Power–Efficient Mobile Backhaul Design for CoMP Support in Future Wireless Access Systems

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***Abstract*—Base Stations (BSs) cooperation techniques, also referred to as Coordinated Multi-Point (CoMP) in the 3GPP terminology, promise significant performance gains in future 4G and beyond systems. The counterpart to such gains is represented by the challenging requirements that CoMP puts on the backhaul network, which may prevent the inclusion of certain BSs selected for the cooperative cluster. The consequences of such a failure can be relevant for the overall power consumption. Those BSs which are not eligible for cooperation would be unnecessarily included in the channel estimation process, which consumes power both at the BS side (sending of reference pilots) and on the backhaul network side (exchange of Channel State Information (CSI) between BSs). To limit the detrimental effects of such CoMP cluster "unfeasibility", we discuss the benefits of a cross-layer approach which relates wireless CoMP requests to the backhaul network status. We show how the preemptive exclusion of the non-eligible BSs results in a considerable saving of the overall power consumption. We further complement our system by proposing optical bypass techniques aimed at improving the CoMP support from the backhaul perspective. This results, on one side, in the enhancement of the overall CoMP feasibility performance, and, on the other side, in the reduction of the consumed power thanks to the offload of IP processing to the switching layer[1].**

I. Introduction

BS cooperation in cellular networks is expected to provide high benefits in terms of wireless transmission capacity, inter-cell interference management, and cell edge user experience [1]–[4]. The counterpart for these advantages is represented by the stringent requirements on the backhaul network capabilities necessary for supporting BS cooperation, as well as the economical aspects related to the increase of power consumption costs deriving from it.

We focus on two different aspects that contribute to power consumption in a CoMP–capable cellular network: (i) the channel estimation process, which requires not only the sending of training symbols from every BS of the cooperation set to the User Equipment (UE), which then sends back the estimated CSI, but, in some cases, also the exchange of the resulting CSI estimation between these BSs across the backhaul infrastructure; (ii) and the backhaul network architecture, which, together with the adopted switching technology, is required to process a high amount of traffic due to additional signaling and user data sharing between cooperating BSs.

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Related to the first aspect, different CSI estimation mechanisms have been proposed so far. A recent overview of them is contained in [5], which additionally proposes a CSI estimation scheme for cooperative transmission that is able to reduce by a factor of 280 the amount of signaling exchanged over the backhaul network. Looking at the power consumption aspects, authors of [6], propose, for a MIMO system in which channel estimation is subject to delay and error constraints, an antenna selection scheme able to minimize the power consumed both at the transmitter and the receiver during the estimation process. Several solutions have also been proposed to minimize the computational cost required for CSI estimation, thus resulting in considerable gains in terms of power consumption [7], [8]. Note that the improvement of the channel estimation process from the energy perspective only affects the power consumption at the BS. In a cooperative MIMO capable system, the distribution of the CSI estimation between cooperating BSs, as well as the related processing, play a big role in the overall power consumption, as we prove along the paper. In this regard, the backhaul transport network architecture critically affects the overall power consumption of the system. The choice of the appropriate hardware technology as well as switching paradigm can strongly reduce the energy requirements for the deployment of BS cooperation, while improving the support for the CoMP transmission/reception.
In relation to the backhaul network architecture, the use of certain CoMP techniques poses important requirements on its capabilities. End-to-end latency and link capacity play a crucial role in the support of CoMP deployment. As we discuss along this paper, in some scenarios some of the BSs which were selected for participating in the CoMP might not able to take part to it because of the limited capacity or high end-to-end latency introduced by the backhaul architecture. In this case the CoMP procedure incurs in a cluster "feasibility" issue, which might result quite detrimental in terms of power consumption. Such non-eligible BSs in fact would take part to the CSI estimation and distribution process, even though they cannot take part to the CoMP transmission/reception. This turns out in to a unnecessary power consumption which could be eventually avoided if a pre-knowledge of what we call "feasible" cluster would have been preemptively available.

In that regard, we propose a CoMP architecture that, taking into account the "feasibility" of the desired wireless cooperative cluster, is able to reduce the amount of CSI-related signaling in the overall system, thus contributing to

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the overall power reduction in the mobile network. Such a scheme is based on the pre-calculation of the set of BSs which can effectively take part to MIMO cooperation, and excludes from the CSI estimation process those which are not capable because of backhaul network inefficiencies like excessive latency or limited limited capacity.
We finally take into account different backhaul technologies and switching paradigms, showing how they can further contribute to the overall power consumption [9], [10]. To the best of our knowledge, this aspect has not been yet investigated in the related literature.

In this paper we focus on the Joint Processing CoMP technique, which is the most challenging among the available cooperation schemes but it is also the most promising in terms of achievable throughput performance. It requires not only to exchange CSI signaling between the cooperating BSs, but also to share the user data of the UEs between them.

II. Joint Processing

In a CoMP system which adopts joint processing, the user data is sent from multiple BSs to the user terminal at the same time, such that the signals interfere constructively at the UE to maximize the received energy. The user data of a cooperatively served UE needs to be available at all BSs participating in the CoMP cluster.

The user data distribution process is achieved by exploiting the backhaul network architecture that connects the BSs to the core network infrastructure. 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. The user data received at each cooperating BS undergoes a precoding process before being sent over the wireless channel. The purpose of such a precoding operation is to jointly contribute to the throughput performance at the receiving UE.

Referring to the Long Term Evolution (LTE) and LTE–Advanced logical architecture [11], the user data has to be distributed from the serving eNB (enhanced Node–B), which receives it from the PDN–gateway, to all eNB participating in the CoMP cluster. The resulting distribution architecture is then a star-like one, from the "master" eNB to the "slave" eNBs (Fig. 1).

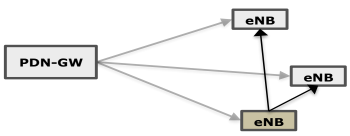

Fig. 1. Logical distribution architecture for the 3GPP LTE system.

We assume that the precoding process can happen at each BS. In this sense, a so called "Controlling Unit", co-located with each BS, is in charge of the calculation of the precoding weights which have to be applied to the user data before the wireless transmission. Whether this precoding calculation occurs only at the serving BS or locally at each cooperating one is discussed in next subsection.

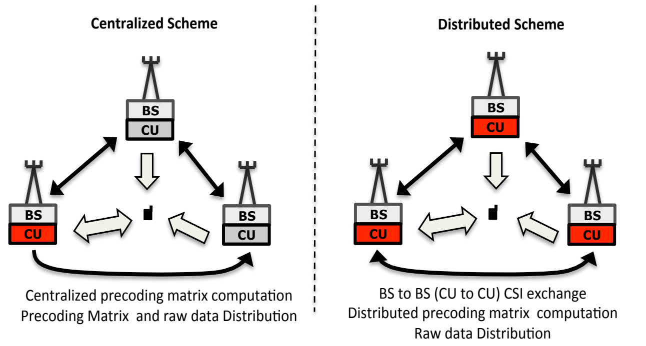

Fig. 2. Centralized Precoding Weigths Calculation vs. Distributed Precoding Weights Calculation.

Note that the assumption of having Controlling Units at each BS is in line with what it is currently discussed in the 3GPP LTE standardization body[2].

A. Channel State Information Exchange Architectures

In order to benefit from Joint Processing, the user data at each cooperating BS needs to be precoded with specific weights (also referred to as precoding matrix). These weights are calculated at the Controlling Units co-located with the BSs and are based on the estimation of the channel condition (CSI) measured by the UE in regard of each cooperating BS. Precisely, the estimation process of the channel state (also referred to as CSI) is based on the use of training pilots sent from each cooperating BS. After receiving the reference pilots, the UE can estimate the CSI and feed it back to the serving BS. Note that the calculation of the precoding matrix also depends on the CSI fed back from the other UE connected to the other BSs. Once the complete channel state information is globally available, the calculation of the precoding matrix can take place. To this end, two architectural approaches are possible: centralized and distributed.

In the centralized scheme (please refer to the leftmost part of Fig. 2), upon wirelessly receiving the CSI collected by the UE, the Controlling Unit located at the serving BS is able to compute the precoding matrix to be applied to the raw user data. Once calculated, the precoding matrix is is distributed to all the cooperating BSs together with the raw data.

In the distributed scheme, every Controlling Unit located at the cooperating BS locally computes the correspondent precoding vector. To this purpose, the CSI estimated at each cooperating point needs to be shared among the participants to the cooperative cluster (e.g., by using a control channel over the backhaul network). Each cooperating BS will be then able to apply its correspondent precoding vector to the raw data (please refer to the rightmost part of Fig. 2).

[2]Alternatively, one or more controller can be located in a central location, inside the backhaul network. Nevertheless, this does not influence the results of our evaluations

Both architectures require a considerable exchange of signaling data over the backhaul network. In the centralized approach, the estimated CSIs are not exchanged over the backhaul network. On the other hand, the precoded data occupies higher bandwidth than raw data.
In the distributed approach, only raw user data travels on the backhaul network. Nevertheless, a backhaul control channel will be interested by a considerable exchange of CSI signaling traffic.

As we discuss in the next subsection, the amount of CSI signaling as well as user data exchanged over the backhaul network have an interesting impact on the power consumption of the cellular system.

B. Power Consumption Analysis

Jungnickel et. al [5] calculated the CSI feedback overhead in the distributed precoding matrix calculation setting. Considering 7 cooperating BS equipped with 2 antennas, the amount of CSI exchanged over the backhaul network results approximately equal 224 Mbps. Assuming a *full* IP mesh architecture connecting the cooperating BS, the IP processing cost required for exchanging this CSI, for a single user terminal, at the IP router, is calculated according to [12]: $P = A \cdot C^{\frac{2}{3}} \approx 37$ W, where A [Watt / Mbps] is equal to 1.0[3].

Moreover, channel estimation has a cost that is related to the number of cooperating BS. Considering 128W as the base line power consumption for a BS, the power consumed for CSI estimation (e.g., sending pilots from each BS to the UE) and processing takes roughly 10% of it, thus turning into ≈13W.

We conclude that for a single user the CSI exchange, estimation and processing for the Joint Processing cooperation scheme raises the power consumption of ≈ 50 Watts[4].

It is worth remarking that by using the centralized scheme, no CSI data exchange would occur over the backhaul, thus lowering the overall backhaul power consumption. However, the precoding operation on the raw data increases the size of the information distributed from the master BS to the cooperating BSs, which eventually impacts the power consumption figures related to the data switching over the backhaul network.

III. Backhaul Status Feedback for CoMP Deployment

The deployment of BSs cooperation, and in particular Joint Processing, requires demanding backhaul characteristics, both in terms of capacity, and in terms of latency and synchronization aspects. In a realistic scenario, the selection of a cooperative BSs cluster, ideally necessary for the required service, has to be correlated to the current status of the backhaul links' load. This might result in the unfeasibility of the desired wireless cluster. As a consequence, unnecessarily a significant amount of CSI and user data is exchanged among BSs which are not be eligible for cooperation, from the backhaul point of view, thus translating in higher power consumption during cellular network operation.

A. Comp Cluster Feasibility and Potential Power Savings

To analyze the impact of the "feasibility" problem, we considered different topologies for backhaul deployment, with some limitations in terms of available capacity and achievable latency. Based on such assumptions, we studied the feasibility of BSs cooperation from the backhaul point of view, according to CoMP joint processing requirements. Fig. 3 summarizes the results of this analysis. For our plots, we assume that the network capacity is high enough to accommodate up to 10 times the bandwidth required for cooperatively serving one user. The backhaul density factor indicates the node degree (number of outgoing links) at each BS. The higher the value of this factor, the higher the number of links that connect a certain base station to its neighbors, as shown in the network snapshots reported below the figure. For instance, for the mesh topology, a backhaul density factor of 1.0 corresponds to an average node degree of 2.54 at each BS. The y-axis reports the percentage of feasible wireless clusters. The percentage of feasible clusters indicates the fraction of BSs which are actually eligible for cooperation, considering the backhaul properties, compared to those which were chosen according to the performance requirements of the user.

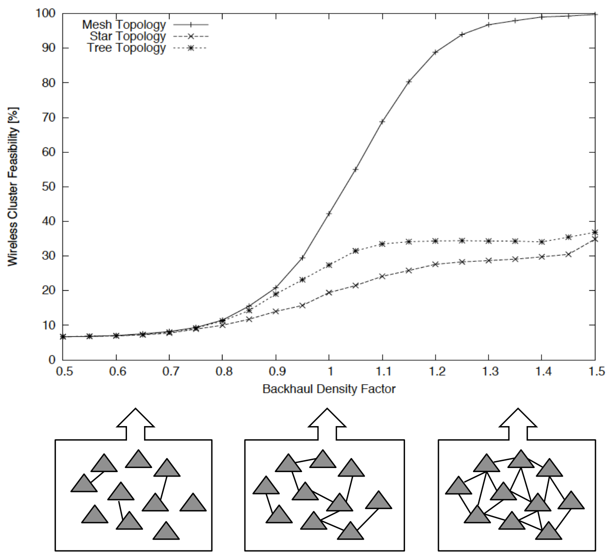

Fig. 3. Achievable wireless cluster size according to current backhaul status for different topologies.

Depending on the topology and on the degree of the nodes connecting the BSs, the feasibility of the CoMP cluster strongly varies from very small values, for scarcely connected backhaul (low backhaul density factor), up to ≈75%, in the case of mesh topologies. Either star or tree topologies do not allow to achieve similar performance even for high

[3] Note that the assumption of a full mesh architecture is quite optimistic, since it implies that a direct connection between neighbor BSs is always available. If multiple IP hops would be present, higher power consumption could be expectable in the backhaul.

[4] This calculation does not include the impact of uplink and downlink MIMO processing, as well as the impact of the user data transfer from the coordinating BS (master) to the cooperating BSs (slaves), which also play a role in the overall power consumption.

density factor. In this case, we can only achieve 40% of the desired cooperative cluster size. This is due to the fact that such topologies offer a limited space of routing possibilities. Depending where the serving BS is located within the tree or the star, the routing is constrained by the shape of the topology itself, which might force the data path through multiple hops. This causes high latencies, which traduce in low CoMP feasibility performance. In a mesh backhaul topology, such routing inefficiencies can be overcome by selecting alternative routes for the connection of the cooperative BSs.

Based on this analysis, we can already intuit the beneficial effects in terms of reduced power consumption. If a "pre-knowledge" of the feasible clusters would be available at the Controlling Unit, a large amount of CSI processing and exchange can be avoided when these BSs are a-priori excluded from the CoMP cluster deployment.

B. Backhaul Cluster Prediction Mechanism

In what follows we describe the functioning of our prediction scheme. As we anticipated before, we perform a pre-check of the eligibility of BS to be part of the established CoMP. This allows for excluding a-priori those BSs which cannot join such a CoMP, thus avoiding unnecessary CSI signaling exchange over the air and over the backhaul network. The overall system architecture is summarized on Fig. 4.

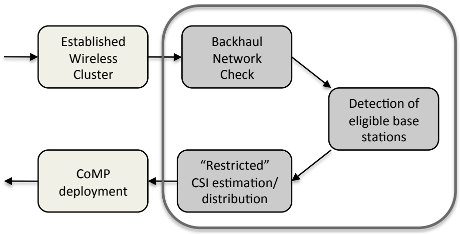

Fig. 4. System architecture for prediction of cluster feasibility.

The core part of the proposed system is constituted by the darker blocks, which respectively perform the operations necessary for collecting the backhaul network status information which is subsequently used for determining which BSs can really join the desired wireless cluster. We refer to this process as *Pre-Clustering*.

An algorithm is required to perform the eligibility check, in order to find out which BSs can actually join the cooperative cluster without violating the requirements of Joint Processing. This algorithm needs to minimally impact the cooperation process, especially for what concerns the computation delay.

It can be shown that the search of the optimal cooperating cluster for a given serving BS can be formulated as a Mixed Integer Linear Programm (MILP) problem. The computation time in this case is extremely high even for small search scenarios. To achieve the same goal with a minimal computation time (and memory cost), we propose a modified Breadth First Search (BFS) heuristic approach. Using a graph representation G of the backhaul network with BSs as vertices and links as edges, the algorithm starts at the desired serving BS and iteratively extends the feasible cluster if the backhaul network properties permit this. For space reasons we do not report the pseudo-code details of the algorithm as well the performance figures. Our algorithm returns feasible cooperative cluster sizes which slightly differ from the optimal ones only in very large (probably unrealistic) cooperating cluster scenarios. Otherwise the provided solution corresponds to the optimal one.
The main advantage lays in the computation time, which is largely below 1 ms. This is perfectly in line with the latency requirements of joint processing, which tolerates up to 1 ms offset for the user data availability at the cooperating BSs.

Running the algorithm consumes a minimal amount of memory and does not require any additional processing power capability at the Controlling Unit.

C. Power Consumption Benefits

We evaluate the reduced power consumption achievable through our prediction scheme. Such gains are strongly related to the amount of useless CSI exchange and processing which are avoided thanks to our procedure. The non-eligible BSs do not have to send the pilots to the UE, for CSI estimation. Additionally, they will not produce any load on the backhaul for the CSI exchange with the master or the other BSs. We assume that the power consumption due to CSI estimation scales linearly according to the number of cooperative nodes.

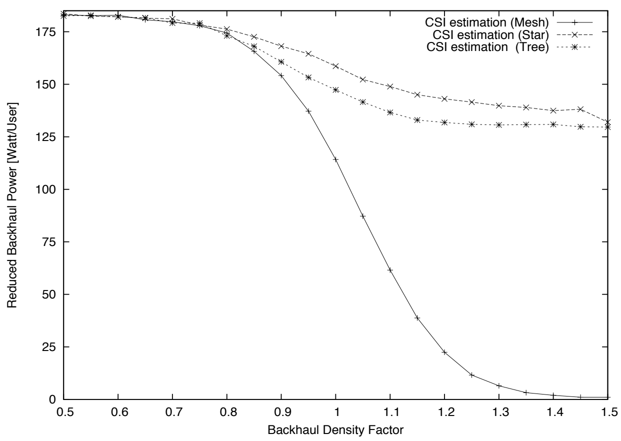

Fig. 5. Reduced power consumption, per UE, using feasible cooperation cluster prediction.

In Fig. 5 we report the effects of our prediction scheme in terms of reduced power consumption. Precisely, we show the amount of power which is saved by using our pre-clustering procedure with respect to the normal CoMP procedure. The reason behind this behavior, especially for the mesh topology, is related to the ratio between eligible BSs and total number of BS candidates: the higher the backhaul connectivity level, the higher the possibility of achieving the desired cluster, the smaller the amount of non-eligible BSs. This traduces into lower performance for our scheme, which is mostly effective when the number of non-eligible BSs is high.

IV. Backhaul Network Improvements

As we have discussed in the previous section, the characteristics of the backhaul topology play a determinant role in the overall the power consumption of the mobile network. The topology that is used for the backhaul network deployment strongly affects the number of BSs which can really take part to the CoMP process, thus leading to unnecessary power consumption in case of low degree of connectivity between the cooperating BSs.

Nevertheless, other factors can contribute to diminish the power consumed for BS cooperation. Assuming that the CoMP system operates according to the ‘feasible” set of cooperative BS, achievable by means of our mechanism, in the following analysis we take into account the use of different transport technologies which, on one side, are able to attain the requirements for CoMP transmission/reception, and, on the other side, can reduce the power consumption due to their characteristics.

Specifically, we consider the impact of optical switching for the implementation of the backhaul network, focusing on techniques which have the capability to offload packet processing from the IP layer.

A. Optical ”tunneling” for power consumption efficiency

Optical technology and related switching techniques are recently attracting the attention of many operators for the high capacity and low power consumption they are able to support [9], [10]. In this regard, we consider the adoption of optical switching paradigms for the backhaul network architecture, which can provide very high energy consumption benefits whereas the IP packet processing is offloaded from the IP level to the optical switch level. In Fig. 6 we report an example of optical bypassing procedure which can improve CoMP feasibility and can provide power consumption reduction.

Basically, once the set of cooperative BSs is known, dedicated lightpaths (or equivalently, optical tunnels) can be allocated such to directly forward data from the Controlling Unit of the master BS to the Controlling Units of the other cooperative BSs. Thanks to this technique, IP processing at intermediate nodes can be avoided, thus achieving power savings. These optical tunnels can be allocated and released on demand, depending on the optical technology, but can also be statically configured for some specific areas where cooperation is quite likely. For this purpose, reconfigurable optical cross-connects or add/drop multiplexers should be used.

Fig. 7 shows the benefits of using optical bypassing in our three reference topologies. The reported results need to be interpreted according to the CoMP “feasibility” considerations already discussed in section III. The mesh backhaul is able to achieve higher CoMP cluster feasibility levels compared to star and tree backhaul topologies. This implies that the number of BSs participating to the CoMP cluster is higher than in those cases. Consequently, the amount of traffic exchanged

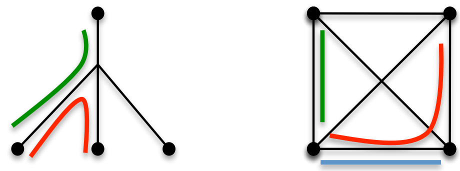

Fig. 6. Optical Bypassing for Power Consumption saving in the backhaul.

over the backhaul network is larger, thus causing higher power consumption compared to the tree and star topologies.

Based on this consideration, the performance gains related to optical bypassing should be regarded relatively to the correspondent backhaul topology deployed with IP routers.

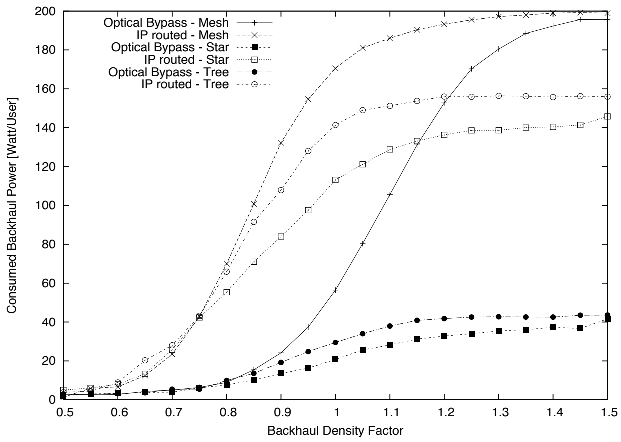

Fig. 7. Optical switching benefits for Power joint processing implementation.

The behavior of all curves is non-decreasing with the increase of the backhaul density factor. The amount of BSs which can take part to the CoMP cluster in fact gets higher as soon as the backhaul connectivity level grows. We can observe that for the same backhaul density factor, the implementation of optical tunnels brings down the backhaul power consumption in all the considered scenarios. This is especially remarkable in the mesh backhaul topology, where the possibility of searching among several alternative routes allows for the deployment of optical paths more frequently than in the star and tree backhaul topologies. This is not possible for the star and tree topologies, where the alternative routes search is limited by the shape of the topology itself. This explains why the curves saturate beyond a certain density factor.

B. Backhaul Technology and Power Consumption

To complete our study, we looked at different technologies for backhaul implementation. In particular, we referred to the Microwave technology, which allows for cheap deployment

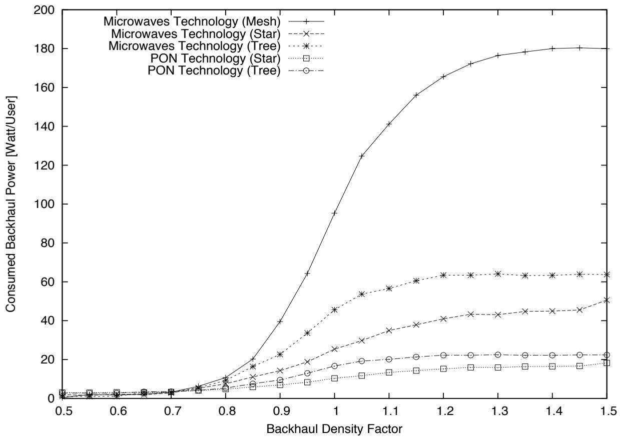

Fig. 8. Impact of backhaul technology on power consumption in joint processing capable systems.

costs (no fiber digging) and good power consumption figures (40W per 1.25 Gbps load [12]), and PON (Passive Optical Network) technology, which is a new emerging technology which promises very high data rates at very low power consumption. PON technology can be used to establish all-optical routes between cooperating BSs. Because of companies undisclosure agreements, we cannot provide the PON power models utilized for our evaluation.

Fig. 8 shows how the PON technology, suitable only for tree and star topologies, provides higher power efficiency compared to the correspondent backhaul topologies implemented through microwave links.

The microwave technology is limited both in terms of reach ($\approx$ 1Km) and in terms of data rates ($\approx$1.25 Gbps). A single point-to-point microwave link could not be sufficient for transporting the traffic exchanged for BSs cooperation. We simulate this effect by adding additional transmitters whenever the feasibility of the CoMP cluster can be improved.

For the star and tree topologies, the routing constraints discussed before make the installation of such additional transmitters useless in terms of cluster feasibility. The dominating factor here is always represented by end-to-end latency requirements which are hardly fulfilled. For the mesh topology, the possibility of finding alternative low latency routes makes the use of additional transmitters beneficial for the CoMP cluster "feasibility", although requiring high power consumption. However, the overall consumed power still results smaller than in the equivalent scenario where IP routers are used (as visible on Fig. 7, in the curve corresponding to the "IP-routed mesh").

V. CONCLUSIONS

In this paper we have discussed the impact of the backhaul network design in the power consumption of a CoMP system. Differently from previous works, we have shown how the backhaul topology design affects the overall consumed power. In particular, based on the "feasibility" of the established wireless cluster, we have modified the usual CoMP procedure by adding a prediction phase which pre-checks the status of the backhaul network and determines which BSs can take part to the CSI estimation and subsequent signaling and user data distribution process.

We evaluated the reduced power consumption achievable with our system, showing remarkable power savings especially when the level of inter-BSs connectivity through the backhaul is not high. By adopting such a scheme, we analyzed the possibility of using optical technologies and switching schemes for further reducing the overall power consumption. We conclude that the use of what we referred to as optical tunnels has a great potential for reducing the overall consumed power.

Finally, we evaluated the effect of different technologies for the backhaul implementation. We found out that WDM-PON based backhauls hold the potential of strongly reducing the power consumption, but suffer from topology constraints which might limit the CoMP cluster feasibility. Alternatively, low cost microwave-based mesh backhaul can achieve the desired performance in terms of cluster feasibility while keeping the power consumption levels smaller than the correspondent IP-routed case.

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