Automatic Planning Algorithm of 300 GHz Backhaul Links Using Ring Topology

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Abstract—In the future, the base stations are expected to be deployed with higher density. To save cost and man forces, wireless links operating at 300 GHz can replace conventional cable-based backhaul connections. One of the goal of Horizon 2020 EU-Japan project ThoR is to design automatic planning tools for 300 GHz wireless backhaul network. To accomplish this task, a novel planning tool has been developed to plan backhaul links with the usage of a ring topology. To evaluate the proposed tool's functionality, system-level simulations are conducted with an in-house developed mobile network simulator. In this paper, the algorithm of the new planning tool for 300 GHz wireless backhaul network is introduced and the SINR characteristics of the planned THz links are evaluated using 3D ray optical path loss predictions. For that, a realistic scenario of an ultra-dense cellular network in Hanover, Germany, is used with the diverse tropospheric climate conditions.

Index Terms—THz communication, Sub-mm communication, automatic planning algorithm, wireless backhaul network, ring topology.

I. INTRODUCTION

According to [1], the demand of mobile data traffic of user devices steadily increased and is expected to reach up to 164 exabytes per month by 2025. Furthermore, the usage of mobile devices shows a tendency towards data rate critical services such as video streaming. One of the most promising options to support the high traffic requirements is to install more base stations and thus create a denser network to reduce the coverage area of an individual cell. Apparently, the data traffic has to be transferred between the base stations and the backbone network. This communication channel is so called backhaul link and it should support up to tens of Gbit/s of aggregated data.

Based on IEEE Standard 802.15.3d in 2017 [2], above 100 Gbit/s data transmissions are viable using 300 GHz frequency spectrum range, so called THz or sub-mm frequency. ThoR will support technical solutions for such a high data transmission and thus is working towards the demonstration of the feasibility and the scalability of the full IEEE standard.

The common way of providing the communication channels between base stations and the backbone network is using underground fibre connections. It is however too costly and time-consuming to link base stations and the backbone network with those wire connections. Furthermore, in some cases, it is not feasible to use cables due to some geographical issues or inappropriate circumstances. Regarding this matter,

backhaul links via radio channel are an attractive alternative for network operators. By substituting wireless backhaul links for fibre backhaul connections, network operators can reduce the total amount of a capital expenditure (CAPEX) as well as an operating expense (OPEX).

While manually planning wireless backhaul connections for a simple network might be possible, it is however obviously not an option for complex networks such as dense heterogeneous cellular networks in metropolitan areas. For such a network, an automatic planning tool is eligible to plan the backhaul links efficiently. In [3], a planning algorithm for 300 GHz wireless backhaul network has been introduced as one of the time saving and cost effective interlinking method based on the star topology. A star topology is a networking configuration concept in which nodes are individually connected to a central hub. It has however a huge drawback due to its constellation feature: a lack of redundancy. This absence of redundancy leads to the burst cell outages in complete area if one single cell site with fibre connection (anchor site) goes out of service. Then, all of the base stations wirelessly connected to this anchor cell sites consequently go out of service. For this reason, a new algorithm has been developed considering a ring network pattern. In a ring networking topology, each nodes are connected to two other nodes and shaping a single ring pathway. With this new feature, the automatically planned backhaul network operates more stable in terms of link failure since a redundancy of wireless links is secured by the ring shape configuration. Furthermore, the flexible assignment of the anchor cell sites is another beneficial consequence of the new algorithm. In the following section of this paper, the planning algorithm for 300 GHz wireless backhaul network using a ring topology is introduced and its performance is evaluated by conducting system-level simulations in a realistic network environment.

II. APPROACH

As wired backhaul connections are cost-intensive and time-consuming, the general concept of the given automatic planning algorithm is to reduce the number of fibre backhaul connections of the given cells as much as possible (i.e., the optimization factor of this algorithm is to reduce entire cost). The optimization factor This is done by heuristic process in such a way that so called anchor sites will provide wireless backhaul connections to the rest of given cells by relaying 300 GHz

wireless links. This will lead to a minimization of the number of fibre backhaul connections that would be provided only for anchor sites. The performance of the suggested algorithm is evaluated through system-level simulations by investigating signal-to-interference-plus-noise-ratio (SINR) values of every single links considering diverse weather conditions.

III. AUTOMATIC PLANNING ALGORITHM

The overall principle of the developed automatic planning algorithm is identical to the one suggested in [3]. There are many aspects which affect the system's performance. In this paper, for identifying suitable wireless backhaul links, the automatic planning tool considers mainly three factors: maximum distance of wireless links, line-of-sight (LoS) condition between two antennas and a safety margin for angle between adjacent antennas. The basic assumption of the currently developed automatic tool is that the THz wireless links are only affordable in case of the LoS condition due to the high path loss of the THz waves. Further, the maximum wireless link distance ensures that the received power of the radio signal exceeds the required receiver sensitivity. This ensures an error free reception at the Rx. The safety margin for angle between adjacent antennas guarantees that the signals of two distinguished links on the same cell sites cannot strongly interfere each other. During the computation, two antennas are considered to face the same direction if the difference of the spherical angle of an antenna pair is less than the safety margin.

To give a general overview of the automatic planning tool, a simplified algorithm flow is provided in Fig. 1. As it can be seen, the overall procedure of the automatic planning algorithm with ring topology consists of five steps.

First, the algorithm identifies the neighbour cell sites of the each of the given cell sites. Doing so, LoS conditions between the cell sites and the maximum wireless link distance are taken into account for setting up the neighbour list.

Once this is done, the algorithm tries to find all possible cliques based on the neighbour list that has been previously achieved. Here, the term of clique refers to a sub-cluster of nodes in which every pair of nodes within the sub-cluster are adjacent. To complete this task, a recursive method of Bron-Kerbosch algorithm [4] has been used.

In the third step, the cliques are extended with a heuristic searching algorithm. In this context, the extension of cliques means that several cliques are merged in such a way that allows them to build a ring shape. The automatic planning tool picks a cell randomly and gathers all cliques which contain the chosen cell site. While doing this, all cliques with two nodes are collected as well. From the result of this process, the automatic tool tries to find a possible combination of these multiple cliques with a heuristic procedure. In every single merging step, the tool checks for a Hamiltonian-cycle. If such a cycle is found, the cliques are merged and extended. The size of merged cliques is limited by a predefined number of allowed hops to limit the accumulated delay. In the simulations, the number of maximum hops is provisionally set to ten. This

process is repeated until every cell site has been selected at least once and examined for the extension of cliques.

In the fourth step, the algorithm attempts to find the minimum set of extended cliques. Thereby, the possibly shortest path length within the extended clique is selected under consideration of the safety margin of the angle between adjacent links. In order to ensure that the minimum number of cliques is picked, the cliques are selected in a descending order of the number of mutually overlapped nodes (cell sites) without backhaul connection. At this state, a random decision is unavoidable. Therefore, the fourth step is iterated to provide a diversity of the automatic planning of a backhaul network.

After this, the final decision of the backhaul network is completed according to the operator's policy.

Fig. 1. A simplified flow of the automatic planning tool with ring topology.

IV. SIMULATION ENVIRONMENT

A. Simulation Scenario

To analyse the automatic planning tool's performance, a scenario of ultra-densely deployed base stations specified in [5] is used for the system level simulation. This scenario contains a high traffic demand zone in Hanover, Germany such as the main train station, commercial promenade, the business quarter as well as residential district. In this scenario, 300 new cell sites have been randomly deployed at 1m height above the roof top of the buildings. The building data in Hanover region and the location of cell sites are visualized in Fig. 2.

Fig. 2. 2D map of the simulation scenario in Hanover, Germany with UTM coordinates.

B. Simulation tool

The system-level simulation is accomplished with the help of an in-house developed simulator for mobile networks (SiMoNe) [6]. It has been originally developed for simulating realistic cellular networks with hundreds of radio cells and thousands of mobile subscribers. Considering the various interaction types of waves, the simulator finds the existing paths between cell sites based on the 3D ray-tracing method with collaboration of 3D building data. Consequently, it determines multiple indicators such as received power, power delay profile, angle of departure and angle of arrival.

C. Propagation channel model

The propagation behaviour of Thor's target transmission frequency of 300 GHz is distinguished by the commonly used frequency range for the current mobile communication. In the 300 GHz spectrum range, rays suffer more sensitively from the atmospheric environment. The following factors are considerable components to arise the additional attenuation on the propagating radio signal at the THz frequency range.

- Water vapour and oxygen content of air
- Droplets of rains
- Liquid content of clouds and fogs

To compute the influences of the tropospheric climate on the radio signal, the mathematical models recommended by ITU [7],[8],[9] were integrated into the simulator.

D. 3D Antenna Model

In addition to the atmospheric attenuation at 300 GHz carrier frequency, propagating rays are subject to the high free-space path loss (FSPL) of approximately 122 dB at a distance of 100 m. To compensate for the high FSPL, high gain antennas even up to 50 dBi both on Tx and Rx are indispensable.

To achieve realistic simulation results, SiMoNe requires a antenna pattern. An antenna diagram of 50 dBi antenna based on ITU mathematical model [10],[11] is used for that

purpose, as seen in Fig. 3. The antenna diagram provides 1 degree accuracy in the range from -180 to 180 degrees in the azimuth angle and -90 to 90 degrees of the elevation angle. After the ray-tracing optical path loss computation, the results are overlaid with the given antenna diagram using bilinear interpolation to account for the intermediate values.

Fig. 3. Mathematical model of antenna pattern of 50 dBi antenna recommended by ITU.

V. SIMULATION RESULTS

The preliminary results of the automatic planning algorithm are visualized in Fig. 4. In this figure, the red points indicate anchor cell sites that require fibre connection since they do not fulfil the preconditions for a wireless backhaul connection, while blue points indicate cell sites with possible 300 GHz backhaul connection in ring formation. The wireless connections between cell sites coloured in blue are represented by the green lines.

In Fig. 4, the internal anchor cell sites of each single ring constellation are not indicated since the anchor cell sites can be flexibly designated within the ring network's element. For this result, the average wireless link distance of planned backhaul network is approximately 144 m.

A comparison of the automatic planning algorithm's efficiency of the ring topology and the star topology is resulted in the given table I and this is accomplished by the number of required anchor cell sites and the number of 300 GHz wireless links.

TABLE I
COMPARISON OF TWO TYPES OF NETWORKING TOOLS

	Networking topology	
	Star	Ring
Number of anchor sites	88	143
Number of wireless links	212	410

Using the same simulation environment, the star topology results in 88 anchor sites and 212 wireless links. In contrast, 143 anchor sites and 410 wireless backhaul links are required

Fig. 4. Result of backhaul network with automatic planning algorithm.

for ring topology. The required number of anchor cell sites with the ring topology is however driven with the assumption that two orthogonal cell sites within the single ring pathways are selected as anchor sites. In case of just one anchor site (no redundancy), the required number is reduced down to 81. The number of wireless links with ring topology is almost doubled comparing with the one with star topology. This stems from constellation shapes of the networking topology. Star topology requires one wireless connection to link a node with a central hub (anchor), while ring topology requires two wireless connection at each node in order to interlink the nodes into ring shape.

Fig. 5. Histogram of the number of single way ring path elements.

Fig. 5 shows a histogram of the number of ring path elements. Here, the x-axis shows the number of elements within a ring shaped backhaul network and its probability is indicated in y-axis. About one half of ring pathways of planned network contain ten nodes which is the pre-defined value for maximum components of the ring shape. This is the case because the automatic tool tries to find extended cliques with the highest possible number of elements as ring candidates

first in order to reduce the number of required anchor cell sites.

In Fig. 6, SINR values of planned links are shown under the consideration of multiple weather conditions. The wireless

Fig. 6. SINR values of the planned backhaul network under various weather conditions.

backhaul network is the fundamental of the network's stability and functional performance and therefore the SINR values are important to ensure high throughput for the wireless links. Since the wireless backhaul links are a typical outdoor application case, the reliability of backhaul networks should be ensured through the whole year regardless of long-term seasonal climate changes as well as short-term extreme meteorological events. For that, various categories of weather conditions were taken into account for simulations. The standard clear weather condition (neither rain nor cloud and fog) were assumed with 15 °C temperature and 7.5 g/m³ standard ground-level surface water vapour density [7]. Two types of raining conditions were assumed with 20 mm/h and 50 mm/h rain rate labelled, as heavy rain and extreme rain case respectively. Besides, a hazy weather condition together with 0.5 g/m³ of liquid water vapour density inside of cloud and fog is set as a cloudy weather condition with typical visibility range of 50 m. Herewith, for the transmission, 5 GHz is assumed as a standard bandwidth of the transmission signal, and an additional curve with 50 GHz bandwidth under extreme raining conditions (50 mm/h) has been considered as the worst case. The impact of weather conditions on the reliability of wireless backhaul networks is clearly seen in this figure.

It is remarkable though that SINR values of automatically planned backhaul links mostly exceed 22 dB, which is the standard demand for SINR level defined in [2] and enables the usage of the highest modulation and coding scheme. Here, approximately 99.4 % of links exceed the standard demand of SINR value under any weather condition with 5 GHz bandwidth, while even almost 99 % of the links with 50 GHz bandwidth and 50 mm/h rain rate satisfy this value. However, this is not to say that under 1 % of the wireless links go fail. They are operating anyway with the suitable modulation and coding schemes. This leads to the conclusion that even under

severe weather conditions, wireless backhaul connections at 300 GHz maintained their links stable and are therefore a feasible substitute for the conventional cable-based links.

VI. CONCLUSION

In this paper, a novel approach for the automatic planning of wireless backhaul links with ring topology is suggested for cellular networks. The suggested method automatically solves the backhaul networking problem in such that it identifies as many base stations as possible, whose backhaul links can be provided via 300 GHz wireless links from the conventional fibre backhauled base stations. This method compared favourably with the proposed algorithm based on the star topology in the previous work [3]. Firstly due to the redundancy, a ring topology brings better performance in terms of cell outage reliability than a star topology. Furthermore, anchor cell sites with fibre connection can be flexibly assigned in ring topology. The backhaul network's performance was analysed under various atmospheric conditions in terms of achieved SINR values. This revealed that approximately 99% of the wireless links with large bandwidth reached the required SINR value for the highest modulation and coding schemes delineated in [2] even under the extreme weather condition. The proposed tool showed slightly better performance compared to the star topology based approach. By use of the automatic planning algorithm with ring topology, the backhaul links of around 73% of the cell sites can be replaced by the 300 GHz wireless links providing one anchor cell sites on each ring line, while roughly 71% of cell sites replaced using same environment with star topology. This tool demonstrated that 52% of wireless links could be replaced by wireless link under the assumption that two totally orthogonal cell sites would be used as fibre backhauled cell sites in every ring. Future work within the ThoR project is to develop the suggested automatic planning tools more sophisticated way and to consider the design of non-line-of-sight (NLOS) links as THz backhaul links as well. With this work, the backhaul network system's performance is expected to be enhanced even further.

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