Abstract—Mobile backhaul system based on a wireless mesh network using point-to-point millimetre wave links is a promising solution for dense 5G small cell deployments. While mmW radio technology can provide the sufficient capacity, the management of transport delays over multiple wireless hops is challenging especially if TDD backhaul radios are used. Earlier, we have proposed the Self-Optimizing WMN concept and presented routing and link scheduling principles that can be used for backhaul nodes with single radio unit. In this paper, we are extending the concept to support backhaul nodes that can have multiple radio units with own beam steering antennas covering non-overlapping sectors. The proposed system is based on dividing the task in separate phases. In the first phase, an active network topology is created by selecting a suitable subset of all available links. In the next step, the routing information and transmission sets are generated. Finally, the link schedule is optimized by finding an optimal ordering of transmission sets. In this paper, we are proposing a feedback loop from transmission set generation to topology management. We show that this feedback loop removes efficiently "troublesome" links from the active topology making it easier to find optimal link schedules.

I. INTRODUCTION

Network densification [1], that is, augmenting macro cell capacity with a large number of small cell base stations (SB), is considered to be one of the viable solutions to meet 5G capacity demand. New types of installation locations for SBs (light poles, bus stops) create a new challenge due to lack of existing optical fiber connectivity. Thus, wireless backhaul (BH) utilizing high frequency millimeter wave (mmW) connections is proposed [2], [3]. These connections utilize high gain beam forming antennas that support high bandwidth, high spatial reuse factor, and thus high areal capacity.

The mmW BH networks rely mostly on line-of-sight (LOS) links and thus attenuation and blocking can cause serious problems to reliability. Moreover, direct connectivity between SB site and BH gateway (GW) node with fiber optic connectivity cannot be always guaranteed, which makes it necessary to have multihop wireless paths. The multihop connectivity makes the reliability problem even more pronounced. To overcome these problems, partial mesh topology or wireless mesh network (WMN) can be used to provide multi-path connections and thus much improved fault tolerance.

We have proposed a wireless mesh network WMN based mmW BH system [4] that utilizes a set of routing, link scheduling and queueing algorithms to provide high reliability and low delays over BH segment [5]–[7]. The proposed system was based on a WMN node (WN) architecture with single mmW radio unit (RU). In this paper, we extend that concept by introducing support for multi-RU WNs with beam steering sector antennas. The new WN architecture brings new constraint to link scheduling algorithm as all RUs in one WN can either transmit or receive at the same time. Furthermore, we have modified the routing and link scheduling process by having tighter integration between subsequent steps and a feedback loop between topology management and link scheduling.

II. WMN BASED BACKHAUL

Our Self-optimizing WMN (SWMN) concept is based on using high capacity E–band mmW radio links with high gain beam steering antennas [4]. We are assuming that interference is not a limiting factor for the total throughput [8]. Thus, our link scheduling algorithm is focused on minimizing worst case transport delays [6]. The fault tolerance is provided by multipath routing that is based on Multiple Disjoint Spanning Trees (MDST) [5]. Those spanning trees are constructed so that the number of node disjoint routes to GW nodes are close to maximum. Furthermore, the unfairness problem with multihop wireless connections is solved by a specific fair queueing mechanism [7].

A. System architecture

In the earlier work, we have assumed that each WMN Node (WN) is composed of single TDD BH radio unit with a beam steering antenna system that can cover full 360°. Now we are considering a node architecture, where each WN has multiple BH radios that cover non-overlapping sectors. All radio units are still operating in TDD mode and in the same frequency. There are also some assumptions about physical system configuration and construction. The components of single WN unit should be tightly integrated into a compact rugged casing, which means that the system dimensions are quite close to the antenna dimensions. Furthermore, the system should be cost optimized meaning that there cannot be any expensive components to mitigate internal interference between RUs.

Otherwise, the network architecture is the same (see figure [1]). All WNs perform periodically neighbor search and they also constantly monitor the link quality. Any changes to network topology or link performance are reported to WMN
Centralized Controller (WCC) via gateway nodes (GW). WCC is responsible of computing a new network configuration consisting of the selected active links, routing trees and link schedule when necessary. The routing trees provide multiple disjoint routes for each WN to one or more GWs and each WN is responsible of selecting dynamically the most suitable route for each traffic flow considering detected link faults and possible congestion. This means that while the network configuration is centrally computed and more or less semi-static, the network can react, e.g., link failures at real-time.

B. System requirements and limitations

The proposed node architecture implies one critical constraint. Due to near-field interference between RUs in the node one RU can not transmit when any of the physically adjacent RUs is receiving and vice versa. To overcome this we have selected architectural approach where all the RUs in one node can either send or receive at the same time. This means that the link scheduling algorithm should also consider link directionality and whether the link end-points are in suitable mode (TX/RX).

As in our earlier work, we assume that end-to-end delay is the most important optimization criteria in WMN BH. Due to natural delays caused by TDD links, we have determined that to meet mobile BH delay requirements, it is necessary to have short cyclic (semi)permanent link schedules. Thus, we take a similar approach with this new type of node architecture and try to maximize the network capacity by maximizing the number sectors (instead of links) that can be active simultaneously.

III. ROUTING AND LINK SCHEDULING ALGORITHM

The proposed new routing and link scheduling algorithm has four main phases as shown in figure 2:

1) In “Select active links” phase, a subset of all available links are chosen to be included in routing and link scheduling (so called “active topology”)
2) In “Compute routing trees” phase, a set of spanning trees are computed to be used for routing and a primary path is allocated to each node.
3) In “Create transmission sets” phase, a set of maximal transmission sets $TSS$ is created to be used in link scheduling.
4) In “Optimize schedule” phase, an optimal ordering for transmission sets is sought.

The process has one iterative feed-back loop between last two phases. If the chosen active topology requires a large $TSS$ to cover all active links, the optimization of link schedules would be computationally challenging. Thus, if $|TSS|$ exceeds certain threshold, the links that causes most troubles in $TSS$ creation, are added to “links to avoid” list and the whole process is started again from the 1st phase. When the overall performance is considered, this is quite justified as the last phase is the only computationally challenging phase.

A. Active link selection

Our primary target is to minimize the maximum end-to-end delay. There are two major factors that define the range of worst case delays: path length and schedule length. While the link schedule determines the actual delays for each node, those two factors set the boundaries to link schedule optimization. Thus, it is important to try to choose such active topology that would lead to optimal schedule and path length combination.

1) Optimal fan-out: We have found that both of these factors depend on fan-out $k$, that is, number of active links per sector [9]. If we assume that all active links are carrying traffic and thus need time in the schedule, the link schedule
maximum path length $p$ in a network with $N$ nodes is related to $\max|p| \sim \log_k N$. By combining these two relations, it can be argued that maximum delay $d$ is approximately bounded by $\max d \sim k \log_k N$.

Actually, the situation is a bit more complicated, especially if we take partial mesh topology and spatial constraints into account (see [9] for detailed analysis). However, this relation holds quite well and it indicates that we should use a quite small number of active links (2–3) per sector.

2) Link selection algorithm: The active link selection algorithm works as follows:

1) All links are given weight value according to traffic estimates or actual traffic statistics
2) All GW nodes are set as starting points by inserting them to “current nodes” list
3) For each node in the list
   a) For each sector in the node
      i) Until max number of links have been added for the sector, add new link to topology if the other end of the link is connected to a RU with less than max no. of links
   b) Make a new “current nodes” list from the new nodes that were just added to active topology and repeat 3) until list is empty

If there are nodes that are left without any active links, the procedure can be repeated with increased maximum number of active links.

This is a greedy algorithm that operates without the global view. However, it seems to produce quite reliably such active network topologies that provide sufficient resilience as well as low worst case delays. This means that the resulting topology is such that the routing algorithm can find multiple node disjoint routes and the link scheduling algorithm can construct a short cyclic link schedule where all primary routes meet the delay constraint.

3) Constrained topologies: The link selection algorithm described above contains only one constraint, i.e., maximum number of links per sector. This does not limit the network topology besides setting an upper limit to node degree. As a consequence, there will be odd cycles that are know to be more difficult for link scheduling (ref. link coloring) than even cycles. We can force the network topology to contain only even cycles by ensuring that the network graph is bipartite. From the properties of bipartite graphs, it is known that a bipartite graph has an edge coloring using number of colors that is equal to maximum node degree $[10]$. This should make finding an optimal link schedule much easier.

One way to restrict network topology to bipartite graphs is to color vertices with two colors and to allow links only between differently colored vertices. The basic link selection algorithm can be modified to do vertex coloring incrementally as new nodes are being added to active topology. This requires two modifications:

1) Link availability depends not only on maximum number of links per sector but also node colors — link can be selected only if end-points are of different color, or the other end is colorless
2) If a link with a colorless end-point is selected, the colorless end-point is colored with the other color than the already colored end-point

In one sense, the selected WMN architecture is quite well suited for such coloring as each node can either transmit or receive at the same time. Thus, two-color vertex coloring can serve as a TX/RX schedule for WNs.

While it might be easier to find a link schedule for bipartite network topology, the overall impact on worst case delays, resilience, and network capacity is not so clear. This constraint may lead to sparser network and longer paths and thus it is necessary to evaluate both unrestricted and bipartite network cases.

B. Routing trees

We are using a multipath routing algorithm that is based on the earlier work presented in [5]. Routing is based on multiple spanning trees (MDST) that are constructed so that there are multiple node disjoint routes between each node and the GW nodes. MDST configuration is computed at WCC and distributed to WNs. Each WN uses MDST information to construct local forwarding tables that are used to make the route selection for each packet flow. In this way, the system can react to link failures immediately.

MDST computation uses a greedy algorithm that is quite similar to link selection algorithm. The process is composed of three phases:

1) The links (active links selected in the previous step) are weighted by computing shortest path from each WN to all GWS and allocating the estimated traffic to shortest path links.
2) Stems are constructed for each ST
   - All STs are rooted at GW node
   - Each link connected to GW serves as a starting point for a ST
   - New links are added to stems starting from highest weight
   - Each WN can belong to only one stem and the process end when all WNs belong to some stem
3) Each stem is expanded to a full ST by adding new links according to weight values.

While also this algorithm operates without global view, it tends to produce sufficient amount ($\geq 2$) of node disjoint routes. The main difference to the original algorithm is that all stems are grown at the same time instead of one GW at the time. This modification allows to algorithm to handle WMNs with high GW-to-WN ratios.

After MDST routing trees are generated, so called primary path is allocated to each plain WN. The primary path is usually
the lowest cost path to a GW node but if there are multiple (almost) equal cost paths then some coarse load balancing between GWs and routing trees can be done. These primary paths are given as an input to link scheduling process.

C. Link scheduling

Link scheduling is based on earlier algorithm presented in [6]. We are using short cyclic link schedule that is computed by WCC. So called transmission set defines which links can be active in a time-slot. The link schedule spans over multiple time-slots and contains different transmission sets that cover all the active links. The algorithm has two phases:

1) Construction of maximal transmission sets
2) Link schedule optimization by finding an optimal ordering for transmission sets

The new modification to this algorithm is that it is now clearly separated in to these two phases and a feedback loop to link selection step is added between them. Furthermore, the system constraint where all RUs in one node can either transmit or receive at a time is taken into account.

1) Construction of transmission sets: Transmission sets (TS) are generated using the GREEDYTWICE algorithm from [6]. The algorithm is based on selecting new, non-conflicting links to TS according to weigh values and favouring the links that are not yet included in any TS. The link weights are computed by counting how many primary paths cross a specific link. In this way, the most important links are given more importance in link selection procedure.

GREEDYTWICE requires few modifications to handle the TX/RX constraint. First of all, the links must be directional so that the TX and RX end-points can be defined in the link schedule. This was not necessary for 1 RU nodes that could use one time-slot for bi-directional communications. Furthermore, for each time-slot, the algorithm must define, which nodes are in TX mode and which in RX mode. Then the link selection must ensure that the end-points of the link are in correct TX/RX mode.

This modification is done by populating the link list, that is used by the algorithm, with directional links. In the original version there was just undirected link \((u, v)\) and now we are having two directed links \((u, v)\) and \((v, u)\). The link selection has an additional step, i.e., for link \((u, v)\):

- If \(u\) is in TX mode or \(v\) is in TX mode, link is rejected
- If TX/RX mode for \(u\) is not defined, the mode is set to TX
- If TX/RX mode for \(v\) is not defined, the mode is set to RX

For each TS construction round, TX/RX mode for all nodes are cleared and thus the link scheduling step also defines the TX/RX schedule for the nodes.

In the original algorithm, the new links are selected one by one. The same can be done with the multi-RU WMN but optionally we can try to select also link for all sectors for a node. This is done by an additional step to link selection: if a link is selected and it has an end-point without TX/RX mode set, the correct mode is set and one link for each free sector is selected if possible.

2) Feedback loop: The feedback loop is based on finding out, which links are causing a large number of transmission sets to be created to cover all links. As it happens, the GREEDYTWICE algorithm can used to perform this task by minor modifications. It turns out that the links that are last to be included to a transmission set, are the most likely “troublesome links”. Because they are selected last, it is likely that they have low weight value (i.e., they have lesser importance) and they are in conflict with many other links.

The feedback loop is activated at the end of transmission set construction. If the number of transmission sets is larger than a threshold value (e.g., 8), the links that were not included in any transmission set before the last round of GREEDYTWICE are added to “links to avoid” list. Then the whole routing and link scheduling process is restarted from “Select active links” step with this list as an input.

This is repeated until the number of transmission sets is within desired limits. In some pathological cases, adding links to “avoid” list may lead to a loss of network wide connectivity. In such cases, longer link schedules have to be accepted.

3) Link schedule optimization: The link schedule optimization procedure for multi-RU architecture is very similar to the previous one RU case. If the schedule length is short (e.g., \(\leq 8\)), a brute force method is used, i.e., all permutations are evaluated. For longer schedules, random shuffling and simulated annealing are applied. However, thanks to the new feedback loop, long link schedules are very rare.

While the link schedule is optimized only for primary paths, it turns out that other high order paths usually have low delays. The reason for this is that such paths contain only one unoptimized hop (the first one) while the rest of the path is an optimized primary path for neighboring node.

IV. Tests

Test were conducted using actual WCC code that is written in Python. The code uses mainly standard Python libraries but NetworkX [11] is used to provide some basic data structures for network topology operations and PyMongo for accessing network topology and configuration database at WCC.

We are evaluating four different strategies denoted by BS: bipartite topology, select links one by one, BA: bipartite topology, select all available links, FS: free form topology, select links one by one, FA: bipartite topology, select all available links.

A. Topology model

We are using 2.5D model where location of each node is defined by three coordinates but all antenna planes must be perfectly vertical. The topology model is trying to emulate normal urban environment.

As there are virtually no existing reference topologies with fixed node locations, we are using a topology generator to make sample network deployments that should have the typical
dense urban are characteristics. We are assuming that the WMN BH network would contain three types of nodes:

- Street level nodes that have limited range due to blocking
- Roof-top nodes that have better range due to higher placement and that can provide BH connectivity to street level nodes
- Gateway nodes that have the best visibility to other nodes as they are, e.g., co-located with macro cell base stations

The core of the topology generator is a simple perturbed grid generator which is used to create nodes for each of the three layers. The layers are differentiated by defining different grid sizes and height ranges for each layer. In practise, the street level has smallest grid cell size that results in largest number of nodes while there will be only a few GW layer nodes. The grid cell size of the intermediate roof-top level is something between the two other layers. After the node locations are generated, each node pair is evaluated if there is a link between them. This depends on the distance of the nodes as well as their z-coordinate that are used to calculate a probability of LOS between the nodes. A uniformly distributed random value is then drawn to decide if the link exists or not.

For the following evaluations, we have a set of 16 networks with number of nodes ranging 66–70 and number of links 284-504. All networks have 4 GW nodes.

B. Runtimes

The runtimes of generation of new network configuration were evaluated in “Mid 2015” Apple MacBook Pro with 4-core 2.8 GHz Intel Core i7 CPU and by using PyPy 6.0.0. The runtimes were measured by utilizing `getrusage()` function from `resource` library. The distribution of runtimes is shown in figure 4 (top panel). The overall observation is that on the average the runtimes are relatively low and thus a new network configuration can be computed whenever needed. When different strategies are compared, it seems like that having minimal constraints (FS) leads to consistent runtimes. However, the longest runtimes are caused by one network topology and we will investigate if the algorithm could be improved to handle such cases better.

C. Link selection and feedback loop

The distributions of the ratio of selected links (“links in selected topology”/“links in original topology”) are shown in figure 4 (bottom panel). While bipartite graph topologies lead to shorter runtimes, it seems like it the cost is that the resulting network has clearly less links compared to free form network.

The feedback loop was activated 4 times in 64 test runs (4 strategy combinations × 16 sample networks) and most often one round of feedback loop was sufficient. While the size of the “links to avoid” set was up to 56, the count of selected links reduced minimally after new rounds of active link selection. Histograms of “links to avoid” set size and reduction in selected link count are shown in figure 5. The results seem to indicate that the proposed feedback loop is very efficient in removing conflicting links from the topology and, at the same time, finding new alternative links to avoid reduction in connectivity.

D. Path delays

The primary path delays for different strategies in both downstream and upstream directions are shown in figure 6. There seems to be very few differences between different strategy combinations. This would indicate that while it should be easier to find an optimal link schedule for a bipartite graph topology, it does not matter when all the factors are combined. Thus, the selection of the best strategy should be based on, e.g., reliability of the resulting network configuration.

The distribution of the downstream delays for one network using “bipartite” and “allocate all links at once” strategy is
shown in figure 8. This distribution indicates that the process produces a large number of alternative paths that provide low delays. Thus, paths can change due to faults or congestion with minimal effect on transport delays.

The introduction of feedback loop should have positive effect on path delays. However, the nodes with rejected links could suffer due to potentially longer paths to GW. In figure 8, the distributions of changes in delays of primary paths are shown. The comparison is between optimized schedules before and after feedback loop. As it can be seen, the shorter link schedule resulting from feedback provides delays that are on average two time slots shorter. In few cases, the delays have increased up to four time slots but this can be allowed as the worst case delay went down in all cases by 1–2 time slots.

E. Disjoint paths

The distributions of node disjoint paths and nodes without disjoint paths are shown in figure 9. The distributions seem to be more or less identical which indicates that in this case bipartite network topology would not impose any penalties on reliability.

F. Capacity

The total network capacity is related to the number of active links in each time slot. The results for different strategies are shown in figure 10. It seems like that the number of active links is closely related to the ratio of selected links (figure 4) and thus the bipartite graph topology does not provide any advance over free form network. It seems that the
feedback loop is so efficient in removing “hard to schedule” links that the remaining odd cycles in free form networks do not cause any noticeable inefficiencies in link schedules. Thus, the conclusion seems to be that forcing bipartite graph topology does not provide any real benefits but results in reduced total network capacity. However, the real throughput is not necessarily 1:1 related to the number of active links and dynamic simulations would be needed to find out the exact figures.

Figure 10. Distribution of the average number of active links in one time slot.

V. SUMMARY

A new process to compute routing topology and link schedule for SWMN is presented in this paper. The main contributions to existing algorithms is a new active link selection algorithm and a feedback loop from link scheduling to that phase. Together these features allow for selecting a suitable subset of links that are used to transport traffic. The results of evaluation runs with a set of randomly generated networks indicate that avoiding “hard to schedule” links via feedback loop does not reduce the number of selected links noticeably.

The other modification to existing algorithms is to add support for nodes with multiple RUs with a constraint that all RUs at a node can either transmit or receive at the same time. When the algorithms were modified for this, it was thought that free form networks with odd cycles could cause problems for finding an optimal link schedule. Networks with bipartite graph topology should be easier to schedule and thus an optional constraint was added to active link selection algorithm. However, the evaluation results show quite clearly that free form networks have much better performance which emphasize the efficiency the feedback loop.

The overall results did show that the original target of minimizing the worst case delay and proving multiple almost equal cost paths can be achieved with these new and modified algorithms.

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