On the Impact of Heterogeneous Backhauls on Coordinated Multipoint Transmission in Femtocell Networks

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Abstract—The choice of a suitable backhaul constitutes one of the main performance bottlenecks in the emerging femtocell networks. In this paper, we study the impact of adopting a heterogeneous backhaul (i.e., wired or over-the-air) with realistic quality-of-service requirements on coherent coordinated multipoint (CoMP) transmission in the downlink of femtocell networks. We formulate a cooperative game with continuum among the femtocell access points (FAPs) for performing CoMP in order to maximize the downlink rate while accounting for the constraints on the heterogeneous backhaul. In this respect, we propose a distributed algorithm that enables the FAPs to jointly decide on their cooperative partners as well as the choice of a backhaul strategy. In this respect, the proposed algorithm jointly addresses the problem of coalition formation as well as the optimization of the tradeoff between OTA and wired backhaul transmission modes, each of which is limited by a different factor such as delay or spectrum resources availability. We show that the proposed algorithm converges to a stable partition which constitutes the continuum core of the studied cooperative game. Simulation results show that our proposed scheme yields interesting gains in terms of the average downlink rate per FAP, reaching up to 26% relative to the classical of non-cooperative transmissions.

I. INTRODUCTION

The deployment of femtocell access points (FAPs) in next-generation cellular networks is envisioned to significantly increase the spectral efficiency and the achievable wireless data rates. An FAP is a small base station that can be installed indoor or outdoor in order to improve the capacity and coverage of a wireless network. One of the benefits of deploying FAPs is its plug-and-play capability as it can operate while being connected to an existing backhaul such as DSL. However, these interesting characteristics of femtocells are accompanied with several technical challenges such as an increased co-channel interference and performance constraints at the backhaul.

Recently, cooperative techniques have emerged as a key solution for mitigating cross-tier interference in femtocell networks [1], [2]. For instance, in [1], it is shown that cooperation between competing FAPs leads to a locally optimized interference resolution and allows for a coherent exploitation of the interference. In this respect, coordinated multipoint (CoMP) transmission has emerged as a promising cooperative method that can locally solve the problem of co-channel interference while reaping the gains of transmission diversity [2]. However, in order to benefit from the performance gains of CoMP, a preliminary data exchange between the FAPs, in which each FAP acquires the counterpart’s data is required prior to the coherent multipoint transmission. The data exchange occurs over the backhaul that interconnects the FAPs and which can be of different types (e.g., wired, X2 interface, or fiber link). This heterogeneous nature of the backhaul may limit the benefits of CoMP due to the costs during information exchange.

In this respect, although a number of interesting research efforts have recently considered CoMP in the context of interference management and coordinated beam selection such as [1–3], only few works have considered models with a limited and constrained backhaul [4–7]. Due to the time sensitivity of the exchanged data during CoMP, the quality-of-service requirements on the backhaul between the FAPs are often stringent. In particular, the backhaul is required to have high capacity and low latency. While wired backhauls can provide virtually error-free transmissions, they can incur high delays due to the traffic congestion due to the fact that the wired medium (e.g., DSL or others) is shared between FAPs and possibly different network operators. As an alternative, the FAPs can use a wireless link to exchange data. The wireless link ensures a lower latency, however, it requires sacrificing in-band resources and can lead to an increased interference. Therefore, the choice of a backhaul strategy for implementing cooperation in femtocell networks is a very challenging task, and a centralized approach comes at the cost of high complexity. Moreover, the solution is highly sensitive to various factors such as the network structure and the traffic pattern of the femtocells.

The main contribution of this paper is to devise a scheme that can jointly decide on the FAPs cooperation and the backhaul strategies in a femtocell network. In particular, we focus on the issue of optimizing the backhaul usage (wireless or wired) for the purpose of enabling CoMP transmissions among cooperative FAPs. To this end, we model the backhaul constraint using a cooperation cost, in terms of an initial delay for preliminary data exchange, which accompanies the benefits from CoMP transmission, in terms of an increased rate in the remaining portion of the superframe. We formulate the problem as a coalitional game in which the FAPs are the players. In this game, the FAPs needs to jointly choose their cooperative partners and a backhaul strategy so as to maximize a utility function, which captures the benefits from cooperation, in terms of downlink transmission rates and the costs in terms of delay for preliminary data exchange. We solve the game using the concept of a continuum core for finite coalitions [8] which is a key solution for games in which the coalitions need to decide, not only on their cooperative strategy but also on other factors such as the backhaul. Hence, this concept allows to jointly address
the problem of coalition formation and self-optimization. We show that the proposed approach enables the FAPs to self-organize into a stable partition while jointly optimizing their cooperative and backhaul strategies. Simulation results show that the proposed approach yields significant gains in terms of the average downlink rate per FAP, reaching up to 26% relative to classical case with non-cooperative transmissions, and a reduction of 153% of the delay during the CoMP data exchange.

The rest of the paper is organized as follows. In Section II, we present the proposed system model. In Section III, we formulate a continuum game between the FAPs and present a distributed algorithm for solving the game. The numerical results are discussed in Section IV and, finally, the conclusions are drawn in Section V.

II. SYSTEM MODEL

Consider the downlink of a single macrocell network (e.g., LTE-Advanced) in which \( N \) FAPs are deployed. All transmitters and receivers are single-antenna nodes. For multiple access, each FAP uses an Orthogonal Frequency Division Multiple Access (OFDMA) technique over a dedicated portion of the macrocell spectrum. Let \( \mathcal{N} = \{1,\ldots,N\} \) denote the set of all FAPs. Every FAP \( j \in \mathcal{N} \) serves \( L_j \) femtocell user equipments (FUEs) by scheduling them over a subchannel of bandwidth \( W \). Let \( \mathcal{L}_j = \{1,\ldots,L_j\} \) denote the set of FUEs served by FAP \( j \). Full knowledge of channel state information is assumed at each transmitter and, as the FUEs perform single user detection, any source of interference is treated as noise. The FAPs are assumed to be perfectly synchronized and operating in a half-duplex mode. Moreover, all the FAPs in the same sector \( S \) are connected to a common third party wired backhaul (e.g., DSL). The channel gains are assumed uniform over the considered band and encompass the path loss, antenna gains and shadowing.

In order to improve their transmission rates, the FAPs can cooperate and form a coalition \( C \subseteq \mathcal{N} \). We let \( \Pi \subseteq \mathcal{N} \) denote the set of all partitions of \( \mathcal{N} \) (each partition is a set of disjoint coalitions). By forming a coalition, the FAPs can perform coordinated multipoint transmission. To do so, the FAPs need to exchange both uncoded user data and a quantized version of the transmit signal, as discussed in [9]. This operation might occur either using a shared wired backhaul or an over-the-air (OTA) wireless transmission. This information exchange incurs a delay which is equivalent to a portion \( 0 < \alpha \leq 1 \) of the superframe (for transmitting and receiving). The achievable rate at FUE \( i \) serviced by FAP \( j \) and the cooperative FAPs in coalition \( C \) becomes:

\[
r_i = (1 - \alpha)W \log_2 \left( 1 + \frac{|h_{ji}p_{ji}|^2 + \sum_{z \in \mathcal{N} \setminus C} |h_{zi}p_{zi}|^2}{\sigma_i^2 + I_i} \right),
\]

where \( h_{ji} (h_{zi}) \) and \( p_{ji} (p_{zi}) \) are the channel coefficient and the transmit power between the serving FAPs \( j \) (coalition member \( z \in C \)) and the FUE \( i \), respectively. We denote by \( \sigma_i^2 \) the received Gaussian noise power over the band \( W \) and by \( I_i = \sum_{k \in \mathcal{N} \setminus C} |h_{ki}p_{ki}|^2 \) the co-channel interference from the other non-cooperative FAPs.

In the following subsections, we study two different modes for data exchange between cooperative FAPs.

A. Wired Backhaul based CoMP

In practice, each FAP operates using a broadband wired backhaul which connects it to the core network. Hence, cooperative FAPs can use this wired backhaul as a basis for exchanging information during CoMP. Each sector \( S \) of the macrocell has one backhaul line of capacity \( \mu_{BH} \) which is shared by all the FAPs located in the same sector. The data transmission over the wired backhaul is not affected by interference, but as the line is shared by all the FAPs in the same sector, traffic congestion often leads to excessive delays. For example, if we consider a coalition of two FAPs \( j \) and \( z \) located in the same sector \( S \), the wired backhaul in \( S \) can be modeled as a M/D/1 queue, where the input traffic is \( \lambda_{jz} + \lambda_S \), \( \lambda_{jz} = \alpha T \) (in bps) and \( \lambda_S \) is the traffic already existing on the wired backhaul, from other coalitions within sector \( S \). We express the average delay incurred per FAP by Little’s law [10]:

\[
D_{jz}^{BH} = \frac{\lambda_{jz} + \lambda_S}{2 \mu_{BH} (\mu_{BH} - \lambda_{jz} - \lambda_S)}.
\]

It is important to stress that, in order to guarantee the stability of the queue, the following condition must hold: \( \lambda_{jz} + \lambda_S < \mu_{BH} \). The delay from FAP \( z \) to FAP \( j \) \( D_{jz}^{BH} \) can be obtained by inverting the subscripts, throughout subsection II-A. Note that the delay over the backhaul generally depends on the scheduling policy at the backhaul server (e.g., pre-emptive or high priority scheduling), however, in (2) we consider a first-in-first-out equal priority scheduling. Similar to the OTA case, no retransmissions are considered and a packet is automatically dropped if the delay exceeds a timeout \( \tau \), i.e., \( D_{jz}^{BH} > \tau \).

B. OTA based CoMP

The OTA transmission mode is known for allowing low-delay data transmissions at the cost of using precious spectral resources and an increased interference. When an OTA transmission mode is used to exchange information between FAPs involved in CoMP transmissions, the transmit data to be delivered to FUE \( i \) is quantized and appended with additional overhead information on FUE \( i \). An OTA transmission is accompanied by a delay \( D_{jz}^{OTA} \) which is equivalent to the data transmission plus the propagation delay. For the scope of this work, we assume no retransmissions over the FAP-to-FAP links. Therefore, corrupted packets are automatically dropped and no CoMP transmission occurs\(^1\). The above data exchange phase takes place over a portion \( \alpha \) of the superframe \( T \), using the subchannel which is initially occupied by the FAP. It is worth stressing that OTA transmissions occur over in-band resources and, hence, they suffer from interference from the other femtocells operating on the same frequency subchannel. As a result, the achievable rate between cooperative FAPs \( j \) and \( z \) in coalition \( C \) is:

\[
r_{jz}^{OTA} = \alpha W \log_2 \left( 1 + \frac{|h_{jz}p_{jz}|^2}{\sigma_z^2 + I_z} \right),
\]

\(^1\)The proposed scheme can be modified to accommodate the case with retransmissions.
where $h_{ij}$ and $p_{iz}$ are the channel coefficients and the transmit power between the cooperative FAPs, respectively. The received noise power at the receiver FAP $z$ is denoted by $\sigma_z^2$ and $I_z = \sum_{k \in \mathcal{M} \setminus \{z\}} |h_{kz}p_{kz}|^2$ represents the interference from the FAPs outside $C$, which are transmitting over the same subchannel. To account for the errors during the transmission phase, we consider that a packet is correctly received if the signal to interference and noise ratio ($\gamma_{OTA}^j$) at FAP $z$ is above a threshold $\gamma_{OTA}$. Naturally, as CoMP transmitters perform symmetrical operations, the achievable rate for the transmission between FAP $z$ and $j$ is obtained by inverting the subscripts in (3), and the requirement $\gamma_{OTA}^j > \gamma_{OTA}$ stands.

The above considerations show that the wired backhaul and the OTA schemes are respectively limited by opposite factors. In fact, while the OTA scheme has to cope with in-band interference, and thus is penalized by erroneously received packets, the wired backhaul is characterized by virtually error-free transmissions which come at the expense of an increased delay. Consequently, from the femtocell network’s perspective, there exists a non-trivial tradeoff between using OTA or the wired backhaul which depends on the scenario in which the FAPs are operating.

### III. Femtocell Optimization and Backhaul Selection through a Continuum Game

Our main objective is to devise the most rewarding network partition for exchanging CoMP data, given that each FAP can independently select a backhaul strategy (e.g., a backhaul type) which has minimum requirements on the time sensitivity and the transmit rate. It is worth noting that the choice of a cooperative strategy (network partition), backhaul strategy, and the associated cost for cooperation is a challenging problem with many constraints.

#### A. The Core of Continuum games

One interesting solution concept suitable for analyzing this cooperative problem is given by the *Core of Continuum Games* with finite coalitions [8]. In such games, a large number of players can form finite coalitions in order to increase their own payoffs and thus self-organize into a desired network partition. It is then possible to transform a large game to a smaller one composed of finite coalitions and answer to the question: “How can a large network become cooperative and how can the players optimize their cooperative strategy choice?”

In our proposed game, for each FAP, a change in the combination partition-strategy-cost of cooperation affects the other FAPs’ payoff in a continuous way. Thus, by modeling this payoff using a continuum game, we can jointly solve the problem of selecting a coalition partner and a backhaul strategy which minimizes the delay in CoMP preliminary data exchange. We are mainly interested in CoMP transmissions that are coordinated between FAPs which are underlaid over the same spectrum. Each FAP is represented by a set of available backhaul strategies, namely OTA and wired backhaul transmission mode, and the attribute $\alpha$ which is the initial CoMP delay, modeled as a continuous variable.

In order to mathematically model the femtocell cooperation problem, we formulate a coalitional game with the FAPs $j \in \mathcal{N}$ being the players. In this game, the FAPs need to jointly choose a coalition partner for CoMP transmissions and one strategy between OTA and the wired backhaul transmission mode to exchange CoMP data, given that each single medium is harnessed by interference and delay, respectively. In essence, we consider the network $\mathcal{N}$, in which groups of FAPs join a coalition and induce a network partition $\Pi$ of $\mathcal{N}$, which maximizes the gains at the respective FUEs and accounts for a realistic condition of the backhauls. Hence, the proposed framework for modeling the femtocell cooperation problem is that of a continuum game with finite coalitions defined as follows:

**Definition 1:** A continuum game with finite coalitions is defined by a pair $(\mathcal{N}, v)$ where $\mathcal{N}$ is the set of players, $\Pi$ the network partition and $v$ is a value function that assigns, for every coalition $C \subseteq \mathcal{N}$ with a finite number of players, a vector of real numbers. Each one represents the total utility (benefit) that each player in $C$ can achieve and is a continuous function of $\Pi$.

Given the set of FAPs $\mathcal{N}$, our next step is to define a suitable value function $v(C, \alpha)$ that reflects the total benefit that coalition $C$ achieves, given the cost of cooperation $\alpha$. For any coalition $C$, each FAP $j \in C$ reaps the benefits of diversity transmission gain, after a preliminary data exchange which requires a portion of the superframe. In detail, for any coalition $C = \{j, k, \ldots\} \subseteq \Pi$, the value function $v(C, \alpha)$ can be defined as the set of the individual achievable rates of FUE $i \in \mathcal{L}_j$ over the initial delay:

$$v(C, \alpha) = \left\{ \frac{r_j}{D_{ij}} \right\}, \quad (4)$$

where $x \in \{OTA, BH\}$ are the available backhaul strategies. The value in (4) captures the intrinsic tradeoff between transmission diversity, achieved by the CoMP scheme, and the associated cost of data exchange, expressed in terms of delay. Each element of the value in (4) represents a non-transferable utility, that is the individual benefit of belonging to coalition $C$, and captures the tradeoff existing between the wired backhaul and the OTA scheme, as discussed in Section II. We now introduce the maximum coalition value in case the other FAPs in the same sector are using the same transmission mode to exchange CoMP information, defined as:

$$\bar{v}(C, \alpha) = \min_{x, k \in \mathcal{S} \setminus \{C\}} \max_{x, \alpha} v(C, \alpha). \quad (5)$$

Clearly, $\bar{v}(C, \alpha)$ represents the optimum performance in the worst case scenario, since all the FAPs are sharing the same wired backhaul or using an OTA transmission mode. Inherently, this allows for individual strategy choices at each FAP, which are independent from the strategies in use at the other FAPs [11].

For given channel conditions, a change in the cost $\alpha$ is reflected by the value $v(C, \alpha)$. Therefore, we have the following:

$$\exists \Pi \subseteq \mathcal{N}, C \subseteq \Pi, |\bar{v}(C, \alpha) - v(C, \alpha)| \to 0, \quad (6)$$

where $\alpha$ denotes the optimal cost for cooperation. Finally, the core of the continuum game with finite coalitions (f-core) is defined as [8]:

$$\mathcal{E}_\mathcal{N} = \left\{ \bar{v}(C, \alpha) \in \mathbb{R}^{|C|} \right\}. \quad (7)$$
The $f$-core dictates how to partition the network in order to optimize the coalition value $v(C, \alpha)$ by choosing a cooperative strategy (i.e., OTA or wired backhaul and the respective $\alpha$) in a decentralized fashion. Similar to the traditional concept of core in characteristic form games, no coalition can further improve its value by choosing another strategy, therefore, the outcomes in the $f$-core are stable in the sense that any deviation from the current partition would be detrimental. Before discussing the conditions for the nonemptiness of the $f$-core, we introduce some preliminary definitions [8].

**Definition 2:** (per-capita bound) A game $(N, v)$ is per-capita bounded with respect to a partition $\Pi$ of $N$ iff given a positive real number $K$ and distinct coalitions $C, T_1, \ldots, T_j \subset \Pi$, $|C \cap T_1| = \cdots = |C \cap T_j|$ and (b) the benefit of belonging to coalition $C$ is the same for each member. As a result, the payoff for each player is strictly bounded by $K$.

We note that (a) in Definition (2) is a requirement on the number of members which belong to more than one coalition. This condition is met by focusing on disjoint coalitions (thus, having null intersection) within which CoMP transmission can occur. Moreover, (b) can be verified by modeling symmetrical operations between cooperative FAPs. Hence the limitation of the achievable payoff is a result of having disjoint coalitions and symmetrical conditions among cooperative FAPs.

**Definition 3:** ($r$-property) A game $(N, v)$ has the $r$-property with respect to a partition $\Pi$ of $N$ iff for each $C \subset \Pi$, the value $v(C, \alpha)$ converges to $\tilde{v}(C, \alpha)$ when $\alpha$ tends to $\tilde{\alpha}$; and (b) all the players in $\Pi$ are identical with respect to the coalitional value function $v(C, \alpha)$.

One can notice that condition (a) in Definition 3 implies that, in order to achieve the partition which maximizes the players payoff, an optimal value of $\tilde{\alpha}$ must exist. We guarantee that $\tilde{\alpha}$ always exists, since its value can also be zero, which represent a non-cooperative strategy in which the FAPs are exclusively serving their own FUEs. Finally, for the proposed solution, $v(C \cup \{j\}, \alpha) = v(\{j\})^C(v(C, \alpha))$, which verifies (b) in Definition 3. Having considered this, we are now in a position to discuss under which conditions the $f$-core is nonempty. An important result is given by the authors of [8] in the following:

**Theorem 1:** Let $(N, v)$ be a continuum game. If $(N, v)$ has the $r$-property and is per-capita bounded with respect to a partition $\Pi$, then the $f$-core of the game is nonempty.

Theorem 1 provides non-restrictive (i.e., sufficient) conditions for the nonemptiness of the $f$-core given that only finite coalitions can form. Therefore, for the proposed FAPs coalitional game, the nonemptiness of the $f$-core is guaranteed as long as the per-capita bound and the $r$-property are verified, as it has been discussed above. Thus, the $f$-core core is a solution concept that is used to generate the partition of the network $N$ jointly with the optimal cost for cooperation $\alpha$ for each coalition, so as to maximize the individual payoff.

In a nutshell, for the proposed FAPs coalitional game, one can use the concepts of continuum games for finite coalitions in order to find a partition in the $f$-core, i.e., a stable and efficient partition. In order to reach a partition in the $f$-core, we propose the distributed algorithm described in Algorithm 1.

**Algorithm 1** Distributed coalition formation algorithm for backhaul selection in CoMP femtocell networks

- **Initial State:** The network is partitioned by $\Pi = \{1, \ldots, N\}$ with non-cooperative FAPs.
- **Proposed Coalition Formation Algorithm**
  - **Repeat**
    - **Phase I - Neighbor Discovery**
      - a) Each FAP collects RSSI of the neighboring FAPs from each of its own FUEs.
      - b) The FAPs with the strongest RSSI are included in a list of potential coalitional partners.
    - **Phase II - Femtocell Coalition Formation** for all FAPs in the list do
      - a) Each FAP sequentially engages in pairwise negotiations with the neighbor FAPs in the list to measure both the round-trip time $D_{BH}^j$ and the estimate the interference received at each FAP over the originally assigned subchannels.
    - **Phase III - Coalition-level CoMP transmissions**
      - a) Within each coalition, cooperative FAP CoMP transmissions as described in Section II are initiated.

- **B. Distributed implementation of the $f$-core**

Algorithm 1 is composed mainly of three phases: Neighbor discovery, femtocell coalition formation, and coalition-level CoMP transmission. The network is initially partitioned by $|I|$ singleton coalitions (which reflects a non-cooperative strategy at each FAP). Each FAP periodically requests Received Signal Strength Indicators (RSSIs) measurements from its FUEs to identify the presence of neighbor FAPs which might provide higher downlink throughput through CoMP transmissions. Successively, the potentially cooperative FAPs are enlisted and sorted by the strongest associated RSSI as the most eligible CoMP partners are the FAPs in the vicinity or experiencing good channel gains.

Starting from the top of the list, an FAP $j$ estimates the round-trip time $D_{BH}^j$ to transmit to FAP $\gamma$ over the wired backhaul using known estimation techniques such as ping [12]. Furthermore, each FAP measures the level of interference received over the used subchannels. If $D_{BH}^j \leq D_{BH}^z$, respectively for both FAPs $j$ and $z$, they mutually agree to cooperate, they form a coalition, and set up a connection over the wired backhaul. Otherwise, when the delay on the wired backhaul exceeds $\gamma$, each FAP checks if an OTA transmission mode incurs a delay smaller than $\gamma$ and if the level of interference allows for an OTA transmit rate of at least $\gamma_{OTA}$ bps. In case both conditions are respected, the delay $\gamma$ is updated based on the resulting backhaul strategy. In addition, if the OTA transmission mode does not meet the QoS requirements, the FAP remains non-cooperative and it will exclusively serve its own users. Finally, the individual payoff is updated based on the new value of $\alpha$.

The $f$-core is reached at the end of the second phase of Algorithm 1 by considering that only the payoff-maximizing coalitions are formed. The proposed algorithm is distributed since the FAPs make individual decisions to form a coalition.
By doing so, the FAPs reach a stable partition, i.e., they have no incentives to break away from the belonging coalitions since it would lead to lower payoffs. Finally, once the coalitions have formed, the members of each coalition initiate the CoMP transmissions described in Section II.

IV. NUMERICAL RESULTS

For system-level simulations, we consider a single hexagonal macrocell with a radius of 500m within which \( N \) FAPs are randomly distributed outdoor. The FAPs are allocated over a bandwidth of 5 MHz, while the macrocell users use a dedicated bandwidth. Each FAP \( j \in N \) serves \( L_j \) FUEs, each one scheduled over one orthogonal subchannel [13]. FAPs and FUEs are equipped with one omnidirectional antenna and the FAP’s maximum transmit power is set to \( P_{\text{max}} = 10 \) dBm. Transmissions are affected by distance dependent path loss shadowing according to the 3GPP specifications [14]. Each superframe has a duration of 10 ms and the timeout \( \tau = 5 \) ms. At each FAP, we assume that power control fully compensates for the path loss. The minimum SINR required for OTA data exchange is \( \gamma_{\text{OTA}} = 5 \) dB. To leverage channel variations, statistical results are averaged on 10000 simulation rounds.

Fig. 1 shows the average downlink rate per FUE as a function of the network size and the maximum coalition size \( K \). For small network sizes \( N < 60 \), the CoMP and traditional non-cooperative schemes have a similar performance as the FAPs do not cooperate due to spatial separation. For larger networks, neighboring FAPs have an incentive in forming a coalition to achieve higher rates by combining up to \( K \) CoMP transmissions. Fig. 1 also shows that cooperating FAP can gain up to 26% with respect to the non-cooperative case in a network with \( N = 300 \) FAPs. Finally, for \( K > 3 \), the gains of transmission diversity and thus the average rates eventually saturate. In a nutshell, Fig. 1 demonstrates that the proposed coalitional game model has a significant advantage over the non-cooperative case, which increases with the probability of having FAPs in proximity.

The performance of the backhaul during the proposed coalition formation approach is further assessed in Fig. 2, where we show the individual average delay for the preliminary CoMP data exchange as a function of the network size and different OTA QoS requirements. For example, in a network of \( N = 300 \) providing an alternative OTA transmission scheme helps the FAP to reduce its traffic over the wired backhaul and, thus, leads to delays that scale linearly, especially for low OTA QoS requirements. However, for larger network sizes, the interfering FAPs can no longer meet the minimum \( \gamma_{\text{OTA}} \), and, thus, they redirect their signaling to the wired backhaul. Therefore, Fig. 2 shows that providing a set of different backhaul strategies at the FAP can reduce the average delay for preliminary CoMP transmissions of 153% for a network with 300 MUEs.

Fig. 3 shows the optimal cost for cooperation \( \hat{\alpha} \) as a function of OTA minimum QoS requirement \( \gamma_{\text{OTA}} \), for different \( N = 50,150 \). This figure demonstrates that, when the wireless signaling requirements are lower than 10 dB, less than \( \hat{\alpha} = 12\% \) of the superframe is required by each FAP for exchanging CoMP data. In contrast, for \( \gamma_{\text{OTA}} > 20 \) dB, the CoMP information exchange becomes more demanding. For example, in a network of \( N = 150 \) FAPs, it is required to dedicate \( \hat{\alpha} = 22\% \) of the superframe size. Further, in Fig. 3, the area below the curve of \( \hat{\alpha} \) denotes the region in which a wired backhaul outperform the OTA scheme. Therefore, for data exchanges requiring \( \alpha < \hat{\alpha} \), the use of a wired backhaul is preferred to the OTA scheme. However, this area decreases for large network sizes, due to the increased congestion on the shared backhaul. In summary, Fig. 3 shows that the choice of a backhaul strategy and the associated cost highly depend on the signaling quality requirements and the topology of the backhaul network.

Fig. 4 shows the cumulative distribution function of the average delay per FAP required for the CoMP data exchange, for a network of \( N = 200 \) FAPs and a QoS requirement of \( \gamma_{\text{OTA}} = \)
20 dB. In this figure, we compare the proposed algorithm to three different schemes. In the first two, only OTA signalling or a wired backhaul are respectively available, while the third scheme computes the best backhaul strategy for each FAP in a centralized fashion, accounting for the data transmissions in the whole network. Fig. 4 shows that the proposed scheme allows for a significant delay reduction when compared to the wired backhaul scheme. For example, for a network with 200 FAPs, the average delay for the proposed algorithm is smaller than 46 ms with a probability of 0.75 versus 88 ms of the wired signalling mode. Fig. 4 also shows that by adopting the proposed algorithm using a heterogeneous backhaul, one can achieve a performance that is very close to the optimal solution. For instance, the gap between our algorithm and the optimal solution is only 8 ms for a probability of 0.8.

V. CONCLUSIONS

In this paper, we have studied the impact of the backhaul on the performance gains resulting from coordinated multipoint transmission in femtocell networks. In particular, we have formulated a cooperative game in which the FAPs can jointly decide on their cooperative partners as well as on whether to use a wired or a wireless backhaul for information exchange. In this game, the FAPs make their decisions so as to optimize a coalitional value function that accounts for the tradeoff between the improved throughput due to cooperation and the transmission delay due to the choice of a backhaul for exchanging information. To form coalitions, we have proposed a distributed coalition formation algorithm that enables FAPs to autonomously decide on the CoMP partners, the preferred backhaul strategy, and the optimal amount of data to exchange. This choice accounts for the QoS requirements and constraints of the available backhauls as well as the tradeoff between the cooperation gains, in form of increased rate and the costs in terms of a preliminary delay for CoMP data exchange. Simulation results have shown that the FAPs can significantly improve their average utility by jointly choosing their backhaul and cooperation strategies instead of relying solely on a single backhaul type or acting non-cooperatively.

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