Accepted at The 8th Annual Computing and Communication Workshop Conference, IEEE CCWC 2018

Optimal Pilot Reuse Factor based on User Environments in 5G Massive MIMO

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***Abstract*—Massive MIMO is designed to improve capacity and performance of the network by using hundreds or even thousands of antenna and terminals attached to the base station. However, the fundamental limitation of this technology is pilot contamination problem during uplink which limits throughput. Pilot contamination problem can be solved by using pilot reuse factor value higher than one and to get maximum area throughput in the system, this factor must be switched dynamically according to the environment and number of active users. As of now increasing either bandwidth or cell density has been considered but the other factor increasing area throughput, i.e., spectral efficiency has been untouched. In this paper, we find the optimal values of pilot reuse factor to always run the system at maximum spectral efficiency to get higher area throughput. The experiment was simulated in six different environments with the variable number of active users in the cell and results through MATLAB simulations show that with appropriate use of the value of pilot reuse factor based on environment and number of active users, we can always run the system with maximal spectral efficiency and achieve higher area throughput.**

***Index terms*—Massive MIMO, pilot contamination, spectral efficiency, pilot reuse factor**

I. INTRODUCTION

With globalization, present-day networks are facing high traffic demands and to fulfill these needs the cellular systems are deployed within few hundred-meter distances, and wireless local area networks are available almost everywhere. According to Martin Cooper "Wireless traffic has doubled every two and half years since the beginning of wireless communication technologies." This trend is likely to continue with modern technologies and innovations. The future generation of wireless networks called the fifth generation ‘5G' must both accommodate more wireless traffic and address current limitations on data rates, reliability, and energy efficiency. The main issue with the ongoing development of the cellular network is that it is dependent upon either increasing bandwidth or densifying the cell to improve area throughput, but these resources are probably reaching their saturation point. On top of that, these resources also make the system more expensive, increases latency, and decreases the signal to noise ratio. Even with these improvements, the primary factor affecting area throughput, i.e., spectral efficiency, has remained mostly untouched and unchanged. The relation between area throughput, spectral efficiency, bandwidth and cell density is given by [1]:

$$Area\ throughput(bits/\ s/\ km^2) = \text{Bandwidth (Hz)} * \text{Cell density(cell/km}^2) * Spectral\ efficiency\ (bits/\ Hz/\ cell) \tag{1}$$

Recently, the “massive multiple input multiple output” (MIMO) concept has been proposed in [2], which dramatically improves the performance of these networks. Massive MIMO is an adaptation of MIMO technology, which involves using hundreds or even thousands of antennas and terminals attached to a base station. These hundreds of antennas are used to focus the transmission and reception of signal energy into smaller regions. The key here is asymptotic orthogonality properties of large dimensional random vector allied with massive MIMO and the considerable array gain that massive MIMO provides. In massive MIMO, the base station should have detailed information of the channel during both uplink and downlink because massive MIMO is dependent on spatial multiplexing [3]. In massive MIMO each user equipment or terminal send pilots to the base station and based on these pilot signals, the base station estimates the channel behavior for every user equipment. Time division duplex (TDD) is considered suitable for massive MIMO rather than frequency division duplex(FDD) because uplink and downlink signals will experience independent fading if we use FDD. Contemporary MIMO system has very low spectral efficiency and compared to that massive MIMO offers a considerable gain in spectral efficiency and array gain [4] and [5]. There are many advantages of massive MIMO given in [6]. Out of many benefits, the use of low power components in the base station is one of the significant advantages of massive MIMO and along with that massive MIMO provides robustness to internal jamming and interference as well.

Along with these advantages, massive MIMO comes up with certain challenges as well. In massive MIMO orthogonal pilots are reused in many cells because there is limited channel coherent time due to mobility and this reuse of pilots causes pilot contamination which is a major cause of throughput limitation. Pilot contamination and some of its mitigation techniques are described in [7]. To improve the spectral efficiency in massive MIMO, appropriate use of pilot reuse factor is required which maximizes the system throughput to a certain extent. In this paper, we find the optimal value of pilot reuse factor according to the number of users at different environments to run the system at possible maximal spectral efficiency. As path loss and standard deviation change based on the environmental conditions, according to that six different environments conditions namely suburban, Urban, obstructed by building, obstructed by factories, shadowed urban and inside building with the line of sight are used for this experiment [8]. These values of pilot reuse factor will increase the throughput of the system without increasing bandwidth and cell density. The rest of the paper is organized as follows. In section II, we will discuss pilot reuse factor, and in section III, related work is presented. Section IV explains the system model used in this experiment, in section V simulation parameters are defined, section VI gives the result of the MATLAB simulation, and finally, section VII presents the conclusion of the work.

II. Related Work

A significant amount of research has already been done on this field which has investigated the use pilot reuse factor to mitigate the effect of inter-pilot contamination. The sources and impact of pilot contamination on the performance of massive MIMO is described in [9]. There are several mitigation techniques to minimize the effect of pilot contamination described in massive MIMO. Mitigation by pilot reuse and power control schemes is described in [10]. A partial sounding resource reuse (PSRR) method is described in [11] which aims to guarantee the quality of service as well. Apart from this, many research has been done to improve spectral efficiency to achieve higher area throughput. In [12] author analyses the diverse ways to optimize the spectral efficiency of massive MIMO in time division duplex architecture. In [13] author explains that by adding more user antenna we can increase the spectral efficiency when there are few active users in the system. In [14] author presents a transmission protocol which leverages successive cancellation decoding and zero forcing at the user and provides higher spectral efficiency.

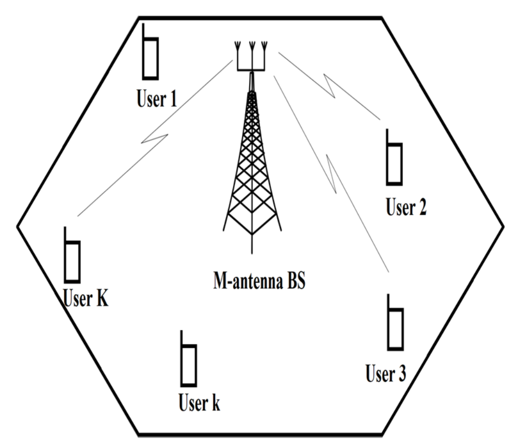

Fig. 1 Massive MIMO Systems [16]

III. Pilot Reuse Factor

Pilot reuse factor is designed in such a way that different orthogonal signals are assigned to each cell within the cluster. Pilot reuse factor is required to mitigate pilot contamination effect that occurs in Massive MIMO, and this factor is calculated similarly as frequency reuse factor as given in [8]:

$$N = i^2 + i * j + j^2 \tag{2}$$

Where N > 1 is pilot Reuse factor, and i and j are non-negative integers. So, we get symmetric pilot reuse factor value from the above equation as (1,3,4,7….). Fig. 2 shows the different pilot reuse pattern created by four pilot reuse factor values in a cellular network. The cells with the same color use the same pilot sequence and cause the pilot contamination to each other. There is no contamination between the cells with distinct color. The value of pilot reuse factor must be chosen precisely according to environment and number of active users in the cell to achieve higher spectral efficiency.

IV. System Model

We consider a multi-cell massive MIMO system with BS (base station) in each cell equipped with the substantial number of antennas as shown in Fig. 1. These BS communicate with K number of users having a single antenna. In general, a user has more than one antenna, but to make calculations easier, we assume that the user has a single antenna. We presume that BS and the user have perfect CSI and time division duplex (TDD) protocol is considered. Since the system is using TDD, no downlink signaling is required since system process both Uplink and downlink due to the channel reciprocity. Now, received uplink signal y_{uplink} at the BS is the modeled according to [15]:

$$y_{uplink} = \sqrt{p_{uplink}} \sum_{K=1}^{K} h_k x_k + n_o \tag{3}$$

Here, p_{uplink} is the average signal to noise ratio, $h_k$represents the Mx1 channel vector between the kth user and the BS, n_o is the additive noise vector, and x_k is the signal transmitted from the kth user.

Effective uplink Signal to Interference noise ratio(SINR) form UE k to cell j is considered to calculate effective Spectral Efficiency given as [17]:

$$SINR_{jk}^{(uplink)} = \frac{p_{jk}\left|E_{\{h\}}\left\{g_{jk}^{H} h_{jjk}\right\}\right|^2}{\sum_{l\in L}\sum_{m=1}^{K} p_{lm}\, E_{\{h\}}\left\{\left|g_{jk}^{H} h_{jlm}\right|\right\}^2 - p_{jk}\left|E_{\{h\}}\left\{g_{jk}^{H} h_{jjk}\right\}\right|^2 + \sigma^2\, E_{\{h\}}\left\{||g_{jk}||\right\}^2} \tag{4}$$

Where, $SINR_{jk}^{(uplink)}$ is effective signal to noise ratio from UE k to cell j, $E_{\{h\}}$ is expectation with respect to the channel realization, p_{jk} is uplink transmit power, g_{jk} is receive combining vector that a BS j applies. This receive combining vector g_{jk} discards the unwanted signal that is coming from the undesired UE and the signal that is coming from the desired UE is amplified. In our case our desired UE will be the kth UE. The channel response h_{jlm} is the response between UE m in cell l and BS j and the channel response, h_{jjk} is the response between UE k in cell k and BS j, and σ^2 is the noise variance. [17]. Non-Universal pilot reuse scheme is applied, and Zero-Forcing combining is used which suppresses inter-cell interference. Spectral efficiency in uplink and downlink of a UE k in cell j is given as [17]:

$$\mathrm{SE} = \zeta^{(\mathrm{uplink})}\left(1-\frac{B}{S}\right)E_{\{Z\}}\left\{\log_2\left(1+SINR_{jk}^{(uplink)}\right)\right\} \tag{5}$$

Where $\zeta^{(\mathrm{uplink})}$ is fixed fraction allocated for uplink, B is the number of symbols dedicated to uplink pilots, and S is the number of symbols dedicated to uplink data, and $E_{\{Z\}}$ is expectation with respect to UE position and $SINR_{jk}^{(uplink)}$ is an effective signal to noise ratio from UE k to cell j.

Here location of all UE is generated randomly, and location of BS j is given by integer pair which is defined in [17] as:

$$b_j = \sqrt{3}\begin{bmatrix}\sqrt{3}R/2\\ R/2\end{bmatrix}\beta_j^1 + \begin{bmatrix}0\\ \sqrt{3}R\end{bmatrix}\beta_j^2 \tag{6}$$

Where R is the radius of hexagonal cell and two different cells are uniquely identified by β_j^1 and β_j^2. As, path loss and standard deviation change based on the environmental conditions so,

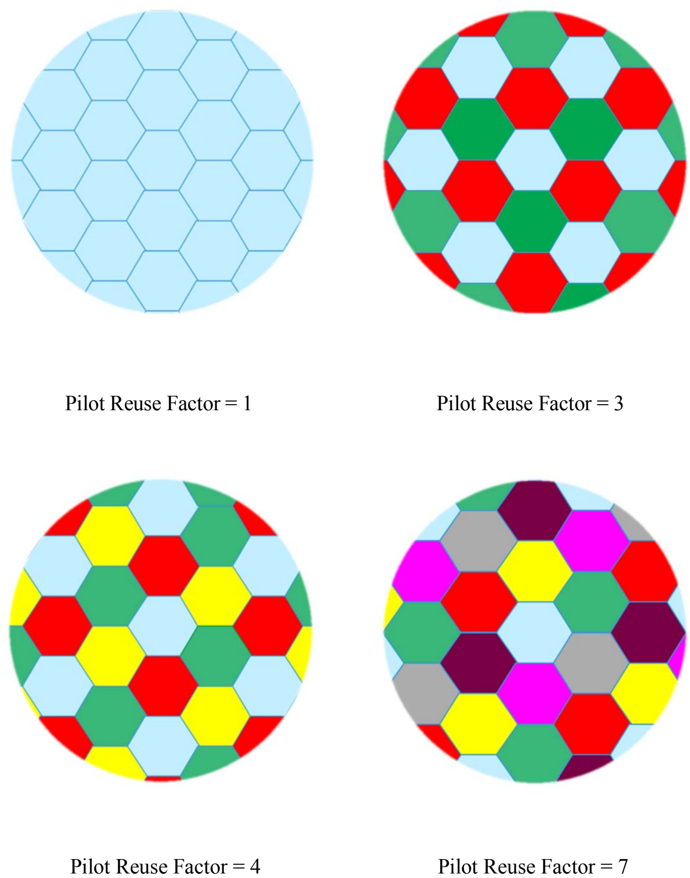

Fig. 2 Reuse pattern created by different pilot reuse factor in cellular networks with hexagonal cells.

according to that six different environments conditions namely suburban area, urban area, urban area obstructed by building, urban area obstructed by factories, shadowed urban area and area inside building with a line of sight are used for this experiment. For differentiating various environments, we have used different path loss exponent value obtained in various mobile radio environments which are used in log-distance path loss model given by Table I [8]. The distance between the transmitter and receiver is b, close in reference distance is a, and n is the path loss exponent. Then, average path loss P_{Loss} for a transmitter- receiver is given by [18]:

$$P_{Loss}(dB) = c(a) + 10n\log\left(\frac{b}{a}\right) \tag{7}$$

V.SIMULATION PARAMETERS

Table II. shows the list of simulations parameters used for the research. The system model presented above is simulated using

TABLE I
PATH LOSS EXPONENT VALUE FOR DIFFERENT ENVIRONMENT

Environment	Path loss Exponent, n
Free Space	2
Urban Area Cellular Radio	2.7 to 3.5
Shadowed Urban Cellular Radio	3 to 5
In Building Line of Sight	1.6 to 1.8
Obstructed in Building	4 to 6
Obstructed in Factories	2 to 3

MATLAB. With the defined system model and simulation parameter, this simulation will find the optimal value of pilot reuse factor according to the number of users at six different environments. These values of pilot reuse factor will ensure that system will always run at maximal spectral efficiency to obtain higher area throughput. Fig. 4,5,6,7,8 and 9 show the spectral efficiency Vs. Number of users at six different environments using pilot reuse factor value of 7,4,3 and 1.

VI. NUMERICAL RESULTS

In this section, we assess the performance of the massive MIMO systems at six different environments: urban area, suburban area, urban area obstructed by factories, urban area obstructed by building, shadowed urban area and area inside a building with LOS. In doing so, we have adopted similar setup as given in [17]. With the maximum of 50 active users, Fig. 4-9 shows Number of Users vs. Spectral Efficiency plots obtained for these six environments. From Table III and Fig. 3, We can infer that for sub-urban area if number of users is less than 5,

TABLE II
SIMULATION PARAMETERS

Parameter	Value
System Bandwidth	5 MHz
Subcarriers	25
Coherence Interval	200 symbols
Coherence Bandwidth	200 kHz
Maximum Number of Users	50
Cell Radius	1000m
Number of Hexagonal Tiers	2
Signal to Noise Ratio	10 dB
Number of BS Antenna	100
Precoding Scheme	Zero-Forcing
Channel Model	Uncorrelated Rayleigh Fading

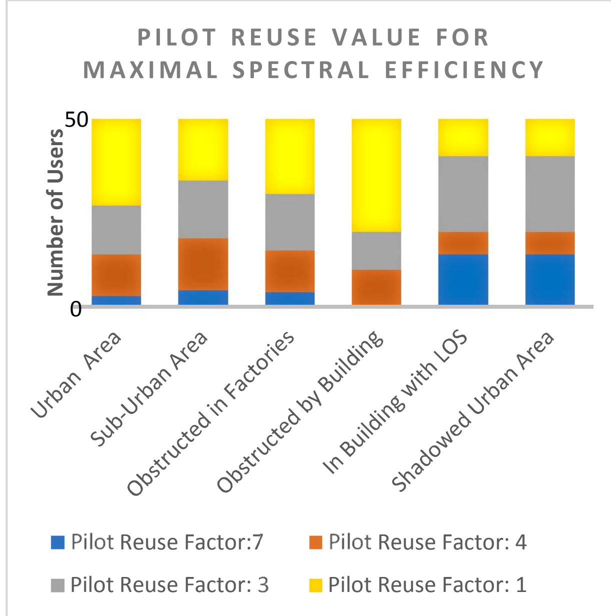

Fig. 3 Pilot Reuse Factor for Maximal Spectral Efficiency for different number of users

then pilot reuse factor value of 7 yields maximal spectral efficiency, if the number of users are between less than 5 and more than 15 then pilot reuse factor value of 4 yields maximal spectral efficiency, if the number of users is less than 15 and more than 32 then pilot reuse factor value of 3 yields maximal spectral efficiency and if the number of users are more than 32 and less than 50 then pilot reuse factor value of 1 yields maximal spectral efficiency. For an urban area, if the number of users is less than 3 then pilot reuse factor value of 7 yields maximal spectral efficiency if the number of users is more than 3 and less than 14 then pilot reuse factor value of 4 yields maximal spectral efficiency, if the number of users is between more than 14 and less than 27 then pilot reuse factor value of 3 yields maximal spectral efficiency and if the number of users is between more than 32 and less 50 then pilot reuse factor value of 1 yields maximal spectral efficiency.

For urban area obstructed in the building, pilot reuse factor value of 7 is not recommended to use, since it will not yield maximal spectral efficiency with any number of users. If the number of users is less than 10 then pilot reuse factor value of 4 yields maximal spectral efficiency, if the number of users is between more than 10 and less than 20 then pilot reuse factor value of 3 yields maximal spectral efficiency and if the number of users is between more than 20 and less 50 then pilot reuse factor value of 1 yields maximal spectral efficiency. Similarly, we can find the optimal values of pilot reuse factor for other environments as such as urban area obstructed by factories, shadowed urban area and area inside building with a line of sight.

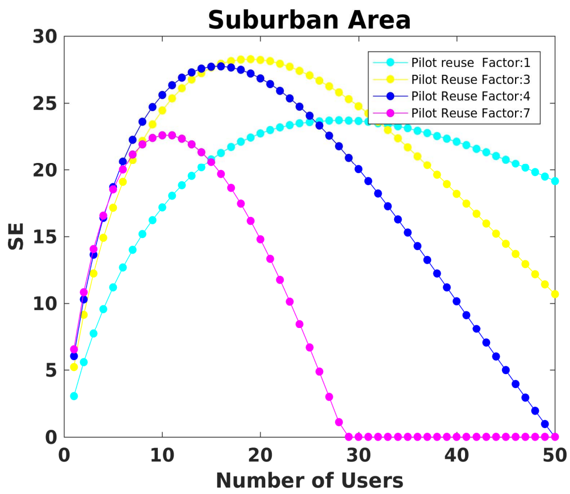

Fig. 4 Suburban Area

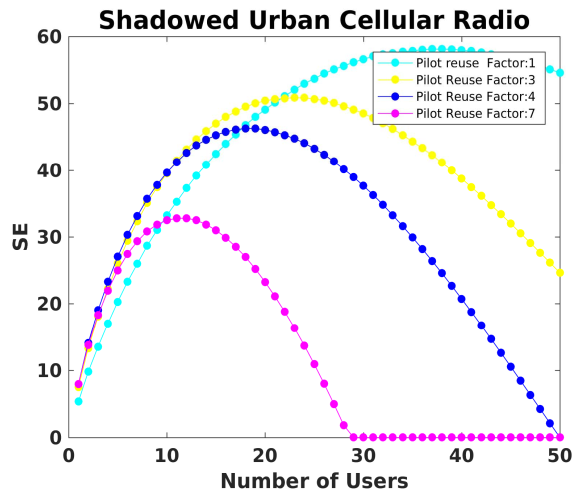

Fig.7 Shadowed Urban Area

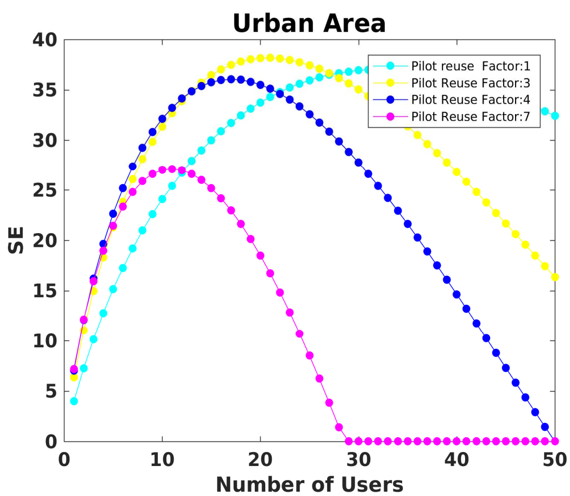

Fig. 5 Urban Area

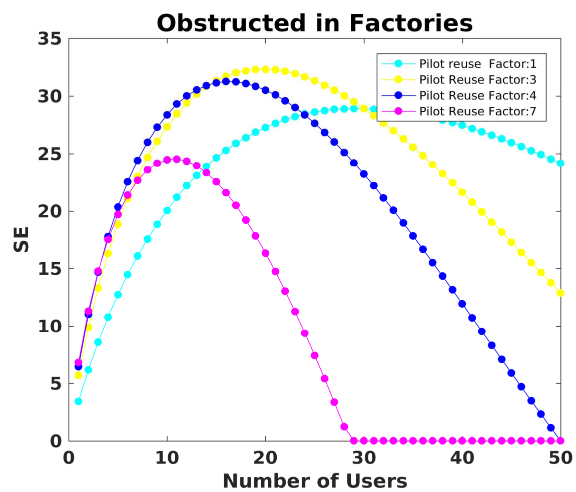

Fig. 8 Obstructed in Factories

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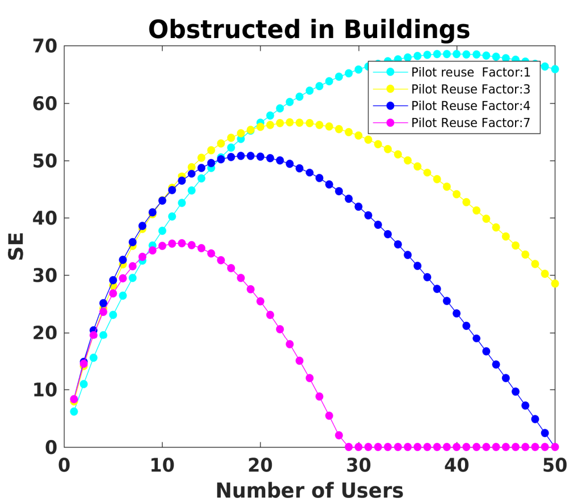

Fig. 6 Obstructed in Building

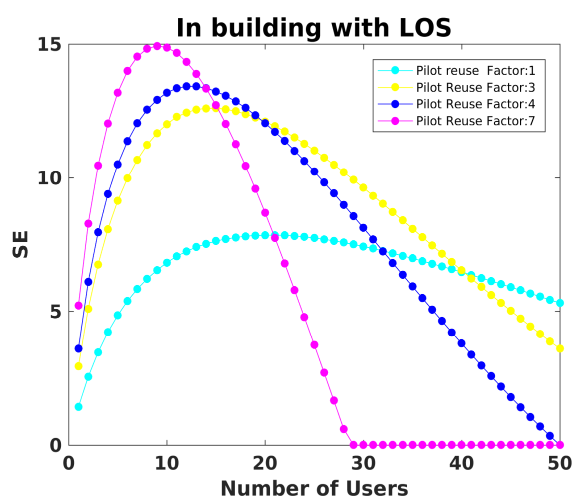

Fig. 9 In-Building with LOS

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TABLE III

NUMBER OF USERS AND CORRESPONDING PILOT REUSE FACTOR VALUE AT DIFFERENT ENVIRONMENT TO ACHIEVE MAXIMAL SPECTRAL EFFICIENCY

Pilot Reuse Factor	Suburban Area	Urban Area	Urban Area Obstructed by building	Urban Area Obstructed by Factories	Shadowed Urban Area	Area inside a Building with Line of Sight
7	1-5	1-3	-	1-4	-	1-14
4	5-15	3-14	1-10	4-15	1-11	14-20
3	15-32	14-27	10-20	15-30	11-22	20-40
1	32-50	27-50	20-50	30-50	22-50	40-50

VII. CONCLUSION

Pilot contamination is one of the significant problems in Massive MIMO systems and using pilot reuse factor greater than one is one of the ways to minimize this problem. In this paper, we found the optimal value of pilot reuse factors at six different environments based on the environment of the user and number of active users. These optimal values of pilot reuse factor ensure that the system always runs at maximum Spectral Efficiency. With the higher value of spectral efficiency, we can achieve higher area throughput without increasing bandwidth and cell density which is the major requirement of current and future cellular networks. Hence, with these simulations, we showed that by changing the value of pilot reuse factor dynamically according to environment and number of active users, we can always run with maximal spectral efficiency to obtain higher area throughput. In this experiment, we made about 20-fold improvement in spectral efficiency when compared to current 4G cellular technology which has the spectral efficiency of 3 bits/s/Hz according to IMT-Advanced (International Mobile Telecommunication). The effectiveness of this work can be further explored by developing less complex, and spectrally efficient precoding and detection algorithm to obtain higher spectral efficiency. Another future work for this experiment will include integrating several realistic network parameters in the proposed model and evaluate downlink performance, power control implementation in real conditions. Comparison between various algorithm during both precoding and detection should be considered in the future work, and it would be very interesting to compare the energy efficiency between these schemes.

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