Minimum-Cost Wireless Backhaul Network Planning with Full-Duplex Links

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***Abstract*—In this work we address the joint design of the wireless backhauling network topology, as well as the frequency/power allocation on the wireless links, where the nodes are capable of full-duplex (FD) operation. The proposed joint design enables the coexistence of multiple access/backhaul links at the same channel, resulting in an enhanced spectral efficiency. Moreover, it enables the usage of FD capability when/where it is gainful. In this regard, a mixed-integer-linear-program (MILP) design framework is proposed, aiming at a minimum cost design for the wireless backhaul network, considering the required rate demand at each base station, as well as the various operational limits. The numerical simulations show a reduction in the network cost via the utilization of the proposed designs, thanks to the coexistence of multiple links on the same channel due to the FD capability.**

I. Introduction

Deployment of small cell base stations (SCBS) is a necessary paradigm to meet the rapid increase of rate demand in the context of the fifth generation cellular wireless networks (5G). In particular, small cells enable high capacity radio access due to the short distance coverage, facilitating a higher energy and spectral efficiency [1]. However, with the expected dense deployments of SCBS, the main challenge for the operators will be to provide backhaul solutions at a reasonable cost, in order to handle the data traffic to (from) the SCBS sites from (to) the core network. In this regard, application of wireless backhaul solutions appears to be a good alternative to the traditional fiber connections, due to the lower capital expenditure and ease of deployment [2]. However, wireless backhaul links are known to suffer from occasional failure/degradation due to blockage and weather conditions, limited information capacity compared to the traditional fiber connections, as well as the additional consumption of energy and spectrum. In order to overcome the aforementioned drawbacks, several works have been dedicated to the efficient design of the wireless backhaul networks from the aspects of link/topology planning and resource allocation [3]–[9], as well as exploring promising technologies with the goal of enhancing the performance of the traditional line-of-sight (LOS) point-to-point microwave links. This includes, e.g., establishment of non-LOS links for resolving blockage situations [10], [11], or technologies with the potential to enhance spectrum utilization, e.g., operating in unlicensed millimeter-wave bands [12], optical links [13], as well as the realization of in-band backhauling, i.e., the co-existence of access and backhaul links at the same channel [14]–[17].

Among the promising technologies for the efficient usage of spectrum, full duplex (FD) capability is introduced as the transceiver's capability to transmit and receive at the same time and frequency, however, resulting in a strong self-interference. Recently, effective methods for self-interference cancellation (SIC) are proposed [18], motivating further studies on wide range of related applications [19]. It is shown in [20]–[25] that the application of FD capability improves the spectral efficiency of the point-to-point or multi-hop wireless communications, relying on an optimized resource allocation and power control. In particular, the utilization of the FD capability at wireless backhaul links is presented as a promising use case, due to the zero-mobility conditions and the utilization of directive antennas, hence showing a potential to reduce the cost of spectrum [19]. The performance of an FD in-band backhauling system is analyzed in [17], by means of stochastic geometry, where the superior performance of an FD-enabled system is observed compared to the half-duplex (HD) counterparts. An adaptive FD/HD backhauling system is then studied in [16], and extended with the considerations of system sum-rate analysis and optimization [14], [15].

A. Contribution

In this paper we address the topology design and resource allocation in a wireless backhaul network where FD capability is enabled at the wireless links, with the goal of minimizing the collective network cost. The contributions of this paper are summarized as follows:

- In contrast to [14], [15], [17] where FD capability is utilized to enable in-band backhauling in a fixed star topology, we consider a network where FD capability can be fully utilized; by enabling a general topology with the co-existence of multiple backhaul/access links on the same channel, however, requiring an efficient interference management scheme. In order to facilitate this, we consider a framework where the interference conditions for backhaul-to-access, as well as the backhaul-backhaul links may be obtained via the utilization of a wave propagation simulator, suited for dense urban scenarios where accurate environment information is available [26]. This is in contrast to the designs in [6] assuming no interference from backhaul links and separating the spectrum used in acces and backhaul, or the recent works [7], [8] which simplify the impact of interference to link crossings and low arrival angle situations.
- Unlike the connected graph approaches proposed in [6]–[8] or the frequency planning with fixed topology [27], [28], we jointly address the design of the network topology as well as the planning of frequency and transmit power at each link. This is since the aforementioned factors jointly impact the network interference pattern and the resulting link throughput, especially for a dense SCBS deployment. In particular, this enables a flexible usage of FD capability, when/where it is gainful. In this regard, a mixed-integer-linear-programming (MILP) design framework is proposed to obtain a minimum cost network operation, complying with required quality of service (QoS), as well as the operational network constraints.

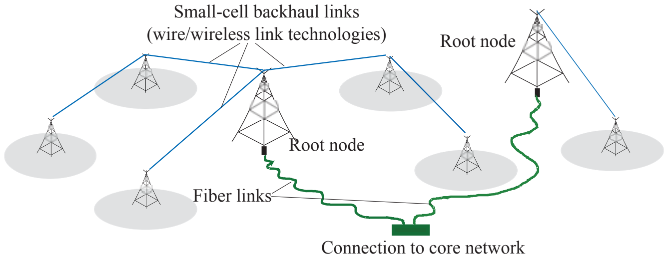

Figure 1. Backhauling network; including wireless/wired link technologies for small cells, and fiber connections for root nodes to the core network.

Table I. USED SYMBOLS AND NOTATIONS

Parameter	Description
$\mathbb{R}, \mathbb{M}, \mathbb{N}$	Set of root nodes, non-root nodes, and all nodes
$\mathbb{L}$	Set of all feasible wireless links
$(i, j) \in \mathbb{L}$	The wireless link from the node $i \in \mathbb{N}$ to the node $j \in \mathbb{N}$
$\mathbb{F}, \mathbb{F}_a$	Set of all frequency subchannels, and those used in access network
$X_{ij,f}$	Transmit power at link $(i, j) \in \mathbb{L}$ at frequency subchannel $f \in \mathbb{F}$
$\Lambda_{ij,f}$	The desired channel strength, relating the transmit and received power, for the link $(i, j) \in \mathbb{L}$ and subchannel $f \in \mathbb{F}$
$\Gamma_{ij,lk,f}$	Interference channel strength to the wireless link $(i, j) \in \mathbb{L}$ from $(l, k) \in \mathbb{L}$, at subchannel $f \in \mathbb{F}$
$\Omega_{ij,k,f}$	Interference channel strength from the link $(i, j) \in \mathbb{L}$ to the cell associated with the node $i \in \mathbb{N}$ at the frequency subchannel $f \in \mathbb{F}$
$P_{\max,ij}$	Maximum transmit power at link $(i, j) \in \mathbb{L}$
$P_{\max,i}$	Maximum transmit power at the node $i \in \mathbb{N}$
$W_{ij,f}$	Noise variance at the at the link $(i, j) \in \mathbb{L}$, at frequency $f \in \mathbb{F}$
$R_{\text{ul},i} (R_{\text{ul},i})$	Required uplink (downlink) information rate at the node $i \in \mathbb{N}$
$I_{\text{th},k,f}$	Maximum interference temperature from the backhaul network to the small cell associated with $k \in \mathbb{N}$, $f \in \mathbb{F}$.
$C_{ij,0}$	Available link capacity through pre-existing technologies
B	Bandwidth of each frequency subchannel
$C_{ij,f}$	The achievable information capacity for the link (i, j), at frequency f

Numerical simulations indicate that a reduction in the network cost is achieved via the utilization of the proposed design, thanks to the coexistence of multiple wireless links on the same channel due to the FD capability.

II. NETWORK MODEL

We consider a network of backhaul nodes, including root nodes and non-root nodes, whereby the data traffic is carried to (from) the access network from (to) the core network, see Fig. 1. The root nodes are connected to the core network via high capacity fiber connections, whereas the non-root nodes set up wireless links directed to the root nodes, or to the other non-root nodes which relay their data traffic through the network. For each wireless link the transmit power can be adjusted for different frequency subchannels, enabling an effective interference control and spectrum-saving mechanism. The operation of the network is expressed via the defined parameters in Table I.

A. Acquisition of network information

In order to deliver a mathematical description of the network operation, the following information is obtained via direct observations and measurements, or via post-processing of the network information:

1) Initial network topology: In the first step, the location of the deployed root and non-root nodes is obtained. Moreover, based on the location of the nodes, the potential wireless links are determined. This can be identified via the existence of a line-of-sight (LOS) between two nodes, and that the corresponding link does not exceed a maximum distance limit [7], [8].

2) Large-scale channel parameters: Given the network topology, the large-scale channel parameters associated with the desired (Λ) and interference paths (Γ) are obtained for each potential wireless link, and used as a basis for network planning. This includes the expected channel strength, i.e., ratio between the transmit and receive power at each link. Note that the exact channel information may not be obtained via direct measurements, as the potential links may not exist prior to the network planning/realization. However, the large-scale channel conditions can be estimated at each link via the application of a wave propagation simulator [26] utilizing the used antenna specifications as well as the related environment information, e.g., city map and node locations. See Section IV for the detailed procedure[1]. The interference channel strength between a link and the access network (Ω), e.g., from a wireless link to a remote base station, can be obtained by following a similar methodology. The impact of a limited SIC level, as known from [18], is modeled as the attenuation factor $\Gamma_{ij,ki,f}$, relating the transmission power to the resulting residual self-interference power at the node $i \in \mathbb{N}$ and from the link (i, j) to $(k, i) \in \mathbb{L}$.

3) Power budget: The maximum transmit power at each wireless link ($P_{\max,ij}$), as well as the total maximum transmit power at each node ($P_{\max,i}$) should be respected in the design of network parameters. Note that the value of $P_{\max,ij}$ is usually limited by the range of the transmit chain elements, e.g., power amplifier (PA), whereas the $P_{\max,i}$ is limited by the available power sources, e.g., when the node is battery-powered, or relies on the harvesting sources.

4) Required information rate: The required information rate for uplink (UL), i.e., $R_{\text{ul},i}$, and at downlink (DL), i.e., $R_{\text{dl},i}$, can be estimated considering the expected number of users associated with a backhaul node, and also observing the previous demands.

5) Pre-existing links: Other than the wireless backhaul links, the network may make use of the pre-existing wired links, e.g, pre-existing cooper connections. The available collective link capacity from the other technologies is denoted as $C_{ij,0}$, for the link $(i, j) \in \mathbb{L}$.

6) Interference temperature threshold: Interference temperature threshold ($I_{\text{th},k,f}$) gives a trade-off between the protection of the access network against the interference from backhaul wireless links, and the coexistence possibility for backhaul and access links at the same frequency. For instance, it can be chosen equal to the the noise variance, i.e., keeping the interference below the noise floor.

B. Wireless link quality

Once a wireless link is established, the link quality, in terms of the signal to interference-plus-noise ratio (SINR) is obtained as

$$\gamma_{ij,f} = \frac{\Lambda_{ij,f} X_{ij,f}}{\sum_{(l,k) \in \{\mathbb{L} \setminus (i,j)\}} \Gamma_{ij,lk,f} X_{lk,f} + W_{ij,f}}, \quad (1)$$

where $\gamma_{ij,f}$ is the SINR, resulting in

$$C_{ij,f} = B \log_2 (1 + \gamma_{ij,f}), \quad (2)$$

where B is the bandwidth of each frequency subchannel, and $C_{ij,f}$ is the achievable information rate for the wireless link (i, j) at the subchannel f. Note that the equality (2) holds for a Gaussian transmit signaling and employing an arbitrarily long coding block length at the wireless links, and can be otherwise treated as an approximation.

[1]Note that for the studied backhaul network this process reaches a high accuracy, due to the static wireless links with LOS connections and almost zero mobility, which reduces the environment randomness.

Table II. SET OF DECISION VARIABLES

Set	Description
$\mathbb{P}$	Set of the variables $X_{ij,f}$, $\forall(i,j) \in \mathbb{L}$, $f \in \mathbb{F}$
$\mathbb{C}_U (\mathbb{C}_D)$	Set of the variables $C_{\text{ul},ij} (C_{\text{dl},ij})$, $\forall(i,j) \in \mathbb{L}$
$\mathbb{J}_L (\mathbb{J}_F)$	Set of the all link (subchannel) activity indicator binary variables

C. Role of network planning

As mentioned, each node may setup a wireless link among the identified feasible set $\mathbb{L}$, as a usual planning choice in the context of wireless backhaul planning [6]–[8], [29], [30]. In this work, we also assume that the available spectrum is divided into multiple frequency subchannels, where the transmit strategy at each frequency subchannel can be adjusted separately for each link. This results in an effective interference management, considering the self-interference in the FD mode, interference to the other backhaul links, as well as the interference to the access network. In particular, it facilitates a proper incorporation of the FD capability by enabling different duplexing modes, which are chosen depending on the link/interference conditions, see Fig. 2. Moreover, the required transmission rates can be obtained by adjusting the transmit powers, reducing un-necessary additional costs due to excessive spectrum/power usage.

III. Minimum-Cost Network Planning and Optimization

In this part, an MILP-based network planning and optimization framework is proposed, where the planning choices explained in Subsection II-C including the network topology, operational frequency bands and the transmit power of wireless links, are made in order to setup a minimum-cost wireless backhaul network.

A. Decision variables

The following decision variables are expected to be the outcome of a design algorithm, see Table II:

1) Transmit strategies $X_{ij,f}$: The main decision variables $X_{ij,f}, (i,j) \in \mathbb{L},\ f \in \mathbb{F}$, determine the transmit strategies of the wireless network.

2) Used link capacity for UL (DL) $C_{ul,ij}(C_{dl,ij})$: These variables determine the information flow within the network, regarding the used capacity of each link $(i,j) \in \mathbb{L}$ dedicated to UL (DL) traffic.

3) Auxiliary variables; link and subchannel activity indicator J_{ij}, J_f: The binary variables $J_{ij} \in \{0,1\}$ observe the usage of the link $(i,j) \in \mathbb{L}$, where the binary variable $J_f \in \{0,1\}$ defines the activeness of a frequency subchannel. A wireless link (subchannel) is active iff the transmit power associated with any of the associated subchannels (links) is non-zero.

B. Network cost model

The main required expenditures for the successful function of the wireless backhaul network can be expressed into the following three parts:

1) Power consumption: The cost of power can be formulated as $W_p \sum_{(i,j)\in\mathbb{L}} \sum_{f\in\mathbb{F}} X_{ij,f}$, where W_p is the cost of power. Note that the value of W_p may be chosen with the direct consideration of the actual market price, as well as an extra emphasis on energy saving in order to reduce the consequent CO_2 emissions, which is a rising criteria for the design of wireless networks [31], [32].

2) Wireless links: The establishment of the wireless links is considered as one of the main capital expenses (CAPEX) of the wireless backhaul network, including the establishment of directive antennas suitable for backhaul links, as well as the corresponding transmit/receive chains. This can be expressed as $W_l \sum_{(i,j)\in\mathbb{L}} J_{ij}$, where W_l is the overall cost of establishing a wireless link.

3) Spectrum usage: With almost all of the sub-6 GHz spectrum already utilized, the cost of obtaining a dedicated spectrum license is considered as a major cost of a wireless network, motivating research regarding efficient spectrum utilization, as well as the usage of higher frequency bands [12], [13]. In this respect, the coexistence capability of bidirectional links at the same frequency, via FD capability, as well as the coexistence with the access network spectrum via an interference-aware planning is expected to reduce the required spectrum cost dedicated to backhaul. The overall cost of spectrum can be expressed as $W_f \sum_{f\in\mathbb{F}\setminus\mathbb{F}_a} J_f$ where W_f represent the cost of each frequency subchannel.

Consequently, the collective cost of the backhaul network is expressed in relation to the decision variables as

$$\mathcal{V}(\mathbb{P}, \mathbb{J}_L, \mathbb{J}_F) = W_p \sum_{(i,j)\in\mathbb{L}} \sum_{f\in\mathbb{F}} X_{ij,f} + W_l \sum_{(i,j)\in\mathbb{L}} J_{ij} + W_f \sum_{f\in\mathbb{F}\setminus\mathbb{F}_a} J_f. \quad (3)$$

C. Constraints

Formulation of the system constraints are essential in order to ensure a feasible solution; considering the operational limits, e.g., maximum transmit power, as well as the service requirements, e.g., successful transportation of the required UL/DL traffic.

1) Auxiliary variables: The value of the defined auxiliary variables are inferred from the main decision variables $X_{ij,f}$, via the imposition of the following constraints:

$$\text{C0:} \quad X_{ij,f} \geq 0, \ \ \forall(i,j) \in \mathbb{L},\ f \in \mathbb{F},$$

$$\text{C1:} \quad \sum_{f\in\mathbb{F}} X_{ij,f} \ \leq J_{ij}\tilde{P}_{\text{max}},\ J_{ij} \in \{0,1\},\ \forall(i,j) \in \mathbb{L},$$

$$\text{C2:} \quad \sum_{(i,j)\in\mathbb{L}} X_{ij,f} \leq J_f \tilde{P}_{\text{max}},\ J_f \in \{0,1\},\ \forall f \in \mathbb{F},$$

where C0 enforces the domain of the power values, and $\tilde{P}_{\text{max}}$ is any arbitrary upper bound on the total network power consumption, e.g., $\tilde{P}_{\text{max}} = \sum_{i\in\mathbb{N}} P_{\text{max},i}$. It is observed that the value of J_{ij} (J_f) is 1 if any of the corresponding power values are non-zero. Moreover, as it will be later clarified, they are forced to 0 if the corresponding link (frequency subchannel) is inactive, to reduce the cost function.

2) Transmit power constraints: The per-link power constraint, as well as the constraint on the power budget at each node are respectively formulated as

$$\text{C3:} \quad \sum_{f\in\mathbb{F}} X_{ij,f} \leq P_{\text{max},ij}, \ \ \forall(i,j) \in \mathbb{L},$$

$$\text{C4:} \quad \sum_{(i,x)\in\mathbb{L}} \sum_{f\in\mathbb{F}} X_{ix,f} \leq P_{\text{max},i}, \ \ \forall i \in \mathbb{N},$$

see Subsection II-A.

3) Interference threshold on access network: The coexistence of the backhaul and access network is conditioned on respecting the tolerable collective interference threshold $I_{\text{th},l,f}$, see Subsection II-A. This is expressed as

$$\text{C5:} \quad \sum_{(i,j)\in\mathbb{L}} \Omega_{ij,l,f} X_{ij,f} \leq I_{\text{th},l,f}, \ \ \forall f \in \mathbb{F}_a,\ l \in \mathbb{N}.$$

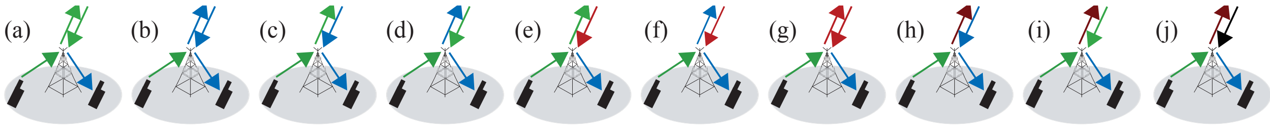

Figure 2. Possible duplexing modes for wireless backhaul connections. Different colors represent different frequency bands. Depending on the interference intensity, provided SIC quality, and network requirements, different modes may be used at the backhaul links. This includes the possibility of multiple coexisting links at the same frequency (a), (b) to the complete separation of the links at different bands (j).

4) Link information flow constraint: The physical information capacity on each link, including the wired and wireless connections, need to be sufficient for the dedicated UL/DL information rates, i.e., $C_{\text{ul},ij}, C_{\text{dl},ij}$. This is expressed as

$$\text{C6:} \quad C_{\text{ul},ij} + C_{\text{dl},ij} \leq C_{0,ij} + \sum_{f \in \mathbb{F}} C_{ij,f}, \quad \forall (i,j) \in \mathbb{L},$$

where $C_{ij,f}$ is related to the other variables from (2), and $C_{0,ij}$ indicates the available link capacity via wired technologies.

5) Network information flow constraint: The preservation of the network information flow, separately at the root nodes and non root nodes are formulated as

$$\text{C7:} \quad R_{\text{ul},i} = \sum_{(i,x)\in\mathbb{L}} C_{\text{ul},ix} - \sum_{(y,i)\in\mathbb{L}} C_{\text{ul},yi}, \quad \forall i \in \mathbb{M},$$

$$\text{C8:} \quad R_{\text{dl},i} = \sum_{(x,i)\in\mathbb{L}} C_{\text{dl},xi} - \sum_{(i,y)\in\mathbb{L}} C_{\text{dl},iy}, \quad \forall i \in \mathbb{M},$$

$$\text{C9:} \quad \sum_{i\in\mathbb{M}} R_{\text{ul},i} = \sum_{i\in\mathbb{R}} \sum_{(j,i)\in\mathbb{L}} C_{\text{ul},ji},$$

$$\text{C10:} \quad \sum_{i\in\mathbb{M}} R_{\text{dl},i} = \sum_{i\in\mathbb{R}} \sum_{(i,j)\in\mathbb{L}} C_{\text{dl},ij},$$

where C7-8 indicate the flow conservation at each node, and C9-10 represent the conservation of the information over the network.

D. Network planning: an MILP model

In this part we provide an MILP framework, addressing a minimum cost wireless backhaul network design. The corresponding optimization problem is formulated as

$$\underset{\mathbb{P},\mathbb{C}_U,\mathbb{C}_D,\mathbb{J}_L,\mathbb{J}_F}{\text{minimize}} \; \mathcal{V}(\mathbb{P}, \mathbb{J}_L, \mathbb{J}_F) \quad \text{s.t. C0-C10}, \tag{4a}$$

where the sets $\mathbb{P}, \mathbb{C}_U, \mathbb{C}_D, \mathbb{J}_L, \mathbb{J}_F$ represent the decision variables, see Table II. It is observed that the cost function, as well as the constraints C0-C5 and C7-C10 comply with the intended mixed integer-linear structure. However, the above problem is not an MILP due to the non-linear constraint C6. In order to observe this, we recall from (2) that the achievable information rate at each link is related to the power of the desired and interfering links as

$$C_{ij,f} = f_1(\mathbb{P}) - f_2(\mathbb{P}), \tag{5}$$

where

$$f_1(\mathbb{P}) := B\text{log}\left(\sum_{(l,k)\in\{\mathbb{L}\}} \Gamma_{ij,lk,f} X_{lk,f} + W_{ij,f} \right), \tag{6}$$

$$f_2(\mathbb{P}) := B\text{log}\left(\sum_{(l,k)\in\{\mathbb{L}\setminus(i,j)\}} \Gamma_{ij,lk,f} X_{lk,f} + W_{ij,f} \right), \tag{7}$$

which holds a difference of concave functions over the decision variables $\mathbb{P}$. Unfortunately, this formulation is challenging for the standard numerical solvers due to *i)* the non-convexity of the resulting feasible set in C6, and *ii)* the logarithmic concave-convex expressions. In order to comply with the intended MILP framework, we undertake three steps. Firstly, we introduce the achievable link capacity $C_{ij,f}$ as an auxiliary variable in the optimization and directly impose (5) as a constraint, thereby linearizing the constraint set C0-C10. Secondly, the equality in (5) is relaxed as an inequality constraint, i.e., $C_{ij,f} \leq f_1(\mathbb{P}) - f_2(\mathbb{P})$. However, it is easily verified that the relaxed constraint will be tight at the optimality, resulting in zero relaxation gap[2]. And third, we apply linear conservative approximations on the non-linear terms f_1 and f_2. In this respect, the logarithmic term f_1 is approximated as a piecewise linear function, i.e., approximating the concave expression as a maximum of multiple affine functions, denoted as $\mathcal{L}_p(\mathbb{P}; \mathbb{P}_0)$, such that

$$\mathcal{L}_p(\mathbb{P}; \mathbb{P}_0) \leq f_1(\mathbb{P}), \quad \mathcal{L}_p(\mathbb{P}_0; \mathbb{P}_0) = f_1(\mathbb{P}_0), \tag{8}$$

where $\mathbb{P}_0$ is the initial point where the approximation is tight. Moreover, the logarithmic term f_2 is approximated as an over-estimating affine, denoted as $\mathcal{L}(\mathbb{P}; \mathbb{P}_0)$, such that

$$\mathcal{L}(\mathbb{P}; \mathbb{P}_0) \geq f_2(\mathbb{P}), \quad \mathcal{L}(\mathbb{P}_0; \mathbb{P}_0) = f_2(\mathbb{P}_0), \tag{9}$$

which is directly obtained via the first-order Taylor's expansion at the point $\mathbb{P}_0$[3]. The wireless link capacity constraint can be hence satisfied by imposing

$$C_{ij,f} \leq \mathcal{L}_p(\mathbb{P}_0, \mathbb{P}) - \mathcal{L}(\mathbb{P}_0, \mathbb{P}). \tag{10}$$

Note that the satisfaction of (10) consequently ensures that the wireless link realizes the capacity value $C_{ij,f}$, due to the proposed conservative approximation. However, this may result in an inefficient solution, due to the approximation gap[4]. In this regard, an iterative design update is applied, where the obtained variable set $\mathbb{P}$ at each iteration is set as the approximation point, i.e., $\mathbb{P}_0$, for the next design iterations. The minimum-cost network design problem can be hence formulated as

$$\underset{\mathbb{V}^{[m]}}{\text{minimize}} \; \mathcal{V}\left(\mathbb{P}^{[m]}, \mathbb{J}_L^{[m]}, \mathbb{J}_F^{[m]}\right) \tag{11a}$$

$$\text{s.t.} \quad C_{ij,f} \leq \mathcal{L}_p\left(\mathbb{P}^{[m]}; \mathbb{P}^{[m-1]}\right) - \mathcal{L}\left(\mathbb{P}^{[m]}; \mathbb{P}^{[m-1]}\right), \tag{11b}$$

$$\text{C0-C10}, \tag{11c}$$

where

$$\mathbb{V}^{[m]} := \left\{ \mathbb{P}^{[m]}, \mathbb{C}_U^{[m]}, \mathbb{C}_D^{[m]}, \tilde{\mathbb{C}}^{[m]}, \mathbb{J}_L^{[m]}, \mathbb{J}_F^{[m]} \right\}, \tag{12}$$

and the set $\tilde{\mathbb{C}}$ represents the sets of the variables $C_{ij,f}$, and m denotes the iteration index, see Algorithm 1. The algorithm stops as a stable set of decision variables is obtained, or a maximum number of iterations is expired.

1) Numerical implementation: As intended, the obtained optimization framework (11) is an MILP in each iteration. Note that due to the combinatorial structure, such problems are not convex, and hence the popular interior point methods may not be directly applied [33]. However, efficient variations of branch and bound methods [34] have been recently developed

[2]The proof is obtained via contradiction; if for an optimal design of network parameters the constraint is not tight for the link (i, j) and at the subchannel f, then the transmit power value $X_{ij,f}$ can be reduced until the constraint is tight. This will reduce the objective (cost), while does not violate any of the design constraints.

[3]A tight affine approximation of a convex (concave) function obtained via Taylor's approximation, is also a global lower (upper) bound [33].

[4]A large deviation of approximated piecewise linear function $\mathcal{L}_p - \mathcal{L}$ with the original nonlinear expression results in the under-utilization of the wireless link capacity, and consequently additional costs.

and implemented in the framework of the standard numerical solvers, e.g., CPLEX, Groubi, resulting in efficient numerical solutions for the MILP problems with large dimensions.

2) Algorithm initialization: The algorithm starts by activating all feasible physical links, frequency sub channels, as well as the maximum power consumptions at all wireless links, respecting the constraints C0-2. Note that the initialization choice corresponds to a strong link/network capacity. However, it corresponds with the maximum utilization of the network resources, resulting in the maximum cost.

3) Convergence: The convergence behavior of the algorithm is of interest, due to the proposed iterative structure. Via to the application of the branch and bound update by the numerical solver, the solution experiences a monotonic enhancement in each iteration. Note that such monotonic reduction of the cost function holds at the internal solver iterations of the branch-and-bound method, as well as the external iterations by updating the approximations, see Algorithm 1, step 4. This results in a necessary algorithm convergence, due to the fact that the problem objective is bounded from below. Further analysis regarding the algorithm convergence behavior and computational complexity is conducted via numerical simulations in Section IV.

Algorithm 1 MILP-based minimum cost network planning.

1: $m \leftarrow 0$; $\mathbb{P}^{[0]} \leftarrow$ Subsection III-D2; ▷ initialization
2: **repeat**
3: $m \leftarrow m + 1$;
4: $\mathbb{P}^{[m]}, \mathbb{C}_U^{[m]}, \mathbb{C}_D^{[m]}, \tilde{\mathbb{C}}^{[m]}, \mathbb{J}_L^{[m]}, \mathbb{J}_F^{[m]} \leftarrow$ solve (11);
5: **until** a stable point, or a maximum number of m reached
6: **return** $\left\{\mathbb{P}^{[m]}, \mathbb{C}_{UL}^{[m]}, \mathbb{C}_{DL}^{[m]}, \mathbb{J}_L^{[m]}, \mathbb{J}_F^{[m]}\right\}$

IV. Numerical evaluation

Table III. Required CPU Time

$\|\mathbb{N}\|$	$\|\mathbb{L}\|$	$\|\mathbb{F}\|$	Problem Size	Execution Time in seconds
8	12	6	72	360 s
15	24	6	192	1020 s
23	40	10	400	10200 s
30	120	10	1200	30050 s

In this part we evaluate the impact of the proposed designs in terms of the total network cost, benefiting from the FD capability at the wireless links, via numerical simulations. The simulated network is obtained from the city map of Aachen, Germany, see Fig. 4, employing our developed wave propagation simulator [26], in combination with the urban micro-cell scenario from WINNER II model [35]. The antenna type is chosen with directivity gain of 13 dBi and directivity angle of 15 degrees in accordance with the European Standard [36]. The evaluations of the channel properties are carried by keeping the center frequency of 5 GHz and with bandwidth of each frequency sub-channel of 20 MHz. The planning algorithm determines the wireless links to be established, as well as the operating power and frequency bands at each link. Unless otherwise is stated, the following values define the default setup: $W_{ij,f} = -97$ dBm, $B = 20$ MHz, $P_{\text{max},ij} = 30$ dBm, $P_{\text{max},i} = 30$ dBm, $R_{\text{req}} = R_{\text{ul},i} = R_{\text{dl},i} = 100$ Mbits/sec, $|\mathbb{N}| = 23$, $|\mathbb{F}| = 8$, $|\mathbb{L}| = 100$, $I_{\text{th},k,f} = -97$ dBm, $C_{0,ij} = 0$. The self-interference cancellation is assumed to be perfect, i.e., $\rho_{\text{si}} = \Gamma_{ij,li,f} = 0$. The network cost model is set following [37], as $W_p = 1$, $W_l = 20$, $W_f = 10$. In Fig. 3 (a) the average convergence behavior of the algorithm is depicted. A monotonic decrease in cost is observed, where the convergence is obtained within $4 - 8$ iterations. In Figs. 3 (b), (c) the impact of the rate demand is depicted on the collective network cost. It is observed that the application of FD capability, together with the proposed joint link/frequency planning results in the usage of less frequency subchannels, thereby reducing the total cost by approximately $10 - 30\%$ depending on the traffic load. Moreover, it is observed from Fig. 3 (d) that the observed FD gain suffers as the SIC quality is degraded, and reaches the performance of the network with half-duplex links. In Table III the required CPU time is reported, for different node cluster sizes[5]. It is observed that a larger problem dimension, i.e, $d = |\mathbb{N}| \times |\mathbb{L}| \times |\mathbb{F}|$, results in a higher computational time, however, remains below 10 Hrs for $d \leq 1200$ on a standard user processor.

V. Conclusion

With almost all of the below 6 GHz spectrum already assigned, the need for spectral efficient solutions is apparent in the context of cellular wireless communication systems. In this work, application of FD wireless links is studied as a spectrum-saving mechanism for the wireless backhaul networks. Numerical simulations indicate that for a dense urban deployment, the proposed methodologies result in the reduction of up to 20% in the overall network cost compared to the half-duplex counterparts, thanks to the coexistence of multiple wireless links at the same channel.

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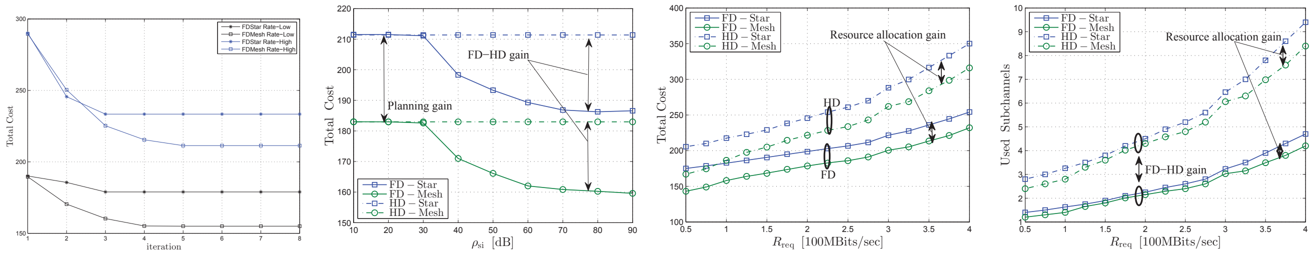
[5]The simulations are performed on a Linux Debian system with processor Intel Core i7 − 3770S CPU @3.10GHz X 4, RAM of 8GB. The version 2016b of MATLAB was used along with CVX 2.1 and Gurobi 7.0 Solver



(a) Convergence (b) Cost vs. SIC level (c) Cost vs. R_{req} (d) Spectrum use vs R_{req}

Figure 3. The algorithm convergence behaviour (a), and resulting netwoek cost for different values of R_{req} and ρ_{si}.

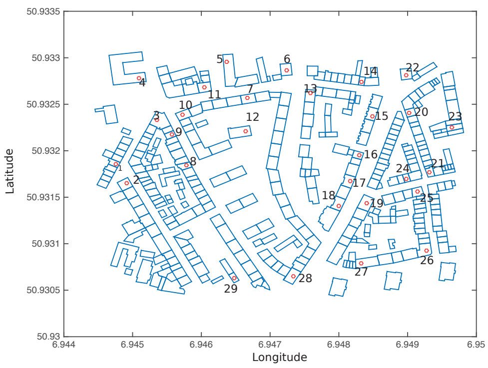


Figure 4. The simulated environment from Aachen city map. Red dots represent the location of the backhaul nodes, put on top of the rooftops, whereas blue squares represent the body area of the buildings.

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