s \in S} \sum_{e=\{i,j\} \in E} x_e(s,n) \leq 1, \forall i \in V, \forall n \in N \tag{4}$$

$$\sum_{s \in S} \sum_{e=\{j,i\} \in E} x_e(s,n) = 1, \forall i \in V, \forall n \in N \tag{5}$$

$$\sum_{e=\{i,j\} \in E} f_e(s,n)\, x_e(s,n) \leq R_s, \forall s \in S, \forall n \in N \tag{6}$$

$$\sum_{n \in N} f_e(s,n) \leq T_s \sum_{i=1}^{|B|} w_{B_i} 1_{e,B_i}, \forall e \in E, \forall s \in S, \forall n \in N \tag{7}$$

$$\sum_{i=1}^{|B|} w_{B_i} = 1, w_{B_i} \geq 0, \forall B_i \in B \subseteq G' \tag{8}$$

The first 4 constraints (3) – (6) are the routing constraints, whereas constraints (7), (8) are the scheduling constraints. In (3), the number of links between each macro-cell (denoted as node n) and all the SC-APs depend on the number of paths and is equal to the variable k (which relies on the slice requirements and can be pre-defined). The higher we set this value, the lower hops are expected in total. More detailed analysis on the k variable is elaborated in [8]. In (4) and (5), the number of incoming links and outgoing links to/from each SC-AP is set exactly or less than one. By this, all the SC-AP must be able to receive traffic; however, it is optional to have outgoing traffic to other links. Constraint (6) is the maximum delay constraint which has to be considered when creating a path. This constraint might be variable depending on the traffic (i.e. lower threshold for URLLC slices and higher one for eMBB slices). Moreover, (7) shows that the cost of the link shall not exceed the pre-defined slice-based time window (T_s); finally (8) implies that the summation of the weights (i.e. the fraction of time each sub-graph is active) is set to one.

IV. Solutions Framework

The problem as proposed in previous section is a NP-hard combinatorial optimization problem. Therefore, our proposed framework decouples the initial problem in two sub-problems. At the first stage, we target to solve the path selection problem (constraints (3)–(8)) which has the form of an Integer Programming problem. Hence, we identify links to activate and the number of slots to dedicate per set of links, such that the BH throughput is optimized. The solution of this sub-problem is found using the Branch-and-Cut exact approach

[11]. The next stage is the selection of the packet to be forwarded from the queues in order to minimize the delay, taking into account the half duplex constraint, the multi-hop requirements and the queue buffers. This problem is solved using a variant of back-pressure scheduling algorithm [12].

Path Selection Algorithm

The objective of this algorithm is to select paths towards SC-APs (with known traffic demands), originating from particular macro-cells, that minimize the total cost for reaching the destination small cells with a given maximum number of hops. As mentioned above, the total cost of the path comprises the per link cost, which depends on the backhaul conditions and the load of the link. Based on the slice requirements, we may have different maximum allowable number of hops to meet a certain latency KPI (this can be defined by k factor). The algorithm follows a branch-and-bound scheme, where lower bounds are computed by solving a Linear Program (LP) relaxation of the problem. This relaxation is iteratively tightened by adding valid inequalities to the formulation according to the cutting plane approach. The exact method is known as a branch-and-cut algorithm and is thoroughly described in [11] for the case of the Integer Programming (IP) problem. Following, we briefly describe the algorithmic steps for allocating paths with respect to each macro-cell:

Initialization: At this stage we transform the initial graph to an edge graph G to be able to solve the IP problem. The resulting edge graph defines the number of variables in the IP problem.

Lower Bound: Having formed the edge graph, the next step is to find the lower bound using an LP relaxation. In our work the initial near-optimal solution for the root node (which is each macro-cell in our case) is derived using Langragian relaxation.

Upper Bound: After finding the lower bound, which is the optimal solution for the relaxed problem, we now aim to find the upper bound to the original problem, which is a set of feasible solutions using local search algorithms and improvement procedures, in similar way as in [11].

Branching: Here, we create a new node in the search tree following the logic of branch and bound to explore the next feasible solution. We consider the branching on variables, the standard approach for branch-and cut. It consists of selecting a fractional edge-decision variable and generating two descendant nodes by fixing its value to either 0 or 1. In our implementation, we use the most fractional branching where we choose variable with fractional value closest to 0.5 (ties are broken by choosing the edge with maximum cost).

Scheduling Algorithms

After obtaining the paths and the number of timeslots that each link is going to be used for all destinations, the next phase is to find how to forward the packets from each macro-cell to all the SC-APs, having a variable number of hops per path with the minimum delay and according to slice requirements. Here, depending on criticality of traffic, we may have to decide whether to use Queue-and Forward at the intermediate nodes or just forward traffic with higher priority. By using the latter, we will manage to meet the low latency KPI which can be critical for some slices (e.g. URLLC slice).

A. Scheduling part for Critical / URLLC Slices:

In the case of URLLC slices, BH scheduling should be tailored to achieve low latency, but at the same time assuring high reliability (since we might prefer non-ideal BH links for the forwarding of the traffic using minimum number of hops). This can be performed by the following policies:

- Forward traffic with minimum allowable number of hops, without queuing at each intermediate small cell (small cell do not need to process the incoming slice traffic) to minimize latency.
- Perform joint transmission/reception from the macro-cell to the destination small cells (via redundant paths, assigned to this slice) at the same carrier frequencies to increase reliability. Here the assumption is that the backhaul between macro-cells is ideal (e.g. using fibers) to allow data exchange for joint transmission / reception.
- For traffic of the same slice, towards a different destination small-cell, use distinct carrier frequencies or redundant paths. Local coordination between macro-cells will be required to avoid cross link/path interference.

B. Scheduling part for eMBB Slices:

For eMBB, the packets are stored in separate queues per destination at the traffic aggregator. The target is to empty all the queues by the end of the given time window. Here, one constraint is related to half-duplexing, i.e. each node can either transmit or receive per time instance. Furthermore, the traffic that is forwarded via more than one hop should be stored in separate queues in the intermediate nodes. In each queue, First In, First Out (FIFO) policy is applied. For the solution of this problem, we showcase a throughput optimal algorithm which follows the back-pressure concept [12]. Assuming slotted time, the basic idea of backpressure scheduling is to select a set of non-interfering links for transmission at each slot. Non-interfering links refer to links that do not have the same transmitting and/or receiving end, such that the half duplex constraint is maintained. Here, the objective is to serve the flow f with the maximum differential backlog. The differential backlog for each node i,j is defined as $\Delta Q_i f = Q_i f - Q_j f$.

The overview flowchart for the aforementioned algorithms is presented below. Initially, the macro based on the slice information for the traffic flow, decides how to map the traffic to different paths and which scheduling policy to follow and. In case of URLLC, the scheduling part is simple since the traffic is transmitted and amplified at the intermediate nodes without queuing delays. For eMBB, the steps are performed for the backpressure algorithm by taking into account also possible delays due to URLLC traffic (in case of sharing of the same carrier by both slices).

As can be seen also in Fig. 2, for the scheduling part of eMBB slices, in Step 1, the weights $w_{i,j,t}$ based on differential backlogs are calculated per time slot. In Step 2, the links that maximize are selected, i.e. $x^*(t) := \sum_t w_{i,j,t} x_{i,j,t}$, where $\sum_t x_{i,j,t} = x_e : e = \{i,j\} \in E$. Finally, in Step 3, the packets of the selected flows are transmitted to the next hops.

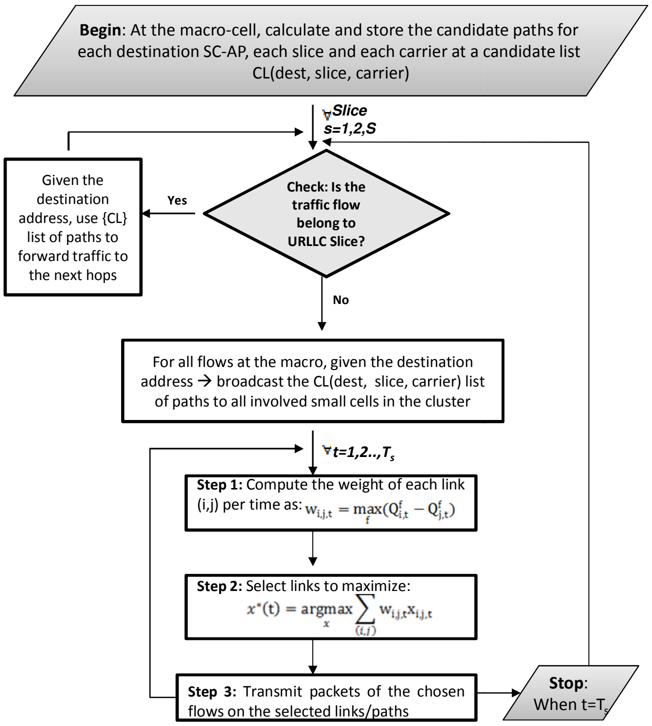

Fig.2: Overview Flowchart

V. Evaluation Results

To evaluate our work, Monte Carlo simulations for a 9-cell deployment are performed in a wide area scenario, where 4 macro-cells are placed around the cluster (as can be seen in Fig. 1). In particular, Table 1 provides a summary of the simulation parameters.

Table 1 Simulation Parameters

SC-APs	9
ISD	20m
Users	Poisson arrivals per cell (λ=2.5)
Traffic	eMBB Slice: Random traffic demand per user (10-50Mbits) URLLC Slice: 1Mbits
Carrier	60GHz (BH)
Bandwidth	4 carriers of 100MHz (1 carrier to be used per macro-cell for the backhaul)
Max. number of beams	4 per node (half duplex)
TTI size	0.1ms
BH channel model	For the capacity computation, the 60GHz path-loss models in LoS and nLoS are used by [13]
Processing	L1 Processing ~0ms
Delay	L2 Processing ~0.2ms
Snapshots	5000

The metrics used for the evaluations are: (i) the average BH link throughput (for eMBB) in case we have BH diversity by multiple paths (using different carriers), (ii) the Cumulative Distribution Function (CDF) of BH Signal-to-Noise-Ratio (SNR) (for URLLC case) with and without path diversity and (iii) the average delay from each of the macro-cell to reach each destination SC-AP for both slice types. In the evaluation, users of the same slice were randomly dropped assuming to have similar requirements; thus not requiring differentiation on the routing and scheduling. The implementation of this scheme consists of two stages. The first stage is the extraction of results for the path selection problem for each of the *n* macros. Here, we adjust the number of paths (based on the variable *k*), so as to find the optimal path selection in different cases. For URLLC slices, k is very high (*k=7*) and there is also a constraint on the maximum hops not to exceed 2 (from each macro-cell to destination SC-AP). For eMBB, multiple sizes of *k* are considered for the extraction of paths; hence we tested scenarios with different path selection modes (path selection modes 1 to 4, are translated to *k*'s from 2 to 6). For the scheduling part, URLLC traffic is forwarded without queuing and with high priority. This will slightly affect the delay of other types of traffic. For the rest traffic, the backpressure scheduling is used.

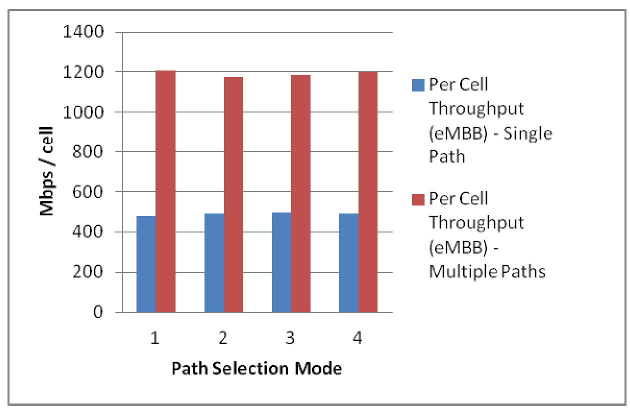

Fig.3: BH Throughput comparison

Fig.3, shows the comparison in BH throughput for the case of a single macro-cell (single depot in Vehicular Routing Problem (VRP) problem as in [9]), versus the case that multiple macro-cells (multiple depots) which can provide extra capacity by utilizing more links. Huge gains in terms of performance are oberved, which is similar for all path Selection Modes (different hops based on the variable *k*). This outcome shows that if we have a form of BH diversity via redundant paths and coordination of multiple macro-cells for a cluster of small cells (which can be a hotspot, e.g. stadium, square), we can achieve high throughput, which can be translated to significant enhancement ot users' performance.

Moreover, Fig.4 shows the CDF of BH link SNR for URLLC (for which reliability is KPI), which can be significantly improved when enabling multi-connectivity via redundant paths. The BH throughput metric is not evaluated for this slice type, since the rate requirement is low. This result highlights the SNR as a means of showing the trend for the reliability for the BH links. Here, we should observe the tail of the CDF which shows the minimum achievable SNR per destination small cell. Using redundant paths for URLLC at the same carrier, we increase the achievable SNR; hence allowing for 99.999% reliability (from the macro to the end user).

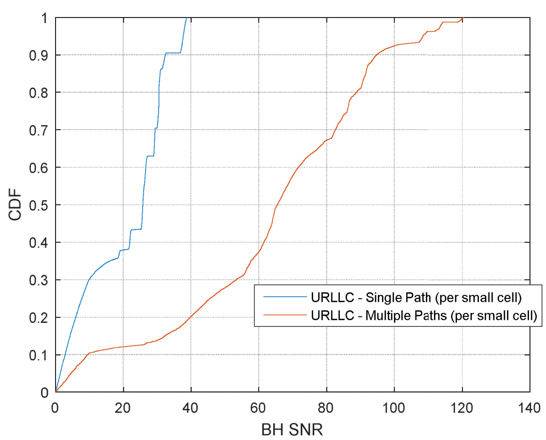

Fig.4: BH SNR comparison

Another interesting result, which is illustrated in Fig.5 is the average expected delay for different slices, by employing the proposed scheduling. Delay refers to queuing, processing and propagation delays assuming multiple hops from each macro towards the destination small cell. For the URLLC slice, the delay is kept very low, since we do not have queuing delays and the number of hops is limited; hence we can achieve latencies under 1ms (assuming TTIs of 0.1 ms). For eMBB, the delay can be between 10-12 ms assuming queuing delays, L2 processing at small cells and higher number of hops. This shows that using the particular graph-based framework, which can be tailored to different slice requirements, we can achieve ultra low latencies for the cases of URLLC, whereas for eMBB, which can tolarate a latency of 10ms, using a higher number of hops we can enhance the BH capacity.

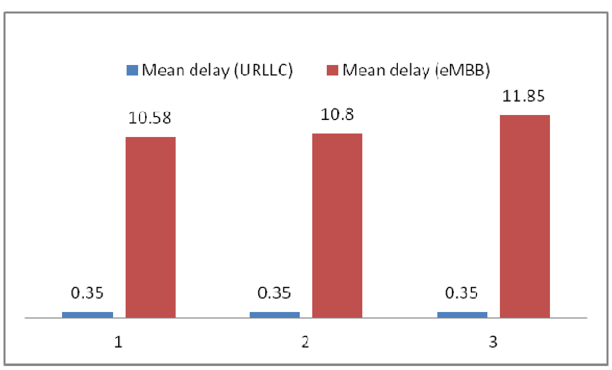

Fig.5: Mean Delay (in ms) for URLLC and eMBB Slices

VI. CONCLUSION

This paper provides a novel multi-tenant framework for the joint path selection and scheduling problem in a cluster of small cells for supporting multiple slices assuming a mm-Wave backhaul. The proposed framework is based on the SDN paradim introducing the notion of the local coordinator to meet strict per slice requirements in a dynamic wireless environment. We provided a tune-able and adaptive solution, which involves different polices for the routing and scheduling, assuming two slices types. In particular for URLLC slices, we employ routing via multiple redundant paths with low number of hops and limited processing at the small cells to achieve high reliability and ultra low latency. On the other hand, for eMBB slices, we provide tailored routing and scheduling via higher number of hops to achieve high end-to-end throughput.

ACKNOWLEDGEMENT

This work has received funding from the European Unions Horizon 2020 research and innovation programme under grant agreement No. 671551 (5G-XHaul project). The European Union and its agencies are not liable or otherwise responsible for the contents of this document; its content reflects the view of its authors only.

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