Cost-Constrained Transmit Processing in Wireless Cellular Networks with Universal Frequency Reuse

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Abstract— **To improve link reliability and data throughput in wireless communications, it is well known that we can exploit both the spatial and the temporal domain by precoding and scheduling, respectively. For cellular networks, however, most of these gains can only be obtained when frequency resources are carefully allocated to the different base stations as otherwise, they are compromised by the presence of intercell interference. To achieve universal frequency reuse among base stations, the idea of base station cooperation has recently attracted much attention. Unfortunately, the costs of this cooperation in terms of channel state information diminish most of the benefits. This paper proposes scheduling and precoding techniques under universal frequency reuse that address these costs to recover the gains of temporal scheduling and spatial precoding in the downlink of cellular *multiple input single output* (MISO) systems with multiple non-cooperative users per cell.**

I. INTRODUCTION

Multiple input multiple output (MIMO) technologies have been proven both in theory and in practice to facilitate high data rates and to improve reliability [1]–[3]. After more than a decade of research, MIMO technologies are well studied and understood. This is true even for the multi-user case where one central transmitter (e.g., the base station) serves multiple non-cooperative users each employing multiple antennas [4]–[9]. The capacity region is known for both the *broadcast channel* (BC) and the *multiple access channel* (MAC). Nevertheless, research on MIMO technologies has mostly focused on the single-cell case, i.e., only one base station was considered.

A network of multiple base stations allows users to move freely without losing connections. This freedom comes at the price of increased interference emitted from neighboring base stations, namely, *intercell interference* (ICI), especially when high frequency reuse is desired to ensure economical bandwidth usage. *Orthogonal frequency-division multiplexing* (OFDM) keeps simultaneous transmissions within a cell orthogonal by dividing the bandwidth into non-interfering sub-carriers. However, since each cell gets to use the entire frequency spectrum, there will be ICI. The multi-cell scenario with universal frequency reuse and multiple antennas at both the transmitting and receiving ends has only recently attracted much attention in the research community [10]–[28].

While base stations can cooperatively process the transmitted signals of multiple users in a single cell, current network architectures do not allow for sophisticated cooperation among base stations. Consequently, existing algorithms that have proven to be very powerful in non-cellular networks, e.g., successive interference cancellation [6], [9] or linear precoding [7], may not be directly applicable in cellular networks because the base stations lack the knowledge of *channel state information* (CSI) for all channels. One may argue, in principle, that a cellular system can be modeled as one "super cell" with spatially distributed antennas. However, the displacement of cooperative transmitters presents practically insurmountable obstacles to the implementation of techniques like *dirty paper coding* (DPC) [4] that require making shared data and CSI available to all base stations. This is further complicated through spatial precoding by means of multiple transmit antennas in conjunction with temporal scheduling and universal frequency reuse. As such, ICI becomes a non-stationary phenomenon [25] which is a fundamental problem in next-generation networks.

The two-phase scheduler proposed in [27] addressed the problem of non-stationary ICI. However, it required CSI to be fed back from the user equipment to the base station in addition to requiring the exchange of CSI among base stations. This was, in part, because the base stations were required to know the interference channels from all base stations to a particular user. In this paper, we focus our attention away from interference channels to so-called leakage channels. In addition, by averaging CSI estimates from the uplink, the resulting algorithms neither require CSI to be fed back to the base stations, nor to be exchanged among base stations, thus reducing the overall signaling overhead. We compare these algorithms to opportunistic beamforming, which requires no CSI, and to DPC, which requires perfect CSI. Our findings unveil that the two-phase scheduling increases average per cell sum-rate by about 40-85% depending on the precoding algorithm that is used. For average CSI, we show how most of the performance can be preserved while no CSI has to be fed back from the users to the base stations.

The remainder of the paper shall detail the challenges and the precoding and scheduling algorithms we propose to overcome these challenges. Before the paper is concluded in the last section, simulation results are also presented.

Notation: Vectors and matrices are denoted by bold lower and upper case letters, respectively, and $(\bullet)^*$, $(\bullet)^{\mathrm{T}}$, and $(\bullet)^{\mathrm{H}}$ denote complex conjugation, transposition, and conjugate transposition.

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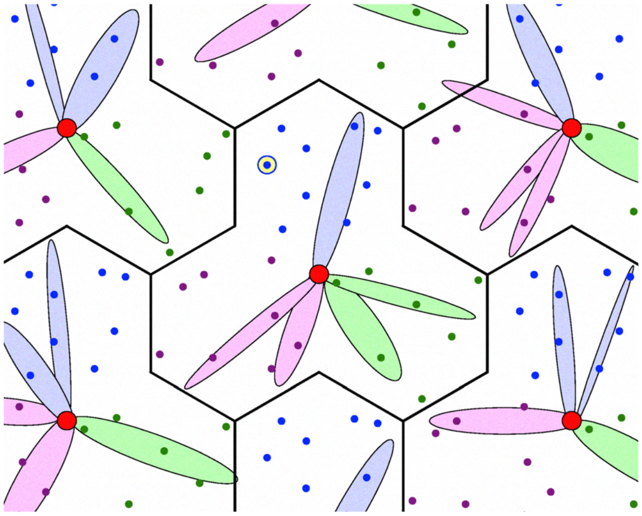

Fig. 1. Since there is no "beam" directed at the circled user, it can support a high data rate due to a low interference power level. Thus, the base station in the center decides to schedule this user, i.e., to serve it in the next time slot. It encodes the data according to the large rate it thinks that user can support. Meanwhile, adjacent base stations also schedule users for the next transmission frame.

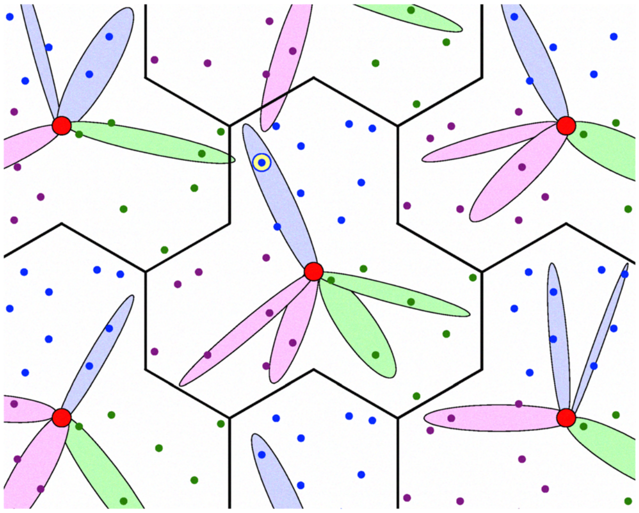

Fig. 2. In the next time slot, the base station in the center serves the circled user as depicted by the beam. However, this user now experiences a very high interference power level and hence cannot support high data rates anymore. Consequently, it cannot decode the message from the base station in the center and an outage occurs, and the achieved data rate is zero.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We investigate network topologies as in [15], [16], [25]. Since the number of users per cell generally is large, temporal scheduling has to be performed at the base stations [27]. Consequently, the intercell-interference-plus-noise powers for users $\{k\}$ in cells $\{b\}$, viz.,

$$\sigma^2_{i_{b,k}}[m] = \sigma^2_\eta + \sum_{\substack{b'=1\\b'\neq b}}^{B} \sum_{i=1}^{K} \boldsymbol{h}^{[m],\mathrm{T}}_{b,k,b'} \boldsymbol{Q}^{[m]}_{b',i} \boldsymbol{h}^{[m],*}_{b,k,b'} \tag{1}$$

vary quickly over time, where $\boldsymbol{h}^{[m]}_{b,k,b'} \in \mathbb{C}^{N_\mathrm{a}}$ is the vector channel from base station b' to user k in cell b, $\boldsymbol{Q}^{[m]}_{b',i}$ is the transmit covariance matrix of user i in cell b' during time slot m, and σ^2_η is the noise variance (cf. [27]). B, K, and N_a are the number of cells, users per cell, and transmit antennas per base station, respectively. Thus, *ICI is a non-stationary phenomenon (even with constant channels) when scheduling and spatial filtering are performed at the transmitters* [25].

The maximal achievable sum-rate $R^{[m]}_b$ in cell b is given by

$$R^{[m]}_b = \sum_{k=1}^{K} \log_2 \left(1 + \frac{\boldsymbol{h}^{[m],\mathrm{T}}_{b,k,b} \boldsymbol{Q}^{[m]}_{b,k} \boldsymbol{h}^{[m],*}_{b,k,b}}{\sigma^2_{i_{b,k}}[m] + \sum\limits_{k'=1}^{\substack{k-1\ \text{[DPC]}\\ K\ \text{[linear]}}} \boldsymbol{h}^{[m],\mathrm{T}}_{b,k,b} \boldsymbol{Q}^{[m]}_{b,k'} \boldsymbol{h}^{[m],*}_{b,k,b}} \right) \tag{2}$$

for dirty-paper coding and linear approaches. If the base stations do not cooperate, they have no means to predict $\sigma^2_{i_{b,k}}[m]$ for the next transmission frame and system performance will suffer in terms of sum-rate and outage [25]. This can easily be illustrated with Fig. 1 and Fig. 2.

It is commonly believed today that base station cooperation that coordinates transmission from multiple senders can greatly improve spectral efficiency, reliability, and performance of wireless communication networks. Various methods and algorithms have been proposed and analyzed and huge gains were indeed demonstrated by theoretical studies as well as simulations. However, most, if not all, of those algorithms do not explicitly take into account the cost (in terms of CSI) in deriving the optimum solutions. In single transmitter "networks," this can be a valid approach since the overhead of CSI acquisition is small. The resources, such as bandwidth, power, and time, that are needed for feedback are negligible compared to those needed for the data carrying link. In cellular networks, however, CSI acquisition turns out to be a pivotal overhead issue. For a rather small network with two tiers of base stations and only two antennas per base station, the number of CSI coefficients *per user* already amounts to 6498. In essence, the cost of CSI acquisition can be huge and should no longer be neglected.

In [27], the authors proposed a two-phase scheduler as a powerful tool to meet the above challenges:

- It only requires a very coarse synchronization. Base stations do not need to be synchronized symbol by symbol; rather, only the scheduling frames have to be synchronized.
- It is not tied to a specific signal processing scheme. Each transmitter in each cell could utilize its own precoding scheme (linear, non-linear, single or multi-user, ...) allowing different operators to use the same frequencies in adjacent cells.
- It only requires modest changes to the MAC layer protocols. Users simply have to feed back their respective ICI powers between the two phases of the scheduler. Hence, only very limited resources are spent on the feedback overhead while achieving significant gains.

In this paper, we further exploit this idea by shifting our focus from interference-based to leakage-based algorithms in order to maximize the throughput in networks. In single-cell systems, the idea behind leakage-based algorithms was to decouple precoders in multi-user systems [29]–[32]. In cellular networks, leakage-based schemes offer considerable advantages in terms of CSI acquisition. In practice, cellular networks are set up in such a way that each user can only feed back to one base station. Thus, the problems of CSI acquisition and the availability of interference channels $\{\boldsymbol{h}_{b,k,b'}^{[m]}\}_{b'=1}^{B}$ and those of leakage channels $\{\boldsymbol{h}_{b',k',b}^{[m]}\}_{b',k'=1}^{B,K}$ are fundamentally different, and this difference ought to be taken into account in the derivation of optimal solutions. Equation (1) reveals that interference-based schemes heavily rely on the vector channels $\{\boldsymbol{h}_{b,k,b'}^{[m]}\}_{b'=1}^{B}$, i.e., the channels from all base stations in the network to a particular user k in cell b (*interference*). This particular user, however, can only communicate with its own base station. Consequently, all those vector channels $\{\boldsymbol{h}_{b,k,b'}^{[m]}\}_{b'=1}^{B}$ (BN_a complex coefficients per user) have to be estimated at the user equipment, fed back to one base station, and then distributed to all other base stations via a backhaul network that interconnects all base stations.

Leakage- or MSE-based schemes [15], [26], [29]–[33], on the other hand, require the knowledge of $\{\boldsymbol{h}_{b',k',b}^{[m]}\}_{b',k'=1}^{B,K}$, i.e., the vector channels from one base station b to all users in the network (*leakage*). In a *time-division multiple access* (TDMA) system, each base station could estimate these channels–by means of pilots–in the uplink and then apply them in the subsequent downlink. This would not work in a *frequency-division multiple access* (FDMA) system, since the channel parameters generally depend on the carrier frequency. However, covariance-based schemes [34], [35] that only require average channel information would still be able to utilize the measurements from the uplink in the downlink assuming that the uplink and downlink frequency bands are not spaced too far apart [36], [37]. Furthermore, in order to keep interference low in the pilot phase, there should be only one user signaling per orthogonal channel in the entire network. Thus, all base stations could estimate $\{\boldsymbol{h}_{b',k',b}^{[m]}\}_{b',k'=1}^{B,K}$ simultaneously and no additional resources (power, time, or frequency) are required. Hence, leakage- or MSE-based schemes that only require average CSI would neither need any kind of backhaul communication nor any additional resources for feedback.

III. PROPOSED PRECODING ALGORITHMS

Let the channel covariance matrix $\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}}$ for the corresponding vector channel $\boldsymbol{h}_{b,k,b'}^{[m]}$ be given by

$$\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}} = \frac{1}{N_\text{T}} \sum_{m=1}^{N_\text{T}} \boldsymbol{h}_{b,k,b'}^{[m]} \boldsymbol{h}_{b,k,b'}^{[m],\text{H}} = \sum_{\zeta=1}^{N_\text{a}} \xi_{b,k,b',\zeta} \boldsymbol{q}_{b,k,b',\zeta} \boldsymbol{q}_{b,k,b',\zeta}^{\text{H}}, \tag{3}$$

where $\{\xi_{b,k,b',\zeta}\}_{\zeta=1}^{N_\text{a}}$ and $\{\boldsymbol{q}_{b,k,b',\zeta}\}_{\zeta=1}^{N_\text{a}}$ are the eigenvalues and eigenvectors of $\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}}$, respectively. To simplify notation, suppose that the eigenvalues are ordered, viz., $\xi_{b,k,b',1} \geq \xi_{b,k,b',2} \geq \ldots \geq \xi_{b,k,b',N_\text{a}} \geq 0$. Furthermore, we consider paired frequency bands, i.e., uplink and downlink transmissions take place in different frequency bands. However, we assume that the two bands are not spaced too far apart. We refer to CSI as being "average" if N_T is sufficiently[1] large. In this case, $\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}}$ can be obtained from uplink measurements. Moreover, we refer to CSI as being "instantaneous" if $N_\text{T} = 1$. Uplink-downlink-reciprocity does not hold for instantaneous CSI since fast fading is not sufficiently averaged and $\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}}$ will depend on the frequency band in which it was estimated.

In order for the base stations to encode the data, they have to know the intercell-interference-plus-noise powers $\sigma_{i_{b,k}}^2[m]$ (cf. (2)). However, since all base stations transmit in the same frequency bands employing spatial precoding and temporal scheduling, $\sigma_{i_{b,k}}^2[m]$ changes rapidly for each user k in cell b with each time slot m. Since these fluctuations are also non-stationary, they are hard to predict and accordingly, it is nearly impossible for the base stations to encode the data accurately resulting in huge losses due to frequent outages [25]. To increase system performance and per-cell sum-rate, the authors proposed a so-called *two-phase scheduler* in [27]. We will now present this scheduler in a much broader framework. In addition, we no longer require the mobile terminals to estimate and feed back all vector channels $\left\{\boldsymbol{h}_{b,k,b'}^{[m]}\right\}_{b'=1}^{B}$ as postulated in [27], thus reducing the required signaling overhead considerably. As a consequence, base stations do not have to share any CSI as opposed to our previous publication [27]. Hence, the resulting scheduling and precoding techniques can be performed entirely locally. We will focus on precoders that maximize the *signal-to-leakage-and-noise ratio* (SLR) and compare those to opportunistic beamforming and dirty-paper coding in terms of achievable sum-rate. Opportunistic beamforming shall serve somewhat as a lower bound since it does not require any channel state information, while DPC is known to achieve the capacity of the Gaussian broadcast channel (upper bound). However, the latter requires perfect channel state information and is computationally very expensive. Dirty-paper coding is the only multi-user scheme we consider, i.e., a single base station serves multiple users per time slot per frequency band. All other schemes employ beamforming, i.e., each base station serves a single user, which we will denote by $\hat{k}$. Note, however, that one such user is served simultaneously in all cells using the same frequency band.

The (average) signal-to-leakage-and-noise ratio for the b-th base station is defined as

$$\overline{\text{SLR}}_b^{[m]} = \frac{\boldsymbol{t}_b^{[m],\text{H}} \boldsymbol{R}_{\boldsymbol{h}_{b,\hat{k},b}}^{*} \boldsymbol{t}_b^{[m]}}{\boldsymbol{t}_b^{[m],\text{H}} \left(\sum\limits_{\substack{b'=1 \\ b' \neq b}}^{B} \boldsymbol{R}_{\boldsymbol{h}_{b',\hat{k},b}}^{*} + \frac{\sigma_\eta^2}{E_\text{tr}} \mathbf{1}_{N_\text{a}} \right) \boldsymbol{t}_b^{[m]}}, \tag{4}$$

where E_tr is the available transmit power, viz., $\sum_{i=1}^{K} \operatorname{tr}\left(\boldsymbol{Q}_{b,i}^{[m]}\right) \leq E_\text{tr} \; \forall b$ and $\mathbf{1}_M$ is a $M \times M$ identity matrix. Furthermore, $\boldsymbol{t}_b^{[m]} = \boldsymbol{t}_{b,\hat{k}}^{[m]}$ is the unit-norm precoder base station b employs at time slot m. Then, the precoder

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[1] depending on the speed of the user and the length of a time slot m

$\boldsymbol{t}_{\mathrm{SLR}_b}^{[m]}$ that maximizes $\overline{\mathrm{SLR}}_b^{[m]}$ is known to be the principal eigenvector of the matrix

$$\left[\left(\boldsymbol{R}_{\mathrm{LEAK}_b}^{*}+\frac{\sigma_\eta^2}{E_{\mathrm{tr}}}\mathbf{1}_{N_{\mathrm{a}}}\right)^{-1}\boldsymbol{R}_{\boldsymbol{h}_{b,\hat{k},b}}^{*}\right], \tag{5}$$

where

$$\boldsymbol{R}_{\mathrm{LEAK}_b}=\sum_{\substack{b'=1\\ b'\neq b}}^{B}\boldsymbol{R}_{\boldsymbol{h}_{b',\hat{k},b}} \tag{6}$$

is the leakage covariance matrix of base station b, i.e., it encompasses how the signal power being emitted form base station b "leaks" into the network [29].

We also define the MMSE covariance matrix of base station b as

$$\boldsymbol{R}_{\mathrm{MMSE}_b}=\sum_{b'=1}^{B}\boldsymbol{R}_{\boldsymbol{h}_{b',\hat{k},b}}=\boldsymbol{R}_{\mathrm{LEAK}_b}+\boldsymbol{R}_{\boldsymbol{h}_{b,\hat{k},b}} \tag{7}$$

and the corresponding precoder

$$\boldsymbol{t}_{\mathrm{MMSE}_b}^{[m]}=\alpha_b\left(\boldsymbol{R}_{\mathrm{MMSE}_b}^{*}+\frac{\sigma_\eta^2}{E_{\mathrm{tr}}}\mathbf{1}_{N_{\mathrm{a}}},\right)^{-1}\boldsymbol{q}_{b,\hat{k},b,1}^{*} \tag{8}$$

where the real scalar α_b is chosen such that $\boldsymbol{t}_{\mathrm{MMSE}_b}^{[m]}$ is of unit norm. Note that for $N_{\mathrm{T}}=1$, i.e., when instantaneous CSI is used, $\boldsymbol{t}_{\mathrm{SLR}_b}^{[m]}=\boldsymbol{t}_{\mathrm{MMSE}_b}^{[m]}$ since $\boldsymbol{R}_{\boldsymbol{h}_{b,\hat{k},b}}$ is of rank one. In this case, $\boldsymbol{t}_{\mathrm{MMSE}_b}^{[m]}$ is motivated by the findings in [26]. For $N_{\mathrm{T}}\gg 1$, it is motivated by the heuristic in [34]. The computation of the precoders for opportunistic beamforming and dirty-paper precoding are detailed in [25] and [16], respectively, to which we refer. Last but not least, when $\boldsymbol{R}_{\mathrm{LEAK}_b}=\mathbf{0}$, we refer to $\boldsymbol{t}_{\mathrm{SLR}_b}^{[m]}$ as coherent beamforming if $N_{\mathrm{T}}=1$ and as eigenbeamforming if $N_{\mathrm{T}}\gg 1$.

IV. PROPOSED SCHEDULING ALGORITHM

The scheduler is the core contribution and in principle, it works for any precoders, not just the ones introduced above. Furthermore, as already mentioned, the only real requirement is that base stations are synchronized with respect to the scheduling frames m. In other words, the "packets" have to be in sync, not the OFDM symbols. The scheduler, to which we refer as *two-phase scheduler*, works as follows:

A. Phase I:

While each base station is transmitting its data, it schedules the users to be served in the next transmission frame $[m+1]$ and computes the corresponding precoders for these users. For opportunistic beamforming and dirty-paper precoding this is detailed in [25] and [16], respectively. For the precoders introduced above, the scheduling is done by

$$\hat{k}=\underset{k=1,\ldots,K}{\operatorname{argmax}}\frac{R_{b,k}^{\mathrm{I},[m+1]}}{\bar{R}_{b,k}^{[m+1]}}\qquad\forall b \tag{9}$$

where $R_{b,k}^{\mathrm{I},[m+1]}$ and $\bar{R}_{b,k}^{[m+1]}$ are given by

$$R_{b,k}^{\mathrm{I},[m+1]}=\log_2\left(1+\frac{E_{\mathrm{tr}}\,\xi_{b,k,b,1}}{\sigma_{i_{b,k}}^2[m]}\right) \tag{10}$$

and

$$\bar{R}_{b,k}^{[m+1]}=\begin{cases}(1-f)\bar{R}_{b,k}^{[m]}+fR_b^{[m]} & k=\hat{k}\\ (1-f)\bar{R}_{b,k}^{[m]} & k\neq\hat{k}.\end{cases} \tag{11}$$

$f\in(0,1)$ is called the *forgetting factor.*[2]

B. Phase II:

When data transmission for slot $[m]$ is finished, all base stations transmit a pilot sequence using the precoders computed for slot $[m+1]$ and all users feed back the interference power level for these precoders to their respective base station, i.e., $\left\{\sigma_{i_{b,k}}^2[m+1]\right\}_{k=1}^{K}$ is known to base station b. If DPC is employed, the base stations encode the data with the precoders used in the pilot phase. If single-user beamforming is employed, each base station serves the user

$$\check{k}=\underset{k=1,\ldots,K}{\operatorname{argmax}}\frac{R_{b,k}^{\mathrm{II},[m+1]}}{\bar{R}_{b,k}^{[m+1]}}\qquad\forall b, \tag{12}$$

where $R_{b,k}^{\mathrm{II},[m+1]}$ is the rate user k in cell b can support with the precoders of phase I. Transmission of data begins and the scheduler is back in phase I.

Note that the only algorithms that require any communication between base stations are the ones employing $\boldsymbol{t}_{\mathrm{SLR}_b}^{[m]}$ or $\boldsymbol{t}_{\mathrm{MMSE}_b}^{[m]}$. All other precoding schemes (opportunistic beamforming, coherent beamforming, eigenbeamforming, and dirty-paper precoding) do not require any inter-base-station communication, thus, no backhaul network connecting all base stations is required. However, none of the algorithms requires CSI of neighboring base stations. In order for base station b to compute $\boldsymbol{t}_{\mathrm{SLR}_b}^{[m]}$ or $\boldsymbol{t}_{\mathrm{MMSE}_b}^{[m]}$, it has to know $\hat{k}$ for each cell. Fortunately, $\hat{k}$ is integer with only $\lceil\log_2 K\rceil$ bits word length, such that finite capacity links suffice to distribute the B integers $\hat{k}$ to all base stations. This is in contrast to most other publications in the context of *network MIMO*, which require all vector channels to be known at all base stations, namely, $B\times B\times K\times N_{\mathrm{a}}$ complex channel coefficients have to be made available at each base station through a backhaul network connecting all those base stations [15], [16]. In comparison, the proposed scheduling and precoding techniques do not require any exchange of CSI among base stations. Furthermore, they ease the burden of CSI acquisition in networks since (a) they only require local CSI which each base station can estimate on its own; (b) they are based on average CSI which is valid for multiple time slots m. Therefore, we can do fast scheduling which is desired to guarantee small delays for user data and

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[2] For $f\longrightarrow 1$, the scheduler approaches the *round robin scheduler*, and for $f\longrightarrow 0$, it approaches the *greedy scheduler*. Hence, the forgetting factor can be used to tune the scheduler between maximum throughput/multi-user diversity and fairness/delay (proportional fair scheduling) [38].

TABLE I

OVERVIEW OF SIMULATION RESULTS

multi-user	linear	coop.	CSI	leakage	sum-rate	5% outage
NO	YES	NO	full	NO	3.84 bpcu	—
YES	NO	NO	full	NO	4.30 bpcu	—
NO	YES	YES	full	NO	5.33 bpcu	1.57 bpcu
NO	YES	YES	full	YES	6.34 bpcu	1.50 bpcu
NO	YES	YES	avr.	NO	5.29 bpcu	1.44 bpcu
NO	YES	YES	avr.	YES	6.08 bpcu	1.17 bpcu
YES	NO	YES	full	NO	7.97 bpcu	3.27 bpcu
NO	YES	NO	none	NO	3.58 bpcu	0.72 bpcu

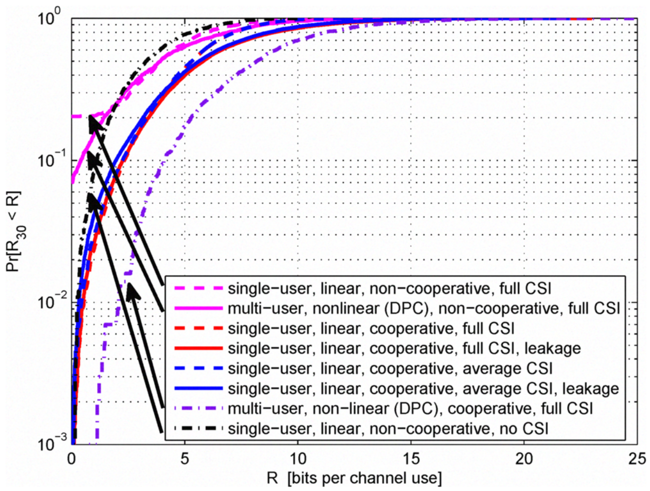

Fig. 3. Sum-rate cumulative distribution function for different precoding strategies employing a two-phase scheduler.

control signaling. Furthermore, fast tracking of CSI allows for better usage of multi-user diversity. In 3GPP Long Term Evolution, for example, the temporal scheduling granularity is 1ms on each sub-carrier. Accordingly, base stations have only very limited time to acquire CSI from and distribute CSI to neighboring base stations.

V. SIMULATION RESULTS

We now discuss the simulation results we obtained for the channel model presented in [27] for a greedy scheduler ($f \to 0$) and low user mobility. In particular, we assume a *sectorized* cellular layout, i.e., three base stations are co-located at the vertices of three cells. The users are uniformly distributed within the area of a cell. The vector channels $\boldsymbol{h}_{b,k,b'}^{[m]}$ are modeled using the 3GPP Spatial Channel Model for MIMO simulations [39] with an angle spread of $\delta = 2°$. The channel model incorporates a maximum antenna gain in boresight direction of $\hat{A} = 14\text{dBi}$, a path-loss exponent of $\gamma = 3.8$, log-normal shadowing, and an antenna beam pattern $A(\theta)$ as in [25], [39]. The carrier wavelength is $\lambda = 15\text{cm}$ and the remaining simulation parameters are $B = 57$, $K = 6$, $N_\text{a} = 4$, $\sigma_\eta^2 = -100.8\text{dBm}$, and $E_\text{tr} = 10W$. The distance between base stations is 2km. See [25], [27] for details.

The single-user schemes are beamforming algorithms, i.e., a single user is served per OFDM narrowband channel. The multi-user scheme employs DPC to serve multiple users per OFDM narrowband channel. For the case of opportunistic beamforming, each base station generates a random beam [25] and the users feed back the rates they can support [40]. In each cell, the user with the largest rate is served. Since the beamforming vectors are generated according to an isotropic distribution, no CSI is required. The non-cooperative schemes demonstrate the state-of-the-art; the cooperative schemes all employ the proposed two-phase scheduler. The single-user linear cooperative schemes with full or average CSI maximize the signal-to-leakage-and-noise ratio. If the word "leakage" is omitted in the legend, it means that the leakage covariance matrix is unknown to the base station further minimizing the amount of required CSI, viz., $\boldsymbol{R}_{\text{LEAK}_b} = \boldsymbol{0}\ \forall b$. Table I summarizes the average sum-rates and the rates for a 5% outage probability in *bits per channel use* (bpcu). For further illustration, the results are also charted in Fig 4. None of the cooperative schemes saturates, i.e., has a minimum outage probability (see Fig. 3). For non-linear schemes, the proposed two-phase scheduler increases the average sum-rate per cell by roughly 85%. Even for linear schemes, it still increases the achievable sum-rate by about 65% when the base station knows the leakage channels. When average instead of instantaneous CSI is used, the algorithms are robust enough to nearly preserve the achievable sum rate.[3] For instantaneous CSI ($N_\text{T} = 1$), knowledge of the leakage channels increases average performance by one bit per channel use. For average CSI ($N_\text{T} \gg 1$), knowledge of the leakage covariance matrix $\boldsymbol{R}_{\text{LEAK}_b}$ still results in better performance of about half a bit per channel use. Note that the gains observed in Table I are in bits per channel use per cell.

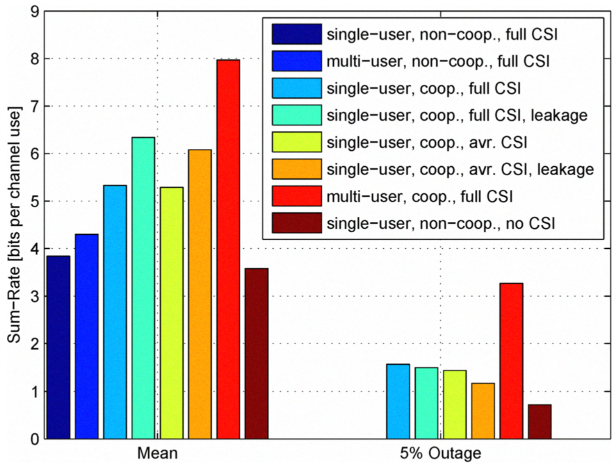

Fig. 4. Overview of simulation results. Average sum-rates in bits per channel use of the considered precoding schemes.

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[3] For $N_\text{T} \gg 1$, $\boldsymbol{t}_{\text{MMSE}_b}^{[m]}$ performs slightly worse achieving 0.04 bits per channel use less than $\boldsymbol{t}_{\text{SLR}_b}^{[m]}$.

VI. CONCLUSIONS

CDMA or OFDM techniques have long been employed in commercial wireless cellular networks [38] to guarantee efficient usage of available resources by universal reuse. Yet, they have failed to deliver the data rates modern communication and multimedia devices demand. We have outlined the reasons for this lag and illustrated why existing technologies that are known to facilitate high data rates do not automatically work in multi-cell networks with universal frequency reuse. Our proposed solutions addressed two particular roadblocks in cellular networks: the coupling of spatially distributed precoders and the cost of acquiring spatially distributed CSI. By exploiting the topology of cellular networks and focusing on leakage channels instead of interference channels, the proposed algorithm can increase the per cell sum-rate by 40-85% without any CSI overhead. The linear approaches only need to relay integers between base stations as compared to complex vector-valued CSI.

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