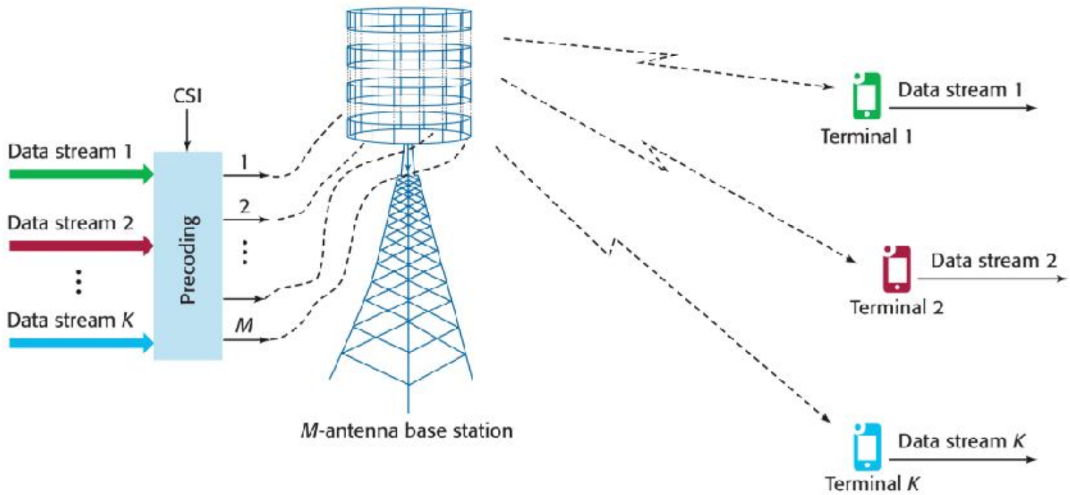
ChapterThree

3.Model

The system model that we have adopted to analyze massive MIMO systems will be introduced here. Massive MIMO is a multi-user MIMO technology in which K single-antenna user equipments (UEs) are serviced simultaneously on the same time-frequency resource by a base station (BS) equipped with a relatively large number M of antennas, i.e., M >> K >>1 . In general, the UEs in a massive MIMO system can be equipped with more than one antennas.

However, to simplify our analysis, discussions in this thesis are limited to systems with single-antenna UEs. Deploying several antennas at the BS results in an interesting propagation scenario called favourable propagation, where the channel becomes near-deterministic because the radio links between the BS and the UEs become nearly orthogonal to each other [9]. This is because the effects of small-scale fading tend to disappear asymptotically in the large M regime.

Significant EE gains can be achieved under favourable propagation because multiple orders of multiplexing and array gains are realizable.The system model is shown in Figure (3.1). The left side presents uplink process, while the right side is downlink process. From this picture, it can be seen that when users try to communicate with base station, their data stream should be pre-coded firstly according to obtained channel state information which is estimated by sending pilot sequence.



Figure(3.1) System Model of uplink and Downlink process.

Based on system model, we can easily obtain mathematical model for massive MIMO systems, from assumption the channel matrix is modeled as independent complex Gaussian randomvariables with zero mean and unit variance. The channel between the BS and the k_{th} user isdenoted by a 1 × Mrow vector h^t_k (K = 1,2,3……. .K).A M× Nchannel matrix H betweenthe BS and all users consists of channel vectors h^t_k. Let $W_k$denote the column vector oftransmit pre-coding and s_k represent the transmit symbol for the kth user at downlink.

Similarly, let w_k denote the column vector of receive combining filter for the kth user atuplink. Also, let n_k be the additive white Gaussian noise vector. Then, the receiver vector isgiven by equation (3.1):

$$y = \sqrt{P_d} + H_x + n = \sqrt{P_d} H W_x + n \qquad (3.1)$$

The received signal at the k_{th} user is expressed by:

$$y_k = \overbrace{\sqrt{P_d} h_k^T w_k s_k}^{\text{Desired signal}} + \overbrace{\sqrt{P_d} \sum_{l=1}^{k} h_k^T w_l s_l}^{\text{interuser interference}} + n_k \qquad (3.2)$$

Where: P_d is transmit power in a downlink.

3.1 Precoding

Precoding provides two fundamental advantages, including eliminate interference and performing beamforming to the desired users. In general, there are two types of pre-coding, non-linear precoding schemes and linear pre-coding schemes. Non-linear pre-coding can achieve both of these two function, while the linear one can only reduce inter-users interference [14].here we will discuss the linear precoding.

In wireless communication system, due to the geographic effect, received signal cannot be obtained simultaneously [15]. Inter-user interference cannot be eliminated by multi-user detection as well. Under this circumstance, precoding will play a significant role in improving system performance.

Compared to nonlinear precoding schemes, the complexity of linear precoding schemes the complexity is remarkably lower. Moreover, due to a massive amount of DoF in massive MIMO, linear precoding schemes are enough to satisfy communication requirements [13,14].

3.1.1 Linear Precoding Schemes:

In conventional multiuser MIMO systems, optimal capacities can be achieved if the BS implements complex signal processing techniques, such as, maximum-likelihood (ML) multiuser detection on the uplink and dirty paper coding (DPC) [6] on the downlink. Unfortunately,such complex signal processing techniques incur large computational burdens which grow exponentially with the size of the system, for example with the number of BS antennas M.

As a result, when M and K are large, such techniques consume large amounts of circuit power, thus becoming highly unsuitable for massive MIMO operations.

Fortunately, in the large M regime, linear signal processing techniques, such as maximum-ratio combining (MRC) on the uplink and maximum-ratio transmission (MRT) on the downlink, can achieve near-optimal throughput performance

In massive MIMO systems, when the amount of transmitted antennas approaches infinity, the system can be simplified as a Single-input-to-Single-output (SISO) systems [11]. Therefore, to optimize spectral resources in massive MIMO systems, pre-coding is used at the transmit side in order to reduce the complexity of system, diminish noise effect and optimize stream data transmission based on channel state information (CSI) [12,13,14]. There are three common linear pre-coding schemes, including MRC, ZF and MMSE.in this thesis we will discuss the MRC and the ZF techniques.

(1) Maximum-ratio combination

This scheme is to maximize SNR by seeking to maximize the power at the receiver combiner. MRC is considered as a viable linear reception scheme for massive MIMO systems since it can be applied in a distributed manner. Moreover, MRC has a satisfactory performance in the low-power regime, even approaching to optimal performance as the amount of antennas grows infinitely. However, as the power increase, systems based on MRC scheme suffer from serious inter-user interference [1].

The received signal at *kth* branch, y_k, and theoutput of the MRC combiner, d, are given by

$$d = \sum_{k=1}^{M} w_k^H y_k \qquad (3.3)$$

$$y_k = h_k u + n \qquad (3.4)$$

$$w_k^H = h_k^H \qquad (3.5)$$

The transmittedsignal, u is corrupted by the channel effects characterized by *hk* , while *wk* isthe associated weight of the *kth* antenna element. From an EE perspective, sucha low signal processing requirement is highly desirable in the large M regime because optimalsignal processing techniques, such as ML detection, consume prohibitively large amounts ofcircuit power when the size of the system is large. Note that MRC detection experiencesperformance degradation in interference-limited scenarios because the effects of inter userinterference are neglected.

(2) Zero-forcing

The ZF scheme is to eliminate inter-user interference by projecting the received signals into the orthogonal elements.Since ZF scheme does not take noise into consideration, system based on ZF precoding scheme has a poor performance in low power regime. The performance in high-power regime approaches to optimal [1].

$$X_{ZF} = (H^H H)^{-1} H^H Y \qquad (3.6)$$

A disadvantage of ZF detection is that it suffers from sudden noise enhancement; hence, the performance of ZF degrades without considering the noise.

(3) MMSE

MMSE scheme seeks to eliminate inter-user interference as well as noise. Compared to MRC and ZF, system complexity of MMSE is relatively higher.
MRC has the lowest complexity among these three precoding schemes. MMSE ruires perfect channel state information [1].

$$X_{MMSE} = G_{MMSE} = (H^H H + \sigma_n^2/\sigma_{nx}^2 l)^{-1} H^H Y \qquad (3.7)$$

Where σ is the variance, H is estimated matrix channel, Y is received signal. In comparison with ZF detection, MMSE detection considers the noise variance and decreases noise enhancement, while the computational complexity of MMSE detection is greater than that of ZF detection.

3.2 Energy Efficiency in Massive MIMO

The Energy Efficiency (EE) of a communication system is measured in bit/Joule and is computed as the ratio between the average sum rate (in bit/second) and the average total power consumption PT (in Watt = Joule/second).

The total EE metric accounting for both uplink and downlink takes the following form.

The total EE of the uplink and downlink is:

$$EE = \frac{\sum_{k=1}^{k}\left(E\left\{R_K^{(UL)}\right\}+E\left\{R_K^{(DL)}\right\}\right)}{P_{TX}^{(UL)}+P_{TX}^{(DL)}+P_{CP}} \qquad (3.8)$$

Where P_{CP} accounts for the circuit power consumption (joule/sec).

And R_K is the user gross rate (bit/sec).

The circuit power consumption PCP is the sum of the power consumed by different analog components and digital signal processing.

3.2.1 Power Consumption Model

Since a large number of antennas are involved in, circuit power consumption which is mainly yielded by radio frequency (RF) chain cannot be neglected [11,19]. In communication system, each antenna is equipped with one RF chain. RF chain in downlink consists of mixer, filter, digital-to-analog converter (DAC) as well as synchronizers, which is shown in fig(3.2)

Figure (3.2) Structure of RF chain [12]

Received signal x is firstly fed into band-selective filter, power amplifier, synchronization, low-pass filer and auto gain control module (AGC). Then, an A/D converter is adapted to converts analogue signal to digital signal by quantization.
In this case, more antennas contribute to more circuit power consumption. As a result, massive MIMO comprises energy efficiency for spatial efficiency. Additionally, system loss associated to hardware for RF seriously threats on system performance. Hardware loss includes quantization error, phase error, phase shift of carrier frequency and sampling frequency, nonlinear power amplifier [30].

In conclusion, a large amount of antennas in massive MIMO systems does improve spatial efficiency and capacity but lead to extra power consumption based on analysis. Therefore, it is important to find a balanced trade-off among different aspects of system performance.

3.2.2 Mathematical Model of Power consumption:

Based on analysis above, we can get the mathematical model for total power consumption,

$$P_{k.total} = \frac{\frac{P_t}{n\left(1-\sigma_{feed}\right)}+P_{cir}+P_{sta}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \qquad (3.9)$$

Where$P_{k,total}$is kth use's total power consumption. $P_{cir}$is circuit power consumption which can be calculated by $P_{cir} = N\left(P_{dac} + P_{mix} + P_{filt}\right) + P_{syn}$, P_{dac} is DAC power consumption. P_{mix} is mixer power consumption. P_{filt} is filter power consumption. N is activated transmitted antennas. P_{sta} is idle power consumption. σ_{DC}, σ_{MS}, σ_{cool}, σ_{feed} are the loss factors of antenna DC-DC power supply, main power supply, active cooling system and antenna feeder respectively [23].

In this project, we ignore loss factors [11].

Therefore, equation (3.8) EE can be given in mathematical way as below:

$$EE = \frac{\sum capacity}{\sum_{i=1}^{k} P_{i,total}} \qquad (3.10)$$

The asymptotic Shannon capacities on the uplink (CUL) and the downlink (CDL) for a multiuser MIMO channel under favourable propagation are given by :

$$C_{UL} = \sum_{k=1}^{K} log_2\left(1 + p_{u,k} M \beta_k\right) \qquad (3.11)$$

$$C_{DL} = max_{(a_k \geq 0, \sum a_{k \leq 1})} \sum_{k=1}^{K} log_2(1 + p_{d,k} M_{a_k} \beta_k) \qquad (3.12)$$

where $p_{u,k}$ and $p_{d,k}$ are the uplink and downlink signal to noise ratios (SNRs) for the kthUE, β_k represents the large-scale fading coefficient for the kth UE, and $\{a_k, k = 1,2, \ldots, K\}$ is an optimization vector to obtain C_{DL}. For simplicity, if we neglect the effect of β_k and assume that each UE transmits with an average signal to noise ratio p_u, the uplink Shannon capacity simplifes to

$$C_{UL} = K log_2(1 + M p_u) \qquad (3.13)$$

A similar argument can be made about downlink transmissions as well. The simplification illustrated above leads us to two important observations (i) the system throughput canbe improved by increasing K, i.e., by multiplexing parallel streams of data to more number of UEs over the same time-frequency resource, and (ii) transmission power per UE can be decreased by increasing M, i.e, the number of BS antennas, while still maintaining the same throughput per UE.

In massive MIMO systems, since a large amount of antennas arrays are implemented, we can achieve a desired capacity with a lower power consumption. Here we will concentrate on the achievable capacity of massive MIMO systems. Methods to Improve Energy efficiency in Massive MIMO Systems are shown in figure(3.3)

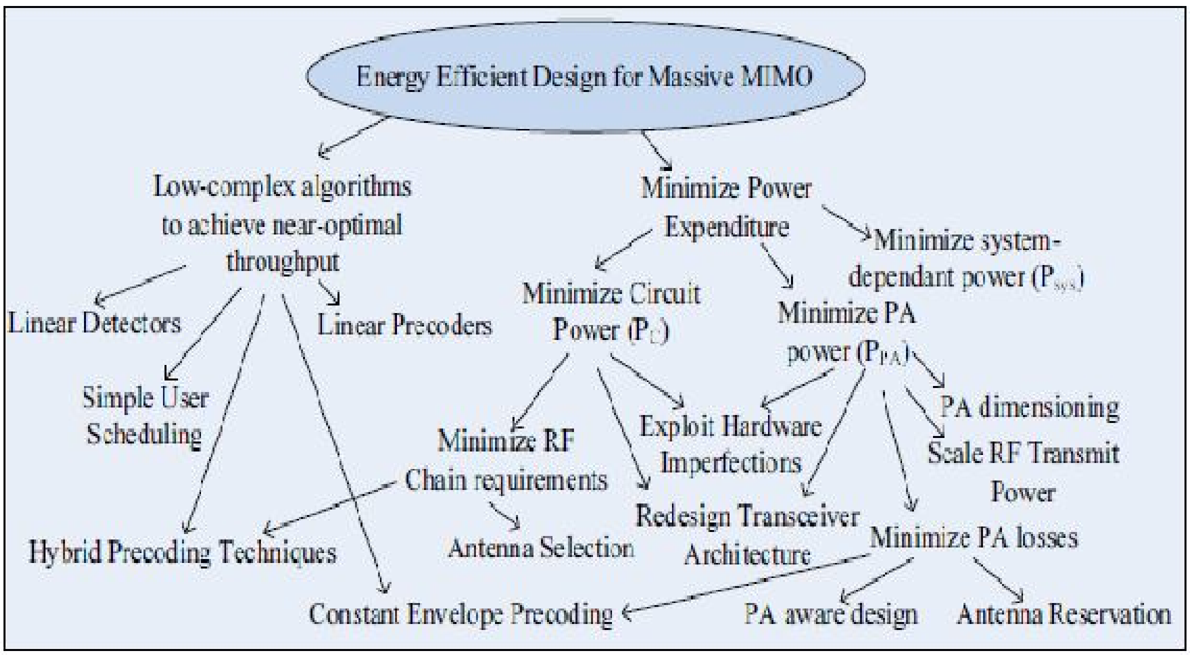


Figure (3.3): Overview of standard EE-maximization techniques for massive MIMO systems.

3.3Achievable capacity under perfect CSI.

We first consider the wireless communication system under perfect CSI, which is known as $\boldsymbol{G}$. Mathematically, assuming a detector matrix $\boldsymbol{A}$ whose dimensions are $\boldsymbol{M}\times\boldsymbol{N}$, where $\boldsymbol{M}$ and $\boldsymbol{N}$ is the number of antenna in BS and the number of users in a cell, respectively. $\boldsymbol{A}$ is dependent on $\boldsymbol{G}$, which is defined as below

$$A = \begin{cases} G for MRC \\ G(G^H G)^{-1} for ZF \\ G\left(G^H G + \frac{1}{P_u} l_k\right)^{-1} for MMSE \end{cases} \quad (3.14)$$

For a receiver with linear detector, the received signal can be written as:

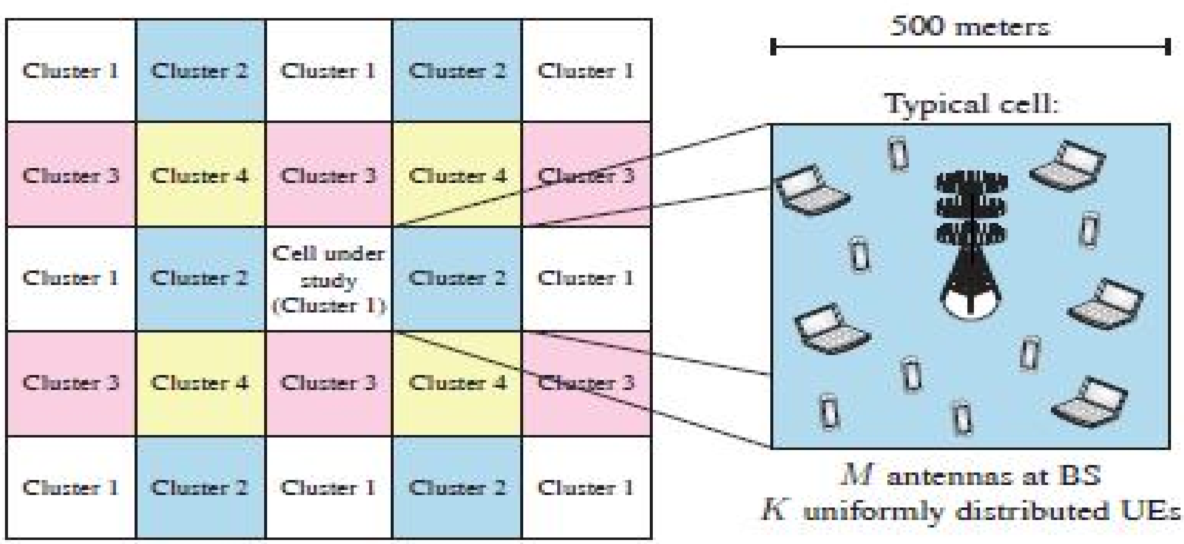
$$r = A^H * y \quad (3.15)$$

The vector r in (3.15) gives the received signals from all the users where A is the linear detector matrix that depends on the channel matrix G and H is the Hermitian operator. In theory, we can encode information over realizations in baseband to obtain this capacity. In practice, however, we can encode source information in wideband domain, such as Orthogonal Frequency-division Multiplexing (OFDM). When we consider that received side has perfect CSI, the receiver can reconstruct signal perfectly. Therefore, the influence of noise and interference caused by channel can be cancelled. In theory, the base station will apply the maximum likelihood detector in order to achieve optimal capacity. Under this circumstance, however, the complexity in received side will be exponentially raised as increase of the number of users. As we discussed previously, in massive MIMO systems, linear coding schemes can also meet our requirements, we will theoretically analyze the system performance of massive MIMO based on ZF, MRC .

3.4 Multicell scenario

The analytic framework and observations of this thesis can also be applied in multi-cell scenarios. To illustrate this, we consider a completely symmetric scenario where the systemparameters M, K, and gross rate are the same in all cells andoptimized jointly. The symmetry implies that the cell shapes, user distributions, and propagation conditions are the same in all cells.

we consider the symmetric multi-cell scenario illustrated in Figure (3.3) and concentrate on the cell in the middle.Each cell is a 500 *500 square with uniformly distributed UEs, with the same minimum distance as in the single-cell
scenario. We consider only interference that arrives from the two closest cells (in each direction), thus the cell under study in figure(3.3) is representative for any cell in the system.Motivated by the single-cell results, we consider only ZF processing and focus on comparing different pilot reuse patterns. As depicted in figure(3.3), the cells are divided into four clusters the same pilots in all cells.



Figure(3.3)Multicell scenario where the cell under study is surrounded by 24 identical cells

Table (3.1) SIMULATION PARAMETERS

Parameter	Value
Cell radius (single-cell): dmax	250 m
Minimum distance: dmin	35 m
Large-scale fading model: l(x)	$10^{-3.53}/\|\|X\|\|^{3.76}$
Transmission bandwidth: B	20 MHz
Channel coherence bandwidth: BC	180 kHz
Channel coherence time: TC	10 ms
Coherence block (symbols): U	1800
Total noise power: Bσ2	-96 dBm
Relative pilot lengths: T(ul); T(dl)	1,2,4
Computational efficiency at BSs: LBS	12:8 Gflops/W
Computational efficiency at UEs: LUE	5 Gflops/W
Maximum number of users	150
Maximum number of antennas	200