# MIMO AND MASSIVE MIMO - ANALYSIS FOR A LOCAL AREA SCENARIO

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## ABSTRACT

The performance of centralized and distributed deployments of massive MIMO in an office building is analyzed both with and without cooperation. It is shown that using twice as many base station antennas as data streams provides most of the massive MIMO benefits. A simple transmission scheme achieves user fairness and operates close to a capacity upper bound. An example scheduling algorithm improves efficiency only for less than twice the number of base station antennas as data streams. The tradeoff between performance and cost for backhauling is evaluated by comparing cooperation of distributed base stations with a single central deployment.

***Index Terms*—** MIMO; massive MIMO; network MIMO; 5G; two stripe building

## 1. INTRODUCTION

One goal of new mobile communication standards (e.g. 5G) is to increase the spectral efficiency per unit area or volume. One way to increase spectral efficiency is by using multiple-input multiple-output (MIMO) methods. MIMO allows one node to transmit several streams to one or more user equipments (UE) using spatial degrees-of-freedom. Massive MIMO, a vast over-provisioning of base station (BS) antennas, lets simple transmission schemes achieve large performance gains over today's systems [1].

The terminology "massive MIMO" is not clearly defined. Massive MIMO may refer to any MIMO configuration beyond the highest MIMO mode in current LTE (at present 8x8), or it may refer to simply a "large" number of antennas at the BSs. A somewhat more precise way to define massive MIMO is to relate it to the ratio of serving antennas to active UEs.

Most massive MIMO studies consider wide area outdoor deployments [2]. However most mobile traffic is generated by indoor users [3]. We analyze the performance of centralized and distributed deployments with and without cooperation for the 3GPP two stripe office building [4]. We fix the number of active, single antenna UEs and sweep the ratio of total number of BS antennas to the number of active UEs from one to 10-times more serving antennas. We find that a ratio of twice as many BS antennas provides most of the massive MIMO benefits. We further find that this ratio is a good tradeoff between number of antennas versus spectral efficiency. We present suboptimal transmission schemes that approach a capacity upper bound. An example scheduler improves performance if there are fewer than twice as many BS antennas. We analyze fairness using Jain's index. Placing a single massive MIMO BS at the center of a building is intuitively not an optimal choice as the UEs suffer from large transmitter-to-receiver distances and high wall penetration loss. We compare this deployment to distributed BSs with cooperation. We find that distributed indoor BSs with cooperation achieve a substantial performance gain at the cost of a backhaul connection, while the gain achieved with cooperation between outdoor small cells and a single indoor BS is smaller.

The following aspects of this study are novel as compared to [5] and [6]: the per-BS power constraint, indoor-outdoor cooperation, the example scheduling algorithm and the analysis of a capacity upper bound and fairness.

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## 2. SYSTEM MODEL

Consider the downlink in the two stripe building in Fig. 1, defined by 3GPP as the A1 indoor office scenario in the WINNER II deliverable [7]. The UEs are served by BSs located inside and outside the building.

We consider single antenna UEs and orthogonal frequency-division multiplexing (OFDM). For each subcarrier we obtain a MISO broadcast channel. The received signal of the $k$-th UE for one subcarrier is

$$y_k = \mathbf{h}_k^{\mathsf{H}}\mathbf{x} + z_k \qquad k = 1, \ldots, K \tag{1}$$

where $\mathbf{h}_k = [\mathbf{h}_{k,1}^{\mathsf{T}}, \ldots, \mathbf{h}_{k,N_{\text{BS}}}^{\mathsf{T}}]^{\mathsf{T}}$ is the collection of the channel coefficients from all $N_{\text{BS}}$ BSs to the $k$-th UE. The $i$-th BS has $M_i$ BS antennas with the channel coefficients $\mathbf{h}_{k,i}$. The length of $\mathbf{h}_k$ is equal the total number of BS antennas $M = \sum_{i=1}^{N_{\text{BS}}} M_i$. The transmitted signals vectors are collected in $\mathbf{x} = [\mathbf{x}_1^\mathsf{T}, \ldots, \mathbf{x}_{N_{\mathrm{BS}}}^\mathsf{T}]^\mathsf{T}$ and $z_k$ is independent proper complex thermal Gaussian noise with variance $\sigma_N^2$. $\mathbf{H}^\mathsf{H}$ denotes the complex conjugate transpose of matrix $\mathbf{H}$. We place the BS antennas with an antenna spacing of $\lambda/2$. Mutual coupling between array elements is ignored. The number of UEs is $K$, which is equal to the number of receive antennas as we consider single antenna UEs. The received signals of all UEs $\mathbf{y} = [y_1, \ldots, y_K]^\mathsf{T}$ for one subcarrier are

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z} \tag{2}$$

where $\mathbf{H} = [\mathbf{h}_1, \ldots, \mathbf{h}_K]^\mathsf{H}$ and $\mathbf{z} = [z_1, \ldots, z_K]^\mathsf{T}$.

For linear precoding the transmitted signals vector $\mathbf{x}$ is

$$\mathbf{x} = \mathbf{W}\mathbf{s} \tag{3}$$

where $\mathbf{W} = [\mathbf{w}_1, \ldots, \mathbf{w}_K]$ is the matrix of the precoding vectors and $\mathbf{s} = [s_1, \ldots, s_K]$ is the vector of transmit symbols. We consider a per-BS sum-power constraint

$$\sum_{f=1}^{N_{\mathrm{SC}}} \left\| \mathbf{x}_i^{(f)} \right\|_2^2 \leq P_i \qquad \forall i \in \{1, N_{\mathrm{BS}}\} \tag{4}$$

where $N_{\mathrm{SC}}$ is the number of subcarriers. We omit the subcarrier index $^{(f)}$ for clarity in the remaining paper.

We assume that ideal hardware and perfect channel state information of the complete network is available at all nodes.

## 3. TRANSMISSION SCHEMES

We use zero forcing beamforming (ZFBF) where the linear precoders are determined according to an interference zero forcing objective. The optimal solution given a sum power constraint is the pseudo-inverse combined with a power allocation [8]

$$\mathbf{W} = \mathbf{H}^\mathsf{H}(\mathbf{H}\mathbf{H}^\mathsf{H})^{-1}\mathrm{diag}(\gamma) \tag{5}$$

where $\gamma$ is the power allocation vector of non-negative reals. With this choice of precoding matrix the received signals are

$$\mathbf{y} = \mathbf{H}\mathbf{W}\mathbf{s} + \mathbf{z} = \mathbf{H}\mathbf{H}^\mathsf{H}(\mathbf{H}\mathbf{H}^\mathsf{H})^{-1}\mathrm{diag}(\gamma)\,\mathbf{s} + \mathbf{z} \tag{6}$$

$$= \mathrm{diag}(\gamma)\,\mathbf{s} + \mathbf{z}. \tag{7}$$

### 3.1. Central Massive MIMO

If there is only one BS and all antennas are located at one physical site, ZFBF eliminates all interference. For a sum rate maximization with a total power constraint, the power allocation can be solved using water filling [8]. We choose to distribute the power equally to the transmission to each UE to ensure fairness between the UEs. The distribution of the per-UE power on the physical resource blocks (PRB) is determined by water filling assuming Gaussian signals. We consider scenarios where the total number of BS antennas $M$ is larger than or equal to the number of UEs $K$. Hence we are able to schedule all UEs in every time frame and on every PRB with ZFBF. We call this Central Massive MIMO.

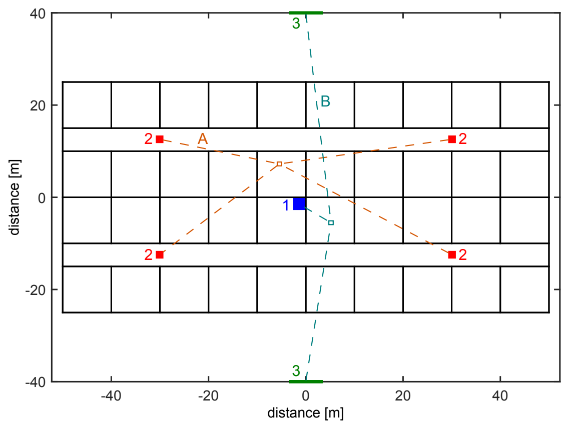


**Fig. 1**. Deployments in the two stipe building.

### 3.2. Network MIMO

For Network MIMO we assume a perfect backhaul between the BSs and treat distributed BSs as a single BS. Then we can apply ZFBF either in a central unit or by exchanging cooperation messages. We initialize the power allocation as for massive MIMO and fulfill the per-BS power constraint (4) by scaling all $\gamma^{(f)}$. A better approach would be to design the precoders and allocate the power (considering a maximal modulation scheme) to maximize the spectral efficiency under a fairness constraint, but this adds complexity.

### 3.3. Local Precoding

If the backhaul cannot enable Network MIMO or any other kind of cooperation or coordination, a BS determines its precoders locally while treating interference from the other BSs as noise. Each UE connects to the BS with the maximum average SNR. If the number of UEs connected to a BS is larger than the number of BS antennas, scheduling with channel decomposition using a capacity upper bound [9] is used. We call this scheme Local Precoding.

## 4. DEPLOYMENTS

We define six different BS deployments which are shown in Fig. 1. The indoor BSs are rectangular arrays mounted underneath the ceiling, while the outdoor BSs are uniform linear arrays (ULA). Indoor Central Massive MIMO is a single central BS that uses Central Massive MIMO ("1" in Fig. 1). Indoor Local Precoding uses Local Precoding for the four BSs on the corridors ("2"), while Indoor Network MIMO requires a backhaul to employ Network MIMO for the corridor BSs ("2"+"A"). Outdoor Only uses only the outdoor ULAs with Local Precoding ("3"). If we add a central BS to the outdoor BSs we obtain Indoor-Outdoor Local Precoding ("1"+"3") and Indoor-Outdoor Network MIMO ("1"+"3"+"B"), which employ Local Precoding, respectively Network MIMO. Note that the BSs are not necessarily optimally placed.

## 5. SIMULATION RESULTS

We fix the number of UEs and compare the spectral efficiencies of the deployments for different numbers of total BS antennas. We define one drop as a random placement of 24 UEs within the two stripe building. For each drop we generate 10 channel realizations.

The channel coefficients for indoor BSs are generated according to the WINNER II A1 indoor channel model [7]. The A1 channel model provides parameter sets for line-of-sight (LOS) and non line-of-sight (NLOS) conditions. For each BS-UE pair, the number of walls between their positions are determined and the appropriate condition is selected. A wall penetration loss of 12 dB (as we assume heavy walls) for every wall beyond the first is applied. When determining the number of walls, paths along the corridors are considered as alternatives to the direct path, which might penetrate more walls. The channel coefficients for outdoor BSs are generated according to the WINNER II B4 outdoor (Urban Micro-Cell) to indoor channel model [7]. Here we assume a LOS path from the BS to the outside wall of the building. The number of walls is determined as mentioned above. We use the QUAsi Deterministic RadIo channel GenerAtor (QuaDRiGa) [10] to generate the channels, which we enhanced to count the number of walls and apply the wall penetration loss.

We use a bandwidth of 20 MHz around a carrier frequency of 2.1 GHz. According to LTE we obtain 100 PRBs, where the precoders and the power allocations are determined per PRB. The simulation parameters are summarized in the Table 1. With these parameters the spectral efficiency in the building without considering control signaling overhead is

$$S = \frac{24 \cdot C_{\mathrm{QAM}}\,\mathrm{bits} \cdot 1200 \cdot 14}{1\mathrm{ms} \cdot 20\,\mathrm{MHz}}, \tag{8}$$

where 24 is the number of UEs, $C_{\mathrm{QAM}}$ is the instantaneous capacity of a memoryless channel with QAM input and continuous output [11], 1200 is the number of subcarriers, 14 is the number of OFDM blocks per subframe, 1ms is the duration of one subframe and 20 MHz is the bandwidth. For 256-QAM the maximal spectral efficiency is $S^* = 161.28$ bit/s/Hz.

In Fig. 2 the average spectral efficiencies of the deployments are shown for 24 to 240 total BS antennas. The 5%-tile and the 95%-tile spectral efficiencies follow the same trend. The Indoor Central Massive MIMO, Indoor Network MIMO and Indoor-Outdoor Network MIMO deployments perform poorly for fully loaded MIMO systems with 24 BS antennas. The performance improves significantly when few antennas are added (Scheduling improves the performance for fully or close to fully loaded MIMO systems as discussed in Section 7). Adding more antennas increases the performance, but the gain from each additional antenna decreases. A ratio of twice as many BS antennas seems to be a good tradeoff between achieved performance and number of antenna elements. The performance loss of the Indoor Central Massive MIMO versus the Indoor Network MIMO deployment (mainly due to wall penetration loss) is analyzed in more detail in [5]. The performance loss of the Indoor-Outdoor Network MIMO versus the Indoor Network MIMO is due to wall penetration loss and building penetration loss. Note that Indoor Network MIMO approaches the maximal spectral efficiency for only 48 BS antennas, while Indoor Central Massive MIMO requires more than 240 antennas to approach the maximal spectral efficiency. The non-cooperative schemes perform worse due to interference. Their performances improve little per additional antenna.

| | |
|---|---|
| Carrier frequency | 2.1 GHz |
| Bandwidth | 20 MHz |
| Used bandwidth | 18 MHz |
| Subcarrier spacing | 15 kHz |
| Number of subcarriers | 1200 |
| Number of PRBs | 100 |
| Antenna Spacing | $\lambda/2$ |
| Wall penetration loss | 12 dB |
| Sum power constraint | 26 dBm |
| Noise level | −124.6 dBm |
| Largest modulation scheme | 256-QAM |
| Number of UEs | 24 |
| Number of drops | 300 |
| Number of channel realizations per drop | 10 |

**Table 1**. Simulation parameters.

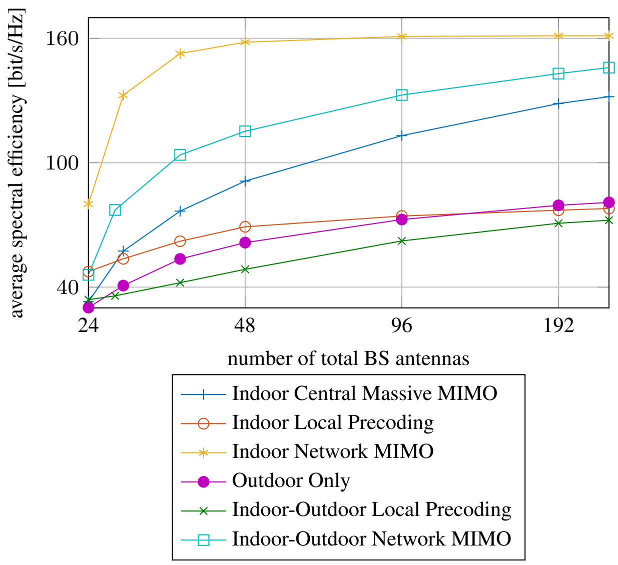


**Fig. 2**. Average spectral efficiencies.

## 6. COMPARISON WITH CAPACITY UPPER BOUND

Each deployment can be upper bounded by a broadcast channel (BC) with a sum power constraint. We allow all BSs of a

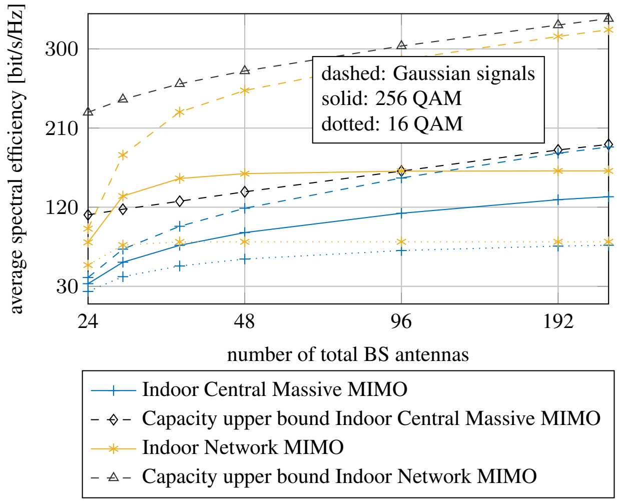


**Fig. 3**. Average spectral efficiencies and capacity upper bounds for the Indoor Central Massive MIMO and Indoor Network MIMO deployment.

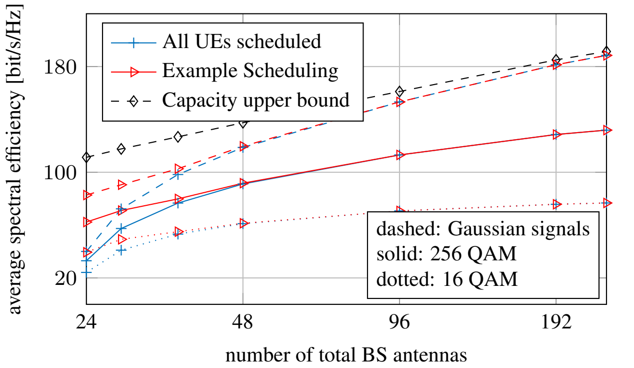


**Fig. 4**. Average spectral efficiencies for the Indoor Central Massive MIMO deployment with and without scheduling.

deployment to cooperate and to act as one BS with distributed antennas, and relax the per-BS power constraint to a sum power constraint. The capacity of a BC is achieved by dirty-paper coding. We find the optimal transmission policy with the algorithms in [12]. As the spectral efficiency is limited by the modulation scheme we examine Gaussian signaling and 16-QAM in addition to 256-QAM. In Fig. 3 the average spectral efficiencies and the capacity upper bounds of the Indoor Central Massive MIMO and Indoor Network MIMO deployment are shown. While the 16-QAM and the 256-QAM schemes limit the average spectral efficiency, Gaussian signaling allows the spectral efficiency to grow and to approach the capacity upper bound. Notice that for a ratio of two BS antennas per UE the gap between the capacity upper bound and our schemes is already small and a good tradeoff between performance and number of BS antennas is achieved also for Gaussian signaling and 16-QAM.

## 7. WHEN IS SCHEDULING NECESSARY

One claim of massive MIMO is that for sufficient randomness and many antennas the channels hardens and scheduling all UEs is optimal, which means that more advanced scheduling does not provide gains [2]. We use an example scheduler to analyze how many BS antennas are required for this claim to be valid in our scenario.

When we use the water filling power allocation as described in Section 3 there is usually no power allocated to some UEs on some PRBs. When no power is allocated to an UE the interference zero-forcing constraint for that UE is unnecessary on that PRB and may be removed. This creates more degrees-of-freedom when determining the precoders for the other UEs, which leads to potentially higher effective channel gains. Algorithm 1 utilizes this idea. Note that fairness is not considered explicitly, but implicitly as the per UE transmit powers are equally distributed.

**Algorithm 1** Example scheduling algorithm

```
Initialize all PRBs as scheduled for all UEs
repeat
    for all PRBs do
        ZFBF with all UEs scheduled on current PRB
    end for
    for all UEs do
        water filling for current UE
        determine new schedule for current UE as all PRBs,
          where a power larger than zero is allocated
    end for
until Convergence of all schedules
```

In Fig. 4 the average spectral efficiencies for the Indoor Central Massive MIMO deployment are shown for all UEs scheduled and for the example scheduling. As expected a performance gain with scheduling can be observed only for less than twice as many BS antennas as UEs. Similar results are obtained for the other deployments.

## 8. FAIRNESS

We analyze fairness qualitatively with Jain's index [13]

$$\mathcal{J}(r_1, r_2, \ldots, r_K) = \frac{(\sum_{i=1}^{K} r_i)^2}{K \cdot \sum_{i=1}^{K} {r_i}^2}, \quad (9)$$

where $r_k$ is the rate achieved by the $k$-th UE. Jain's index approaches 1 when all UEs achieve similar rates and is $1/K$ when only one UE achieves a non-zero rate. The fairness indices are plotted in Fig. 5. The deployments with cooperation approach a fairness index of 1 for an increasing number of antennas as more and more UEs are served with the maximal spectral efficiency. Scheduling helps to increase fairness for a

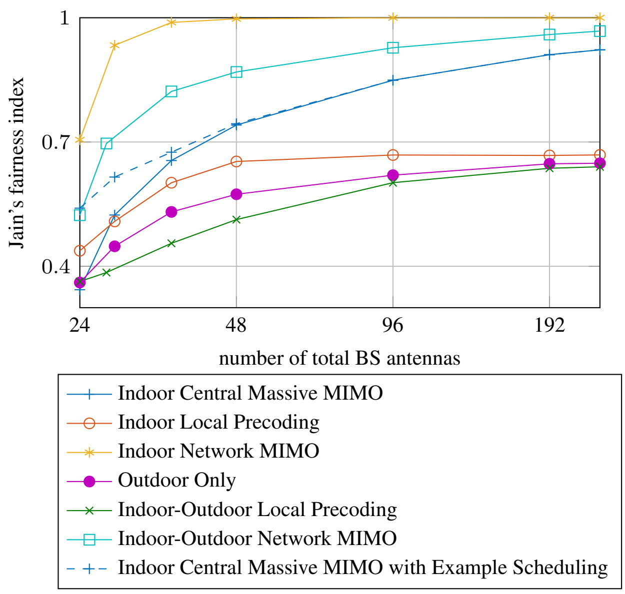


**Fig. 5**. Jain's fairness index.

small number of antennas. The deployments without cooperation saturate at a fairness index of less than 0.7.

## 9. CONCLUSIONS

We compared the performance of different deployments in the 3GPP two stripe office scenario. The same performance is achieved by a single massive MIMO BS or by distributed BSs with cooperation and less antennas. The costs of antenna elements can be traded off with the costs for a backhaul to achieve the same performance. A ratio of twice as many BS antennas as served UEs offers many of the massive MIMO benefits. User fairness and spectral efficiency close to capacity are achieved with a simple transmission scheme.

A spectral efficiency of 113 bit/s/Hz without considering overhead is achievable with the Indoor Central Massive MIMO deployment with 96 antennas and with Indoor Network MIMO with less than 28 antennas. Considering an overhead of 50% the required bandwidth to achieve the goals of the METIS (Mobile and wireless communications Enablers for the Twenty-twenty Information Society) project [14] is

- for the TC1 virtual reality office:
  $0.1$ Gbit/s/m$^2$ x $5000$ m$^2$ / $56.5$ bit/s/Hz $\Rightarrow$ $8.85$ GHz (More UE antennas, more base stations or larger QAM constellations could reduce the required bandwidth),
- for the TC2 dense urban information society:
  $0.7$ Mbit/s/m$^2$ x $5000$ m$^2$ / $56.5$ bit/s/Hz $\Rightarrow$ $62$ MHz.

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