LUT School of Energy Systems

Bachelor's thesis, Electrical engineering

Simulation of Cell-Free Massive MIMO system

Simulaatio soluttomasta massiivisesta MIMO järjestelmästä

27.08.2021

Author: Paavo Pennanen

Supervisor: Dick Carrillo Melgarejo

ABSTRACT

Author	Paavo Pennanen
Title	Simulation of Cell-Free Massive MIMO system
School	LUT School of energy systems
Degree programme	Electrical engineering
Supervisor	Dick Carrillo Melgarejo

This bachelor thesis studies cell-free massive multi-input multi-output (CF mMIMO) network. The purpose of this work was to build ground knowledge on CF mMIMO networks. A simulation model is used to generate a variety of network performance results.

The literature section of this work explains basics of CF mMIMO networks. Afterwards a simulation model is described and explained to understand results of different network setups. Lastly simulation results are shown and described. Results show that a system using minimum mean-squared error (MMSE) method outperformed others in terms of spectral efficiency (SE). Simulation results achieved in this work were in line with prior publications related to this topic.

TIIVISTELMÄ

Tekijä	Paavo Pennanen
Tutkielman nimi	Simulaatio soluttomasta massiivisesta MIMO järjestelmästä
Akateeminen yksikkö	LUT School of energy systems
Koulutusohjelma	Sähkötekniikka
Ohjaaja	Dick Carrillo Melgarejo

Tässä kandidaatintyössä tutkitaan ja simuloidaan solutonta massiivista multi-input multi-output (mMIMO) tiedonsiirtoverkkoa. Työn tarkoitus oli luoda peruskäsitys soluttomasta mMIMO tiedonsiirto verkosta, selittää käytetty simulaatiomalli, sekä esittää simuloituja tuloksia.

Työssä kirjallisuuskatsausosio käy läpi peruskäsitteitä soluttomaan mMIMO tiedonsiirtoverkkoon liittyen luoden lukijalle kuvan järjestelmän toiminnasta. Tämän jälkeen työssä selitetään käytetyn simulaatiomallin toiminta simulaatiotuloksiin liittyen. Lopuksi työssä esitellään simulaatioista saadut tulokset.

Simulaatiotulosten perusteella pienin keskimääräisen neliön virhe (MMSE) metodia käyttävä järjestelmä saavutti parhaan spektrisen tehokkuuden (SE). Saadut simulaatiotulokset olivat myös linjassa aiempien aiheeseen liittyvien julkaisujen kanssa.

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1 Introduction

The purpose of this bachelors thesis is to provide base knowledge regarding cell-free massive multiple-input multiple-output (CF mMIMO) wireless communication architecture and compare it to a traditional cellular wireless communication network, by using a MATLAB-simulation script introduced in paper Björnson & Sanguinetti (2020).

1.1 Background

Massive Multi-input Multi-output(mMIMO) systems are the most important recent advancement in physical layer of the field of fifth generation (5G) wireless communication systems.(**?**) Although mMIMO enables wireless communication system to outperform prior implementations at the centre of the cell, it suffers from edge-cell interference problems. To overcome interference problems caused by cell implementation, a new CF mMIMO system is proposed.(Jin et al. (2021)) In CF mMIMO the idea of cells is abandoned and the network works with shared parameters in order to assure the best performance to all users.(Ngo et al. (2017))

1.2 Methods

The content of this work will be based on a literature review and simulations. The literature review is conducted in order to provide a basic knowledge of a CF mMIMO system. Simulations are made in order to do a fair comparison between CF mMIMO and traditional cellular networks.

1.3 Structure

This work is divided in four sections. The first section introduces the work and methods used on this study. The second section builds basic knowledge of the mMIMO and CF mMIMO systems architecture. The third section explains four different methods of deploying CF mMIMO, which were used in the simulation script. The fifth section discusses the results that were obtained by simulation.

2 System

2.1 Architecture

Massive MIMO (mMIMO) is one of the most promising approaches to supplement the increasing demand for portable Internet access. Although mMIMO offers better spectral efficiency (SE) and connectivity compared to prior implementations, these advantages can be experienced only by users at the center of the cell, due the cellular architecture. In cellular architecture, base stations (BSs) are bound to serve users only in their predefined cells as illustrated in Figure 1.

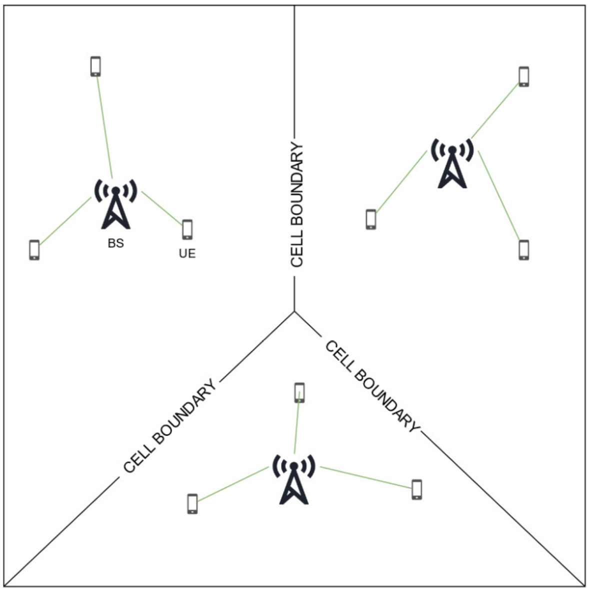

Figure 1: Generic cellular network architecture

In cellular architecture user equipments (UEs) at the edge of cells have a high chance to get inter-cell interference from the other cells. This feature is a natural issue on cellular systems design as show in Figure 2.

To overcome these problems new cell-free architecture is proposed, in which the BSs are not bound to serve UEs in their dedicated cell area.

The system model of CF mMIMO consist of a CPU which is connected to L number of access points (AP) via front-haul. In each access points (APs) there is N number of antennas. These APs serve K number of user equipment. In simulations provided in

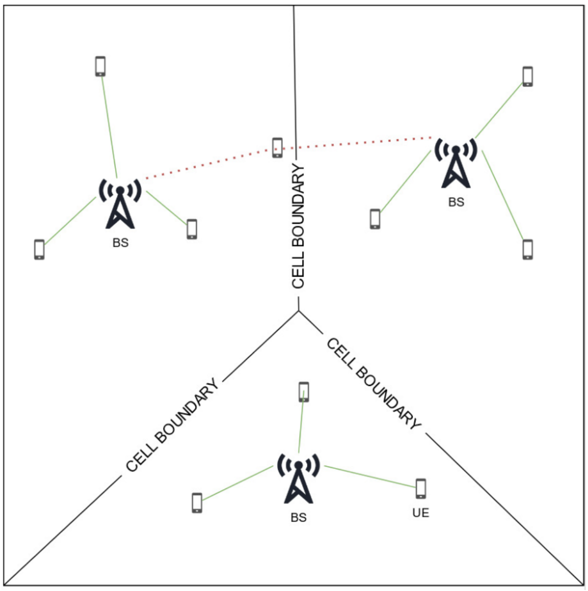

Figure 2: Cellular interference

this work UEs are assumed to have only one antenna per UE (Björnson & Sanguinetti (2020)).

Communication between AP L and UE K is done by using channel $h_k l$. However in order to calculate more accurate results, spatial correlation needs to be realized in the calculation. In the simulation script used in this work it is done by utilizing the correlated Rayleigh's fading method, which gives more realistic results regarding the SE. The implementation of correlated Rayleigh's fading leads to channel model

$$h_{kl} \sim N_{\mathbb{C}}(0, R_{kl}) \tag{1}$$

where $N_{\mathbb{C}}$ is multi-variate circularly complex Gaussian distribution and R_{kl} is the correlated Rayleigh's fading factor, which in this case defines the spatial properties of the channel. Spatial properties consider properties set by the geography of the UE and AP placement, that includes for example fading caused by signal blocking structures.(Zhou et al. (2020))(Björnson & Sanguinetti (2020))

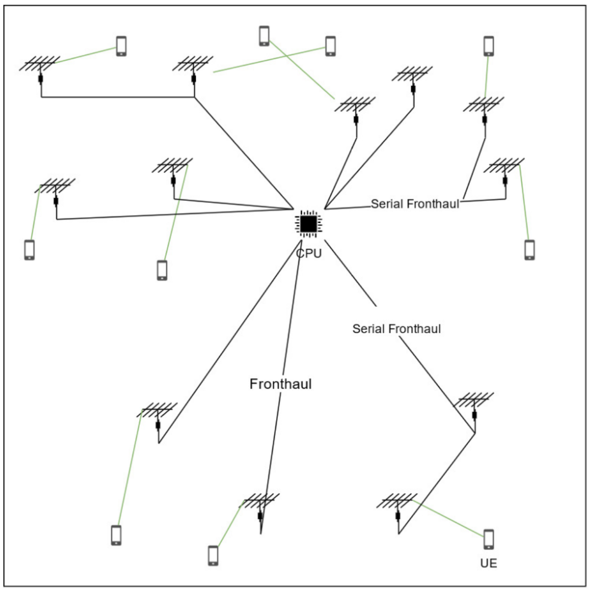

Figure 3: mMimo

2.2 Up-link

Up-link considers signal transmission from UE to BS and the simulation model used in this work concentrates fully on up-link performance. Usually CF mMIMO models are considered to use frequency division duplex (FDD) mode or time division duplex (TDD) mode. Results illustrated in this work, are the same using either of the modes, since uplink gives same results in the both.Björnson & Sanguinetti (2020)

2.3 Piloting

When considering up-link, in order to estimate used channels a so called training phase is needed. During this phase UEs send pilot signals to APs (Mai et al. (2020)). The pilot signal is defined as $Z_l \in C^{N \times \tau_p}$ where τ_p is the length of pilot signals. In the simulation model used in this work the amount of UEs k can be larger than the amount of pilot signals, $k > \tau_p$, and therefore subset ρ for pilots are needed to share the signal with multiple UEs. At the AP the received pilot signal can be illustrated with the equation

$$Z_l = \sum_{i=1}^{k} \sqrt{\rho_i} h_{il} \phi_{t_i}^T + N_l, \tag{2}$$

where transmission power of UE is ρ_i and singal noise gain experienced at AP is N_l.

In order to calculate a channel estimate from the pilot signal, the AP processes the signal with normalized pilot signal $\phi_{t_k}/\sqrt{\tau_\rho}$. This gives a rough signal estimate. (Zhou et al. (2020))(Shaik et al. (2020))(Björnson & Sanguinetti (2020))

$$Z_{t_k l} = (1/\sqrt{\tau_p}) Z_l \phi_{t_k}^* \in \mathbb{C}^N \tag{3}$$

2.4 Data transmission

Data is transmitted from each UE to AP via signal y_l. This signal is received at each AP in form which is illustrated in Equation 4.

$$y_l = \sum_{i=1}^{K} h_{il} s_i + n_l \tag{4}$$

Where h_{il} is the estimated channel and signal containing the payload data is s_i. The noise gain experienced in the receiver end is n_l.(Shaik et al. (2020))(Björnson & Sanguinetti (2020))

2.5 Spectral efficiency

For evaluating the four approaches of CF mMIMO, SE will be used as a measure. The unit of measurement in spectral efficiency is bits/s/Hz and basic calculation of SE consists of pre- or post-log factor and signal to interference and noise ration (SINR).

$$SE = \left(1 - \frac{\tau_p}{\tau_c}\right)(1 + \text{SINR}) \tag{5}$$

Pre-log factor is calculated as 1 reduced with a fraction of number of pilot signals per coherent block τ_p divided by the length of coherent block τ_c as shown in equation.

$$\textit{Pre-log factor} = \left(1 - \frac{\tau_p}{\tau_c}\right) \tag{6}$$

The SINR consist of signal, interference and noise and it can be calculated be using the generic formula like follows.

$$SINR = \frac{\textit{desired signal}}{\textit{interference + noise}} \tag{7}$$

In the simulations done in this work only pre-log factor is used and the difference between SE calculations is based on different methods in calculating SINR (Björnson et al. (2017)Björnson & Sanguinetti (2020)).

2.6 Signal processing

In order to compare signals between UEs and APs, signal processing is required. Simulation model which was used in this work used maximum ration (MR) and minimized mean-squared error (MMSE) as means of comparing different signals. (Björnson et al. (2017))

2.6.1 maximum ration

Maximum ration combining is one of the simplest methods of processing signals at APs in the process of selecting the best signal to serve UE, which can be expressed as:

$$v = h \tag{8}$$

MR combining is defined as a vector which maximizes ration between the power of the desired signal and squared norm of combining vector as shown in Equation 9.Björnson et al. (2017)

$$\frac{|vh|^2}{||v||^2} \tag{9}$$

2.6.2 minimum mean-squared error

Minimum mean-squared error combining vector is a more complex signal processing method, which enables the system to achieve better SE between UEs and APs. MMSE combining is a vector which maximizes the SE between UEs and APs as shown in Equation 10.

$$v_{0k} = \frac{\rho h_{0k}^0}{\rho \sum_{i=1}^{K} h_{0i}^0 (h_{0i}^0)^H + \rho \sum_{i=1}^{K} h_{li}^0 (h_{li}^0)^H + \sigma^2 I_M} \tag{10}$$

As the name of the method describes, signal processing is done by minimizing the mean-squared error (MSE) between desired signal s and combined signal vy. (Björnson et al. (2017))

$$MSE = E[|s - vy|^2[\hat{h}]] \tag{11}$$

3 Simulation model

This chapter will explain the simulation model used in this work. The simulation model has four different methods to implement CF mMIMO, these methods are minimized mean square error (MMSE), two different methods of implementing local-minimized mean-squared error(L-MMSE) and small cells. The difference in SE between the different methods are based on different levels of cooperation between APs and CPU and this section introduces four approaches to implement different levels of AP cooperation based on the simulation script introduced in the paper published by Björnson & Sanguinetti (2020).

3.1 First approach

In the first approach of the system model, centralized computing is heavily utilized and all the processing is done in centralized manner in the CPU. This approach is mathematically the most complex of the four and allows the system to use channel estimates from each of the APs, in the process of choosing AP with best signal quality to serve the UE. Centralized processing means that pilot signals from each APs will be available at the CPU of the node as a combined signal.(Björnson & Sanguinetti (2020))

$$y = \sum_{i=1}^{K} h_i s_i + n \tag{12}$$

Calculation of spectral efficiency requires also error estimates. The estimated error is calculated as shown in Equation 13.

$$\tilde{h}_k = h_k - \hat{h}_k \tag{13}$$

The SE calculated in first approach is calculated as a product of pre-factor and SINR as shown in Equation 14

$$\mathrm{SE}_k^{(1.)} = (1 - \frac{\tau_\rho}{\tau_c})\mathbb{E}\{log_2(1 + \mathrm{SINR}_k^{1.})\} \tag{14}$$

In simulation script the SE is first calculated by using the MR method. MR factor is calculated by extracting combining vector from channel estimate realization matrix and it can be presented as $V_k = \hat{h}_k$ Equation 15 illustrates the mathematical presentation of the channel estimate between UE and AP. (Björnson & Sanguinetti (2020))

$$\hat{h}_{kl} \approx N_c(0, \rho_k \tau_\rho R_{kl} \Psi_{t_k}^{-1} R_k) \tag{15}$$

Then in simulation script, the signal between UE and AP is calculated. The signal is constructed as a product of a transmission power matrix ρ_k and the square of the absolute value from the product of transpose MR combining vector v_k^H and channel estimate realization matrix $\hat{h}_{kl}$ as presented in Equation 16.(Björnson & Sanguinetti (2020))

$$desired\ signal = \rho_k |v_k^H \hat{h}_{kl}|^2 \tag{16}$$

Noise between UE and AP is calculated by summing the squared normalized product of transpose MR combining vector v_k^H, channel matrix realization $\hat{h}_i$ and the diagonal power matrix ρ_i as shown in Equation 17(Björnson & Sanguinetti (2020))

$$interference = \sum_{i=1, i \neg k}^{K} \rho_i |v_k^H \hat{h}_i|^2 \tag{17}$$

And interference is calculated as a product of transpose MR combining vectorv_k^H and MR combining vector v_k multiplied with the sum of error correlation matrix $\rho_i C_i$ and identity matrix $\sigma^2 I_{LN}$ as shown in Equation 18.(Björnson & Sanguinetti (2020))

$$noise = v_k^H (\sum_{i=1}^{K} \rho_i C_i + \sigma^2 I_{LN}) v_k \tag{18}$$

After the signal, interference and noise have been calculated, the SINR is calculated simply by dividing the desired signal with the sum of interference and noise reduced with desired signal.(Björnson & Sanguinetti (2020))(Björnson et al. (2017))

$$\text{SINR}_{MR}^{1.} = \frac{\rho_k |v_k^H \hat{h}_k|^2}{\sum_{i=1, i \neg k}^{K} \rho_i |v_k^H \hat{h}_i|^2 + v_k^H (\sum_{i=1}^{K} \rho_i C_i + \sigma^2 I_{LN}) v_k} \tag{19}$$

After the SE is calculated in simulation script by using the MR method, MMSE is implemented. MMSE combining vector is calculated by summing the product of channel estimate realization $\hat{h}_i$, diagonal power ρ_i and transpose channel estimate realization matrices $\hat{h}_i^H$, with the sum of the estimated error correlation matrix. Then the sum is used to divide the product of channel estimate matrix realization $\hat{h}_k$ and diagonal power matrix ρ_k as shown in Equation 20.(Björnson & Sanguinetti (2020))

$$v_k = \frac{\sum_{i=1,i\neg k}^{K} \rho_i(\hat{h}_i\hat{h}_i^H + C_i) + \sigma^2 I_{LN}}{\rho_k \hat{h}_k} \tag{20}$$

After the MMSE combining factor has been calculated, new SINR is formed using following the same formula as with MR but replacing the MR factor with MMSE factor. Using MMSE leads to SINR as shown in Equation 21Björnson & Sanguinetti (2020)

$$SINR_{MMSE}^{(1.)} = \frac{\rho_k \hat{h}_k^H \hat{h}_k}{\sum_{i=1,i\neg k}^{K} \rho_i \hat{h}_i \hat{h}_i^H + \sum_{i=1}^{K} \rho_i C_i + \sigma^2 I_{LN}} \tag{21}$$

3.2 Second approach

The second approach utilizes local processing at each AP in addition to centralized processing which is still done in CPU. In practice this means that each AP forms channel estimates and then sends those estimates to CPU in order to find APs with best available signal to serve UEs. Due to the usage of local estimates the second approach differs greatly from the first approach in means of calculating the signal. Local estimates s_k are calculated as a sum of local combining vector v_{kl} and signal y as shown in Equation 22.(Björnson & Sanguinetti (2020))

$$\check{s}_{kl} = v_{kl}^H y_l = v_{kl}^H h_{kl} s_k + \sum_{i=1,i\neg k}^{K} v_{kl}^H h_{il} s_i + v_{kl}^H n_l \tag{22}$$

Spectral efficiency for the second approach is calculated with equation

$$SE_k^{2.} = (1 - \tau_\rho/\tau_c) log_2(1 + \text{SINR}_k^{2.}) \tag{23}$$

Calculation of SINR in simulation script is first done by using MR. MR factor is calculated by extracting combining vectors from the channel estimation realization matrix.

Desired signal is calculated as a product of power matrix ρ_k and the squared absolute value of the product of transpose weighted coefficient vector a multiplied with combined channel g_{kk}.The desired signal is illustrated in Equation 25.(Björnson & Sanguinetti (2020))

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$$desired\ signal = \rho_k |a_k^H \mathbb{E}\{g_{kk}\}|^2 \tag{24}$$

Interference is calculated as the product of interference power matrix ρ_i and squared absolute value of the product of transpose weighted coefficient vector a multiplied with combined channel g_{ki} and noise is calculated as product of power matrix σ, transpose weighted coefficient vector a, diagonal combining matrix D and weighted coefficient vector a. Then the sum of interference and noise is reduced with signal.(Björnson & Sanguinetti (2020))

$$noise\ and\ interference = \sum_{i=1}^{K} \rho_i \mathbb{E}\{|a_k^K g_{ki}|^2\} - \rho_k |a_k^H \mathbb{E}\{g_{kk}\}|^2 + \sigma^2 a_k^H D_k a_k \tag{25}$$

Then SINR using MR combining is calculated as:

$$SINR_{MR}^2 = \frac{\rho_k |a_k^H \mathbb{E}\{g_{kk}\}|^2}{\sum_{i=1}^{K} \rho_i \mathbb{E}\{|a_k^K g_{ki}\}|^2 - \rho_k |a_k^H \mathbb{E}\{g_{kk}\}|^2 + \sigma^2 a_k^H D_k a_k} \tag{26}$$

Next the SINR is calculated by using the MMSE method. In this case the channel error information which is used, is only collected locally at each AP, so the method is called local minimized mean-squared error (L-MMSE).

Means-squared error (MSE) $MSE_{kl} = E|s_k - v_{kl}^H y_t|^2 |[\hat{h}_{il}]$ is minimized in combining vector v as shown in equation **??**.(Björnson & Sanguinetti (2020))

$$v_{kl} = \frac{\rho_k \hat{h}_{kl}}{\sum_{i=1}^{K} \rho_i (\hat{h}_{il} \hat{h}_{il}^H + C_{il}) + \sigma^2 I_N} \tag{27}$$

LMMSE combining vector is achieved in CPU by combining vector v and local estimates from AP $\check{s}$ using weighted coefficient vector a which leads to vector as shown in equation **??**. (Björnson & Sanguinetti (2020))

$$\hat{s}_k = \left(\sum_{l=1}^{L} a_{kl}^* v_{kl}^H h_{kl} \right) s_k + \sum_{l=1}^{L} a_{kl}^* \left(\sum_{i=1, i \neg k}^{k} v_{kl}^H h_{il} s_i \right) + n_k' \tag{28}$$

In paper Björnson & Sanguinetti (2020) vector $\hat{s}$ is further reduced by assuming that $g_{ki} = [v_{k1}^H h_{i1} ... v_{kL}^H h_{iL}]^T$, which leads to $\hat{s}$ as in equation 29.(Björnson & Sanguinetti

(2020))

$$\hat{s}_k = a_k^H g_{kk} s_k + \sum_{i=1, i \neg k}^{K} a_k^H g_{ki} s_i + n_k' \tag{29}$$

Signal using LMMSE is calculated as the product of power matrix ρ_k, transpose combined channel matrix g_{kk}^H and combined channel matrix g_{kk}.(Björnson & Sanguinetti (2020))

$$desired\ signal = p_k \mathbb{E}\{g_{kk}^H\} \mathbb{E}\{g_{kk}\} \tag{30}$$

Interference using LMMSE is calculated as the product of power matrix ρ_i, transpose combined channel matrix g_{ki}^H and combined channel matrix g_{ki} and noise as the product of squared power matrix $sigma$ and diagonal combining matrix D. Then sum of interference and noise is reduced with desired signal.(Björnson & Sanguinetti (2020))

$$Interference\ and\ noise = \sum_{i=1}^{K} \rho_i \mathbb{E}\{g_{ki} g_{ki}^H\} + \sigma^2 D_k \rho_k \mathbb{E}\{g_{kk}\} \mathbb{E}\{g_{kk}^H\} \tag{31}$$

SINR is then calculated as shown in Equation 32.(Björnson & Sanguinetti (2020))

$$SINR_{L-MMSE}^{2.} = p_k \mathbb{E}\{g_{kk}^H\} \times (\sum_{i=1}^{K} \rho_i \mathbb{E}\{g_{ki} g_{ki}^H\} + \sigma^2 D_k \rho_k \mathbb{E}\{g_{kk}\} \mathbb{E}\{g_{kk}^H\})^1 \mathbb{E}\{g_{kk}\} \tag{32}$$

3.3 Third approach

The third approach is similar to the second approach, but now, instead of sending channel estimates to CPU AP calculates the average of locally formed estimates and sends it to CPU. (Björnson & Sanguinetti (2020)) Calculation of channel estimate average values can be explained with the equation:

$$\hat{s}_k = 1/L \sum_{l=1}^{L} \hat{s}_{kl} \tag{33}$$

In the third approach the spectral efficiency is calculated as follows:

$$SE_k^{3.} = (1 \frac{\tau_\rho}{\tau_c}) log_2(1 + \mathrm{SINR}_k^{3.}) \tag{34}$$

Signal in third approach is calculated as the product of power matrix ρ_k multiplied with the squared absolute value of sum of LMMSE combining factor v_{kl}^H multiplied with channel estimate matrix h_{kl} as shown in Equation 35.(Björnson & Sanguinetti (2020))

$$desired\ signal = \rho_k|\sum_{l=1}^{L}\mathbb{E}\{v_{kl}^H h_{kl}\}|^2 \tag{35}$$

Interference is calculated as the product of power matrix ρ, LMMSE combining vectorv_{kl} and channel estimate h_{il} and noise as the product of power matrix σ and combining vector v_{kl}. Then interference and noise are reduced with desired signal as shown in Equation 36.

$$interference\ and\ noise = \sum_{i=1}^{k}\rho_i\mathbb{E}\{\sum_{l=1}^{L}v_{kl}^H h_{il}|^2\} - \rho_k|\sum_{l=1}^{L}\mathbb{E}\{v_{kl}^H h_{kl}\}|^2 + \sigma^2\sum_{l=1}^{L}\mathbb{E}\{||v_{kl}||^2\} \tag{36}$$

After signal, interference and noise have been calculated SINR is achieved as shown in Equation 37

$$SINR_k^{3.} = \frac{\rho_k|\sum_{l=1}^{L}\mathbb{E}\{v_{kl}^H h_{kl}\}|^2}{\sum_{i=1}^{k}\rho_i\mathbb{E}\{\sum_{l=1}^{L}v_{kl}^H h_{il}|^2\} - \rho_k|\sum_{l=1}^{L}\mathbb{E}\{v_{kl}^H h_{kl}\}|^2 + \sigma^2\sum_{l=1}^{L}\mathbb{E}\{||v_{kl}||^2\}} \tag{37}$$

3.4 Fourth approach

The fourth approach introduces the usage of small-cells. This means that each AP processes signals between UE and AP and makes its own channel estimates.

In the fourth approach SE is calculated as shown in equation 38.(Björnson & Sanguinetti (2020))

$$SE_k^{4.} = \left(1 - \frac{\tau_\rho}{\tau_c}\right)\max_{l\in[1,\ldots,L]}\mathbb{E}\{log2(1+\mathrm{SINR}_{kl}^{4.})\}(38)$$

SINR is first calculated using MR combining vector v. Signal is calculated as product of power matrix ρ multiplied with squared absolute value of MR combining vector v multiplied with channel estimate realization matrix $\hat{h}$ as shown in equation 39.(Björnson & Sanguinetti (2020))

$$desired\ signal = \rho_k|v_{kl}^H\hat{h}_{kl}|^2 \tag{39}$$

Interference is calculated as the product of power matrix ρ_i multiplied with the squared absolute value of MR combining vector v multiplied with channel estimate realization matrix $\hat{h}$ as shown in equation 40. (Björnson & Sanguinetti (2020))

$$Interference = \sum_{i=1, i \neg K}^{K} \rho_i |v_{kl}^H \hat{h}_{il}|^2 \tag{40}$$

Noise is calculated as the product of transpose MR combining vector v^H multiplied with the sum of product of power matrix ρ estimated error C and the product of noise power matrix σ multiplied with identity matrix I as shown in Equation 41.(Björnson & Sanguinetti (2020))

$$Noise = v_{kl}^H (\sum_{i=1}^{K} \rho_i C_{il} + \sigma^2 I_N) v_{kl} \tag{41}$$

SINR is formed as shown in equation 42.(Björnson & Sanguinetti (2020))

$$\mathrm{SINR}_{kl}^{(4.)} = \frac{\rho_k |v_{kl}^H \hat{h}_{kl}|^2}{\sum_{i=1, i \neg K}^{K} \rho_i |v_{kl}^H \hat{h}_{il}|^2 + v_{kl}^H (\sum_{i=1}^{K} \rho_i C_{il} + \sigma^2 I_N) v_{kl}} \tag{42}$$

Then SINR is maximized by LMMSE combining. Signal is calculated as the product of power matrix ρ multiplied with the squared absolute value of LMMSE combining vector multiplied with channel estimation matrix $\hat{h}$ which lead to signal 43.(Björnson & Sanguinetti (2020))

$$desired\ signal = \rho_k \hat{h}_{kl}^H \hat{h}_{kl} \tag{43}$$

Interference is calculated as the product of power matrix ρ multiplied with the squared absolute value of LMMSE combining vector multiplied with channel estimation matrix $\hat{h}$. Noise is calculated as the product of transpose LMMSE combining vector v^H multiplied with the sum of product of power matrix ρ estimated error C and the product of noise power matrix σ multiplied with identity matrix I. After interference and noise have been calculated the sum is reduced with desired signal. This leads to interference and noise as shown in Equation 44.(Björnson & Sanguinetti (2020))

$$interference\ and\ noise = \sum_{i=1, i \neg k}^{K} \rho_i \hat{h}_{kl} \hat{h}_{kl}^H + \sum_{i=1}^{K} \rho_i C_{il} + \sigma^2 I_N \tag{44}$$

Then SINR is constructed as shown in equation 45.(Björnson & Sanguinetti (2020))

$$SINR_{kl}^{4.} = \frac{\rho_k \hat{h}_{kl}^H \hat{h}_{kl}}{\sum_{i=1, i \neg k}^{K} \rho_i \hat{h}_{kl} \hat{h}_{kl}^H + \sum_{i=1}^{K} \rho_i C_{il} + \sigma^2 I_N} \tag{45}$$

4 Results

4.1 Simulations

In order to compare different approaches of the CF mMIMO architecture four scenarios were simulated. These simulations are concentrated in comparing different implementations of MMSE. The parameters of interest are the number of antennas at AP in CF mMIMO systems and the number of antennas in BS in cellular network, the number of UEs in the network, and transmission power of the UEs.

Simulated area was 1000m x 1000m and the UEs are located as shown in Figure 4 represented by black dots, the APs are represented with blue circles, and finally the BSs are represented with red dots. APs and BSs were located in constant pattern and UEs were located randomly in the simulation area.

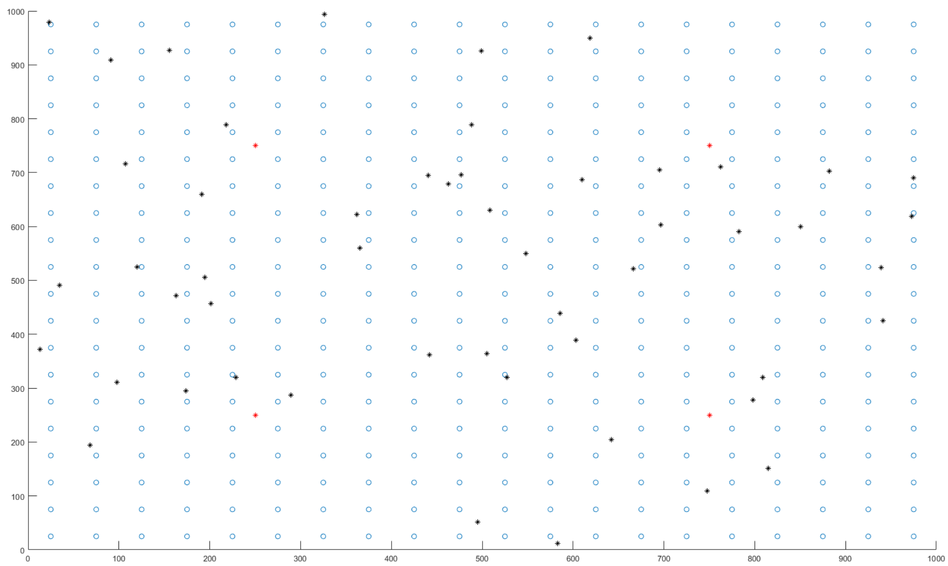
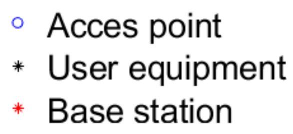


Figure 4: System placement map

In order to achieve higher accuracy in terms of results, each simulation was made with 200 simulated setups and 1000 simulated channel realizations in each setup. In practise this means that a setup like the one shown in Figure 4 was constructed 200 times and 1000 different channels were calculated within the system.



(46)

Figure 5: Description of symbols

A reference simulation was made by using default simulation values as given in the simulation script. Variables in the simulation were the number of APs in the cell-free network(L), the number of BSs in the cellular network which was not possible to be changed(nbrBSs), the number of antennas at the BSs(M), the number of UEs in the network(K), the number of antennas per AP(N), length of the coherence block(τ_c), compute number of pilots per coherence block(τ_p), up link transmit power per UE in milli Watt unit(p).

Default parameter values were:$L = 400, \text{nbrBSs} = 4, M = 100, K = 40, N = 1, \tau_c = 400, \tau_p = K/\text{nbrBSs}, p = 100$.

Figure 6 illustrates results values which were achieved with the default values.

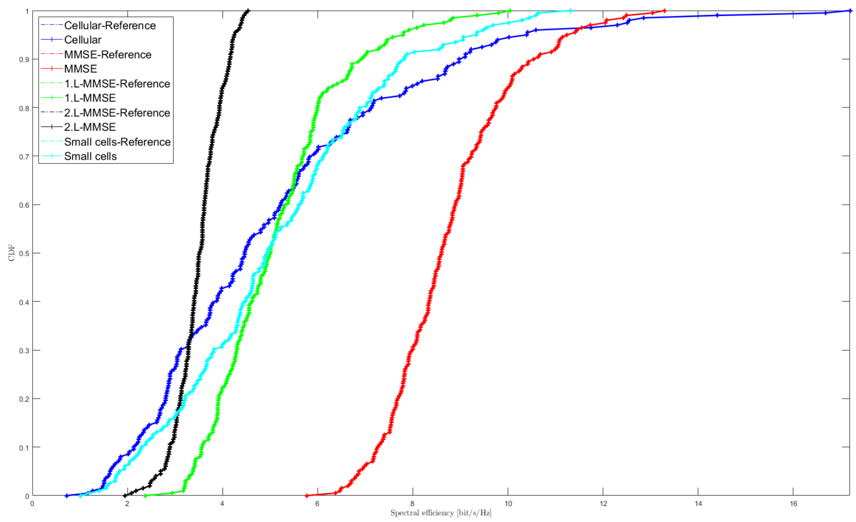


Figure 6: Affect of number of antennas to SE

Figure 6 shows that with default values the first approach of the CF mMIMO achieves far better SE than any of the other approaches.

To study the affect of parameters, results achieved with default values were compared to values from different scenarios in which parameters were changed.

4.1.1 First Scenario

In the first scenario the number of antennas at each AP and BS was increased. The number of antennas at each BS was increased to 400 and the number of antennas at each AP was increased to 10.

Now parameter values were:$L = 400, \mathrm{nbrBSs} = 4, M = 400, K = 40, N = 10, \tau_c = 200, \tau_p = K/\mathrm{nbrBSs}, p = 100$.

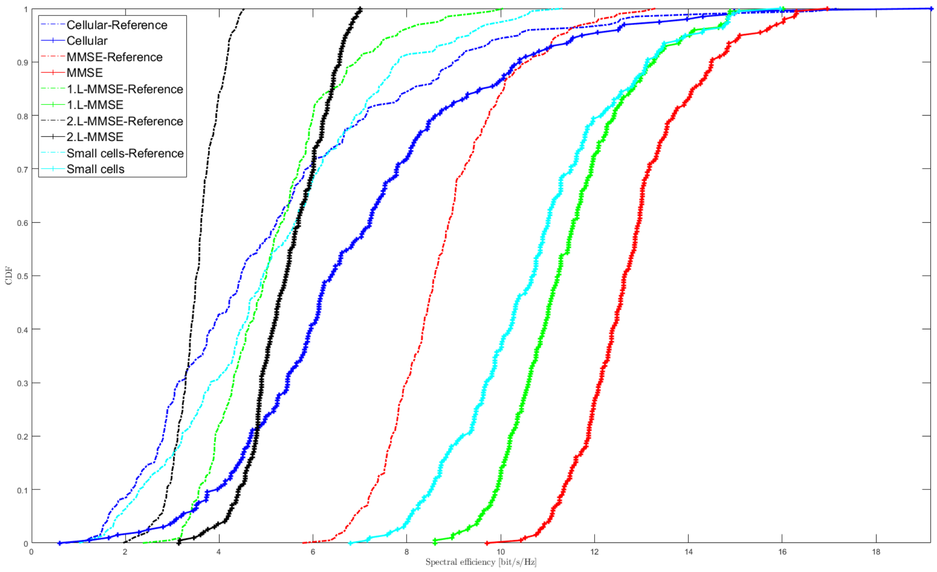


Figure 7: Affect of number of antennas to SE

The Figure 7 shows, that the increase in the number of antennas increases the SE in each of the different system model approaches. This can be explained with the increase in beam coverage and capacity.

Although the SE increases in each of the systems, there are differences between different approaches in the magnitude of the SE increase. The difference could be explained with the level of centralized processing of the channel state information. As the centralized processing of CSI enables the system to estimate the best connection points through out the whole system, which leads CF mMIMO with MMSE processing to achieve far higher results in terms SE, in comparison to cellular network, where the system can only use local CSI.

4.1.2 Second Scenario

The second scenario studies the impact in SE caused by the increase of number of UEs in the network. For this simulation only the number of UEs was increased to 80 and other parameters were kept as default.

Now the simulation parameters were: $L = 400, \text{nbrBSs} = 4, M = 100, K = 80, N = 1, \tau_c = 200, \tau_p = K/\text{nbrBSs}, p = 100$.

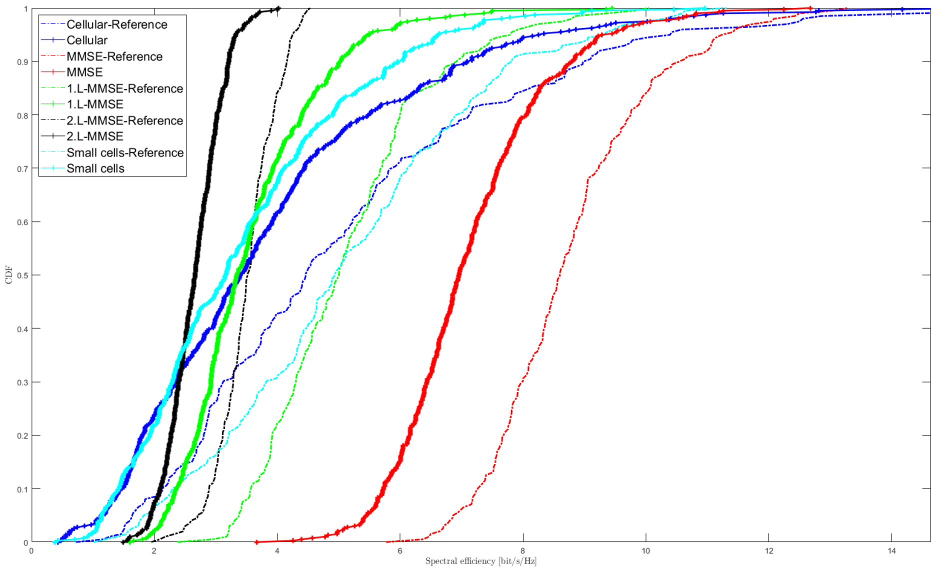


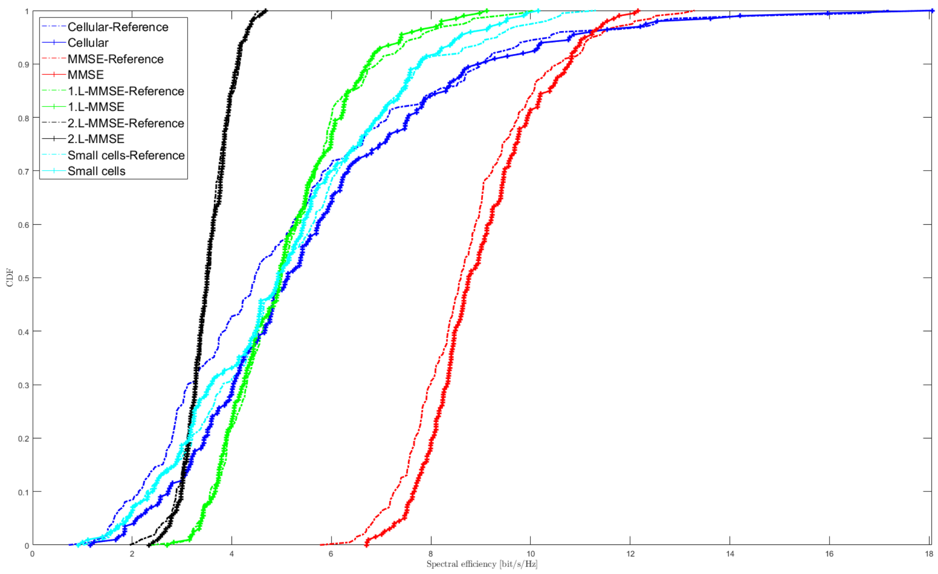
Figure 8: Affect of number of user equipment to SE

Simulation Figure 8 suggests that the increase in the number of UEs in the network decreases SE in each approach, although there is differences in the relative decrease of the SE. Moreover the MMSE- processing seems to perform far better, compared to different models.

4.1.3 Third Scenario

The third scenario studies the effect of the increase of transmission power to SE. In this scenario the transmission power of UEs was increased to 400mW and all the other parameters were kept as given default.

Now the simulation parameters were: $L = 400, \text{nbrBSs} = 4, M = 100, K = 40, N = 1, \tau_c = 200, \tau_p = K/\text{nbrBSs}, p = 400$.



(47)

Figure 9: Affect of user equipment transmission power to SE

As illustrated in Figure 9 an increase in the transmission power shows little to no effect in SE. This can be explained with the increased noise signal as a result of increasing transmission power, which effects negatively to the SE.

4.2 Conclusions and Future Works

Simulation results suggested that CF mMIMO utilizing MMSE Processing performs far better in terms of SE when compared to other architectures and processing schemes introduced in this work. Results are in line with results illustrated in the publication Björnson & Sanguinetti (2020).

Based on this base line, future studies can be done considering different APs deployment schemes, such as Radio Stripes to support scenarios with a high density of users.

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