How Backhaul Networks Influence the Feasibility of Coordinated Multipoint in Cellular Networks

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ABSTRACT

Interference is one of the most challenging problems in current cellular mobile access networks. Coordinated nultipoint transmission/reception, and in particular joint processing, has proven to be a beneficial solution for interference management. Most research so far has investigated the requirements and gains on the wireless side but only superficially showed the impact on and requirements for the backhaul network. We take a different approach by looking at different backhaul topologies and technologies, and analyzing how they can support CoMP cooperation schemes. We study, for different traffic scenarios and backhaul connectivity levels, which base station clusters are actually feasible compared to the ones desirable from the radio access network perspective. We found out that a significant mismatch exists between the desired wireless clusters, as defined by the RAN, and feasible ones, as allowed by the given backhaul characteristics. Based on these findings, we explain how RAN clustering and backhaul clustering have to cooperate to come to feasible solutions. As one possible solution, we present a *backhaul network preclustering* scheme, which is able to predict which BSs are actually eligible for cooperation during the runtime of the network. The gains of this approach are quantifiable in terms of reduced signaling and user data exchange, and reduced MIMO signal processing.

INTRODUCTION

Interference is one of the most challenging problems in cellular mobile access networks, where the spatial reuse of the wireless resources by neighboring base stations (BSs) leads to poor performance, especially for users located at the cell edges. Coordinated multipoint (CoMP) transmission/reception, where multiple BSs form a cluster and cooperate by exchanging signaling and/or user data via the core and backhaul networks, has proven to be a very beneficial solution for interference management. In this direction, research has mainly focused on multiple-input multiple-output (MIMO) theory, showing the benefits of sharing channel state information (CSI) and user data via the wireline core and backhaul networks among multiple BSs to create a big MIMO channel. This technique is referred to as *network MIMO* or joint processing in the literature.

CoMP schemes can be categorized into three different categories, depending on the amount of information that has to be exchanged between the cooperating BSs:

- Intercell interference coordination (ICIC): The coordination of interference between cells here refers to coordinated scheduling. More precisely, the scheduling of cell edge users is coordinated among neighboring BSs such that the interference is reduced. This requires only scheduling information to be exchanged between the BSs; that is, user data and CSI needs to be available only at the serving BS with which a user equipment (UE) device is associated.
- Coordinated beamforming: In the case of coordinated beamforming, only CSI is shared between cooperating BSs. The CSI is used to compute the precoding matrices at the BSs to suppress interference to UE devices in adjacent cells. User data is transmitted to the UE only from the serving BS. Thus, no sharing of user data between cooperating BSs is required in this CoMP scheme.
- Joint processing: Joint processing means that antennas of multiple BSs are virtually combined into a large distributed antenna system (DAS). This way, the number of antennas for transmission/reception is increased via joint precoding/decoding, which is done at a central controller or in a distributed manner among the BSs. There are different schemes to implement joint processing on the air interface. Dynamic cell selection (DCS) and open-loop MIMO require exchanging only user data between cooperating BSs. More advanced techniques, like closed-loop MIMO schemes, especially multiuser MIMO (MU-MIMO), additionally require exchanging CSI in addition to user data, resulting in more stringent delay constraints in the backhaul network. Furthermore, as the transmission/reception at the cooperating BSs happens

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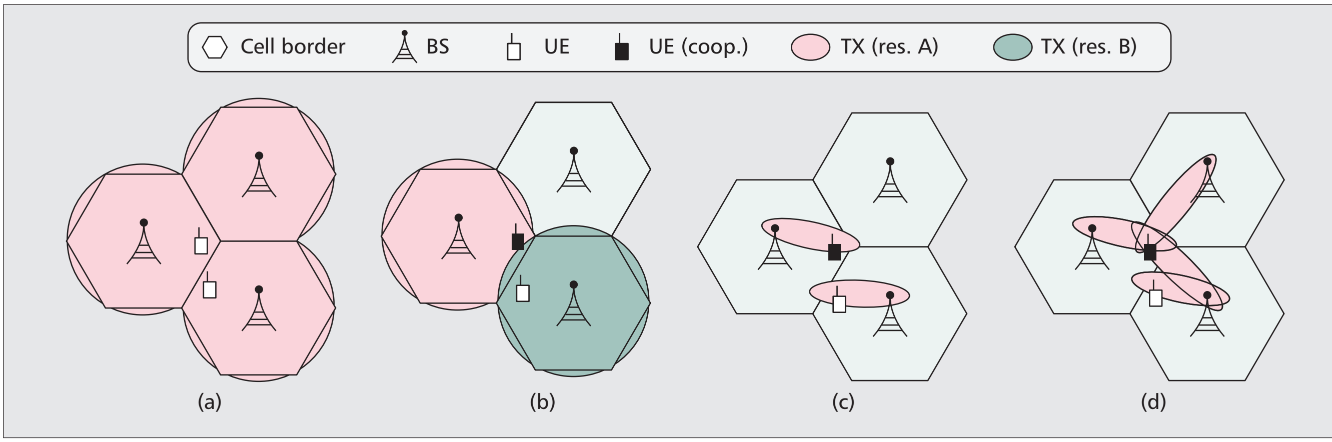

Figure 1. *Different CoMP techniques in the downlink transmission from BSs to UE. The different colors of the wireless transmissions indicate different physical resources: a) no CoMP: BSs transmit on the same physical resources, which causes interference; b) coordinated scheduling: BSs coordinate scheduling decisions to use different resources for cell edge UE device; no user data sharing required; c) coordinated beamforming: BSs beamform to their respective cell edge UE devices to minimize interference; no user data sharing required; d) joint processing: BSs transmit on the same physical resources to create constructive interference at the UE; user data sharing is required.*

simultaneously, synchronizing the transmitted signals is necessary.

Figure 1 gives an overview of the different CoMP techniques. Depending on the CoMP scheme, the amount of shared user data and signaling exchanged between the cooperating BSs differs. This clearly affects both the achievable performance in the wireless part of the network and the requirements on the backhaul infrastructure connecting the different BSs.

Joint processing is the most promising among the described CoMP techniques as high gains in terms of cell capacity are provided by the MU-MIMO scheme. However, it requires exchanging CSI and UE devices' user data between cooperating BSs. This results in very demanding requirements for the backhaul and core networks in terms of latency, capacity, and synchronization precision. If these requirements cannot be fulfilled by the backhaul infrastructure, the performance of joint processing significantly decreases or even becomes infeasible.

Recognizing the extent of these additional requirements posed on the backhaul network, the authors of recent publications have assumed capacity-constrained backhaul networks. In [1], Marsch and Fettweis consider cooperative downlink transmission for a capacity-limited backhaul and partial channel knowledge at BSs and UE devices. The performance of certain cooperation schemes in terms of rate/backhaul trade-off for different interference scenarios is evaluated. Samardzija and Huang study the overall capacity requirements for a backhaul network for supporting different CoMP schemes [2]. They show that when user data sharing between BSs occurs, significantly more capacity is required in the backhaul network, directly proportional to the number of BSs in the cooperating cluster. To achieve the desired data rates at a reasonable backhaul load, they propose to quantize the data exchanged between the cooperating BSs. In [3], Simeone *et al.* discuss some implementation options for CoMP, finding a relation between the desired signal-to-noise ratio (SNR) for the UE and the required backhaul capacity. Zakhour and Gesbert evaluated the data rates the user can achieve in a CoMP system with constrained backhaul, trying to quantify the user data that needs to be exchanged between the cooperating BSs [4]. Based on this analysis, they derive an "achievable rate" for which the backhaul load can be relatively low. Finally, [5] evaluates the CoMP performance on a topologically constrained backhaul where links exist only between neighbor BSs.

These and other related research papers do not look into details of the backhaul network implementation like its actual topology and the used technologies for interconnecting BSs. But these aspects have significant importance for CoMP deployment and are extremely relevant for mobile operators' planning of future network architectures.

Starting from this statement, we approach CoMP from another point of view, and directly address the features and properties of the backhaul network infrastructure. We refer to an overall cellular network system where we explicitly highlight the role of the backhaul and core networks in the cooperation/coordination process. We take into account different backhaul topologies, like mesh or tree structures, evaluating, for different traffic scenarios, capacity, latency, and connectivity levels, and which BS clusters are actually feasible compared to the ones desirable from the radio access network (RAN) perspective.

To the best of our knowledge, this is the first work that discusses in detail the architectural design issues of a backhaul network infrastructure envisioning the support of CoMP. There has been previous work, as mentioned earlier, that also targets backhaul aspects of CoMP. These investigations, however, only look at the backhaul network in a very abstract way (e.g., by only considering a full mesh with a certain packet loss rate). This is not sufficient to gain insights on CoMP feasibility in real network deployments. We create a more realistic back-

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haul network model that reflects real-world topologies, and includes capacity limits and delay properties of real equipment.

Backhaul Network Implementation Issues

This section describes in detail how the backhaul network influences the feasibility of CoMP in real network deployments. We focus on the downlink of the most challenging type of CoMP, joint processing.

For the sake of simplicity, when we use the term *backhaul network* in the remainder of this article, we mean the network that interconnects the different BSs. This can also cover parts of the core network.

Details on Joint Processing

Using joint processing in the downlink means that user data is sent from multiple BSs at the same time such that the signals interfere constructively at the UE to maximize the received energy. Therefore, the user data of a cooperatively served UE device has to be available at all BSs that participate in the cooperative BS cluster. For the flat Long Term Evolution (LTE) and LTE-Advanced architecture, the user data has to be distributed from the serving BS, which receives it from the gateway to the Internet, to all BSs that participate in the cooperative BS cluster. The amount of user data that has to be distributed by the serving BS depends on the number of BSs in the cooperative cluster. The larger the cluster, the more user data has to be sent from the serving BS to the cluster members. This is traffic that has to be transported via the backhaul network in addition to the usual noncooperative traffic.

In addition to the user data, signaling data has to be exchanged between the cooperating BSs. To be able to perform precoding, CSI about the wireless downlink channels from all cooperating BSs to the jointly served UE is required. This CSI is measured and collected by the UE and sent back to the BSs. From the BSs, the collected CSI is sent to a controller[1] where the precoding matrices are calculated and sent to all BSs in the cluster (together with the user data and the scheduling information on when to send the data). Having the user data, and the scheduling and precoding information, the BSs are now able to send the user data simultaneously to the UE.

Requirements

First, there needs to be enough free capacity on the backhaul network links to enable the additional exchange of signaling and user data among the cluster members. Especially the link of the serving BS has to deal with the high load for distributing the user data to the other BSs. One implementation possibility is to exchange the raw user data together with the calculated precoding matrices. In this case, encoding is done at the cluster member BSs, which results in the least possible overhead. Alternatively, the user data is already encoded at the controller. In this case, encoded IQ samples, which are much larger than the raw user data, are sent from the serving BS to the cluster members. The disadvantage of this approach is that a lot more data has to be sent from the serving BS to the cluster members. That is why we focus on the first approach in the following.

Besides the link capacity, the link latencies in the backhaul network also play an important role. The reason for this is that the CSI is only valid for a very limited time as the wireless channel properties change quickly, especially when the UE moves.

A typical time interval for the CSI validity is 1 ms, which corresponds to the duration of an LTE subframe. This means that the duration from the point in time when the CSI is measured at the UE to the point in time when the cooperating BSs simultaneously send the data to the UE must be below 1 ms. During this interval, the CSI must be transferred to the controller, the CSI needs to be processed to calculate the precoding matrices, these matrices and the user data have to be sent back to the cluster member BS, and the user data has to be sent to the UE. Note that for the simpler cooperation techniques (coordinated scheduling and beamforming), the latency constraints are similar to joint processing, but the capacity requirements are much lower. As a result, from the latency point of view the following discussions also apply to these techniques.

Potential Problems

Future cellular networks, like LTE-Advanced, target cell throughputs of 1 Gb/s. This capacity can be provided by the backhaul network with current optical technologies, like wavelength-division multiplexing (WDM) passive optical networks (PONs). When activating joint processing, however, the additionally required capacity scales linearly with the cluster size. This size depends on the scenario, and varies between 3 and 30 BSs [6]. This high amount of additionally required capacity, on the order of several gigabits per second for each BS, makes the backhaul network a major limiting factor for the deployment of joint processing.

In addition to the capacity limitations of the backhaul network, the latency between the cooperating BSs needs to be very low. Deploying a full mesh network between the BSs to minimize the latency is not feasible for an operator. Instead, more cost-efficient topologies, like trees, are used. This, in turn, increases the latency between BSs as the paths between the BSs get longer. Furthermore, forwarding decisions (usually in the IP domain) have to be made at intermediate nodes, introducing further delay.

Figure 2 illustrates two examples where the backhaul network's link capacity and the delay in the network limit the feasibility of wireless cooperation.

For a mobile operator, it is important to understand the influence of the backhaul network architecture on the feasibility of future BS cooperation techniques, like joint processing. It is not sufficient to know the aggregated influence of the overall backhaul network, but it is required to know the influence of, for example, the actually used backhaul technology and the backhaul topology.

[1] *Controllers can be collocated at BSs (i.e., distributed in the network) or located in a central location inside the backhaul network.*

EVALUATION

To get insights into how the actual implementation of the backhaul network influences feasibility of wireless BS clusters, we conducted several simulations. These simulations provide an upper bound for wireless cluster feasibility while taking into account a certain degree of overprovisioning in the backhaul network.

The assumptions we made for our simulations and a description of how we evaluated the wireless cluster feasibility are given. Simulation results of the backhaul network topology influence are presented. The influence of the used backhaul technology and equipment is discussed.

SYSTEM MODEL

In all simulation runs, first, BSs are distributed in the field. Thereafter, links are added between the BSs (i.e., the backhaul network is created). Then UEs are randomly distributed in the field, and a desired cooperation cluster is selected for each UE device. These clusters contain neighboring BSs for which we later have to check whether or not the backhaul network permits cooperation, based on the given backhaul link properties like capacity and latency. Details on each simulation step are given in the following subsections.

Base Station Placement and Backhaul Network — For each simulation run, 100 BSs are distributed in a hexagonal layout of 10×10 BSs. The mean inter-BS distance is set to $\bar{s} = 1000$ m, which corresponds to an urban BS deployment scenario. The positions of the BSs are randomized by shifting their horizontal and vertical positions by two normally-distributed random variables with standard deviation $\bar{s}/8$ and zero mean.

After placing all BSs in the field, backhaul links are generated between them to construct a backhaul network. We evaluate two types of backhaul topologies: mesh and tree. These two scenarios have been chosen because the access part of real backhaul network deployments often consist of such structures.

The *mesh* topology is generated by connecting two BSs whenever the distance between them is smaller than $f_{\text{dens}} \cdot \bar{s}$. The factor f_{dens} defines the backhaul network's link density. We evaluate the range $0.6 \leq f_{\text{dens}} \leq 1.4$, which covers the spectrum from an unconnected to a fully connected mesh topology. Examples of such topologies are shown at the bottom of Fig. 3.

Generating *tree* topologies is done by selecting root BSs for the trees and "growing" a tree from each of these BSs. This growing is done iteratively by adding BSs to the next level of the tree if their distance to one BS in the previous level is smaller than $f_{\text{dens}} \cdot \bar{s}$. Similar to the mesh topologies, the parameter f_{dens} controls the density of the backhaul network. We limit the maximum depth of the tree to d, which we consider as a parameter during the simulations. Example topologies can be found at the bottom of Fig. 4.

Independent of the generated topology, all links have the same properties in terms of capacity and latency. We assume optical links that have a latency of $\bar{s} \cdot 1.45/c$, where s is the link length, c is the speed of light, and 1.45 the refraction index of the fiber. This corresponds to a typical single-mode fiber (SMF) setup.

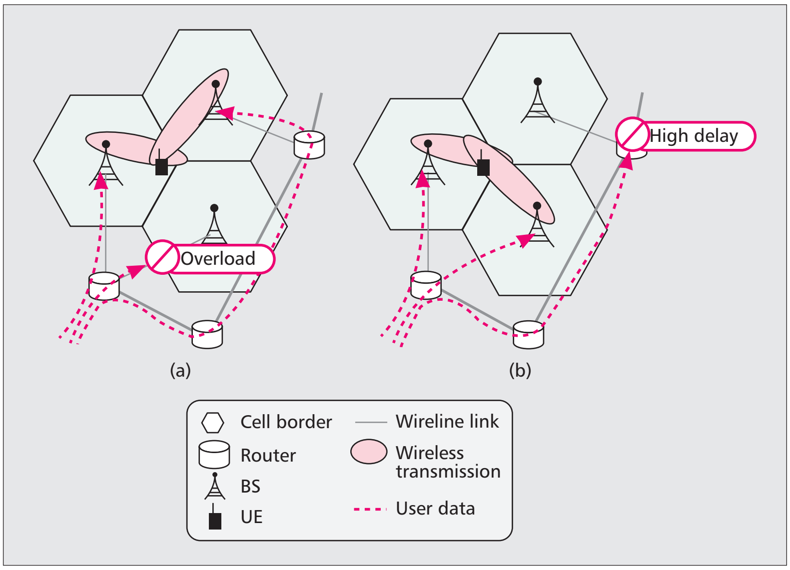

Figure 2. *Example of limited cluster feasibility in two cases. Notice that this applies also for the uplink case: a) one BS cannot cooperate because the backhaul is overloaded; b) the delay introduced by the switching/routing nodes makes cooperation infeasible for one BS.*

The link capacity is a parameter to achieve different levels of overprovisioning in our simulations. To get generic results, we set the capacity of each link in the topology to $f_{\text{lcap}} \cdot d_{\text{coop}}$, where d_{coop} is the average data rate generated by cooperatively served UE devices in the cells. The factor f_{lcap} can be seen as a normalized link capacity and is scaled from 1.25 to 10. A value of 10 already represents a quite overprovisioned backhaul capacity. For the targeted wireless cell rates of 1 Gb/s, this would result in up to 10 Gb/s backhaul capacity per cell, which is not feasible even with near-future WDM PON systems.

Base Station Cooperation and Wireless Clustering — So far, the scenario consists of a grid of BSs that are interconnected via a mesh- or tree-like backhaul network. To find out how this backhaul network influences the feasibility of wireless cooperation between the BSs, we need to select *wireless* BS clusters in which cooperation is desirable from the wireless point of view. In the real world (e.g., depending on the landscape), there will be scenarios where only a few cooperating BSs are useful and other scenarios where large wireless BS clusters (consisting of up to 30 BSs) are reasonable [6].

To cover all these scenarios in our simulation, we choose the set of cooperating BS for a given UE device U as follows. All BSs that are located within a radius of $f_{\text{wls}} \cdot \bar{s}$ are added to the wireless cluster of U. The factor f_{wls} is used to change the resulting wireless cluster size. In the BS arrangements resulting from the procedure described earlier, a value of $f_{\text{wls}} = 1$ corresponds to wireless cluster sizes of approximately three BSs; $f_{\text{wls}} = 3$ leads to 24 BSs per cluster.

For the non-hierarchical RAN system architecture, which will be used in LTE and LTE-

Advanced, we assume a distributed implementation of BS cooperation within the clusters [7]. The cooperation scheme exploits joint processing of the user data: user data of a cooperatively served UE device is simultaneously sent/received by all cluster members. As we focus on the downstream in our simulations, the user data is forwarded by the serving BS to all its cluster members.

Determining Wireless Cluster Feasibility — We generate 50 UE devices per simulation run, distribute them uniformly in the field, and check for each UE device which BS subset of the corresponding desired wireless cluster is actually able to participate in the cooperation, considering the limitations of the backhaul network. Averaging this fraction for all BSs in the input scenario leads to the main metric in the following plots, *wireless cluster feasibility*. Note that we only look at one UE device at a time during this simulation. Hence, the results are independent of the number of UE devices in the simulation and represent an upper bound for feasibility. Having multiple clusters that exist in parallel require more resources and hence cause lower wireless cluster feasibility.

To decide whether BS X can participate, we first check the unused link capacities on the (shortest) path from serving BS S to X. If adding X to the cluster without overloading a link on the path is possible, we increase the load on the link by the amount of one user data stream and continue checking if the latency constraints are fulfilled, too. If adding X to the cluster would overload one link from S to X, X cannot be a cluster member. For simplicity, signaling traffic is neglected as it is small compared to the required user data exchange.

If the check for backhaul network capacity was successful, we continue checking the latency constraints. Serving BS S needs to collect wireless CSI from all cluster members via the backhaul network. Based on this CSI, the precoding vectors are calculated and sent back to the cluster BSs together with the user data. The member BSs then simultaneously send the data according to the precoding information to the UE. All these steps have to be completed while the CSI is valid. We assume 1 ms for this, which corresponds to the duration of an LTE subframe. Furthermore, we reserve 0.5 ms for the processing at the serving BS. The remaining portion can be used for the transport from a potential member BS X to S and back; that is, in our simulations, the round-trip time (RTT) from X to S must be below 0.5 ms.

We neglect additional delay for feeding back CSI from UE devices to BSs, which would occur, according to the current LTE standard, due to scheduling. The effect of this delay increase would be outdated CSI that leads to a decreased CoMP gain, which makes it even more important to reduce delay spent for exchanging information via the backhaul network. Further work is required to reduce this CSI feedback delay in future versions of the standard.

When determining the RTT between S and a potential cluster member X, we take into account the propagation delay in the fiber links and IP processing delay at intermediate nodes. The link delays depend on the fiber lengths and are calculated as described earlier. The IP processing delay is set to 0.1 ms per hop [8].

Data exchange between BSs in LTE-Advanced is done via the logical X2 interface. This interface causes additional protocol delays. As this additional delay occurs only once during the initial handshake and not for each exchanged data packet, we neglect this in our simulation.

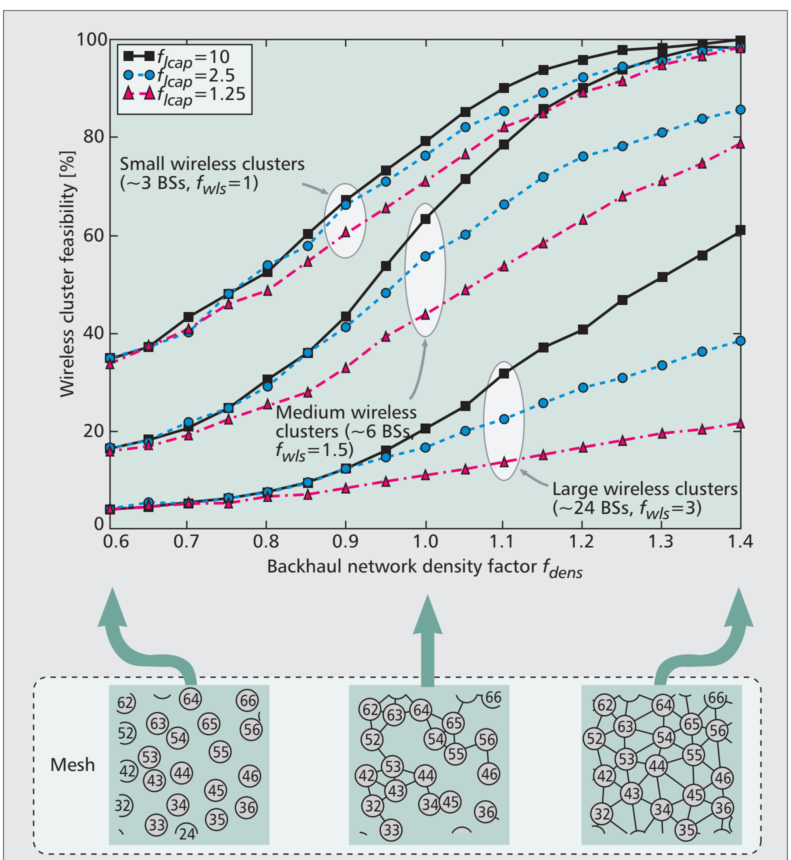

Figure 3. *Wireless cluster feasibility in a mesh-like backhaul network depending on network density, link capacity factor f_{lcap}, and wireless cluster size factor f_{wls}. The three topology excerpts below the x-axis illustrate how the topology looks like for a density factor of 0.6, 1.0, and 1.4.*

Influence of the Backhaul Network Implementation

Simulation results are given in the following subsections for mesh-like and tree-like backhaul topologies. We calculated confidence intervals for all of the plots. The confidence level has been set to 95 percent.

Mesh Topology — In this section, the wireless cluster feasibility is evaluated for different mesh topologies. The main parameter for this evaluation is the backhaul network density factor f_{dens}. It has been varied between 0.6, which corresponds to a very sparse mesh, up to 1.4, which means that the backhaul network is very densely connected. Furthermore, different link capacities are evaluated by setting the link capacity factor f_{lcap} to 1.25, 2.5, and 10. To get also information about the feasibility of different wireless cluster sizes, 1, 1.5, and 3 are chosen as values for f_{wls}. The resulting system behavior is shown in Fig. 3.

The plot shows the expected overall behavior: a more densely connected backhaul network leads to higher cluster feasibility. The feasibility starts at approximately 5, 15, and 35 percent for $f_{dens} = 0.6$ (the serving BS is always a member of the feasible cluster) and raises up to 100 percent for small wireless clusters and high link capacity ($f_{lcap} = 10$, $f_{wls} = 1.5$).

For medium network density ($f_{dens} = 1$), which would be reasonable for a real backhaul deployment, the feasibility is about 70 percent for small wireless clusters and nearly 15 percent for large clusters. Increasing the link capacity here does not improve the feasibility significantly as the connectivity between neighboring BSs is often insufficient. The necessary detour increases the delay and hence prevents cooperation.

The results show that there is a clear trade-off between the network density and its costs and the achieved wireless cluster feasibility.

Tree Topology — As an optical mesh network is hard to deploy for an operator due to the high costs, we evaluated several tree topologies. The first topology we looked at is a tree with a maximum depth of one ($d = 1$), which corresponds to a star. The second tree topology permits a maximum depth of three ($d = 3$). Both can easily be implemented in a real network deployment (e.g., using PON technologies).

Figure 4 shows the wireless cluster feasibility for the two tree-like backhaul network topologies. For the sake of clarity, this plot only includes curves for $f_{lcap} = 1.25$ and 10.

The simulation results show that, compared to the mesh topology, the wireless cluster feasibility in the tree topologies is about 50 percent lower for all evaluated parameter combinations. As a consequence, independent of the link capacity, the feasibility is limited to approximately 55 percent. The reason for this effect is the lower connectivity compared to the mesh topology. Although the reduced cluster feasibility is clearly a disadvantage, the reduced network connectivity, and hence reduced network costs, are the positive side of this trade-off.

The plot also shows that increasing the link capacity by a factor of 8 only marginally improves the cluster feasibility (approximately 15 percent at $f_{dens} = 1$, $f_{wls} = 1.5$). Here, the latency between the serving BS and the potential cluster members becomes the limiting factor. The link latency is also preventing better cluster feasibility when increasing the tree depth d from 1 to 3 for high network densities (both curves for $f_{lcap} = 10$ and $f_{wls} = 1.5$ end at approximately 55 percent).

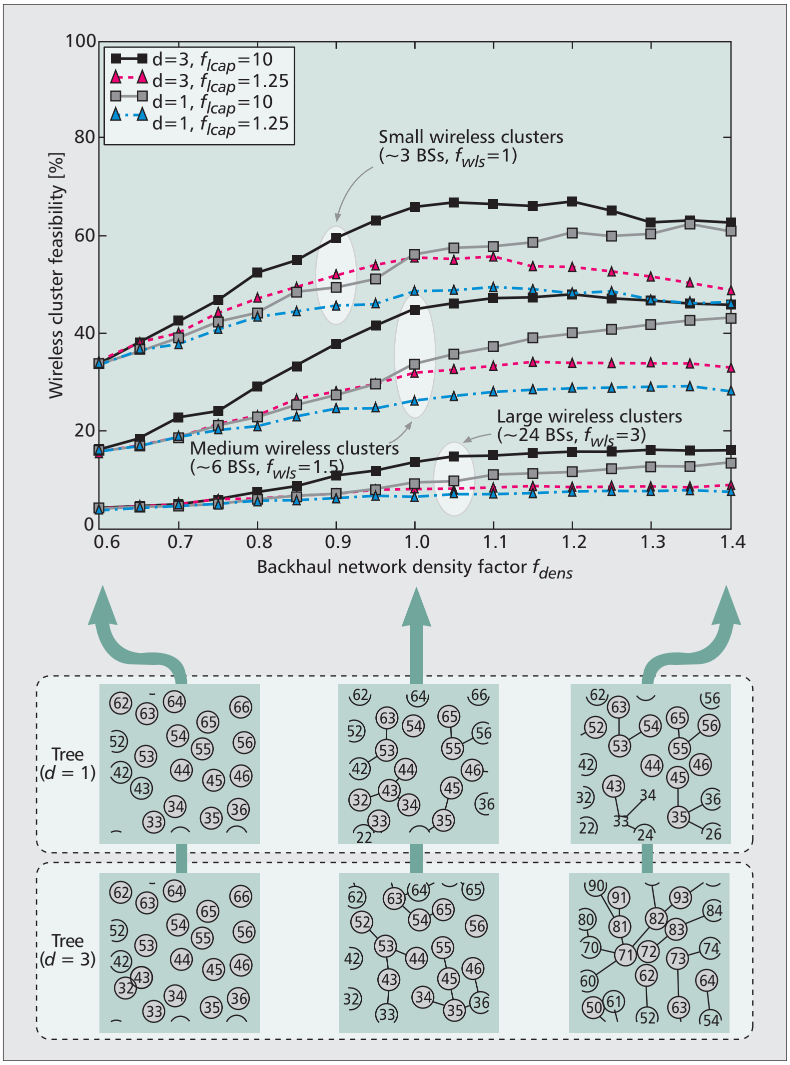

Figure 4. *Wireless cluster feasibility in a tree-like backhaul network depending on network density, maximum depth of the tree* d*, link capacity factor* f_{lcap}*, and wireless cluster size factor* f_{wls}*. The six topology excerpts below the x-axis illustrate how the two different tree topologies (*d = *1 and* d = *3) look like for a density factor of 0.6, 1.0, and 1.4.*

Implementation Technology

Despite the backhaul network topology, the equipment used for implementing the backhaul influences the CoMP cluster feasibility, too. To get an impression of how the wireless cluster feasibility changes when using future mobile-network-oriented backhaul technologies, we run further simulations. For these simulations, we made two changes to our assumptions. First, the backhaul technology supports layer 2 switching to reduce latency (i.e., the IP processing occurs only at the BSs), while data is switched at layer 2 at intermediate nodes between the BSs. Second, the backhaul network supports single-copy multicast: packets can be copied *on their way* from the serving BS to the cluster members. The serving BSs do not need to send data to all cluster members using multiple unicast flows. This saves capacity in the backhaul network.

As shown in Fig. 5a, the mesh topology benefits most from layer 2 switching. This is because multihop connections between BSs experience lower end-to-end latency, which translates into extended reach of the cluster. In tree topology scenarios, the gains depend on the maximum depth d of the trees, as d introduces an upper bound on the possible number of hops between cooperative BSs. Hence, it sets an upper bound on the possible feasibility improvements. In general, for lower link capacities ($f_{lcap} < 10$), the gain of using layer 2 switching reduces, as capacity (rather than delay) becomes the bottleneck. The behavior is similar when decreasing the desired wireless cluster size, as smaller clusters imply fewer hops between the BSs.

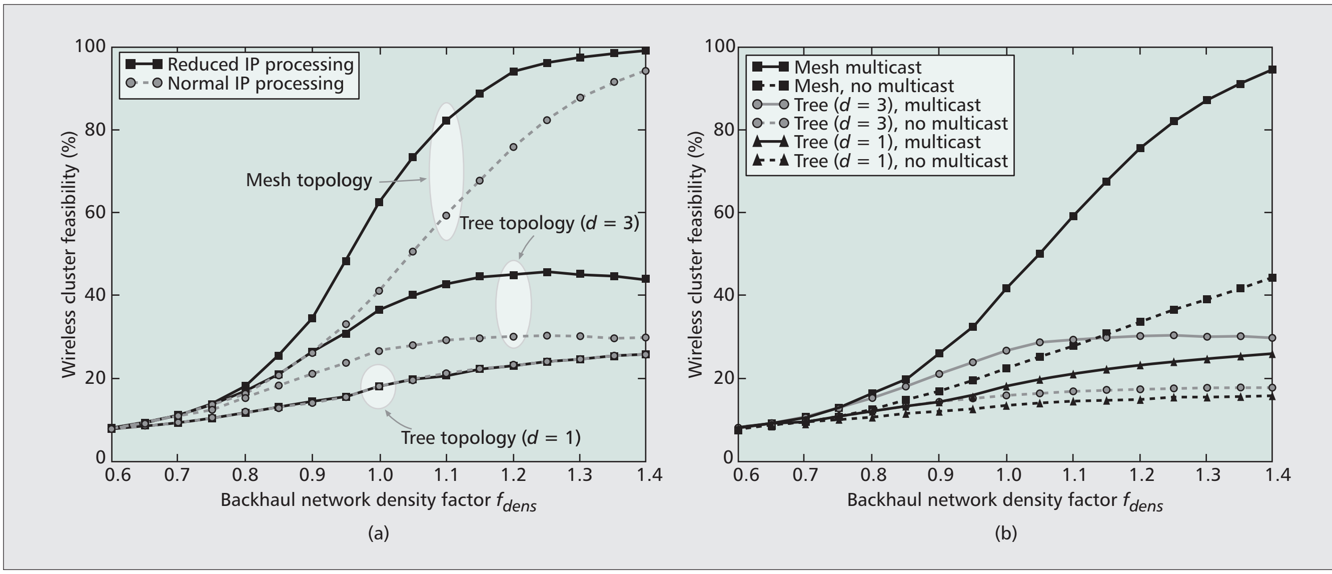

Figure 5. *Influence of backhaul network capabilities on wireless cluster feasibility: a) IP processing influence on wireless cluster feasibility for high backhaul capacity (f_{lcap} = 10) and large desired wireless clusters (16 BSs); b) influence of multicast on wireless clusters feasibility for low backhaul capacity (f_{lcap} = 1.25) and large desired wireless clusters (16 BSs).*

The plot in Fig. 5b shows that single-copy multicast leads to high gains in the mesh topology. The reason is that the probability of two or more flows sharing the same link is high and can occur for any placement of the serving BS within the backhaul network. Then savings in backhaul capacity become high and permit wireless cluster feasibility gains. In the tree topologies, having a multicast-enabled backhaul network is most beneficial in cases where a serving BS is located close to the leaves of the tree. In such cases, the links from the serving BS to the root of the tree are used for transporting multiple unicast flows containing the same data. Multicast capability compresses the unicast flows to one single flow, thus requiring a lower data rate. For a serving BS close to the tree's root, multicast does not help that much as the fanout is already high.

Although the two proposed enhancements for backhaul networks improve the feasibility of CoMP, they are far from removing the burden of a limited backhaul network. The same is true for other techniques that have been proposed recently, like direct optical transfers between BSs connected to the same PON. Furthermore, all these techniques are not yet available in commercial backhaul equipment. Hence, mechanisms are required to deal with limited backhaul networks.

Backhaul Network Preclustering

The evaluations earlier have shown that there will always be situations in which even small wireless clusters cannot be implemented due to the backhaul network's capacity and latency limitations. This happens despite an optical backhaul network deployment, and even when links are overprovisioned up to 10 times the cooperative cell throughput. Hence, choosing BS clusters for cooperation just based on the wireless channel conditions, as done in the current state-of-the-art approaches, degrades performance during the wireless transmission and causes unnecessary exchange of signaling and user data, as the BSs in the cluster cannot cooperate as expected.

To address this problem, we can exclude BSs that cannot participate in the cooperative transmission/reception from the backhaul network's point of view. This avoids additional overhead and leaves more resources for BSs that actually can cooperate. As the wireline network's status and capabilities change less frequently than the wireless channel conditions, we propose to introduce a *backhaul network preclustering* step before clustering based on collected wireless CSI. The resulting system architecture is illustrated in Fig. 6.

The overall system works as follows. As soon as a serving BS detects the necessity for serving one of its UE devices cooperatively (1), backhaul network preclustering is triggered. For this, the current backhaul network's state (consisting of, e.g., link capacities, latencies, and load) is required (2). This information can be collected on demand or read from a database that is updated regularly. Based on this information, the feasible BS cluster is calculated (3), containing all BSs that can potentially join the cooperative transmission/reception. This block is the core part of our approach as it calculates the feasible clusters based on the backhaul network's current status. The necessary algorithms can be implemented in a very computation-efficient way with low memory footprint [9].

During the backhaul network preclustering step, done by blocks (2) and (3), BS cluster candidates are determined to which the backhaul network provides high enough capacity and low enough latency from the serving BS. The actual requirements vary for different cooperation techniques like joint processing, joint beamforming, or joint scheduling.

Thereafter, wireless channel properties, like CSI, are collected only for the BSs that are contained in the previously calculated cluster candidate (4). Based on this information, the final wireless cluster is selected (5) in which cooperation takes place, and cooperative transmission/reception can start.

Following this approach, all signaling and user data transfers are avoided for BSs that cannot participate in the cooperation due to the backhaul network's limitations. This not only saves computation during the cooperation process but also reduces overhead for exchanging user data between BSs in the wireline network and for exchanging signaling information like CSI in the wireline *and* wireless networks.

To get an idea of the savings that can be achieved by the proposed clustering system, we have separately evaluated the resulting cluster sizes for the individual clustering steps. The results are shown in Fig. 7.

For large desired clusters, the proposed additional backhaul clustering step clearly reduces the overhead for infeasible BSs. This is indicated by the large difference between the desired cluster size C_{desired} and the eventually effective size $C_{\text{effective}}$. The relative savings are between 55 and 90 percent for the different topologies.

The situation is similar for small desired clusters, except that the overhead reduction is lower. For sparse backhaul networks, the backhaul still limits the effective cluster size, because the additional backhaul clustering step clearly reduces the overhead for infeasible BSs by up to 65 percent. In medium-dense backhaul networks (f_{dens} 1:0), desired and feasible clusters approach each other, which reduces the benefit of backhaul clustering. Dense backhaul networks even lead to feasible clusters that are larger than the desired ones in the mesh topology. Here, our clustering system sets the effective cluster based on the desired cluster.

Overall, the evaluation shows that in backhaul-limited scenarios, backhaul network preclustering is essential. Without this step, valuable backhaul resources are wasted for infeasible BSs that cannot contribute to improved service quality for UE devices.

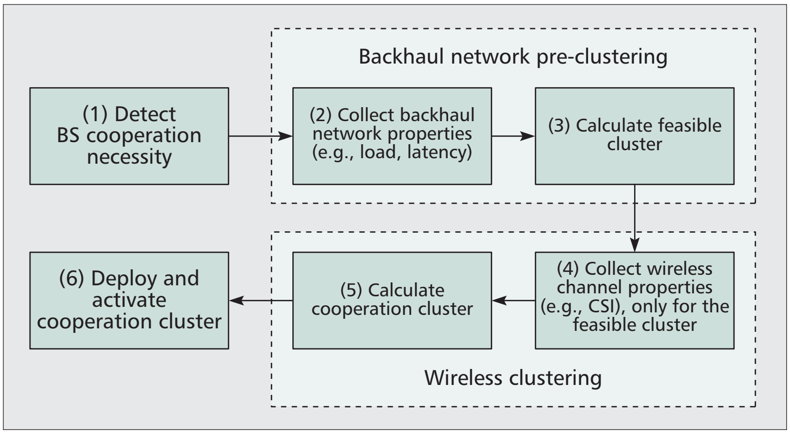

Figure 6. *Flowchart of the backhaul network preclustering system. By calculating feasible BS clusters based on the backhaul network properties before determining cooperation clusters based on wireless CSI, signaling and user data overhead is reduced.*

Conclusions

We have discussed the effect of backhaul network design on the overall wireless clustering procedure in a MIMO-enabled cellular network.

We have shown how different backhaul topologies, as well as backhaul network properties, influence the wireless cluster feasibility in the downlink, pointing out trade-offs between wireless cluster feasibility and the backhaul network connectivity level. A physical mesh backhaul network architecture, which is able to provide the best network MIMO feasibility performance, turns out to likely be "infeasible" due to its high costs. On the other hand, tree-like backhaul architectures provide a reasonable compromise between cluster feasibility and overall network costs.

We have also discussed how the technology used for implementing the backhaul network plays an important role in wireless cluster feasibility. Removing IP processing through layer 2 optical bypassing or using physical multicast features has the potential to improve this feasibility.

Based on the gained results, we have proposed a mobile network system architecture that introduces a backhaul network preclustering step

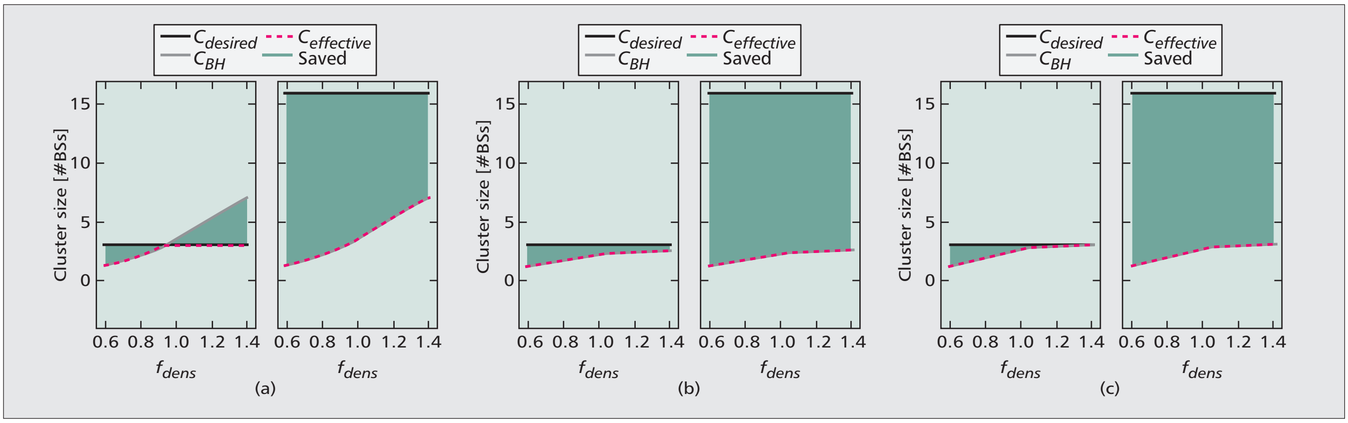

Figure 7. *Desired wireless cluster sizes ($C_{desired}$, determined in step 4 of Fig. 6), feasible clusters according to backhaul network (CBH, from step 3), and resulting effective cluster when using proposed clustering architecture ($C_{effective}$, from step 5). Savings are highlighted by filled areas. Akin to previous plots, the x-axis depicts the backhaul network link density factor f_{dens}: a) mesh topology with small (left, 3 BSs) and large (right, 16 BSs) desired clusters; b) tree topology (d = 1) with small (left, 3 BSs) and large (right, 16 BSs) desired clusters; c) tree topology (d = 3) with small (left, 3 BSs) and large (right, 16 BSs) desired clusters.*

Overall, the evaluation shows that in backhaul-limited scenarios, backhaul network preclustering is essential. Without this step, valuable backhaul resources are wasted for infeasible BSs that cannot contribute to improved service quality for UE devices.

before collecting CSI, thus making wireless clustering decisions only for the set of BSs which can really participate in the cooperation. According to our evaluations, this system allows savings up to 90 percent in terms of reduced CSI gathering, signaling, and user data exchange.

The insights gained during our work show that the properties of the backhaul and core networks play an important role when applying BS cooperation in future mobile access networks. Even future high-capacity optical backhaul/core networks cannot guarantee that cooperation techniques can be applied ubiquitously in the network. Hence, mechanisms and algorithms for deciding where, when, and how to cooperate must not only rely on information from the wireless side, but also incorporate the backhaul and core networks' status.

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