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Enhancing the Network Sum-Rate Without Sharing Channel State Information between Base Stations

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***Abstract*— We consider the downlink of a cellular wireless network where the base stations are equipped with multiple transmit antennas and operate in the same frequency band. Each base station serves one user per *orthogonal frequency-division multiplexing* (OFDM) sub-carrier by means of spatial precoding. Due to temporal scheduling, the active users change rapidly in time and consequently, intercell interference becomes non-stationary limiting the achievable network sum-rate. Under the assumption of perfect channel knowledge at each base station, we optimize both precoding and scheduling in order to maximize the achievable network sum-rate. The solution, however, unveils that both precoding and scheduling can be performed locally at each base station without the need for CSI to be exchanged between base stations if they are solely based on average channel measurements.**

I. Introduction

With the evolution of mobile telecommunications technologies from so-called third generation to fourth generation networks, focus has shifted from peak user to average network spectral efficiency. This development is reflected in the IMT-A road map put forward by the International Telecommunication Union's division ITU-R. Today, *multiple input multiple output* (MIMO) techniques are well understood and have found their way into commercial standards to increase peak user spectral efficiency and cell edge user performance, e.g., IEEE 802.11n, IEEE 802.16e, or 3GPP LTE. To achieve the spectral efficiencies postulated in IMT-A for fourth generation networks, coordinated multi-point transmission, also known as base station cooperation, has been proposed among others and accordingly, this has attracted a lot of attention in the research community, both in industry and academia (see [1] for an overview of publications). However, the huge gains–demonstrated by theoretical studies as well as simulations and measurement campaigns–heavily hinge upon the amount of information that the base stations are allowed to exchange with each other. One can go to such lengths as even allowing data to be exchanged between various base stations to make techniques like dirty-paper precoding possible [2], [3]. Alternatively, one can refrain from exchanging user data and simply share *channel state information* (CSI) [4]–[9]. Ultimately, though, modern communications standards demand fast scheduling and precoding techniques to guarantee small delays for user data and control signaling. Furthermore, fast tracking of CSI allows for better usage of multi-user diversity. Accordingly, base stations have only very limited time to acquire CSI from and distribute CSI to neighboring base stations. Similarly, iterative signal processing algorithms that converge to some (global) optimum solution [10], [11] may be too cost- and time-expensive to actually be applied in commercial deployments.

In this paper, the authors propose a projected gradient based precoding scheme that maximizes the network sum-rate of the downlink of a cellular wireless system where the base stations employ *orthogonal frequency-division multiplexing* (OFDM) to separate users within a cell. To mitigate the heavy intercell interference that users experience due to universal frequency reuse, spatial precoding by means of multiple transmit antennas is used to minimize the signal power that "leaks" from one base station to users in neighboring cells [12]. Simulation results show that the precoders that maximize the signal-to-leakage-plus-noise ratio are a powerful initialization to the above mentioned projected gradient algorithm. The network sum-rate can then be further increased through channel-dependent scheduling. Due to the spatial signal processing and temporal scheduling, the intercell interference power rapidly fluctuates for each user, offering an additional degree of multi-user diversity which can be harnessed to increase average system performance. Last but not least, we show that by averaging channel measurements from the uplink, the resulting precoding and scheduling solutions nearly achieve the same performance as with perfect CSI. However, it is not necessary anymore for base stations to exchange any CSI.

The remainder of the paper will start with describing the system model (Section II), followed by deriving the proposed precoding (Section III) and scheduling (Section IV) algorithms. Before we conclude the paper in the last section, simulation results are presented in Section V.

Notation: Vectors and matrices are denoted by bold lower and upper case letters, respectively. $(\bullet)^*$, $(\bullet)^{\mathrm{T}}$, $(\bullet)^{\mathrm{H}}$, $\|\bullet\|_2$, $\mathbf{1}_M$, and $\mathbf{0}_N$ denote complex conjugation, transposition, conjugate transposition, Euclidean norm, $M \times M$ identity matrix, and $N \times N$ zero matrix, respectively.

II. System Model

We consider the downlink scenario of a cellular network. The base stations are equipped with a uniform linear array of N_{a} transmit antennas spaced at half a wavelength. The mobile users are assumed to be uniformly distributed over the coverage area with single-antenna terminals. In a practical system, scheduling of a user has to take many factors into account, among those are, for instance, type of application, quality of service, risk of buffer overflow, and rate or delay constraints. These factors are channel-independent and may differ considerably for different users. We will assume that a higher system layer ensures that none of these constraints are violated by selecting users accordingly. Let $\Gamma_b^{[m]}$ be the set of users that base station b can schedule at time slot m and let $\mathcal{K}_b^{[m]} = \{1, 2, \ldots, K_b^{[m]}\} \subset \Gamma_b^{[m]}$ be the subset of users assigned to a particular OFDM sub-carrier.[1] For simplicity, let $K_b^{[m]} = K \ \forall b, m$. Consequently, in the physical layer, each user is identified by a tuple $(b, k) \in \mathcal{B} \times \mathcal{K}_b^{[m]}$, where $\mathcal{B} = \{1, 2, \ldots, B\}$ is the set of all cell indices, cf. Fig. 1. Each base station b can schedule a single user to be served on each OFDM sub-carrier. This user is denoted by $(b, \hat{k})$. Then, the intercell-interference-plus-noise power for user (b, k) is given by

$$\sigma^2_{\mathrm{i}_{b,k}}[m] = \sigma^2_\eta + \sum_{\substack{b'=1 \\ b' \neq b}}^{B} \left| \boldsymbol{h}^{[m],\mathrm{T}}_{b,k,b'} \boldsymbol{p}^{[m]}_{b',\hat{k}} \right|^2 . \quad (1)$$

$\boldsymbol{h}^{[m]}_{b,k,b'} \in \mathbb{C}^{N_\mathrm{a}}$ is the frequency-flat vector channel from base station b' to user (b, k), $\boldsymbol{p}^{[m]}_{b',\hat{k}}$ is the beamforming vector that base station b' employs during time slot m, and σ^2_η is the noise variance of the circuitry (cf. [13]). To give meaning to the rate expressions in the sequel, we assume independent and identically distributed Gaussian symbols with zero mean and unit variance. Due to regulatory ordinance, the transmit power at each base station is limited to E_{tr}, viz., $\left\| \boldsymbol{p}^{[m]}_{b,\hat{k}} \right\|_2^2 \leq E_{\mathrm{tr}} \ \forall b$. The network sum-rate is now given by

$$R^{[m]} = \sum_{b=1}^{B} R_b^{[m]} = \sum_{b=1}^{B} \log_2 \left(1 + \frac{\left| \boldsymbol{h}^{[m],\mathrm{T}}_{b,\hat{k},b} \boldsymbol{p}^{[m]}_{b,\hat{k}} \right|^2}{\sigma^2_{\mathrm{i}_{b,\hat{k}}}[m]} \right) \quad (2)$$

and the objective in this paper is to maximize $R^{[m]}$.

III. Maximizing the Network Sum-Rate — Precoding

Two major roadblocks we face are:

1) the problem is highly coupled, i.e., the optimum precoder $\boldsymbol{p}^{[m]}_{b,\hat{k}}$ in cell b depends on the solutions for $\boldsymbol{p}^{[m]}_{b',\hat{k}}$ in the $B-1$ other cells through $\sigma^2_{\mathrm{i}_{b,\hat{k}}}[m]$ (cf. (1));
2) the power is constrained per base station as opposed to a sum-power constraint.

To overcome these obstacles, we use a projected gradient method [14] to find local maxima of (2). The complex gradient of the network sum-rate (2) is given by

$$\frac{\partial R^{[m]}}{\partial \boldsymbol{p}^{[m],*}_{b,\hat{k}}} = \frac{\boldsymbol{h}^{[m],*}_{b,\hat{k},b} \boldsymbol{h}^{[m],\mathrm{T}}_{b,\hat{k},b} \boldsymbol{p}^{[m]}_{b,\hat{k}}}{\sigma^2_{\mathrm{i}_{b,\hat{k}}}[m]} + \sum_{b'=1}^{B} \boldsymbol{h}^{[m],*}_{b',\hat{k},b} \boldsymbol{h}^{[m],\mathrm{T}}_{b',\hat{k},b} \boldsymbol{p}^{[m]}_{b,\hat{k}} \times \\ \times \left(\frac{1}{\sigma^2_{\mathrm{i}_{b',\hat{k}}}[m] + \left| \boldsymbol{h}^{[m],\mathrm{T}}_{b',\hat{k},b'} \boldsymbol{p}^{[m]}_{b',\hat{k}} \right|^2} - \frac{1}{\sigma^2_{\mathrm{i}_{b',\hat{k}}}[m]} \right) \quad (3)$$

and defines the direction of maximum change of $R^{[m]}$. At each time slot m, starting with some initial precoding vector $\boldsymbol{p}^{[m],(0)}_{b,\hat{k}}$, we can successively compute updates $\boldsymbol{p}^{[m],(\delta+1)}_{b,\hat{k}}$ via

$$\boldsymbol{p}^{[m],(\delta+1)}_{b,\hat{k}} = \left\lfloor \boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}} + \alpha^{\nu^{[m],(\delta)}} \boldsymbol{S}^{[m],(\delta)} \frac{\partial R^{[m]}}{\partial \boldsymbol{p}^{[m],(\delta),*}_{b,\hat{k}}} \right\rfloor \quad (4)$$

such that the network sum-rate cannot decrease at any iteration [14]. Because the network sum-rate is bounded, the algorithm must converge. To guarantee that every limit point of $\left\{ \boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}} \right\}_{\delta=0}^{\infty}$ is also a stationary point, we employ Armijo's rule [14] when selecting the step-size $\alpha^{\nu^{[m],(\delta)}}$. The preconditioning matrix

$$\boldsymbol{S}^{[m],(\delta)} = \sqrt{\frac{B E_{\mathrm{tr}}}{\sum_{b=1}^{B} \left\| \frac{\partial R^{[m]}}{\partial \boldsymbol{p}^{[m],(\delta),*}_{b,\hat{k}}} \right\|_2^2}} \mathbf{1}_{N_\mathrm{a}} \quad (5)$$

controls the speed of convergence and the operator $\lfloor \bullet \rfloor$ defined by

$$\left\lfloor \boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}} \right\rfloor = \begin{cases} \boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}} & \left\| \boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}} \right\|_2^2 \leq E_{\mathrm{tr}} \\ \frac{\sqrt{E_{\mathrm{tr}}}}{\left\| \boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}} \right\|_2} \boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}} & \text{otherwise} \end{cases} \quad (6)$$

ensures that $\boldsymbol{p}^{[m],(\delta)}_{b,\hat{k}}$ remains feasible, i.e., it does not violate the transmit power constraint E_{tr}. The iteration is halted if an update increases the network sum-rate by less than c_{th}.

Since the problem at hand is non-convex, the initialization of (4) is important, for different initializations may lead to different stationary points with very different sum-rates. In the sequel, we propose and analyze three initializations for (4).

A. Simple Weighting

A trivial initialization of $\boldsymbol{p}^{[m],(0)}_{b,\hat{k}}$ is:

$$\boldsymbol{p}^{[m],(0)}_{b,\hat{k}} = \sqrt{\frac{E_{\mathrm{tr}}}{N_\mathrm{a}}} \begin{bmatrix} 1 & 1 & \ldots & 1 \end{bmatrix}^{\mathrm{T}} \in \mathbb{C}^{N_\mathrm{a}} \quad \forall b \quad (7)$$

B. Maximizing the Signal-to-Leakage-plus-Noise Ratio

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

$$\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}} = \frac{1}{N_\mathrm{T}} \sum_{m=1}^{N_\mathrm{T}} \boldsymbol{h}^{[m]}_{b,k,b'} \boldsymbol{h}^{[m],\mathrm{H}}_{b,k,b'} = \sum_{\zeta=1}^{N_\mathrm{a}} \xi_{b,k,b',\zeta} \boldsymbol{q}_{b,k,b',\zeta} \boldsymbol{q}^{\mathrm{H}}_{b,k,b',\zeta}, \quad (8)$$

[1]The underlying multiple access scheme shall be *orthogonal frequency-division multiple access* (OFDMA) and the following analysis considers a single OFDMA sub-carrier. All parameters and solutions will thus depend on the frequency of that particular OFDMA sub-carrier. To ease notation, however, we will not indicate this dependency by an additional parameter.

where $\{\xi_{b,k,b',\zeta}\}_{\zeta=1}^{N_a}$ and $\{\boldsymbol{q}_{b,k,b',\zeta}\}_{\zeta=1}^{N_a}$ are the eigenvalues and eigenvectors of $\boldsymbol{R}_{\boldsymbol{h}_{b,k,b'}}$, respectively.[2] 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[3] large. Moreover, we refer to CSI as being "full" if $N_T = 1$. Define the (average) *signal-to-leakage-plus-noise ratio* (SLNR) for the b-th base station as

$$\mathrm{SLNR}_b^{[m]} = \frac{\boldsymbol{t}_b^{[m],\mathrm{H}} \boldsymbol{R}^*_{\boldsymbol{h}_{b,\hat{k},b}} \boldsymbol{t}_b^{[m]}}{\boldsymbol{t}_b^{[m],\mathrm{H}} \left(\sum_{\substack{b'=1 \\ b' \neq b}}^{B} \boldsymbol{R}^*_{\boldsymbol{h}_{b',\hat{k},b}} + \frac{\sigma_\eta^2}{E_{\mathrm{tr}}} \boldsymbol{1}_{N_a} \right) \boldsymbol{t}_b^{[m]}}. \quad (9)$$

Then, the precoder $\boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]} = \boldsymbol{p}_{b,\hat{k}}^{[m]} / \|\boldsymbol{p}_{b,\hat{k}}^{[m]}\|_2$ that maximizes $\mathrm{SLNR}_b^{[m]}$ is known to be the principal eigenvector of the matrix

$$\left[\left(\boldsymbol{R}^*_{\mathrm{LEAK}_b} + \frac{\sigma_\eta^2}{E_{\mathrm{tr}}} \boldsymbol{1}_{N_a} \right)^{-1} \boldsymbol{R}^*_{\boldsymbol{h}_{b,\hat{k},b}} \right], \quad (10)$$

where

$$\boldsymbol{R}_{\mathrm{LEAK}_b} = \sum_{\substack{b'=1 \\ b' \neq b}}^{B} \boldsymbol{R}_{\boldsymbol{h}_{b',\hat{k},b}} \quad (11)$$

is the leakage[4] covariance matrix of base station b, i.e., it encompasses how the signal power being emitted form base station b "leaks" into the network [12]. We propose $\boldsymbol{p}_{b,\hat{k}}^{[m],(0)} = \sqrt{E_{\mathrm{tr}}} \boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$ as another initialization.

C. Beamforming

Last but not least, when $\boldsymbol{R}_{\mathrm{LEAK}_b} = \boldsymbol{0}_{N_a}$, we refer to $\boldsymbol{p}_{b,\hat{k}}^{[m],(0)} = \sqrt{E_{\mathrm{tr}}} \boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$ as the beamforming initialization.

IV. Maximizing the Network Sum-Rate — Scheduling

We now explain how each base station determines the user $(b, \hat{k}) \in \mathcal{B} \times \mathcal{K}_b^{[m+1]}$ to be served at time slot $[m+1]$ on a particular OFDM sub-carrier.

Phase I: Suppose all users have fed back their intercell-interference-plus-noise power and $\left\{ \sigma_{\mathrm{i}_{b,k}}^2 [m] \right\}_{k=1}^{K}$ are known to base station b. While each base station is transmitting its data to user $(b, \hat{k})$ in slot m, it schedules the user to be served in the next transmission frame $[m+1]$ according to

$$\mathcal{K}_b^{[m+1]} \ni \hat{k} = \underset{k=1,\ldots,K}{\mathrm{argmax}} \frac{R_{b,k}^{\mathrm{I},[m+1]}}{\bar{R}_{b,k}^{[m+1]}} \qquad \forall b \quad (12)$$

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

$$R_{b,k}^{\mathrm{I},[m+1]} = \log_2 \left(1 + \frac{E_{\mathrm{tr}}\, \xi_{b,k,b,1}}{\sigma_{\mathrm{i}_{b,k}}^2 [m]} \right) \quad (13)$$

and

$$\bar{R}_{b,k}^{[m+1]} = \begin{cases} (1-f)\bar{R}_{b,k}^{[m]} + f R_{b,\check{k}}^{\mathrm{II},[m]} & k = \check{k} \in \mathcal{K}_b^{[m]} \\ (1-f)\bar{R}_{b,k}^{[m]} & k \neq \check{k} \in \mathcal{K}_b^{[m]} \end{cases}, \quad (14)$$

respectively. $f \in (0,1)$ is called the *forgetting factor*.[5] The optimum precoders can then be computed using (4).

Phase II: When data transmission for slot m is finished, all base stations send a pilot sequence and all users feed back their interference power level $\sigma_{\mathrm{i}_{b,k}}^2 [m+1]$ and request a rate $R_{b,k}^{\mathrm{II},[m+1]}$ for the next time slot. Each base station then serves the user $(b, \check{k})$,

$$\mathcal{K}_b^{[m+1]} \ni \check{k} = \underset{k=1,\ldots,K}{\mathrm{argmax}} \frac{R_{b,k}^{\mathrm{II},[m+1]}}{\bar{R}_{b,k}^{[m+1]}} \qquad \forall b \quad (15)$$

and the scheduler is back in phase I. A more detailed description of this two-phase scheduler can be found in [1], [13].

Remarks:

1.) Note that the user $(b, \check{k})$, that is scheduled by base station b in slot m is served with the precoder $\boldsymbol{p}_{b,\hat{k}}^{[m]}$ and that in general $\hat{k} \neq \check{k}$. This is very important. From (1) observe that $\sigma_{\mathrm{i}_{b,k}}^2 [m]$ would change if one or more $\boldsymbol{p}_{b',\hat{k}}^{[m]}$ ($b' \neq b$) changed. Thus, after the users have fed back $\sigma_{\mathrm{i}_{b,k}}^2 [m]$, it is of utmost importance that the base stations do not change their precoders for time slot m as otherwise, the network sum-rate will be halved on average [11], [16]. The scheduling in (15) provides an additional degree of freedom to harness extra multi-user diversity. However, user $(b, \check{k})$ has to be served with $\boldsymbol{p}_{b,\hat{k}}^{[m]}$.

2.) In order for base station b to compute $\boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$, it has to know $(b, \hat{k})$ for each cell b. Fortunately, $\hat{k}$ is integer with only $\lceil \log_2 K \rceil$ bit word length, such that finite capacity links suffice to distribute the B integers $\hat{k}$ to all base stations [13]. Moreover, if the base stations employ $\boldsymbol{p}_{b,\hat{k}}^{[m]} = \boldsymbol{p}_{b,\hat{k}}^{[m],(0)}$ as precoders, i.e., no iterations are performed at the transmitters, no CSI has to be exchanged among base stations. If uplink and downlink transmissions take place in the same frequency band (*time-division duplexing*, TDD), each base station b could estimate the channels $\{\boldsymbol{h}_{b',k',b}^{[m]}\}_{b',k'=1}^{B,K}$ in the uplink and then apply them in the subsequent downlink. This would not work if uplink and downlink transmissions took place in different frequency bands (*frequency-division duplexing*, FDD), since the channels generally depend on the carrier frequency. However, covariance-based schemes [17], [18] that only require average channel information would still be able to utilize the measurements from the uplink in the downlink assuming that

[2] To simplify notation, suppose that the eigenvalues are ordered, viz., $\xi_{b,k,b',1} \geq \xi_{b,k,b',2} \geq \cdots \geq \xi_{b,k,b',N_a} \geq 0$.

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

[4] see [1] for a discussion of "leakage channels" and "interference channels"

[5] For $f \to 1$, the scheduler approaches the *round robin scheduler*, and for $f \to 0$, 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) [15].

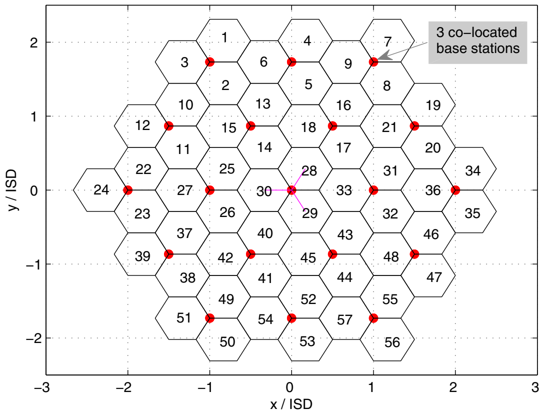

Fig. 1. Topology of the networks under consideration. Three base stations are co-located (sectorization).

TABLE I
OVERVIEW OF SIMULATION PARAMETERS

Number of cells (B):	57 (three tiers of base stations)
Distance between BSs (ISD):	2km
Number of users per cell (K):	6
Number of antennas per BS (N_{a}):	4
Transmit power (E_{tr}):	1-70W (2dB increments)
Thermal noise power (σ_η^2):	-100.8dBm
Carrier wavelength:	15cm
Path-loss exponent:	3.8
Angular spread:	$2°$ or $35°$
Antenna beam pattern:	3-sector
3dB beamwidth:	$70°$
Maximum antenna gain:	14dBi
Maximum antenna attenuation:	20dB
Maximum user velocity:	0km/h

the uplink and downlink frequency bands are not spaced too far apart [19], [20]. 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 are required. Hence, if the base stations compute $\boldsymbol{p}_{b,\hat{k}}^{[m],(0)}$ based on average CSI only and employ $\boldsymbol{p}_{b,\hat{k}}^{[m]} = \boldsymbol{p}_{b,\hat{k}}^{[m],(0)}$ as their precoders, no CSI has to be fed back from the users nor does it have to be distributed among base stations through a backhaul network connecting them.

V. SIMULATION RESULTS

Our simulation results were obtained for networks with a topology like the one depicted in Fig. 1. The vector channels $\boldsymbol{h}_{b,k,b'}^{[m]}$ were generated based on the 3GPP Spatial Channel Model for MIMO simulations [21] using the parameters summarized in Table I. The stopping criterion for the iteration in (4) was set to $c_{\mathrm{th}} = 10^{-4}$. Table II shows the simulation results for greedy scheduling ($f \to 0$), perfect CSI, small angular spread (2 degrees), and $E_{\mathrm{tr}} = 10$W. The average network sum-rate in *bits per channel use* [bpcu] is given if each base station serves user $(b, \check{k})$ (Phase II); serves user $(b, \hat{k})$ (Phase I); serves user $(b, \check{k})$ with $\boldsymbol{p}_{b,\hat{k}}^{[m],(0)}$ (initial). Furthermore, the average transmit power $\sum_{b=1}^{B} \left\| \boldsymbol{p}_{b,\hat{k}}^{[m]} \right\|_2^2$ and the average iteration depth until convergence are displayed. Observe that all initializations end up using nearly the entire available transmit power of $BE_{\mathrm{tr}} = 570$W, which is true for all transmit power constraints we considered (cf. Table I). Figures 2 and 3 summarize the results in Table II for transmit power constraints between $1 - 70$W in 2dB increments. If it is initialized with the precoders that maximize the SLNR, the algorithm always converges to a local maximum larger than the one to which it converges when initialized with simple weighting or the beamforming solution. More interesting is the fact that for all transmit power constraints we considered, the SLNR initialization is so close to the local maximum that we can just use the initialization as the precoder, viz., $\boldsymbol{p}_{b,\hat{k}}^{[m]} = \boldsymbol{p}_{b,\hat{k}}^{[m],(0)} = \sqrt{E_{\mathrm{tr}}}\boldsymbol{t}_{\mathrm{SLNR}_b}^{[m]}$. Hence, we do not have to share any CSI among base stations without sacrificing performance. Figure 3 further unveils the gain by updating the scheduled user $(b, \hat{k})$ to $(b, \check{k})$ in Phase II. For the transmit power constraints considered, this gain amounts to several bits per channel use for large values of E_{tr} and is due to the additional multi-user diversity. Finally, we analyze the performance for different forgetting factors and angular spreads (Fig. 4). As expected, for increasing values of f the network sum-rate decreases as multi-user diversity has to give more and more leeway to fairness among the users. Also, for full CSI, the

TABLE II
OVERVIEW OF SIMULATION RESULTS

	Network Sum-Rate [bpcu] Phase II	Phase I	initial	Transmit Power [W]	Iteration Depth
SLNR	372.22	371.16	371.14	569.65	1.43
Beamforming	350.39	349.30	144.89	556.37	40.78
Weighting	351.05	349.71	192.10	556.66	40.60

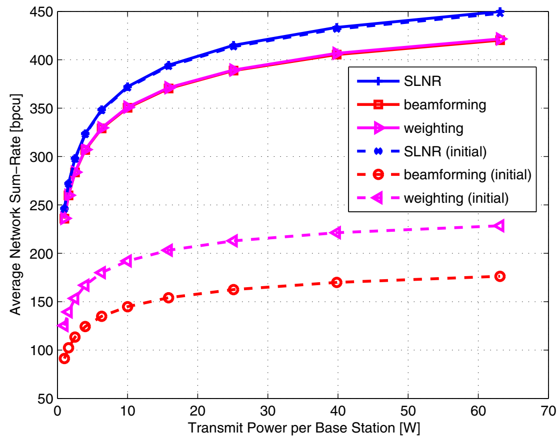

Fig. 2. Average network sum-rate in bits per channel use before and after iteration for different transmit power constraints with greedy scheduling ($f \to 0$), perfect CSI, and small angular spread (2 degrees).

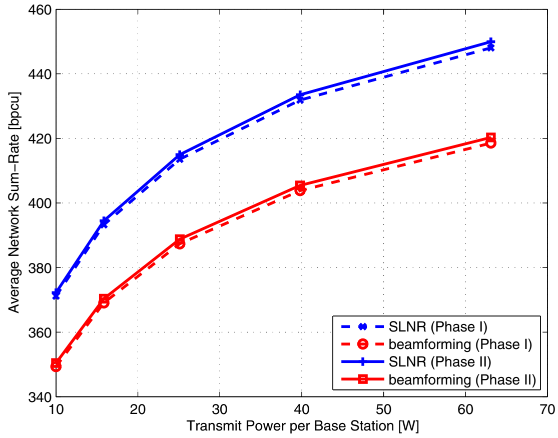

Fig. 3. Additional multi-user diversity through two-phase scheduling (full CSI, small angular spread of 2 degrees, greedy scheduling, i.e., $f \rightarrow 0$, for various transmit power constraints).

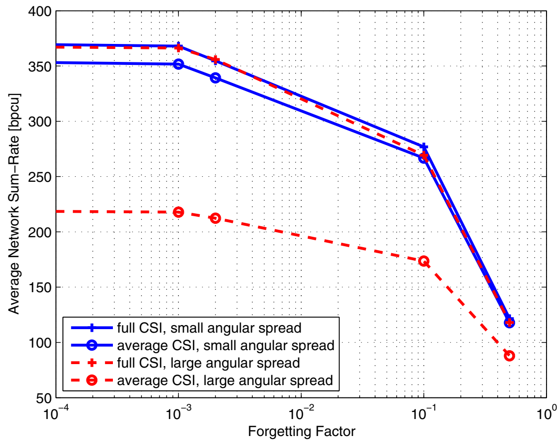

Fig. 4. Average network sum-rate in bits per channel use at $E_{\text{tr}} = 10\text{W}$ for different angular spreads and different forgetting factors.

performance hardly depends on the angular spread. In the case of average CSI, however, angular spread is crucial. Only for small angular spread does average CSI deliver about the same performance as full CSI (cf. [13], Fig. 2).

VI. Conclusion

We presented precoding and scheduling techniques to maximize the network sum-rate in the downlink of a cellular wireless network where the base stations employ multiple antennas to transmit to a single user in each OFDM subcarrier. The proposed scheduler was shown to increase the network sum-rate by harnessing additional multi-user diversity, which is inherently present in cellular systems with spatial precoding, temporal scheduling, and universal frequency reuse, even for constant channels. The precoders were derived using a projected gradient method. However, the proposed initialization turned out to have already achieved the maximal achievable sum-rate and it provided a pseudo-closed-form solution. By averaging channel estimates from the uplink, we further demonstrated that the proposed precoding and scheduling algorithm increases the network sum-rate without interchanging any CSI between base stations. Since only integers have to be distributed between base stations, finite capacity links suffice.

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