Two-Phase Scheduling and Leakage-Based Precoding in Wireless Cellular Networks

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***Abstract*—We consider the downlink of a wireless cellular network where the base stations are equipped with multiple antennas and operate in the same frequency band. Since scheduling changes the spatial transmit signal processing with each time slot, information from neighboring base stations is required for data encoding. This can, in theory, be accomplished by a high-capacity backhaul network through which the base stations exchange channel state information (CSI) and other control signals. In reality, however, the temporal granularity of the scheduler does not allow for timely distribution of CSI among base stations. We propose a two-phase scheduler which optimizes the precoding in the first phase and allows the users to feed back their instantaneous interference power in the second phase. For the single-user case, we present a practical scheme that combines two-phase scheduling with precoders that maximize the signal-to-leakage-plus-noise ratio. If the users feed back the interference power together with a supported rate, communication between base stations can be limited to integers. By comparing the performance to multi-user two-phase scheduling with dirty paper coding and to algorithms that share CSI among base stations we show that two-phase scheduling is a technically and practically feasible solution to deal with non-stationary intercell interference.**

***Index Terms*—Cellular networks, interference channel (IFC), coordinated multi-point (CoMP) transmission, base station cooperation, intercell interference coordination (ICIC), non-stationary interference.**

I. INTRODUCTION

THE ADVENT of mobile Internet devices has led consumers to become accustomed to a rich multimedia experience anytime and anywhere. Hence, traditional voice-centered wireless networks need to be transformed to deliver the same content experience as the wired Internet. Recently, however, it has become increasingly difficult to keep up with the data demand that novel devices impose on these networks as air interface technologies cannot accommodate ever increasing spectral efficiencies without addressing the growing problem of *intercell interference* (ICI).

In this work, we consider the downlink of a wireless cellular network where the base stations are equipped with multiple antennas and employ *orthogonal frequency-division multiplexing* (OFDM). OFDM enables wideband communication over parallel frequency-flat channels to which groups of users can be assigned, so-called *orthogonal frequency-division multiple access* (OFDMA). Furthermore, OFDM can be combined with *multiple input multiple output* (MIMO) techniques to increase peak user rates and average network spectral efficiency as well as cell-edge user performance through transmit diversity, spatial multiplexing, and beamforming. With respect to cellular networks, OFDM and MIMO are particularly appealing for they facilitate the mitigation of ICI, especially when high frequency reuse is desired.

For an isolated cell, it is well known that a base station can process the data for its intracell users in a cooperative fashion by means of linear or non-linear precoding [1]. In fact, it can pre-cancel interference by employing *dirty paper coding* (DPC) [2] whose capacity region is known [3], [4] and can be achieved [5], assuming that perfect instantaneous *channel state information* (CSI) is known. For a cellular network of multiple base stations, however, such cooperation is problematic. Sharing data among multiple transmitters requires precise synchronization and backhaul communication with high capacity. Similarly, estimating and feeding back CSI for multiple cells create immense delays and a large communication overhead.

From an information-theoretic viewpoint, there are two ways to approach this problem. In *network MIMO*, all base stations can transmit data to all users and the whole network effectively represents a MIMO *broadcast channel* (BC) with distributed antennas [6]–[10]. Interference can then be exploited by jointly processing the user data, though symbol-level synchronization is necessary among the base stations. Conversely, if base stations do not exchange data, cellular networks constitute a type of *interference channel* (IFC). If the scheduling is synchronized among the base stations, *intercell interference coordination* (ICIC) is possible by means of joint beamforming in the spatial domain [11]–[17] or joint scheduling and power allocation in the frequency or time domain [18]–[21]. Random beamforming with opportunistic scheduling, for instance, was the subject of [22], [23] whereas game-theoretic ideas were applied in [24], [25]. Other approaches try to partition resources to achieve ICIC. If base stations cooperate, OFDM enables dynamic spectrum allocation to limit the frequency reuse for cell-edge users thus abating the co-channel interference [26]–[28]. For tractable information-theoretic analysis, the *Wyner model* [29] has become very

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popular [30], [31]. Unfortunately, tangible gains are often compromised by practical considerations. Hence, the reduction of overhead signaling and the problem of limited-capacity backhaul and feedback links has been addressed [32]–[35] as well as the delay in signaling [36]–[38] and the impact of imperfect intercell synchronization [39], [40]. A measurement campaign on the topic was also conducted in Berlin, Germany [41].

In this contribution, unlike network MIMO and similar to the IFC, we consider ICI as noise. If a base station decides to serve multiple users on a frequency resource, it can do so in a cooperative fashion by means of DPC. Since the optimization of scheduling, link adaptation, and beamforming is a coupled problem, we assume equal transmit power spectral density constraints per OFDM sub-carrier, i.e., we do not consider an optimal power distribution in frequency through water-filling. Furthermore, we assume that the user grouping and sub-carrier assignments for OFDMA are given for each time slot.

Since spatio-temporal signal processing by means of beamforming, power loading, and temporal scheduling renders ICI non-stationary [42]–[44], it is impossible for a base station to accurately encode the data. The resulting frequent outages severely deteriorate performance even under the assumption of having perfect CSI at the transmitters [45]. This paper starts with the system model and the problem formulation in Sections II and III, respectively. In Section IV, it introduces the concept of two-phase scheduling that stabilizes the random interference power by making it available to the base stations through a secondary feedback phase. The scheduler can be implemented without the need for communication between the base stations and its only requirement is that the scheduling is synchronized. Furthermore, this is highly practical as base stations can be made by different vendors employing different precoding algorithms, numbers of antennas, transmit powers, and so forth. In Section V, we focus on the single-user case and propose a precoder based on the *signal-to-leakage-plus-noise ratio* (SLNR). We show that if the base stations derive the precoders from averaged measurements in the uplink, they can be implemented without the need for any CSI feedback from the mobile user equipment and communication between base stations can be limited to integers. In Section VI, we compare the amount of feedback and backhaul communication that is required for each proposed algorithm and quantify its performance by means of Monte-Carlo simulations. Section VII presents the conclusion of this paper with a summary of our main result—that a large reduction in signaling overhead can be achieved with only moderate performance loss.

Notation: We denote vectors and matrices by bold lower and upper case letters, respectively, whereas italic lower and upper case letters are used for scalars. $\mathbb{E}[\bullet]$, $\mathbb{E}[\bullet|\bullet]$, $\mathrm{j} = \sqrt{-1}$, $\mathbf{1}_M$, $\mathbf{0}_M$, $\|\bullet\|_2$, $(\bullet)^*$, $(\bullet)^{\mathrm{T}}$, and $(\bullet)^{\mathrm{H}}$ denote expectation, conditional expectation, imaginary unit, $M \times M$ identity matrix, $M \times M$ zero matrix, Euclidean norm, complex conjugation, transposition, and conjugate transposition, respectively. $\boldsymbol{e}_i$ is the i-th column of $\mathbf{1}_M$, M given by the context. Furthermore, $\lceil \bullet \rceil$ maps a real number to the smallest following integer.

II. System Model

We consider a hexagonal grid of $B = 57$ cells with three sectors per site where three base stations are co-located [46]. The transmit antennas at the base stations are assumed to be arranged in a uniform linear array with half-wavelength spacing and the underlying multiple access scheme shall be OFDMA with universal frequency reuse. Suppose $\Sigma_b^{[m]}$ is the set of active users in cell b at time m. The process of assigning the users in $\Sigma_b^{[m]}$ to sets of OFDM sub-carriers depends on many factors which are channel-independent—such as type of application, quality of service (QoS), risk of buffer overflow, and other rate or delay constraints—and they are often different from one user to another. Assuming that a higher system layer ensures that none of these constraints are violated, we define $\mathcal{K}_b^{[m,\Omega]} = \left\{1, 2, \ldots, K_b^{[m,\Omega]}\right\}$ as the set which comprises all users that base station b can schedule at time slot m on a particular set of OFDM sub-carriers indexed by Ω. Though finding the optimal sets $\mathcal{K}_b^{[m,\Omega]}$ that maximize the data throughput in the network is an interesting research problem in its own right, our contributions will be oblivious to this optimization problem, i.e., we will assume that $\mathcal{K}_b^{[m,\Omega]}$ is known for each time slot.

This notation is motivated by the *3rd Generation Partnership Project's* (3GPP's) *Long Term Evolution* (LTE) wireless communications standard which defines resource blocks as the smallest entity of the time-frequency resource grid that the scheduler can assign to a user. A resource block is uniquely identified by a tuple $[m, \Omega]$ and consists of a set of consecutive OFDM symbols in time and a set of consecutive sub-carriers in frequency. The time index m denotes the temporal scheduling granularity, viz., it numbers the resource blocks in time, whereas the frequency index Ω signifies the scheduling granularity in the frequency domain, i.e., it enumerates the resource blocks in frequency. For simplicity, let $K_b^{[m,\Omega]} = K$ in the sequel.

Let each user in the network be indexed by a tuple $(b, k) \in \bigcup_{b \in \mathcal{B}} b \times \Sigma_b^{[m]}$, where $b \in \mathcal{B} = \{1, 2, \ldots, B\}$ corresponds to the anchor cell of user k, i.e., the base station from which data can be received. With the assumption that the scheduling is synchronized among all base stations the symbol $\hat{s}_{b,k}[n,\omega] \in \mathbb{C}$, which user (b, k) receives on a particular sub-carrier ω during OFDM symbol n, is given by:

$$
\begin{aligned}
\hat{s}_{b,k}[n,\omega] = {} & \boldsymbol{h}_{b,k,b}^{\mathrm{T}}[n,\omega]\boldsymbol{t}_{b,k}^{[m,\Omega]}\sqrt{P_{b,k}^{[m,\Omega]}}\, s_{b,k}[n,\omega] && \text{desired signal} \\
& + \sum_{\substack{i=1 \\ i \neq k}}^{K} \boldsymbol{h}_{b,k,b}^{\mathrm{T}}[n,\omega]\boldsymbol{t}_{b,i}^{[m,\Omega]}\sqrt{P_{b,i}^{[m,\Omega]}}\, s_{b,i}[n,\omega] && \text{intracell interf.} \\
& + \sum_{\substack{b'=1 \\ b' \neq b}}^{B} \sum_{i=1}^{K} \boldsymbol{h}_{b,k,b'}^{\mathrm{T}}[n,\omega]\boldsymbol{t}_{b',i}^{[m,\Omega]}\sqrt{P_{b',i}^{[m,\Omega]}}\, s_{b',i}[n,\omega] && \text{intercell interf.} \\
& + \eta_{b,k}[n,\omega] && \text{noise}
\end{aligned}
\tag{1}
$$

$P_{b,i}^{[m,\Omega]} \in \mathbb{R}_{0,+}$ is the power loading for the transmitted symbol $s_{b,i}[n,\omega] \in \mathbb{C}$ of user (b, i) in resource element $[n,\omega]$, $\boldsymbol{t}_{b,i}^{[m,\Omega]} \in \mathbb{C}^{N_{\mathrm{a}}}$ is the corresponding unit-norm beamforming vector that multiplexes the data stream onto the N_{a} transmit antennas, $\boldsymbol{h}_{b,k,b'}[n,\omega] \in \mathbb{C}^{N_{\mathrm{a}}}$ is the frequency-flat vector channel from base station b' to user (b, k) assuming single-antenna terminals, and $\eta_{b,k}[n,\omega]$ is a stationary zero-mean additive white Gaussian noise process with variance σ_η^2. To obtain analytically tractable rate expressions, we assume independent and identically distributed stationary Gaussian symbols $s_{b,k}[n,\omega]$ with zero mean and unity variance and that the vector channels are constant for at least one scheduling interval m (block-fading assumption). In other words, the channel coherence time is considerably larger than the scheduling granularity.

In practical cellular systems, *explicit* CSI in the form of channel coefficients is usually not available at the transmitter. Consequently, the base stations choose the precoders based on *implicit* CSI that is fed back from the users. In 3GPP LTE, for instance, the mobile users feed back a *Precoding Matrix Indicator* (PMI), a *Rank Indicator* (RI), and up to two *Channel Quality Indicators* (CQI) with the option for narrowband or wideband reporting [47]. While these reports are based on a predefined fixed codebook of precoders, the base stations can employ arbitrary precoders as long as they can map the CQI report, which is computed assuming a fixed codebook, to the CQI under the channel-dependent precoder. Furthermore, if instantaneous CSI is unavailable at the transmitter, one can still use statistical CSI for the precoder design [48]–[50]. For the joint design of precoders in a network of multiple transmitters, such statistical CSI still needs to be exchanged among the base stations [51]–[53].

Omitting the frequency indices ω and Ω hereafter, let $\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}}$ be an estimate of the channel covariance matrix for a given vector channel:

$$\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}} = \sum_{\zeta=1}^{N_\mathrm{a}} \xi_{b,k,b',\zeta}\, \boldsymbol{q}_{b,k,b',\zeta} \boldsymbol{q}^{\mathrm{H}}_{b,k,b',\zeta} \tag{2}$$

$\{\xi_{b,k,b',\zeta}\}_{\zeta=1}^{N_\mathrm{a}}$ and $\{\boldsymbol{q}_{b,k,b',\zeta}\}_{\zeta=1}^{N_\mathrm{a}}$ are the eigenvalues and eigenvectors of $\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}}$, respectively, and, without loss of generality, we suppose that the eigenvalues are ordered, viz., $\xi_{b,k,b',1} \geq \xi_{b,k,b',2} \geq \ldots \geq \xi_{b,k,b',N_\mathrm{a}} \geq 0$. If N_T is sufficiently large, we refer to CSI as being average; if $N_\mathrm{T} = 1$ we talk of instantaneous CSI. To evaluate the amount of CSI that is required at the transmitting end, consider the following two types of channels:

1) We refer to the vector channels $\{\boldsymbol{h}_{b,k,b'}[n,\omega]\}_{b'=1,b'\neq b}^{B}$ as *interference channels*: The notion behind interference channels is to take a user's viewpoint, (b, k) being fixed, and to look at the channels *from all base stations to one user*.
2) The vector channels $\{\boldsymbol{h}_{b',i,b}[n,\omega]\}_{b',i=1,b'\neq b}^{B,K}$ are referred to as *leakage channels*. Here, the notion is to take a base station's viewpoint and to look at the channels *from one base station to all users*, i.e., how a base station's transmit power leaks into other cells.

If *time-division duplexing* (TDD) is applied, each base station can estimate the leakage channels by using pilots in the uplink without requiring additional infrastructure connecting base stations to exchange CSI. However, this would not work in a *frequency-division duplexing* (FDD) system since some channel parameters are frequency-dependent. Channel covariance information may yet be obtained by averaging uplink measurements at the base station if uplink and downlink frequency bands are not spaced too far apart [54]–[57]. In fact, a recent measurement campaign showed that this reciprocity holds in real world deployments as long as the RF antenna front ends are carefully calibrated and the uplink measurements are transformed with a known offset matrix [58]. The necessary pilot symbols in the uplink are already transmitted since the receiving base station has to estimate the data-bearing channels for coherent detection. Accordingly, all base stations can estimate the downlink leakage channels from pilots in the uplink simultaneously without sacrificing additional resources such as power, time, or frequency. Hence, from an implementation viewpoint, this represents a major difference from an interference channel which needs to be estimated at the user equipment and fed back to the base stations. Due to the cellular architecture, this feedback can only take place between a user and its anchor cell. In order to make it available to all base stations, additional infrastructure is required in the form of a backhaul network [35].

For the purpose of this work, it is important to determine which channel parameters are uplink-downlink reciprocal and what their coherence time is, i.e., for how long they can be assumed to be constant. The covariance matrix of a vector channel depends on the distance and the angle between the user and the base station, the number of penetrated walls, and the shadowing which the user experiences. These parameters are determined by the position of the user and are hence governed by its mobility. The typical duration over which they can be considered constant in time is in the order of seconds [59], which is much longer than the scheduling granularity m and the coherence time of the small-scale fading. Following this convention the channel covariance matrices $\boldsymbol{R}_{b,k,b'}$ and its eigenvectors $\boldsymbol{q}_{b,k,b',\zeta}$ and eigenvalues $\xi_{b,k,b',\zeta}$ are not indexed by time or frequency and are considered uplink-downlink reciprocal [46].

III. PROBLEM FORMULATION

With full frequency reuse in all cells the intercell interference and noise that user (b, k) experiences is given by:

$$i_{b,k}[n] = \eta_{b,k}[n] + \sum_{\substack{b'=1\\ b'\neq b}}^{B} \sum_{i=1}^{K} \boldsymbol{h}_{b,k,b'}^{[m],\mathrm{T}} \boldsymbol{t}_{b',i}^{[m]} \sqrt{P_{b',i}^{[m]}}\, s_{b',i}[n] \tag{3}$$

Given the interference channels and the transmit signal processing at interfering base stations, $i_{b,k}[n]$ is conditionally Gaussian distributed with zero-mean and variance:

$$\begin{aligned}\sigma_{\mathrm{i}_{b,k}}^2[m] &= \mathbb{E}\left[|i_{b,k}[n]|^2 \,\middle|\, \left\{ \boldsymbol{h}_{b,k,b'}^{[m]}, \boldsymbol{t}_{b',i}^{[m]}, P_{b',i}^{[m]} \right\}_{b'=1,b'\neq b,i=1}^{B,K} \right] \\ &= \sigma_\eta^2 + \sum_{\substack{b'=1\\ b'\neq b}}^{B} \sum_{i=1}^{K} P_{b',i}^{[m]} \left| \boldsymbol{h}_{b,k,b'}^{[m],\mathrm{T}} \boldsymbol{t}_{b',i}^{[m]} \right|^2\end{aligned} \tag{4}$$

Hence, ICI is a non-stationary random process for $\boldsymbol{h}_{b,k,b'}^{[m]}$, $\boldsymbol{t}_{b',i}^{[m]}$, and $P_{b',i}^{[m]}$ are constant for the duration of the m-th resource block but vary randomly over time with granularity m. If $R_{b,k}^{[m]}$ is the maximum rate user (b, k) can support, the sum-rate of cell b is defined as

$$R_b^{[m]} = \sum_{k=1}^{K} R_{b,k}^{[m]} = \sum_{k=1}^{K} \log_2\left(1 + \mathrm{SINR}_{b,k}^{[m]}\right) \tag{5}$$

where $\mathrm{SINR}_{b,k}^{[m]}$ is the corresponding *signal-to-interference-plus-noise ratio* (SINR), viz.:

$$\mathrm{SINR}_{b,k}^{[m]} = \frac{P_{b,k}^{[m]} \left|\boldsymbol{h}_{b,k,b}^{[m],\mathrm{T}} \boldsymbol{t}_{b,k}^{[m]}\right|^2}{\sigma^2_{\mathrm{i}_{b,k}}[m] + \sum\limits_{\substack{i=1\\i\neq k}}^{K} P_{b,i}^{[m]} \left|\boldsymbol{h}_{b,k,b}^{[m],\mathrm{T}} \boldsymbol{t}_{b,i}^{[m]}\right|^2} \tag{6}$$

In other words, for a base station to be able to encode the data and to compute its optimal precoders $\boldsymbol{t}_{b,k}^{[m]}$ and powers $P_{b,k}^{[m]}$, it needs information on the scheduling and precoding at all interfering base stations in addition to any CSI that may be required.

IV. TWO-PHASE SCHEDULING: A NEW PARADIGM

As the name suggests, two-phase scheduling splits the scheduling into two phases to make the actual intercell interference power $\sigma^2_{\mathrm{i}_{b,k}}[m]$ in (4) available through a dedicated estimation and feedback phase. First, a common pilot is transmitted from the base stations to all users for the users to estimate their vector channels $\boldsymbol{h}_{b,k,b}^{[m]}$ and feed this information back to the base stations. Then, the base stations can compute beamforming vectors $\boldsymbol{t}_{b,k}^{[m]}$ and power allocations $P_{b,k}^{[m]}$ based on this CSI and the intercell interference power known from the previous time slot $\sigma^2_{\mathrm{i}_{b,k}}[m-1]$. With these beamforming vectors $\boldsymbol{t}_{b,k}^{[m]}$ and transmit powers $P_{b,k}^{[m]}$ a second pilot signal is launched. Now the users can estimate their SINR—the real valued scalar in (6)— and feed that back to their base stations. Each base station thus knows the correct intercell interference power $\sigma^2_{\mathrm{i}_{b,k}}[m]$ and can encode the data accordingly. However, after the feedback of the true $\sigma^2_{\mathrm{i}_{b,k}}[m]$, the base stations must not change their signal processing since that would also change $\sigma^2_{\mathrm{i}_{b,k}}[m]$. Hence, data transmission must take place using the precoders $\boldsymbol{t}_{b,k}^{[m]}$ and powers $P_{b,k}^{[m]}$ computed before the feedback and SINR estimation phase. The precoders and powers used to transmit the pilot sequence may not be optimal in the sense of maximizing the achievable sum-rate under the true interference environment. Nonetheless, the throughput in the network is tangibly enhanced for the base stations are enabled to accurately encode the user data such that no outages occur. While the pilots and the feedback for phase two cost resources (power, time, frequency), the resulting scheduling algorithm does not require CSI to be exchanged among the base stations. Each user feeds back its ICI power $\sigma^2_{\mathrm{i}_{b,k}}[m]$ to its anchor base station b only and there is no need to make it available to neighboring base stations.

A nice feature of this two-phase scheduler is that it offers an additional degree of multi-user diversity in the second phase. Though we cannot change the beamforming or power loading for any user after the feedback of $\sigma^2_{\mathrm{i}_{b,k}}[m]$, we are free to choose any set of users $(b,k) \in \bigcup_{b\in\mathcal{B}} b \times \mathcal{K}_b^{[m]}$ to be served with these precoders. This kind of multi-user diversity is different from the multi-user diversity reported in [60]–[62] as it is still present in the system if all vector channels are constant. The two-phase scheduler harnesses the fluctuations in $\sigma^2_{\mathrm{i}_{b,k}}[m]$, which are governed by the time scale m and not the channel coherence time, to enhance the sum-rate.

Suppose $(b,\hat{k}) \in \bigcup_{b\in\mathcal{B}} b \times \mathcal{K}_b^{[m]}$ denotes the active user in cell b at time slot m. This user may change from slot to slot, however, we refrain from indexing $\hat{k}$ with m, for $\hat{k}$ often merely indexes a parameter that is readily labeled with m, e.g., $\boldsymbol{t}_{b,\hat{k}}^{[m]}$. In case of potential confusion, we shall use $\hat{k} \in \mathcal{K}_b^{[m]}$ to associate a time and an anchor cell with $\hat{k}$. We propose the following scheduler to determine the user to be served in the next transmission frame, although any scheduler can be used instead. In phase one, the user for which we intend to design the precoding is selected by

$$\mathcal{K}_b^{[m]} \ni \hat{k} = \operatorname*{argmax}_{k=1,\ldots,K} \frac{R_{b,k}^{\mathrm{I},[m]}}{\bar{R}_{b,k}^{[m]}} \qquad \forall b \in \mathcal{B} \tag{7}$$

where the estimated rate $R_{b,k}^{\mathrm{I},[m]}$ and the average throughput $\bar{R}_{b,k}^{[m]}$ for user (b,k) are given by

$$R_{b,k}^{\mathrm{I},[m]} = \log_2\left(1 + \frac{E_{\mathrm{tr}}\,\xi_{b,k,b,1}}{\sigma^2_{\mathrm{i}_{b,k}}[m-1]}\right) \tag{8}$$

and

$$\bar{R}_{b,k}^{[m]} = \begin{cases} (1-f)\bar{R}_{b,k}^{[m-1]} + fR_{b,\check{k}}^{\mathrm{II},[m-1]} & k = \check{k} \in \mathcal{K}_b^{[m-1]} \\ (1-f)\bar{R}_{b,k}^{[m-1]} & k \neq \check{k} \in \mathcal{K}_b^{[m-1]} \end{cases} \tag{9}$$

respectively. E_{tr} is the transmit power constraint for each base station and $f \in (0,1)$ is called the *forgetting factor* which is explained in [59]. $\xi_{b,k,b,1}$ is the principal eigenvalue defined in (2). Each base station then computes the beamforming vector $\boldsymbol{t}_{b,\hat{k}}^{[m]}$ and the power loading $P_{b,\hat{k}}^{[m]}$ for this user and transmits a pilot so each user in the network can estimate and feedback $\sigma^2_{\mathrm{i}_{b,k}}[m]$. In phase two, each base station schedules the user

$$\mathcal{K}_b^{[m]} \ni \check{k} = \operatorname*{argmax}_{k=1,\ldots,K} \frac{R_{b,k}^{\mathrm{II},[m]}}{\bar{R}_{b,k}^{[m]}} \qquad \forall b \in \mathcal{B} \tag{10}$$

where $R_{b,k}^{\mathrm{II},[m]}$ is given by:

$$R_{b,k}^{\mathrm{II},[m]} = \log_2\left(1 + \frac{P_{b,\hat{k}}^{[m]} \left|\boldsymbol{h}_{b,k,b}^{[m],\mathrm{T}} \boldsymbol{t}_{b,\hat{k}}^{[m]}\right|^2}{\sigma^2_{\mathrm{i}_{b,k}}[m]}\right) \tag{11}$$

We make the following observations that apply similarly to the multi-user case [63]:

1) Since (8)-(9) only depend on local information that is available at each base station, no inter-base-station communication is necessary in order to determine user $(b,\hat{k})$ with (7).
2) If the base stations lack CSI to compute $R_{b,k}^{\mathrm{II},[m]}$, viz., $\boldsymbol{h}_{b,k,b}^{[m]}$, users can feed back the supported rate $R_{b,k}^{\mathrm{II},[m]}$ in conjunction with $\sigma^2_{\mathrm{i}_{b,k}}[m]$.
3) The active user for time slot m in (10) is re-labeled with $\check{k}$ and whenever $R_{b,\check{k}}^{\mathrm{II},[m]} > R_{b,\hat{k}}^{\mathrm{II},[m]}$, $\hat{k},\check{k} \in \mathcal{K}_b^{[m]}$, the sum-rate increases due to the additional multi-user diversity of the two-phase scheduling.

4) Two-phase scheduling is identical to the gambling algorithm in [64] if the second phase is omitted. Each base station schedules user $(b, \hat{k}) \in \bigcup_{b\in\mathcal{B}} b \times \mathcal{K}_b^{[m]}$ and encodes the data with rate $R_{b,\hat{k}}^{\mathrm{I},[m]}$. Because $R_{b,\hat{k}}^{\mathrm{I},[m]}$ was determined based on $\sigma^2_{\mathrm{i}_{b,k}}[m-1]$ from the previous time slot, there is a very high probability that user $(b, \hat{k})$ experiences an outage [45].

V. LEAKAGE-BASED PRECODING

Jorswieck *et al.* completely characterized the Pareto boundary of the *multiple input single output* (MISO) interference channel described above and showed that for the special case of two transmitters and two receivers the optimal precoders are a linear combination of selfish eigenbeamforming and altruistic zero-forcing, assuming instantaneous CSI is available at the transmitter [65]. For more than two transmitters and receivers, a similar ICIC scheme was proposed in [11], however, without the seamless transition between eigenbeamforming and zero-forcing, and the optimal transmit filter was recently derived in [66]. The results have been generalized for the case of statistical CSI at the transmitter [67] and the case where the base stations jointly serve all users with data [9], [68].

A major problem in the derivation and computation of optimal solutions is the coupling among the transmitters, i.e., the optimal solution for any base station depends on those for all other base stations. Based on their observations in [69] for the *mean square error* (MSE), the authors of [70] proposed sub-optimal precoders based on leakage channels, a concept introduced in [71] to decouple the precoders in the MISO BC with a single transmitter. Similar heuristics have been used in [9], [68] for the case where multiple base stations serve a user with data and in the context of vector quantization for cell-edge users in Wyner-type models at high SINR [35]. Minimizing leakage can also be helpful in networks with interference alignment [72].

Define the (average) SLNR for base station b as

$$\mathrm{SLNR}_b^{[m]} = \frac{\boldsymbol{t}_b^{[m],\mathrm{H}} \boldsymbol{R}^*_{\boldsymbol{h}_{b,\hat{k},b}} \boldsymbol{t}_b^{[m]}}{\boldsymbol{t}_b^{[m],\mathrm{H}} \left(\sum\limits_{\substack{b'=1 \\ b' \neq b}}^{B} \boldsymbol{R}^*_{\boldsymbol{h}_{b',\hat{k},b}} + \frac{\sigma_\eta^2}{E_{\mathrm{tr}}} \mathbf{1}_{N_\mathrm{a}} \right) \boldsymbol{t}_b^{[m]}} \tag{12}$$

where we have dropped the index k such that $\boldsymbol{t}_b^{[m]} := \boldsymbol{t}_{b,\hat{k}}^{[m]}$ assuming a single user $\hat{k}$ is served per frequency resource. Note, however, that the algorithm can easily be extended to the multi-user case. The precoder $\boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$ that maximizes $\mathrm{SLNR}_b^{[m]}$ is known to be the eigenvector corresponding to the largest eigenvalue, namely, the principal component, of the matrix [71]

$$\left[\left(\boldsymbol{R}^*_{\mathrm{LEAK}_b} + \frac{\sigma_\eta^2}{E_{\mathrm{tr}}} \mathbf{1}_{N_\mathrm{a}} \right)^{-1} \boldsymbol{R}^*_{\boldsymbol{h}_{b,\hat{k},b}} \right] \tag{13}$$

where

$$\boldsymbol{R}_{\mathrm{LEAK}_b} = \sum_{\substack{b'=1 \\ b' \neq b}}^{B} \boldsymbol{R}_{\boldsymbol{h}_{b',\hat{k},b}} \tag{14}$$

is the leakage covariance matrix of base station b. Note that if $\boldsymbol{R}_{\mathrm{LEAK}_b} = \mathbf{0}_{N_\mathrm{a}}$ and $N_\mathrm{T} = 1$, $\boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$ is the conjugate complex of the normalized vector channel of the active user in cell b (coherent beamforming). Similarly, if $\boldsymbol{R}_{\mathrm{LEAK}_b} = \mathbf{0}_{N_\mathrm{a}}$ and $N_\mathrm{T} \gg 1$, $\boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$ is the conjugate complex of the principal eigenvector of $\boldsymbol{R}_{\boldsymbol{h}_{b,\hat{k},b}}$ (eigenbeamforming). The following algorithm can be implemented without sharing any CSI among base stations as long as only average channel measurements are used [73]:

```
Pre-select user $(b, \hat{k}) \in \bigcup_{b\in\mathcal{B}} b \times \mathcal{K}_b^{[m]}$ $\forall b$ with (7)
If $\boldsymbol{R}_{\mathrm{LEAK}_b} \neq \mathbf{0}_{N_\mathrm{a}}$, distribute $(b, \hat{k}) \in \bigcup_{b\in\mathcal{B}} b \times \mathcal{K}_b^{[m]}$ $\forall b$
to all base stations
Compute $\boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$ $\forall b$ and set $P_{b,\hat{k}}^{[m]} = E_{\mathrm{tr}}$
Transmit a pilot employing the precoders from
Feed back $\sigma^2_{\mathrm{i}_{b,k}}[m]$ and supported rate $R_{b,\check{k}}^{\mathrm{II},[m]}$
from user $(b, k)$ to base station $b$ $\forall (b, k)$
Schedule user $(b, \check{k})$ $\forall b$ with (10)
Encode data for rate $R_{b,\check{k}}^{\mathrm{II},[m]}$ and start transmission
```

Unfortunately, some additional infrastructure is needed to implement the algorithm since the scheduling decisions from phase one, viz., which user $\hat{k}$ base station b intends to serve, have to be relayed to all base stations. However, instead of exchanging $B^2 N_\mathrm{a} K$ complex numbers with infinite precision, only B integers with finite precision need to be distributed among base stations and the amount of information exchanged between base stations

- is independent of the number of users K and the number of transmit antennas N_a;
- scales linearly in the number of cells as opposed to quadratic scaling when CSI is shared;
- can be encoded with a finite number of bits, namely, $\lceil \log_2 K \rceil$ bit word length.

VI. SIMULATION RESULTS

For a single isolated cell b, the optimal signal processing and scheduling is known. In the case of single-user transmission, the optimal scheduler selects for each resource block m the user $\hat{k} \in \mathcal{K}_b^{[m]}$ that can support the largest data rate $R_{b,\hat{k}}^{[m]}$. Because only one user is served at a time, it is allocated the entire power budget E_{tr} available for that cell. If the base station has perfect knowledge of $\boldsymbol{h}_{b,k,b}^{[m]}$ for all users $k \in \mathcal{K}_b^{[m]}$, the optimal precoder is $\boldsymbol{t}_b^{[m]} = \boldsymbol{h}_{b,\hat{k},b}^{[m],*} / \|\boldsymbol{h}_{b,\hat{k},b}^{[m]}\|_2$. If the base station does not have CSI for *coherent beamforming* (CBF), each base station generates a random beam $\boldsymbol{t}_b^{[m]} \in \mathbb{C}^{N_\mathrm{a}}$ with elements $\zeta = 1, \ldots, N_\mathrm{a}$:

$$\boldsymbol{e}_\zeta^{\mathrm{T}} \boldsymbol{t}_b^{[m]} = \left| \boldsymbol{e}_\zeta^{\mathrm{T}} \boldsymbol{v}_b^{[m]} \right| \exp\left\{ \mathrm{j}\, \pi (\zeta - 1) \sin\left(\nu_b^{[m]} \right) \right\} \tag{15}$$

$\boldsymbol{v}_b^{[m]} \in \mathbb{C}^{N_\mathrm{a}}$ and $\nu_b^{[m]} \in [0, 2\pi)$ are, respectively, an isotropically distributed complex random unit-norm vector and a uniformly distributed real random variable, whose mean is the boresight direction of cell b and whose variance equals $\pi^2/27$. Random beamforming such as that in (15) with opportunistic scheduling is termed *opportunistic beamforming* (OBF) in [59]. For the case that multiple users are served on the same sub-carrier, the optimal signal processing and user selection is given by [5] and together with dirty paper coding the capacity of a single cell is achieved. The exact DPC algorithm used in

TABLE I
OVERVIEW OF SIMULATION PARAMETERS

Number of cells (B):	57 (hexagonal grid, 3 sectors/site)
Distance between BSs (ISD):	2km
Number of users per cell (K):	6
Number of antennas per BS (N_a):	4
Transmit power (E_tr):	10W
Thermal noise power (σ_η^2):	-100.8dBm
Carrier wavelength:	15cm
Pathloss exponent:	3.8
Penetration loss exterior wall:	all users are outdoor
Shadowing standard deviation:	common: 6dB; cluster: 3dB
Angular spread:	2°
Antenna beam pattern:	3-sector
3dB beamwidth:	70°
Maximum antenna gain:	14dBi
Maximum antenna attenuation:	20dB
Min. distance user to BS:	30m
User distribution:	uniform

this section is thoroughly explained in [64]. CBF, OBF, and DPC are the benchmarks we use to assess the performance of the proposed schemes. A detailed description of the genie and gambling algorithms can be found in [45], [64]. Since this correspondence focused primarily on the single-user case, we refer readers to [63] for a detailed description of two-phase scheduling in conjunction with DPC. In addition, a comparison with precoders based on the *minimum mean square error* (MMSE) criterion can be found in [70].[1]

We use the 3GPP Spatial Channel Model for MIMO simulations for an urban macro cell [46] and assume that all the channels on all sub-carriers for all users are independent and identically distributed. Table I summarizes the simulation parameters and Fig. 1 and Fig. 2 compare the *cumulative distribution functions* (CDFs) and the average sum-rates for the cell in the center of the network[2] for greedy scheduling ($f \to 0$) and instantaneous CSI. Genie DPC expectedly performs best with an average sum-rate of 8.34 *bits per channel use* (bpcu). Two-phase scheduling with DPC achieves about half a bit per channel use less at 7.85 bpcu, without requiring CSI to be exchanged between base stations. This suggests that two-phase scheduling is a viable alternative to genie DPC as it does not require any additional infrastructure. More importantly, the required amount of CSI feedback is drastically reduced as each user only has to feed back a single vector channel to the anchor cell as opposed to B vector channels to all base stations in the network. The SLNR-based precoders, which only serve a single user per cell, cannot reach the performance of the two multi-user schemes. On the other hand, at an average sum-rate of 6.50 bpcu, they achieve 3.01 bpcu more than does the opportunistic beamforming that also serves a single user only. While both the single-user (3.75 bpcu) and the multi-user (4.20 bpcu) gambling algorithms outperform opportunistic beamforming in terms of the average achievable sum-rate, they both feature a minimal achievable outage probability of 20.8% and 7.6%, respectively, as can be seen in Fig. 1. Thus, their 5% outage capacity, a common metric for cell-edge users and shown in Fig. 2, is zero. Figure 2 also displays the average sum-rate and 5% outage capacity for coherent beamforming with two-phase scheduling.

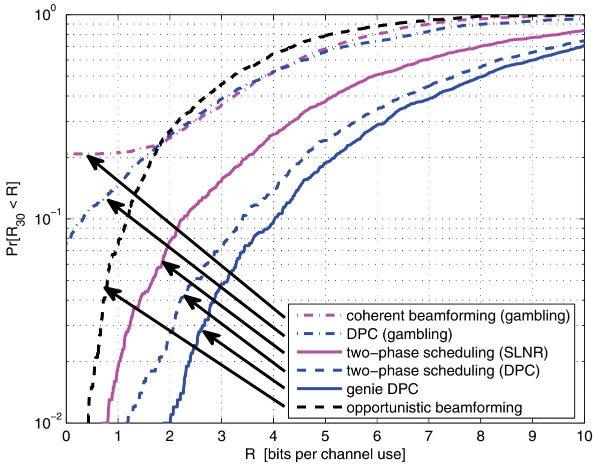

Fig. 1. Sum-rate cumulative distribution functions for different precoding strategies with instantaneous CSI at the transmitter.

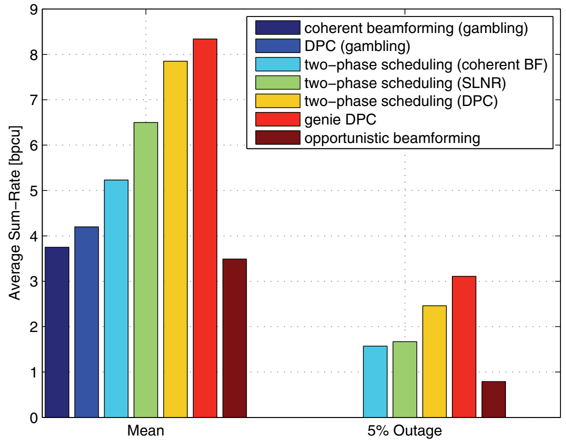

Fig. 2. Average sum-rates in bits per channel use of the considered precoding schemes with instantaneous CSI at the transmitter.

Figures 3 and 4 compare the CDFs and the average sum-rates for two-phase scheduling with eigenbeamforming, SLNR-based, and DPC-based precoding, respectively when only average CSI is available at the base stations. Since DPC requires perfect channel knowledge at the transmitter, the performance is deteriorated accordingly when average CSI from uplink measurements is used to design the precoders. DPC with two-phase scheduling only achieves an average sum-rate of 1.29 bpcu. In this more realistic scenario, where no explicit CSI is fed back from the users, the linear schemes clearly outperform DPC. Eigenbeamforming, which does not require any communication between the base stations, achieves an average sum-rate of 5.06 bpcu. If the base stations are inter-

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[1] since two-phase scheduling makes available the random interference power to the base stations through a secondary feedback phase we expect that a performance gap between two algorithms known for stationary interference translates to a comparable gap under non-stationary interference with two-phase scheduling

[2] since no wrap around is used, we analyze the sum-rate of the cell in the center and the remaining 56 base stations are simply simulated to create interference

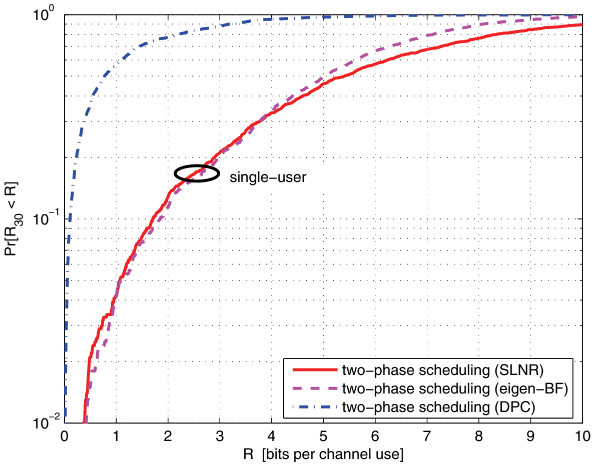

Fig. 3. Sum-rate cumulative distribution function for different precoding strategies with average CSI at the transmitter.

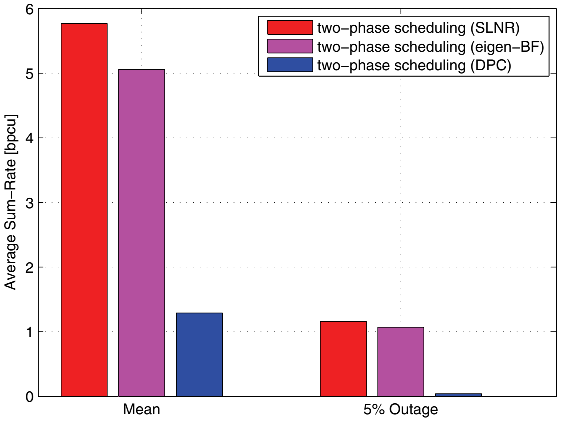

Fig. 4. Average sum-rates in bits per channel use of the considered precoding schemes with average CSI at the transmitter.

connected through a backhaul such that they can interchange the scheduling decisions from phase one, i.e., which user $\hat{k}$ base station b intends to serve, the precoders that maximize the SLNR outperform all other transmission schemes considered here with an average sum-rate of 5.77 bpcu.

Table II compares all algorithms in terms of the required signaling. Feedback from the user equipment to the anchor base station can be complex, e.g., for channel coefficients, or real as in the case of SINR/rate feedback. Communication between base stations through the backhaul network is either complex when CSI is exchanged or integer when user IDs are broadcasted. Feedback is directional from a particular user to its serving base station. Hence, Table II compares the feedback in the number of complex and real coefficients per cell. In contrast, backhaul communication is not directional as each base station broadcasts its information to all base stations in the network. Accordingly, Table II gives the number of coefficients that need to be exchanged through the backhaul in the entire network. The algorithms in Table II are sorted by average cell throughput in ascending order. Two-phase schemes with instantaneous CSI at the transmitter require two feedback phases as the users have to feedback channel coefficients in the first phase and stabilized SINRs in the second phase. Feedback of the supported rate, however, is not necessary by virtue of perfect CSI at the transmitter. All other schemes require a single feedback phase, either for CSI acquisition (genie and gambling) or SINR feedback. Those algorithms based on average channel information at the base station have to augment the SINR report with the supported rate. Two-phase scheduling with eigenbeamforming requires a single feedback phase and no backhaul communication at all. Furthermore, all CSI is acquired in the uplink. The necessary feedback from the user equipment, namely, the SINR and the rate, are already part of current networks such as the CQI reports in 3GPP LTE [47]. If instead of eigenbeamforming the base stations employ precoders which maximize the average SLNR, they have to broadcast the active user to neighboring cells, introducing additional signaling and overhead. However, all backhaul communication is of finite word-length and the amount is independent of the number of users or antennas such that each base station simply broadcasts a single integer. Moreover, no average CSI needs to be exchanged among base stations. The implementation of both algorithms is the same for average and perfect CSI such that they seamlessly transition between the two and the same hardware and software can be used at all base stations. Genie DPC outperforms all other schemes, however, each user has to estimate and feed back the interference channels to all base stations and the backhaul communication grows quadratically in the number of cells and linearly in the number of users and antennas. In contrast, DPC with two-phase scheduling neither requires knowledge of interference channels nor any backhaul communication. Unfortunately, the requirement of perfect CSI at the transmitter might be infeasible for practical networks.

TABLE II
SIGNALING OVERHEAD

	Transmit CSI	Feedback		Backhaul	
		complex	real	complex	integer
two-phase DPC	average	0	$2K$	0	0
OBF	none	0	K	0	0
CBF gambling	perfect	$N_\mathrm{a}K$	0	0	0
DPC gambling	perfect	$N_\mathrm{a}K$	0	0	0
two-phase CBF	average	0	$2K$	0	0
two-phase CBF	perfect	$N_\mathrm{a}K$	K	0	0
two-phase SLNR	average	0	$2K$	0	B
two-phase SLNR	perfect	$BN_\mathrm{a}K$	K	$B^2N_\mathrm{a}K$	B
two-phase DPC	perfect	$N_\mathrm{a}K$	K	0	0
genie DPC	perfect	$BN_\mathrm{a}K$	0	$B^2N_\mathrm{a}K$	0

VII. SUMMARY AND CONCLUSION

Next-generation cellular networks will bring together various technologies to achieve the performance requirements put forward in IMT-Advanced, namely, fast temporal scheduling, spatial signal processing by means of multiple antennas, and universal frequency reuse. Though these technologies are known to enhance the spectral efficiency, we showed that their joint application introduces novel challenges as they lead to non-stationary co-channel interference originating from neighboring cells. The most common approach to mitigating this intercell interference in a particular cell is to make available CSI from neighboring base stations. This, however, requires new and expensive infrastructure which is accompanied by additional error and delay sources. Hence, we presented novel scheduling and precoding techniques that employ DPC to serve multiple users per cell and single-layer beamforming to serve a single user per cell. We discussed their theoretical performance bounds assuming the knowledge of instantaneous ubiquitous CSI and demonstrated large performance gains of up to 98% through computer simulations. Moreover, we derived variations of these algorithms that allow for a practical implementation that does not require CSI to be exchanged between base stations and still offer performance gains of up to 87% (non-linear processing) and 55% (linear processing).

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