Wireless Backhaul Node Placement for Small Cell Networks

Muhammad Nazmul Islam, Ashwin Sampath* , Atul Maharshi*, Ozge Koymen* and Narayan B. Mandayam
WINLAB, Rutgers University, Email: {mnislam,narayan}@winlab.rutgers.edu
* Qualcomm Corporate R&D, Email: {asampath,atulm,okoymen}@qti.qualcomm.com

***Abstract*—Small cells have been proposed as a vehicle for wireless networks to keep up with surging demand. Small cells come with a significant challenge of providing backhaul to transport data to(from) a gateway node in the core network. Fiber based backhaul offers the high rates needed to meet this requirement, but is costly and time-consuming to deploy, when not readily available. Wireless backhaul is an attractive option for small cells as it provides a less expensive and easy-to-deploy alternative to fiber. However, there are multitude of bands and features (e.g. LOS/NLOS, spatial multiplexing etc.) associated with wireless backhaul that need to be used intelligently for small cells. Candidate bands include: sub-6 GHz band that is useful in non-line-of-sight (NLOS) scenarios, microwave band ($6-42$ GHz) that is useful in point-to-point line-of-sight (LOS) scenarios, and millimeter wave bands (e.g. 60, 70 and 80 GHz) that are recently being commercially used in LOS scenarios. In many deployment topologies, it is advantageous to use aggregator nodes, located at the roof tops of tall buildings near small cells. These nodes can provide high data rate to multiple small cells in NLOS paths, sustain the same data rate to gateway nodes using LOS paths and take advantage of all available bands. This work performs the joint cost optimal aggregator node placement, power allocation, channel scheduling and routing to optimize the wireless backhaul network. We formulate mixed integer nonlinear programs (MINLP) to capture the different interference and multiplexing patterns at sub-6 GHz and microwave band. We solve the MINLP through linear relaxation and branch-and-bound algorithm and apply our algorithm in an example wireless backhaul network of downtown Manhattan.**

***Index Terms*—Small cell networks, wireless backhaul, network optimization, millimetre wave, microwave, large MIMO.**

I. Introduction

Demand for wireless services is increasing rapidly. Some industry and academic experts predict a 1000-fold demand increase by 2020 [1], [2]. Improvements in physical layer alone cannot sustain such high data rate [2], [3]. Extreme densification of heterogeneous small cells is necessary to meet this demand [4]. Small cells come with a significant challenge of providing backhaul to transport data to(from) a gateway node (node with existing fiber point, often co-located with a macrocell) in the core network. Fiber based backhaul offers the high rates needed to meet this requirement, but is costly [5] and time-consuming to deploy, when not readily available.

Wireless backhaul can be a valuable option in this regard. One needs to utilize the available bands judiciously to attain the maximum advantage of wireless backhaul. There are multiple candidate bands for wireless backhaul: first, sub-6 GHz band that is useful in non-line-of-sight (NLOS) point-to-multipoint scenarios, microwave band ($6-42$ GHz) that is useful in line-of-sight (LOS) point-to-point scenarios and is currently going through experimental research in NLOS scenarios [6], and millimetre wave band (60, 70 and 80 GHz) that is recently being commercially used in LOS scenarios. Small cells that are located at lamp posts, street corners, low rooftops, etc., may not have line-of-sight (LOS) path to the gateway nodes. An effective way to utilize the available bands for wireless backhaul is to place aggregator nodes at the tall buildings that are located close to small cells. Aggregator nodes can provide high data rate to multiple small cells in NLOS paths, sustain the same data rate to gateway nodes using LOS paths and take advantage of all available bands. Fig. 1 shows the importance of aggregator nodes.

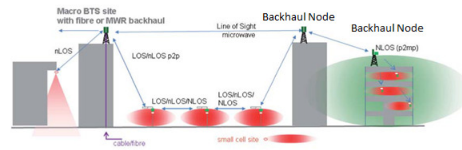

Fig. 1. The macrocell is located at the second building from the left and it has fiber connection. The red bubbles denote coverage of the small cells. The small cells located at the left side can directly communicate with the macrocell. The small cells located at the right side do not have good one-hop wireless links with the macrocell and require routing through backhaul nodes to reach the macrocell. This figure is reproduced from [7]

Deployment of aggregator nodes in roof tops of tall buildings consume operational leasing cost. The network operator needs to minimize the operational expenses while ensuring the network connectivity between the small cell and the gateway node. Hence, optimal aggregator node deployment and network connectivity design to minimize the operational expenses is essential for small cell networks.

We perform joint cost optimal aggregator node placement, power control, channel scheduling and routing to minimize operational expenses of the overall network. We develop a mixed integer non-linear programming (MINLP) formulation and then convert the MINLP to a mixed integer linear program (MILP) using linear relaxation techniques. We apply the MILP based optimization results to solve the network connectivity in an example downtown Manhattan scenario.

A. Related Works

Relay or aggregator node placement problems have appeared in different scenarios, such as wireless sensor networks (WSN) [8], [9], wireless local area networks (WLAN) [10] and IEEE 802.16j WiMAX networks [11], [12].

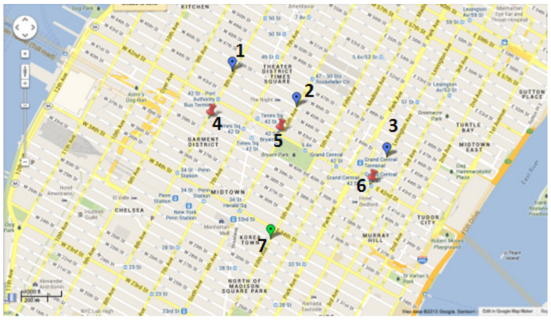

Fig. 2. An example wireless backhaul network in downtown Manhattan scenario. Blue, green balloons and red markers denote edge, gateway and candidate aggregator node locations respectively. Our objective is to minimize the aggregator node deployment cost while ensuring the network connectivity between edge and gateway nodes. Figure taken from [13]

In [8], the authors assume a radius coverage based propagation model, and deploy sensor and relay nodes optimally among an unconstrained number of candidate locations to solve the connectivity and routing problem. The authors of [9] deploy sensor and relay nodes among a constrained set of candidate locations but assume a radius coverage based propagation model. The authors of [10] solve the relay placement problem in WLAN with uniformly distributed mobile users. In [12], the authors solve relay placement problem in IEEE 802.16j networks while assuming an arbitrary user distribution and distance based propagation. The authors of [11] also focus on IEEE 802.16j networks, assume nomadic relay nodes and place relays for time varying user demand.

Backhaul node placement in urban small cell networks differs from the mentioned relay placement problems in the following aspects. First, link gain between a candidate aggregator location and two nearby small cells in a metropolitan setting can vary significantly because of difference in diffraction angles. Coverage radius based backhaul node placement becomes inapplicable. Second, a large subset of relay placement algorithms that assume an unconstrained number of candidate locations cannot be applied here since only a subset of building rooftops can be leased. Third, both sub-6 GHz and microwave bands are candidate spectrum for future generation small cells. The nature of interference pattern and spatial multiplexing capability varies between the two scenarios and leads to different network optimization problems. Our work encapsulates all these features. We assume an interference free region and time/frequency division multiple access while considering microwave band, and protocol interference model with space division multiple access while considering sub-6 GHz band. Using these assumptions, we optimize the wireless backhaul network in a metropolitan scenario.

The paper is organized in the following way: Section II shows interference pattern at different bands. Section III and IV show the network optimization problems in microwave band based backhaul and sub-6 GHz band based backhaul respectively. Section V presents how we solve the network optimization problems through linear relaxation techniques and branch-and-bound algorithm. After showing the simulation results in section VI, we conclude in section VII.

II. Interference Models

Throughout this work, we denote small cells by edge nodes (EN) and backhaul nodes by aggregator nodes (AN). We assume that aggregator nodes communicate with gateway nodes in millimeter band using LOS path. Edge nodes can connect with aggregator or gateway nodes in microwave band or sub-6 GHz band using NLOS path. We use 5.8 GHz band, 28 GHz band and 60 GHz as representatives of sub-6 GHz, microwave and millimeter wave band respectively.

A. Interference limited versus interference free setting between edge and aggregator/gateway nodes

Typically, the antennas that operate at 28 GHz have high gain and very narrow beam width. We assume that aggregator nodes perform switched beams and cannot communicate with multiple edge nodes at the same time slot. On the other hand, due to the narrow beam width at both transmitter and receiver antennas, substantial interference suppression is achieved between non-adjacent links, i.e., two links that do not share a common node. We consider time/frequency division multiple access and interference free regime while considering microwave band between edge nodes and aggregator nodes.

The antennas that operate at sub-6 GHz typically come with wide beam width. An aggregator node can communicate with different small cells simultaneously using space division multiple access (SDMA) techniques. However, edge nodes that intend to communicate with a particular aggregator node generate interference to neighbouring aggregator nodes. We consider the spatial multiplexing capability of aggregator nodes and use a power control based protocol interference model to capture the interference pattern in sub-6 GHz band.

B. Interference free setting between aggregator and gateway nodes

We assume that aggregator nodes - located at the roof tops of tall buildings - get LOS paths to gateway nodes and can use millimeter band for communications to/from the gateway nodes. Typically, the antennas that operate at millimeter wave band have narrow beam width. We assume that non-adjacent links do not interfere with each other and nodes cannot perform space division multiple access due to the complexity of multi-beam operation. Hence, similar to the microwave band, we assume an interference free setting and time/frequency division multiple access based fractional resource allocation in the links that connect aggregator and gateway nodes.

The next two sections provide the network optimization formulations in the following two scenarios: first, edge nodes communicating to aggregator or gateway nodes using microwave band and second, edge nodes communicating to aggregator or gateway nodes using sub-6 GHz band.

Notation	Description
$\mathcal{N}$	Set of all nodes
$\mathcal{EN}$	Set of edge nodes
$\mathcal{AN}$	Set of aggregator nodes
$\mathcal{GN}$	Set of gateway nodes
y_j	Binary decision variable for AN deployment
c_{y_j}	Operational expense of deployment at node j
$\mathcal{M}_{5.8}$	Set of channels at 5.8 GHz
M	Number of channels
f_{ij}	Flow between channel i and j
d_i	Demand of edge node i
W	Bandwidth of each channel
N_0	Noise spectral density
p_{ij}^m	Allotted power between node i and j in channel m
g_{ij}^m	Link gain between node i and j in channel m
x_{ij}^m	If node i and j communicate in channel m
x_j^m	If node j uses channel m
x^m	If channel m is used
T_j	Maximum number of radios at node j
C_{p_i,W_j}	Capacity of link evaluated at power p_i and bandwidth W_j

TABLE I
LIST OF NOTATIONS

III. MICROWAVE BAND IN NLOS PATHS - INTERFERENCE FREE NETWORK OPTIMIZATION

We consider a two-hop network with $\mathcal{EN}$ set of edge nodes and $\mathcal{GN}$ set of gateway nodes. Edge nodes act as sources (sinks) and gateway nodes act as sinks (sources) of data traffic in the uplink (downlink). Let $\mathcal{AN}$ denote the set of possible node locations of aggregator nodes. Aggregator nodes just relay data between sources and sinks. Fig. 2 shows an example wireless backhaul network in downtown Manhattan.

Let us focus on the uplink of a backhaul network. Assume that d_i denotes the demand of each small cell. Let W_{ij}, p_{ij} and f_{ij} denote the allotted bandwidth, power and flow of link ij respectively. Let y_j denote a binary decision variable at node j, i.e., it represents whether one should place an aggregator node at the candidate location j. Let $W_{max,b}$ and $p_{max,b}$ denote the maximum allowed bandwidth and power *per radio* in band b. Node j can deploy up to T_j number of radios. Table I summarizes the list of notations.

Fig. 3 shows the network optimization formulation of this scenario. Eq. (1a) denotes the objective function where we minimize the aggregator node deployment cost. Eq. (1b) and (1c) denote the flow conservation constraints. First, each edge node's outgoing data traffic to the aggregator nodes and gateway nodes should equal the edge node's demand. Second, each aggregator node's incoming flow should equal its outgoing flow. Eq. (1d) and (1e) couple the flow, bandwidth and power variables at each link. It is assumed that edge nodes use 28 GHz and aggregator nodes use 60 GHz. Equation (1f)-(1i) denote the maximum available bandwidth and power constraints at each node. Equation (1g) couples all other constraints with the the aggregator node deployment variable of the optimization objective. Equation (1j) describes the variables of the optimization problem.

The optimization problem of Fig. 3 is a mixed integer non-linear program (MINLP). Next, we describe the optimization formulation of sub-6 GHz transmission based networks.

$$\min \sum_{j \in \mathcal{AN}} c_{y_j} y_j \tag{1a}$$

$$\sum_{j \in \mathcal{AN}} f_{ij} + \sum_{k \in \mathcal{GN}} f_{ij} = d_i \quad \forall i \in \mathcal{EN} \tag{1b}$$

$$\sum_{i \in \mathcal{EN}} f_{ij} = \sum_{k \in \mathcal{GN}} f_{jk} \quad \forall j \in \mathcal{AN} \tag{1c}$$

$$f_{ij} \le W_{ij} \log_2\big(1 + \frac{p_{ij} g_{ij,28}}{N_0 W_{ij}}\big) \ \forall i \in \mathcal{EN}\,, \forall j \in \mathcal{AN}, \mathcal{GN} \tag{1d}$$

$$f_{ij} \le W_{ij} \log_2\big(1 + \frac{p_{ij} g_{ij,60}}{N_0 W_{ij}}\big) \ \forall i \in \mathcal{AN}\,, \forall j \in \mathcal{GN} \tag{1e}$$

$$\sum_{j \in \mathcal{AN}, \mathcal{GN}} W_{ij} \le W_{max,28}\,, \sum_{j \in \mathcal{AN}, \mathcal{GN}} p_{ij} \le p_{max,28} \ \forall i \in \mathcal{EN} \tag{1f}$$

$$\sum_{i \in \mathcal{EN}} W_{ij} \le y_j \cdot T_j W_{max,28} \ \forall j \in \mathcal{AN} \tag{1g}$$

$$\sum_{i \in \mathcal{EN}} W_{ij} \le T_j \cdot W_{max,28} \ \forall j \in \mathcal{GN} \tag{1h}$$

$$\sum_{k \in \mathcal{GN}} W_{jk} \le W_{max,60}\,, \sum_{k \in \mathcal{GN}} p_{jk} \le p_{max,60} \ \forall j \in \mathcal{AN} \tag{1i}$$

$$f_{ij}, W_{ij}, p_{ij} \ge 0 \, \forall (i,j) \in \mathcal{E}\,, y_j \in \{0,1\} \ \forall j \in \mathcal{AN} \tag{1j}$$

Fig. 3. Network optimization formulation when edge and aggregator nodes communicate in an interference free setting

IV. SUB-6 GHZ IN NLOS PATHS - PROTOCOL INTERFERENCE BASED NETWORK OPTIMIZATION

Due to the wide beam width of antennas at sub-6 GHz, non-adjacent links can interfere with each other. To tackle this interference, we split the overall bandwidth at sub-6 GHz into a set of discrete channels. The edge nodes use these channels to communicate with aggregator or gateway nodes. We schedule and allocate power in these channels optimally so that non-adjacent links do not interfere with each other.

Let x_{ij}^m, p_{ij}^m and g_{ij}^m denote the binary scheduling variables, power allocation and gain at link ij in channel m respectively.

$$x_{ij}^m = \begin{cases} 1, & \text{if node } i \text{ transmits to node } j \text{ using channel } m. \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

We use protocol interference model in our work. Assume that node i transmits to node j in channel m, i.e., $x_{ij}^m = 1$. Another node k can transmit to node h in channel m if p_{kh}^m causes negligible interference in node j.

$$p_{kh}^m + (p_{max} - \frac{P_I}{g_{kj}^m}) x_{ij}^m \le p_{max} \, \forall \, k \in \mathcal{N},\, h \in \mathcal{N},\, k \ne h \tag{3}$$

where P_I is the interference threshold.

Due to the wide beam width of sub-6GHz antennas, an aggregator or gateway nodes can cover multiple edge nodes using SDMA technology. Hence,

$$\sum_{i \in \mathcal{EN}} x_{ij}^m \le A\,, \forall m \in \mathcal{M}_{5.8}\,, \forall j \in \mathcal{AN}, \mathcal{GN} \tag{4}$$

$$\min \sum_{j\in\mathcal{AN}} c_{y_j} y_j \tag{5a}$$

Equations (1b), (1c), (1i), (1e).

$$f_{ij} \leq \sum_{m\in\mathcal{M}_{5.8}} W \log_2\big(1+\frac{p_{ij}^m g_{ij}^m}{N_0 W}\big) \quad \forall i\in\mathcal{EN}\,, \forall j\in\mathcal{AN},\mathcal{GN} \tag{5b}$$

$$p_{kh}^m + (p_{max} - \frac{P_I}{g_{kj}})x_{ij}^m \leq p_{max} \quad \forall k\in\mathcal{EN},\, h\in\mathcal{AN},\mathcal{GN},\, k\neq i,\, h\neq j \tag{5c}$$

$$\sum_{i\in\mathcal{EN}} x_{ij}^m \leq A y_j\,, \forall m\in\mathcal{M}_{5.8}\,, \forall j\in\mathcal{AN} \tag{5d}$$

$$\sum_{i\in\mathcal{EN}} x_{ij}^m \leq A\,, \forall m\in\mathcal{M}_{5.8}\,, \forall j\in\mathcal{GN} \tag{5e}$$

$$\sum_{j\in\mathcal{AN},\mathcal{GN}} \sum_{m\in\mathcal{M}_{5.8}} x_{ij}^m \leq T_j \ \forall i\in\mathcal{EN} \tag{5f}$$

$$\sum_{m\in\mathcal{M}} x_j^m \leq T_j \ \forall j\in\mathcal{AN},\mathcal{GN} \tag{5g}$$

$$p_{ij}^m \leq p_{max} x_{ij}^m \quad \forall (i,j)\in\mathcal{E},\, \forall m\in\mathcal{M} \tag{5h}$$

$$x_{ij}^m \leq x_j^m \, \forall i\in\mathcal{EN},\, j\in\mathcal{AN},\mathcal{GN},\, m\in\mathcal{M}_{5.8} \tag{5i}$$

$$p_{ij}^m,\, f_{ij}\geq 0,\, x_{ij}^m,\, y_j,\, x_j^m \in\{0,1\}, \quad \forall i\in\mathcal{EN},\, j\in\mathcal{AN},\mathcal{GN},\, m\in\mathcal{M}_{5.8} \tag{5j}$$

$$f_{jk},\, p_{jk,60},\, W_{jk,60}\geq 0,\, \forall j\in\mathcal{AN},\, k\in\mathcal{GN} \tag{5k}$$

Fig. 4. Network optimization formulation when edge and aggregator nodes communicate using a protocol interference model

where $\mathcal{M}_{5.8}$ is the set of discrete channels at 5.8 GHz and A is the maximum number of edge nodes that one radio of aggregator/gateway node can cover using SDMA technology. For simplicity, we assume that the aggregator or gateway node can employ very large number of antennas at their end and fully suppress the interference among covered edge nodes by using a minimum-mean-squared-error decoder when the ratio of number of antennas to number of edge nodes becomes very high [14]. Our model can accommodate the case of imperfect interference suppression as a gap to capacity.

Fig. 4 shows the network optimization formulation with the protocol interference and spatial multiplexing constraints. The optimization objective of (5a), flow conservation constraints of (1b), (1c) are same as Fig. 3. Power and bandwidth allocation equations between aggregator and gateway nodes (equation (1i) and (1e)) re-appear in Fig. 4.

Equation (5d) couples aggregator node deployment decision variables to all other constraints by ensuring that a candidate location must be selected for deployment if it uses any channel. Power control based protocol interference model appears at (5c). Spatial multiplexing capability of aggregator and gateway nodes appear at (5d) and (5e). Eq. (5f) shows that the number of channels that an edge node can use is limited by the maximum number of allowed radios in that node. Eq. (5g) denotes that an aggregator or gateway node j can place up to T_j number of radios. Eq. (5h) couples the power allocation and scheduling variables. Eq. (5i) couples the link scheduling and node scheduling variables. Eq. (5j) and (5k) describe the variables of the optimization program.

The optimization problem of Fig. 4 is also a MINLP. Section V shows how we solve these MINLP's.

V. Solution of the Optimization Problem

We convert the MINLP's to mixed integer linear programs (MILP) to speed up the optimization convergence and to be able to use free solvers. We relax the log functions of the capacity equations into a set of linear functions, solve the resultant MILP using branch-and-bound algorithm and find a feasible solution of the optimization problem from the relaxed solution. We describe these steps in the next three sub-sections.

A. Linear relaxation of the capacity function

The capacity functions of (1d), (1e) and (5b) are concave functions with respect to the allotted power p and bandwidth W [15]. Hence, each capacity function can be upper bounded into a set of linear functions by taking slopes at different points [16]. Let us define a set of power variables $\mathcal{P}_I = \{p_1, \cdot, p_i, \cdot, p_{max}\}$ and bandwidth variables $\mathcal{W}_J = \{W_1, \cdot, W_j, \cdot, W_{max}\}$ for a link with gain g. Let $C = W\log_2(1+\frac{pg}{N_0 W})$ denote the capacity function and $C_{p_i,W_j} = W_j \log_2(1+\frac{p_i g}{W_j})$ represent the capacity with power p_i and bandwidth W_j. We bound the flow f in the link by taking first order Taylor approximation in each of the power-bandwidth pairs:

$$f \leq C_{p_i,W_j} + m_{p_i}\cdot(p-p_i) + m_{W_j}(W-W_j) \quad \forall p_i\in\mathcal{P}_I\,, \forall W_j\in\mathcal{W}_J \tag{6}$$

where,

$$m_{p_i} = \frac{\partial C}{\partial p}\bigg|_{p=p_i}\,,\ m_{W_j} = \frac{\partial C}{\partial W}\bigg|_{W=W_j} \tag{7}$$

We relax the non-linear equations of (1d), (1e) and (5b) in this way and the MINLP's of Fig. 3 and 4 convert to MILP's.

B. Branch-and-bound algorithm

We use YALMIP [17] and GNU Linear Programming Kit (GLPK) [18] to solve the MILP's. GLPK uses branch-and-bound algorithm to solve the MILP. Branch-and-bound algorithm branches in each binary variable. In each branch, the algorithm calculates a lower bound using continuous relaxation of the binary variables and an upper bound by finding a feasible solution. The algorithm updates the global lower and upper bound and stops when their difference becomes smaller than the pre-defined optimality gap [19].

Branch-and-bound algorithm suffers from exponential worst-case complexity. We select a partitioning approach to speed up the convergence of the branch-and-bound algorithm.

Line	Operation
1	Assume each edge node (EN) uses its maximum power and bandwidth.
2	Calculate the capacity between each edge node to all aggregator node(AN) and gateway nodes (GN).
3	A link between between EN and AN/GN exists only if it can sustain the demand of the EN.
4	Find the coverage of each AN and GN.
5	Select the GN with the maximum coverage.
6	Assign all adjacent EN's to this GN.
7	Remove the selected EN's and GN from available set. Go to line 5. Iterate until all GN are selected or all EN's are covered.
8	If all EN's are covered, stop. Else, proceed.
9	Select the AN with the maximum coverage.
10	Assign all adjacent EN's to this AN.
11	Remove the selected EN's and AN from available set. Go to line 9. Iterate until all EN's are covered

TABLE II
POLYNOMIAL TIME AGGREGATOR NODE PLACEMENT ALGORITHM

We find that aggregator node placement decision variables (y_j) are more important than scheduling variables (x_{ij}^m). Hence, aggregator node placement decision variables are branched before scheduling variables. Using GLPK [18] and branch-and-bound method, we can solve an MILP, consisting of roughly 1000 binary variables, in 30 minutes with 0.5 optimality gap. We can accept this time complexity since aggregator node deployment is an offline planning task.

C. Feasible solution

The feasible solution of MILP may not be a feasible solution of the original MINLP since we relaxed the capacity function into a set of linear functions. Some edge nodes' flow may exceed the capacity of their links with the allotted power and bandwidth. We find a feasible solution in the following ways.

- *Tightening the relaxation gap:* We increase the granularity of piecewise linear approximation.
- *Checking for spare bandwidth:* We ensure that each aggregator node uses its entire allocated bandwidth before declaring infeasibility. We find this by fixing the scheduling and deployment variables of the MILP output, and running the MINLP for bandwidth, power and flow variables which is a convex optimization problem.
- *Iterate the process:* If previous step does not provide a feasible solution, we iterate the whole process by reformulating the MINLP where the currently infeasible edge nodes form the new set of edge nodes and unselected aggregator nodes form the new set of aggregator nodes.

D. Special Case: Greedy Set Covering based Aggregator Node Placement

We can obtain a feasible solution of the optimization problem of Fig. 6 in polynomial time with the following assumptions: first, there is no limitation on the number of available discrete channels and second, an edge node can only talk to one aggregator or gateway node. A greedy weighted set covering algorithm can solve this problem. We summarize the algorithm briefly in Table II assuming equal deployment cost among all candidate locations. We skip the details due to lack of space. Our future work will extend this algorithm to the scenario where the number of channels is limited.

Features	5.8 GHz	28 GHz	60 GHz
Rain Attenuation (dB) [20]	0	2.5	10
Oxygen Absorption (dB) [20]	0	0.5	15
Antenna gain (dB)	17 [6]	38 [6]	38 [21]
Maximum transmit power (dBm)	19 [6]	19 [6]	25
Fading margin (dB)	15	25	25
Channel width (MHz)	40 [6]	56 [6]	160 [21]
Number of channels	6	6	6

TABLE III
BACKHAUL FEATURES AT DIFFERENT BANDS

VI. NUMERICAL RESULTS

Channel gains, obtained using ray tracing, are taken with the backhaul features of Table III to obtain link capacities. We assume equal deployment cost for all aggregator nodes' locations and 100 Mbps demand from all edge nodes.

A. Network connectivity with microwave band

At first, we use the 28 GHz link gains between the edge and aggregator/gateway nodes and 60 GHz link gains between aggregator and gateway node. We run the network optimization problem of Fig. 3. Fig. 5 shows the network connectivity in this scenario. Two candidate aggregator locations – highlighted with green rectangle marker around them – get selected for aggregator node deployment. The optimality gap is 0%.

Our resultant network is free of primary interference. Adjacent links use different bandwidth in the network scenario of Fig. 5. However, non-adjacent nearby links are allowed to share bandwidth. This happens since we assumed an interference free regime in the network optimization formulations of microwave band. We now check the validity of our assumptions. Assuming that antennas have no side lobes, we find that the maximum interference among non-adjacent links that use microwave band fall 19 dB below the noise threshold.

B. Network connectivity with sub-6 GHz band

In this setup, we use the 5.8 GHz link gains between edge and aggregator/gateway nodes and 60 GHz links gains between aggregator and gateway nodes. Using these link gains, we run the optimization problem of Fig. 4. We assume an aggregator/gateway node can cover up to four edge nodes in the same channel using SDMA at 5.8 GHz.

Fig. 6 shows the associated network connectivity. Each solid colored line represents a discrete channel of 5.8 GHz channel set. Some aggregator/gateway nodes communicate to multiple edge nodes in the same discrete channel using spatial multiplexing capability. Two non-adjacent nearby links perform power allocation and get colored in such a way so that no edge interferes with each other. One Edge node (highlighted with orange rectangle marker around it) does not have good enough link gain with any aggregator or gateway node to sustain its demand. It becomes an infeasible edge node. The rest of the edge nodes require the deployment

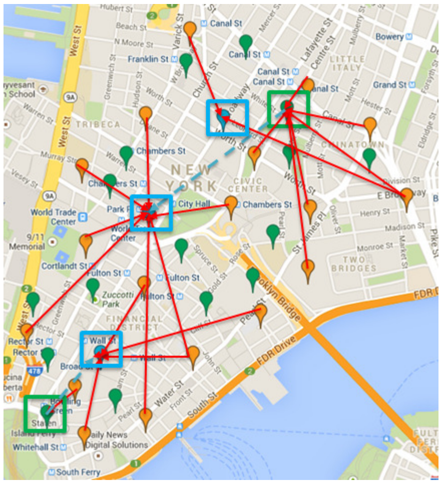

Fig. 5. Network connectivity when edge nodes (orange markers) transmit in 28 GHz (red lines) to aggregator nodes (green markers) and gateway nodes (highlighted with light blue rectangle around it). Aggregator nodes transmit in 60 GHz (dashed blue lines) to gateway nodes. Figure taken from [13]

of five aggregator nodes – highlighted with green rectangle marker around them – to meet their demand. The optimality gap is 40% in this case. We ran MILP of both sub-6 GHz and microwave band for 30 minutes. Optimization problem of Fig. 4 contains higher number of binary variables (both scheduling and node placement variables) than that of Fig. 3 (only node placement variables). Hence, sub-6 GHz based network optimization converges slowly.

We do not model many practical aspects such as antenna alignment, material reflectivity, etc. that affect the link gain at 28 GHz. We do not intend to compare sub-6 GHz and 28 GHz band. We just contrast their respective optimization problems.

VII. Conclusion

Small cells can keep up with the increasing demand of wireless networks; but require backhaul to transport data to(from) a gateway node. Wireless backhaul can provide an inexpensive option to small cells. Aggregator nodes, located at roof tops of tall buildings near small cells, can provide high data rate to multiple small cells in NLOS paths , sustain the same data rate to gateway nodes in LOS paths and take advantage of all available bands for wireless backhaul.

This work performed joint cost optimal aggregator node placement, power allocation, channel scheduling and routing to optimize the wireless backhaul network. We investigated wireless backhaul network using both sub-6 GHz and microwave bands. We considered the different interference patterns and multiple access features in these bands and incorporated them in backhaul network optimization. Future works will include SINR based interference methodology (rather than protocol) and mixed wired/wireless bakchaul optimization.

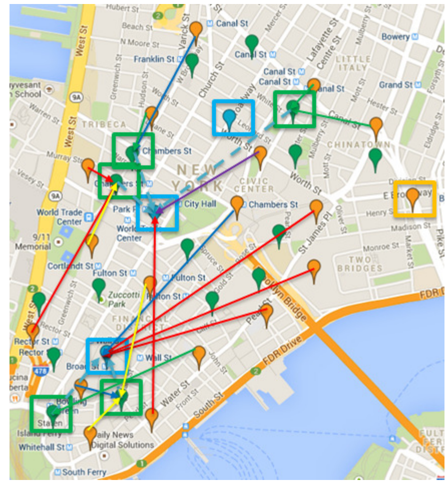

Fig. 6. Network connectivity when edge nodes transmit in 5.8 GHz and aggregator nodes transmit in 60 GHz. Figure taken from [13]

References

[1] "Qualcomm data challenge," accessed February 2014, http://www.qualcomm.com/media/documents/wireless-networks-rising-meet-1000x-mobile-data-challenge.

[2] J. Andrews, "How can cellular networks handle 1000x data?," Technical talk at University of Notre Dame, 1998.

[3] M. Dohler, R. W. Heath, A. Lozano, C. B. Papadias, and R.A. Valenzuela, "Is the PHY layer dead?," *IEEE Communications Magazine*, vol. 4, pp. 159–165, Apr 2011.

[4] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: a survey," *IEEE Communications Magazine*, vol. 46, pp. 59–67, Sep 2008.

[5] Ceragon, "Mobile backhaul: Fiber vs. microwave case study analyzing various backhaul technology strategies," White Paper, Oct. 2009.

[6] J. Hansryd, J. Edstam, B. Olsson, and C. Larsson, "Non-line-of-sight microwave backhaul for small cells," *Ericsson Review*, vol. 3, pp. 2–8, Feb 2013.

[7] NGMN Alliance, "Small cell backhaul requirements," White Paper, June 2012.

[8] P. Maulin, R. Chandrasekaran, and S. Venkatesan, "Energy efficient sensor, relay and base station placements, for coverage, connectivity and routing," in *Proc. IEEE IPCCC' 2005*, Apr. 2005, pp. 581–586.

[9] D. Yang, S. Misra, X. Fang, G. Xue, and J. Zhang, "Two-tiered constrained relay node placement in wireless sensor networks: Computational complexity and efficient approximations," *IEEE Trans. Mobile Computing*, vol. 11, pp. 1399–1411, Aug 2012.

[10] A. So and B. Liang, "Enhancing WLAN capacity by strategic placement of tetherless relay points," *IEEE Trans. Mobile Computing*, vol. 6, pp. 522–535, May 2007.

[11] B. Lin, P. Ho, L. Xie, and X. Shen, "Optimal relay station placement in IEEE 802.16j networks," in *Proc. ACM IWCMC' 2007*, Aug. 2007, pp. 25–30.

[12] H. Lu, W. Liao, and F. Y. Lin, "Relay station placement strategy in IEEE 802.16j WiMAX networks," *IEEE Transactions on Communications*, vol. 59, pp. 151–158, Jan 2011.

[13] "Downtown Manhattan: Google map," accessed February 2014, https://www.google.com/maps/.

[14] J. Hoydis, S. T. Brink, and M. Debbah, "Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?," *IEEE JSAC*, vol. 31, pp. 160–171, Feb 2013.

[15] S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, Cambridge,MA, 1999.

[16] Y. Shi, T. Hou, S. Kompella, and H. Sherali, "Maximizing capacity in multihop cognitive radio networks under the SINR model," *IEEE Transactions on Mobile Computing*, vol. 10, pp. 954–967, 2011.

[17] J. Lofberg, "YALMIP : A toolbox for modeling and optimization in MATLAB," in *Proc. CACSD Conference*, Taipei, Taiwan, 2004.

[18] "GLPK GNU linear programming kit," accessed February 2014, http://www.gnu.org/software/glpk/.

[19] D. Bertsimas and J. N. Tsitsiklis, *Introduction to Linear Optimization*, Athena Scientific and Dynamic Ideas, LLC, Belmont,MA, 1997.

[20] E-band Communications, "Overview of the 71-76 & 81-86 GHz frequency bands," White Paper, 2010.

[21] "The future of wireless backhaul, liberator V-320," accessed February 2014, http://www.sub10systems.com/wp-content/uploads/2013/02/Liberator_V320_DataSheet_Jan13.pdf.