

Increasing Mobile Rates while Minimizing Cost per Bit - Cooperation vs. Denser Deployment

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Abstract—It is known that future cellular communication systems must meet an ever increasing demand for mobile data rates, i.e. must consequently improve spectral efficiency. Two degrees of freedom to address this issue are to use a denser deployment or introduce cooperation between base stations. This paper introduces models to capture both achievable rates and the costs connected to these two options (addressing capex, opex, energy and backhaul), and yields an insight into their impact on the overall cost per bit.

I. INTRODUCTION

Future generations of mobile communication systems need to meet an exponentially increasing demand for mobile data rates, predicted to at least double each year until 2014 [1]. On network level, basically two means to raise overall system capacity can be identified: Increasing base station density (or equivalently introducing additional radio access points such as micro cells, femto cells or relays) and introducing cooperation between base stations, for example using multi-cell joint signal processing. The impact of these two levers on spectral efficiency has been discussed in [2], and that of base station density has been analyzed from a cost [3] and energy consumption perspective in [4]. Our paper provides a more comprehensive model for the *cost per bit* of uplink and downlink communication, taking into account imperfect channel knowledge, pilot overhead, and costs for capital and operational expenses, as well as for power dissipation and backhaul. Given the increasing rate demand and the two stated degrees of freedom in network deployment and usage, our proposed model yields an insight into the potential way forward in the evolution of mobile communications systems.

The paper is organized as follows. Section II introduces an information-theoretic model to derive achievable rates and required backhaul as a function of site distance and cooperation size. Section IV then discusses a model to estimate average cost per area, again as a function of the two degrees of freedom. Section V merges both quantities to a *cost per bit* expression and provides simulation results. The paper is concluded in Section VI.

II. TRANSMISSION MODELS

We consider a cellular system with M base stations (BSs) serving M sectors. The BSs are grouped into $M/3$ sites with an inter-site distance d_{ISD} . Adjacent sites are connected via a mesh of backhaul links, as shown in Fig. 1, enabling joint

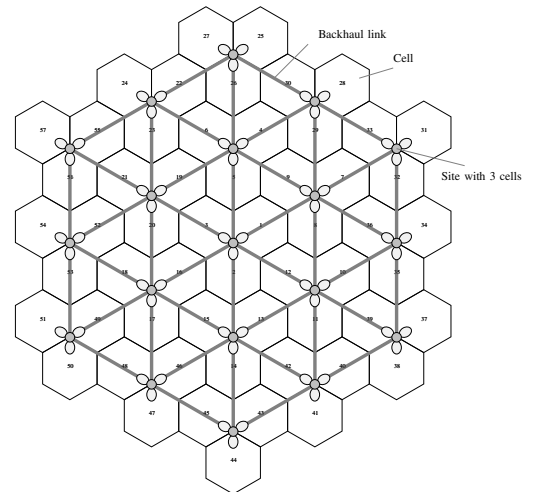


Fig. 1. Cellular setup considered in this work.

signal processing not only among co-located BSs, but also across sites. We observe both uplink and downlink, assuming that each user equipment (UE) has one transmit and receive antenna, while each BS has $N_{\text{bs}} = 2$ antennas. The latter are assumed to be cross-polarized and hence subject to uncorrelated fast fading. For reasons of analytical simplicity, we assume that orthogonal frequency division multiplex (OFDM) is employed in both link directions, and from now on focus on a single frequency-flat sub-carrier of this system.

A. Transmission Equations

Assuming that each BS has assigned exactly one UE to the observed sub-carrier, we can state the *uplink* transmission of M UEs to M BSs in each OFDM symbol as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (1)$$

where $\mathbf{y} \in \mathbb{C}^{[MN_{\text{bs}} \times 1]}$ are the signals received by the BSs, $\mathbf{H} \in \mathbb{C}^{[MN_{\text{bs}} \times M]}$ is the instantaneous fast fading realization of the channel on this sub-carrier between the UEs and BSs, which we assume to be constant during the transmission of a large codeword. $\mathbf{x} \in \mathbb{C}^{[M \times 1]}$ are the symbols transmitted by the UEs, and $\mathbf{n} \in \mathbb{C}^{[MN_{\text{bs}} \times 1]}$ denotes thermal noise. While this is not necessarily optimal, we assume that transmit signals and noise are zero-mean Gaussian with $E\{\mathbf{x}\mathbf{x}^H\} = \mathbf{P} = \text{diag}(\mathbf{p})$ and $E\{\mathbf{n}\mathbf{n}^H\} = \sigma^2\mathbf{I}$, respectively.

The *downlink* transmission from M BSs to M UEs in each OFDM symbol can be stated similarly as

$$\mathbf{y} = \mathbf{H}^H \mathbf{W} \mathbf{x} + \mathbf{n}, \quad (2)$$

where $\mathbf{y} \in \mathbb{C}^{[M \times 1]}$ and $\mathbf{n} \in \mathbb{C}^{[M \times 1]}$ now denote the signals and noise received by the UEs, respectively, again with $E\{\mathbf{n}\mathbf{n}^H\} = \sigma^2 \mathbf{I}$. Channel \mathbf{H} and terminal-related symbols \mathbf{x} are as defined before. $\mathbf{W} \in \mathbb{C}^{[MN_{\text{bs}} \times M]}$ is a linear precoding matrix employed at the BS side. For the downlink, we assume without loss of generality that $E\{\mathbf{x}\mathbf{x}^H\} = \mathbf{I}$, i.e. power control is implicitly contained in precoding matrix \mathbf{W} .

B. Modeling Imperfect CSI

It is known that the performance of multi-cell cooperative signal processing - as an example of coordinated multi-point (CoMP) - is strongly subject to the channel state information (CSI) available at transmitter and receiver side. In this work, we specifically model imperfect CSI at the *receiver* side, while we assume the CSI at the *transmitter* to be the same. Clearly, this is unrealistic as any CSI feedback will always be subject to quantization and delay, leading to a strictly less accurate CSI at the transmitter side than at the receiver, but this assumption strongly simplifies our model. We will later consider a large amount of CSI feedback in the uplink, and assume that downlink CoMP is only provided to slowly moving UEs, so that above assumption should be fairly reasonable. For uplink and downlink, let us assume that the channel matrix from Section II-A can be split into

$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E}, \quad (3)$$

where $\hat{\mathbf{H}}$ is an unbiased minimum mean square error (MMSE) channel estimate, and \mathbf{E} the uncorrelated channel estimation error. It is then known from [5], [6] that the uplink and downlink transmissions from (1) and (2) can be modified to

$$\mathbf{y} = (\hat{\mathbf{H}} + \mathbf{E}) \mathbf{x} + \mathbf{n} = \hat{\mathbf{H}} \mathbf{x} + \mathbf{u} + \mathbf{n} \quad \text{and} \quad (4)$$

$$\mathbf{y} = (\hat{\mathbf{H}}^H + \mathbf{E}^H) \mathbf{W} \mathbf{x} + \mathbf{n} = \hat{\mathbf{H}}^H \mathbf{W} \mathbf{x} + \mathbf{v} + \mathbf{n}, \quad (5)$$

respectively. If $\mathbf{u} = \mathbf{E} \mathbf{x}$ and $\mathbf{v} = \mathbf{E}^H \mathbf{W} \mathbf{x}$ are now modeled as spatially white Gaussian random variables with $\mathbf{u} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, E\{\mathbf{E} \mathbf{E} \mathbf{E}^H\})$ and $\mathbf{v} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, E\{\mathbf{E}^H \mathbf{W} \mathbf{W}^H \mathbf{E}\})$, this leads to an overestimation of the impact of channel estimation error [5], as a Gaussian distribution maximizes entropy for a given variance. Furthermore, treating these terms as random variables with a different realization in each channel access also overestimates their impact due to Jensen's inequality. Hence, computing capacity based on (4) or (5) will always result in a *lower bound* on capacity. In order to obtain reasonable values for the variance of the elements in \mathbf{E} , we may use the Kramer-Rao lower bound [7] given as

$$\sigma_{\mathbf{E}}^2 = \frac{\sigma_{\text{p}}^2}{N_{\text{p}} \cdot p_{\text{pilots}}}. \quad (6)$$

Here, σ_{p}^2 is the variance of the noise channel estimation is subject to, N_{p} is the number of pilots used, and p_{pilots} is pilot

power. Note that σ_{p}^2 may deviate from σ^2 if pilot sequences of multiple cells are designed to be orthogonal, while data transmission in these cells is subject to mutual interference not addressed by CoMP. In this work, we assume $\sigma_{\text{p}}^2 = \sigma^2$ and that pilot power equals data power. With the definition of estimation error \mathbf{E} in (3), we can now state

$$\forall i, j : E \left\{ e_{i,j} (e_{i,j})^H \right\} = \frac{E \{ |h_{i,j}|^2 \} \cdot \sigma_{\mathbf{E}}^2}{E \{ |h_{i,j}|^2 \} + \sigma_{\mathbf{E}}^2}. \quad (7)$$

Note that (4) and (5) are based on a particular channel estimate $\hat{\mathbf{H}}$. If we want to compute achievable rates of a given *actual* channel over many channel estimation processes, however, performance can be approximated by replacing $\hat{\mathbf{H}}$ in (4) and (5) by the *expectation value* of the channel estimate [8], which is a power-reduced *effective* channel $\bar{\mathbf{H}}$ with [6]

$$\forall i, j : \bar{h}_{i,j} = \frac{h_{i,j}}{\sqrt{1 + \sigma_{\mathbf{E}}^2 / E \{ |h_{i,j}|^2 \}}}. \quad (8)$$

The before stated approximation is very accurate as long as the term $p_{\text{pilots}} \cdot E \{ |h_{i,j}|^2 \}$ is at least a few dB larger than the absolute channel estimation error variance $\sigma_{\mathbf{E}}^2$ [8].

In the sequel, let us denote by \mathcal{M} and \mathcal{K} the sets of all BSs, and all UEs assigned to the observed OFDM sub-carrier. Sets $\mathcal{M}_C \subseteq \mathcal{M}$ and $\mathcal{K}_C \subseteq \mathcal{K}$ further denote the subsets of BSs and UEs within a particular cluster of N_C cooperating cells.

C. Uplink Rate Calculation

In the uplink, we assume that all UEs in \mathcal{M}_C are received by all $N_{\text{bs}} \cdot N_C$ antennas of the cooperating BSs and equalized via a linear MMSE filter. Based on (4), the achievable rate of each UE k can be bounded as [6]

$$r_k^{\text{UL}} \leq \log_2 \left| \mathbf{I} + (\Phi_{\text{ii}} + \Phi_{\text{hh}} + \sigma^2 \mathbf{I})^{-1} \bar{\mathbf{h}}_k^{\mathcal{M}_C} p_k \left(\bar{\mathbf{h}}_k^{\mathcal{M}_C} \right)^H \right|, \quad (9)$$

with the interference and noise terms

$$\Phi_{\text{ii}} = \bar{\mathbf{H}}_{\mathcal{K} \setminus k}^{\mathcal{M}_C} \mathbf{P}_{\mathcal{K} \setminus k} \left(\bar{\mathbf{H}}_{\mathcal{K} \setminus k}^{\mathcal{M}_C} \right)^H \quad \text{and} \quad (10)$$

$$\Phi_{\text{hh}} = E \left\{ \mathbf{E}^{\mathcal{M}_C} \mathbf{P} \left(\mathbf{E}^{\mathcal{M}_C} \right)^H \right\}. \quad (11)$$

Term Φ_{ii} refers to the interference from all other UEs except UE k , while Φ_{hh} is connected to channel estimation related noise. Term $\bar{\mathbf{h}}_k^{\mathcal{M}_C}$ denotes the effective channel from UE k to all BS antennas within the cluster, while $\bar{\mathbf{H}}_{\mathcal{K} \setminus k}^{\mathcal{M}_C}$ is the effective channel from all other UEs to the same BSs. A similar notation is used for the estimation error \mathbf{E} and transmit covariance \mathbf{P} .

While (9) denotes theoretically achievable rates in *bits per channel use*, a certain part of uplink capacity has to be invested into CSI feedback and pilots. We hence derive *net* uplink rates, after the subtraction of the overhead stated before, in (12). Here, ρ denotes the pilot density, and N_{fb} is the number of quantization bits used for the feedback of each received pilot. The pilot overhead scales with the cooperation size N_C , as orthogonal pilots are needed for all UEs in the cluster to enable joint detection. The CSI feedback, however, scales linearly in the overall number of BS antennas $N_{\text{bs}} \cdot N_C$ within the cluster. Clearly, there is a limitation in the cooperation size N_C , as at some point the complete uplink is used for pilots.

$$\forall k : r_k^{\text{UL}, \text{net}} \leq \max \left(0, \min(r_k^{\text{UL}}, 8) \cdot \left(1 - \underbrace{N_c \cdot \rho}_{\text{Relative pilot overhead}} \right) - \underbrace{N_c N_{\text{bs}} N_{\text{fb}} \cdot \rho}_{\text{Absolute CSI feedback overhead}} \right) \quad (12)$$

D. Downlink Rate Calculation

In the downlink, we assume that a Wiener filter is used to serve all N_c UEs within a cluster by all $N_{\text{bs}} \cdot N_c$ BS antennas, calculated redundantly by each involved BS. The part of the precoding matrix connected to the cluster is given as

$$\mathbf{W}_{\mathcal{K}_C}^{\mathcal{M}_C} = \alpha \cdot \left(\bar{\mathbf{H}}_{\mathcal{K}_C}^{\mathcal{M}_C} \left(\bar{\mathbf{H}}_{\mathcal{K}_C}^{\mathcal{M}_C} \right)^H + \frac{\text{tr} \{ \Phi_{\text{ii}} + \Phi_{\text{hh}} + \sigma^2 \mathbf{I} \}}{N_c \cdot P_{\text{DL}}} \cdot \mathbf{I} \right)^{-1} \bar{\mathbf{H}}_{\mathcal{K}_C}^{\mathcal{M}_C}, \quad (13)$$

now with the interference and noise terms

$$\Phi_{\text{ii}} = \frac{P_{\text{DL}}}{N_{\text{bs}}} \cdot \Delta \left(\left(\bar{\mathbf{H}}_{\mathcal{K}_C}^{\mathcal{M} \setminus \mathcal{M}_C} \right)^H \bar{\mathbf{H}}_{\mathcal{K}_C}^{\mathcal{M} \setminus \mathcal{M}_C} \right) \quad \text{and} \quad (14)$$

$$\Phi_{\text{hh}} = \frac{P_{\text{DL}}}{N_{\text{bs}}} \cdot E \left\{ \left(\mathbf{E}_{\mathcal{K}_C} \right)^H \mathbf{E}_{\mathcal{K}_C} \right\}. \quad (15)$$

Factor α in (13) assures that $\text{tr} \{ \mathbf{W} \mathbf{W}^H \} = N_c \cdot P_{\text{DL}}$, i.e. that the BSs use an average transmit power of P_{DL} per sub-carrier. Note that (14) and (15) are based on the assumption that all interference from outside the cooperating cluster as well as the channel estimation related noise term are based on identity precoders. This yields a suboptimal precoding matrix, but corresponds to the practical case where UEs measure the interference level from outside the cluster *averaged* over time. The rate of each UE k can now be bounded as

$$\forall k \in \mathcal{K}_C : r_k^{\text{DL}} \leq \log_2 \left(1 + \frac{|\bar{\mathbf{h}}_k^H \mathbf{w}_k|^2}{\sigma_i^2 + \sigma^2} \right) \quad \text{with} \quad (16)$$

$$\sigma_i^2 = \underbrace{\sum_{j \in \mathcal{K}_C, j \neq k} |\bar{\mathbf{h}}_k^H \mathbf{w}_j|^2}_{\text{Interf. from inside clust.}} + \underbrace{\sum_{j \in \mathcal{K}_C} E \left\{ |\mathbf{e}_k^H \mathbf{w}_j|^2 \right\}}_{\text{Chn. est. impact}} + \underbrace{\frac{P_{\text{DL}}}{N_{\text{bs}}} \left(\bar{\mathbf{h}}_k^{\mathcal{M} \setminus \mathcal{M}_C} \right)^H \mathbf{1}}_{\text{Interf. from outside clust.}}$$

where $\bar{\mathbf{h}}_k$ and \mathbf{w}_k are the effective channel vector and precoding vector connected to UE k , respectively.

The *net* data rates achievable in the downlink are given as

$$r_k^{\text{DL}, \text{net}} = \max \left(0, \min(r_k^{\text{DL}}, 8) \cdot \left(\frac{11}{14} - \left(\frac{N_{\text{bs}}}{2} + 1 \right) N_c \rho \right) \right), \quad (17)$$

where we consider the fact that in an LTE Release 8 system, some OFDM symbols are reserved for control information, as well as pilot overhead. Note that in the context of downlink CoMP, we need both orthogonal pilots (at reduced density) such that the receiver side can estimate and feed back the channel matrix \mathbf{H} , as well as *precoded* pilots for each transmitted stream, such that the UEs can equalize and decode data¹. This is the reason why in total $(N_{\text{bs}}/2 + 1) \cdot N_c$ orthogonal pilot sequences are needed. As in the uplink, downlink CoMP cooperation size is also limited by the fact that at some point the complete transmission is used for pilots.

¹Alternatively, the BSs could also feed-forward chosen precoding matrices.

III. BACKHAUL CALCULATION

In this section, we compute the extent of backhaul that is required for BS cooperation in uplink and downlink.

In the *uplink*, the received signals from all BSs within a cooperation cluster of N_c cells have to be gathered at one of these BSs, such that the linear equalization assumed in Section II-C can take place. Intuitively, this quantization should be performed in frequency domain, as then only the received symbols on the relevant sub-carriers need to be quantized. In addition, the equalizing and decoding BS has to forward the decoded data to the network. The average overall backhaul in *bits per channel use per cell* can be calculated as

$$\beta_{\text{UL}}(\mathcal{M}_C) = \underbrace{\frac{N_c - L(\mathcal{M}_C)}{N_c} \cdot N_{\text{b}} N_{\text{bs}}}_{\text{Needed for cooperation}} + \bar{r}^{\text{UL}, \text{net}} \quad (18)$$

where N_{b} denotes the number of quantization bits applied to each complex symbol, and $\bar{r}^{\text{UL}, \text{net}}$ is the average achieved uplink net rate. We have to consider that cooperating BSs which are co-located do not require backhaul infrastructure. This is taken care of by the term $L(\mathcal{M}_C)$, which denotes the maximum number of cells within the cooperation cluster that are located at the same site. Only the remaining cooperating cells outside this site need then forward quantized signals to this site. Note that we assume that not only data, but also pilot symbols are quantized and forwarded, such that an additional exchange of channel knowledge among BSs is not required.

In the *downlink*, each of the sites involved in a cooperation must be provided with the data bits of all jointly served UEs. In addition, the CSI feedback decoded in the uplink has to be distributed among the BSs. The overall backhaul effort in *bits per channel use and cell* can be stated as

$$\beta_{\text{DL}}(\mathcal{M}_C) = \underbrace{S(\mathcal{M}_C)}_{\text{Distribution of user data}} \bar{r}^{\text{DL}, \text{net}} + \underbrace{(S(\mathcal{M}_C) - 1) N_c N_{\text{bs}} N_{\text{b}} \rho}_{\text{Distribution of channel knowledge}} \quad (19)$$

where $\bar{r}^{\text{DL}, \text{net}}$ is the mean achievable downlink net rate, and $S(\mathcal{M}_C)$ the number of sites involved in the cluster \mathcal{M}_C .

IV. COST EVALUATION MODEL

We now introduce a second model to estimate the *cost per area* connected to a particular choice of parameters d_{ISD} and N_c . Obviously, any choice of subsequent constants will depend very strongly on various operator- and country-specific issues, but we believe that the model is still of major value to describe certain tendencies. We generally consider

Base station costs (CAPEX), where we assume that BS equipment serving 3 sectors costs 30.000€ plus 30.000€ setup-related costs, and the equipment becomes obsolete after 10 years. This leads to $C_{\text{cap}} \approx 6.000\text{€}$ per site and year.

TABLE I
PARAMETERS USED FOR SIMULATIONS.

Path loss model	$PL = 130.5 + 37.6 \cdot \log_{10}(d/km)$ [dB]
Antenna pattern loss	$AL = \min(12 \cdot (\theta/70^\circ ^2), 20)$ [dB]
Antenna gain	0 dBi (uplink), 14 dBi (downlink)
Noise floor (uplink)	$\sigma^2 = -169$ dBm/Hz (5 dB noise figure)
Noise floor (downlink)	$\sigma^2 = -165$ dBm/Hz (9 dB noise figure)
No. pilots Kramer-Rao	$N_p = 2$, motivated in [8]
System bandwidth	$B = 10$ MHz
Downlink tx power	$P_{DL} = \min(57.3+37.6\log_{10}(d_{ISD}/km), 46)$
Max. uplink tx power	$P_{UL} = 20$ dBm
Number of BS ants.	$N_{bs} = 2$
Pilot density	$\rho = 8/168$, as in LTE Rel. 8
Quant. bits / cmpl. sym.	$N_b = 16$
Quant. bits / rcvd. pilot	$N_{fb} = 4$, motivated in [11]

Base station costs (OPEX). We assume rental costs of 600€ per site and month, and maintenance costs of 50% of CAPEX expenses, leading to $C_{op} \approx 10.200$ € per site and year.

Base station energy costs. We focus on the overall power dissipated depending on downlink transmit power P_{DL} (where a linear dependency can be assumed [9]), and that connected to signal processing. The *total* power consumption *per site* for $N_{bs} = 2$, $P_{DL} = 46$ dBm and non-cooperative signal processing is about 1.300 W [4]. Of this, roughly 10% are due to baseband signal processing [9]. In a particular implementation in [10], 8% and 6% of this effort are due to uplink channel estimation and MIMO precoding or equalization, respectively (assuming interference rejection combining (IRC) or maximum ratio transmission (MRT) in uplink and downlink, respectively). While channel estimation effort increases linearly in N_c , the effort for each equalization or precoding process grows cubically in N_c . In the uplink, however, computation is performed only once for N_c cells, i.e. the overall effort here grows quadratically in N_c . With 0.1€ per kWh, the energy related base station costs *per site and year* can now be stated as $C_{pwr}(P_{DL}, N_c) =$

$$\left(0.9 \frac{P_{DL}}{46\text{dBm}} + 0.086 + \frac{0.8}{100}N_c + \frac{0.3}{100}N_c^2 + \frac{0.3}{100}N_c^3\right) \cdot 1140\text{€}$$

Backhaul costs. We assume a Microwave backhaul link with a net capacity of 300 Mbit/s costs 10k€, the installation costs 1000€, and the equipment becomes obsolete after 10 years. We also consider maintenance expenses of 1000€ per year. This leads to backhaul costs of $C_{bh} = 0.22$ € per Tbit.

This leads to an overall cost per area of

$$C(d_{ISD}, N_c) = C_{bh} \cdot B(d_{ISD}, N_c) + \dots + \tilde{S}(d_{ISD}) \cdot (C_{cap} + C_{op} + C_{pwr}(P_{DL}, N_c)), \quad (20)$$

where $\tilde{S}(d_{ISD}) = 2/(\sqrt{3} \cdot d_{ISD}^2)$ is the number of sites per km^2 .

V. RESULTS

We now discuss Monte Carlo simulations. For each user drop, the channel matrix stated in (1) is obtained via a standard path loss model, antenna model and Rayleigh fading, with key parameters summarized in Table I. Imperfect CSI is modeled with $N_p = 2$, which is representative for an LTE pilot density, urban delay spread and pedestrian UE speed [8].

We assume power control in the *uplink*, where a target receive power density at the BS side is chosen for each value of inter-site distance d_{ISD} , so that 5% of UEs are operating at their power limit of $P_{UL} = 20$ dBm. In the *downlink*, the total transmit power per BS is a function of d_{ISD} as stated in Table I, which is then invested equally into sub-carriers.

We generally compute achievable rates with or without BS cooperation in uplink and downlink. We then compare the case where CoMP is always applied (dashed lines) to a flexible usage of CoMP that maximizes the *sum rate* achievable in uplink and downlink (solid lines). Note that the latter case also reduces backhaul and computation power.

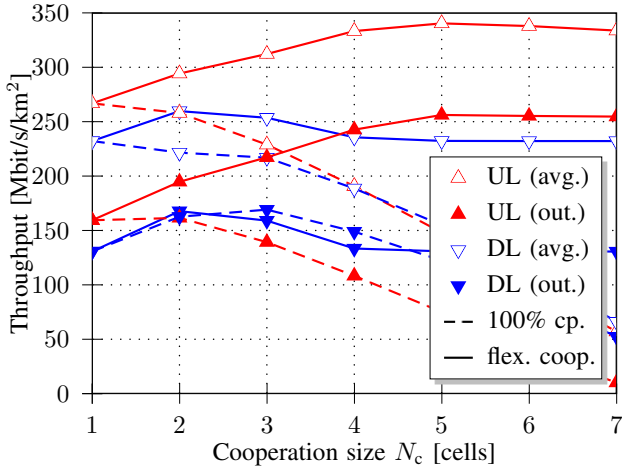
Figure 2(a) shows the average and 10th percentile outage throughput per area as a function of cooperation size N_c . We can see a clear benefit of applying CoMP adaptively, and see optimal cooperation sizes of $N_c \approx 5$ and $N_c \approx 2$ for uplink and downlink, respectively, due to the vast pilot and CSI feedback overhead for large N_c . Figure 2(b) shows throughput as a function of inter-site-distance d_{ISD} , where both axes are of logarithmic scale. Clearly, throughput decreases quadratically in d_{ISD} (except in regimes of large distance, where thermal noise becomes an issue in the uplink), showing that the main spectral efficiency driver is site density, not cooperation.

Figures 2(c) and 2(d) show cost per area as a function of N_c and d_{ISD} , respectively. Uplink backhaul can be a major cost issue even for moderate cooperation sizes, but quickly saturates as (18) converges to $N_b N_{bs}$ for large N_c . While the backhaul requirements in the downlink are in general less severe, these may become an issue if CoMP is consequently applied to large clusters, as the term $S(\mathcal{M}_C - 1)N_c N_{bs} N_b \rho$ in (19) grows quadratically in N_c . Costs connected to signal processing power appear to be a minor issue (unless downlink CoMP is applied consequently in large clusters), while the transmit power reduction for $d_{ISD} < 500$ m, as stated in Table I yields a visible cost reduction in Figure 2(d).

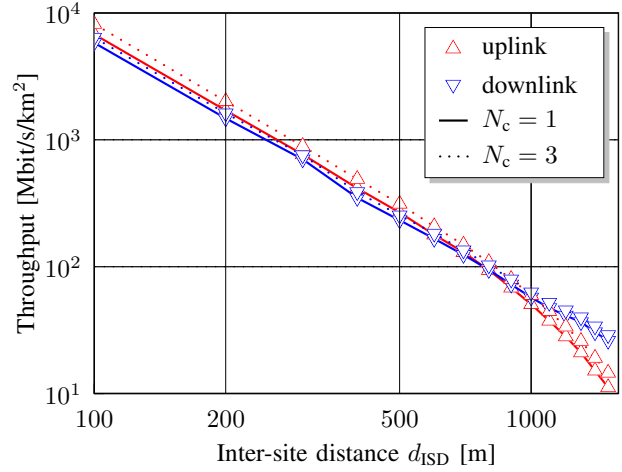
Figure 3 finally shows cost per bit as a function of both N_c and d_{ISD} . Clearly, densification is the stronger lever for rate growth and reduction of cost per bit, while cooperation is a complementary option requiring less modification of existing systems. Note that the monetary benefit of cooperation depends strongly on the availability of reasonably priced backhaul, as assumed in this work. Our results differ strongly from those in [2], as we model imperfect CSI, CSI feedback and pilot overhead (strongly limiting the gains of CoMP) while assuming a fully loaded system regardless of inter-site-distance d_{ISD} (overestimating the effect of densification).

VI. CONCLUSIONS AND FUTURE OUTLOOK

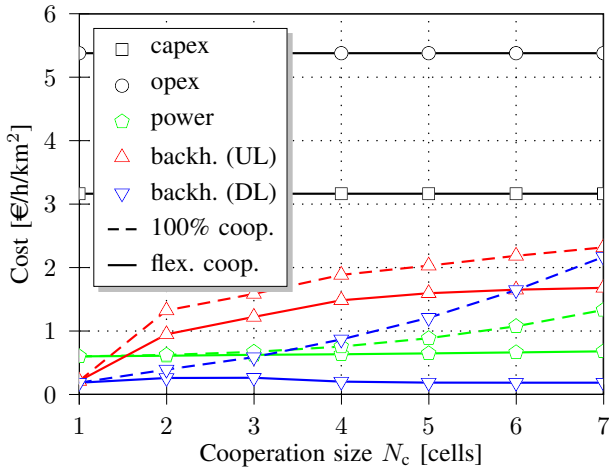
We have introduced models to capture achievable rates under base station cooperation and different inter-site-distances, as well as involved capex, opex, energy and backhaul costs, to determine cost per bit. Future work will address even smaller inter-site-distances, requiring a modified model for micro site capex and opex, low-distance path loss, and system load.



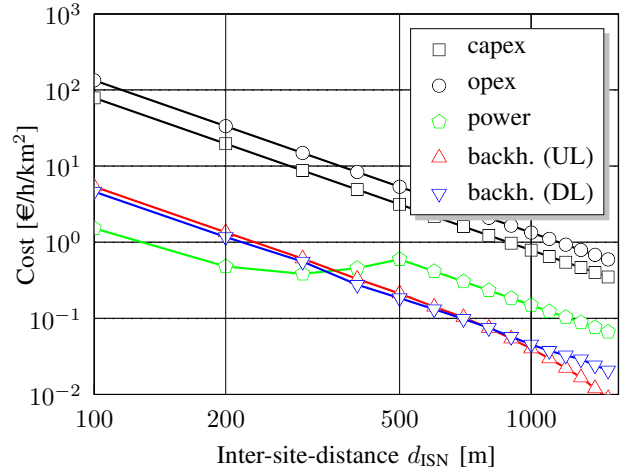
(a) Throughput vs. cooperation size, for $d_{\text{ISD}} = 500$ m.



(b) Throughput vs. inter-site-distance.



(c) Cost vs. cooperation size, for $d_{\text{ISD}} = 500$ m.



(d) Cost vs. inter-site-distance, for $N_c = 1$.

Fig. 2. Throughput and cost as a function of cooperation size N_c and inter-site-distance d_{ISD} .

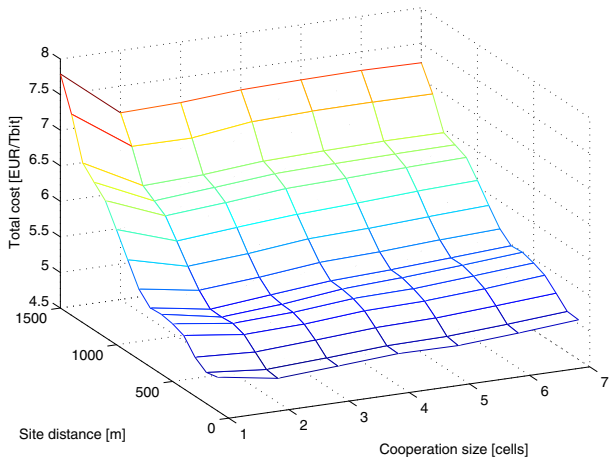


Fig. 3. Cost per Tbit as a function of d_{ISD} and N_c .

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