COMP5327

Wireless Networking and Mobile Computing

Group Project Report

MIMO: History, Mechanism, Application and Challenges

Group 7

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Contribution Table:

Name	**Contribution**	**Percentage**
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Abstract

The Multiple-Input Multiple-Output (MIMO) have become a key technology of multiple wireless communication standards since the last decade. In this paper, the full picture of MIMO will be shown through surveying the key components of MIMO, its applications, and challenges. In addition with its history and the reason why this technology becomes a compulsory part of modern wireless communication standards.

1. Introduction

Multiple-Input Multiple-Output (MIMO) is a radio frequency technology utilising multiple antennas on both receiver side and transmitter side to carry signals, which have been widely adopted in most of the cellular network standard in the last decade, including 3G, LTE, 5G, Wi-Fi (IEEE 802.11) and WiMAX (IEEE 802.16). Currently the MIMO technologies is still evolving with few types developed since the 90s, including original point-to-point MIMO, MU-MIMO and massive MIMO, to fulfil the increasing demand and requirements of wireless communications.

2. Why MIMO

Modern era of mobile usage such as the advent of radio wireless systems, smartphones occupy a substantial amount of frequency bandwidth and network bandwidth. Although frequencies and capacity are increasing at a steady rate, the load keeps increasing exponentially [1, 2]. Spectral bandwidth has become a valuable commodity [1]. People demand a more stable network connection, faster network response while not sacrificing any data transmission drop and any previous technology benefits, as known as Quality of Service (QoS) [1, 2].

The challenge is to ensure the quality is maintained, such as network reliably and uniform network strength with an ever-increasing wireless throughput [2, 3]. MIMO is the remedy of this, as it offers significant increase in data throughput and link range without installing additional hardware for more power or upgrading bandwidth [2]. Additionally, it reduces fading effect, interference, power transmission [4]. Giving it an excellent candidate for tackling the problem.

3. History

The foundation of diversity communication can be traced back to the early 1900s, which RCA engineers Harold H. Beverage and Harold O. Peterson noticed the signal strengths varied when two wireless signals were transmitted half mile apart, concluding the theory of diversity system which improved the audio quality by introducing two antennas that the distance between the antennas should be at least one wavelength long to support reliable operation [5]. The foundation became further mature during the 40s and 50s, as two legacy papers were introduced in 1948 by Shannon and Wiener, which significantly inspired the development of MIMO 60 years later.

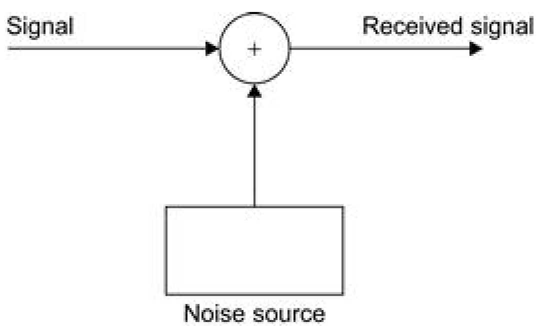

Fig. 1. Model introduced by Shannon in 1948 [6]

The paper by Shannon introduced a probabilistic model based on a statistical nature of the communication medium for calculating the accurate maximum transmission rate, which the model is applicable using today [6].

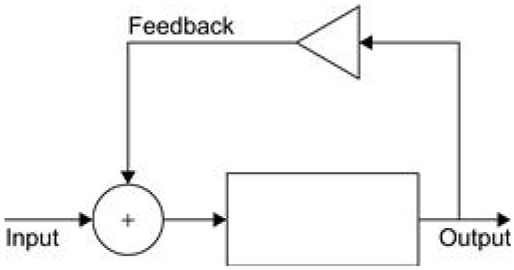

Fig. 2. Model introduced by Wiener in 1948 [6]

On the other hand, Wiener introduced the same capacity formula with feedback in the communication scheme like Fig. 2 which offers output control without the need of explicit model – “black box” [6].

The use case of spatial diversity was limited to maximize the best signals by limiting the degradation of multipath up until the 90s, where few initial proposals of MIMO was introduced [1]. First of all, a patent related to multiple transmit antennas located as the same transmitter to strengthen the attainable link throughput was issued to Arogyaswami Paulraj and Thomas Kailath in 1993 to 1994 [1, 2]. Then, a paper introduced by Bell Laboratories in 1996 proposed a large communication capacity system which included multiple transmit and receive antennas by assuming transmission radio has no knowledge on utilizing multiple antennas for transmission, and had been successfully prototyped in 1998 [1, 2, 5]. Meanwhile, a paper by Raleigh and Cioffi utilized the Bell Laboratories’ theory in 1996 and demonstrated the communication capacity could be even larger when the transmitter has knowledge on the channel itself [5]. Finally, Alamouti suggested using precoding when the transmitter does not know multi-antenna transfer function [5].

In 2000s, with the 3rd Generation Partnership Project (3GPP), MIMO had been introduced to the Release 8 of the Mobile Broadband Standard as a component of Wi-Fi (IEEE 802.11n), 4G LTE and 5G, which MIMO have since widely adopted on most of the wireless communication technology we used every day [7].

4. Types of MIMO

4.1 Point to Point MIMO

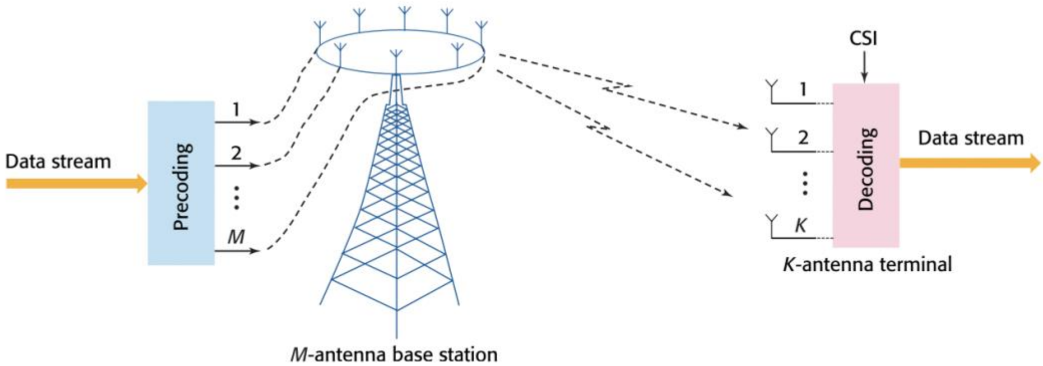

Fig. 3. Point-to-Point MIMO architecture [3]

Point-to-Point MIMO which also known as single user MIMO (SU-MIMO), is the original type of MIMO, serving a single user at a time. As shown in Fig. 3, both base station of Point-to-Point MIMO and the user end equips multiple antennas which increase the data transfer rate compared to Single-Input Single-Output (SISO) system significantly, without the needs to increase the bandwidth nor signal-to-noise ratio [8]. In order to serve multiple users, they are assigned with different frequency blocks by combination of time division and frequency division multiplexing [3].

Point-to-Point MIMO utilize vector-valued signal which contains distinct pieces of information for transmission, and it is multiplied by the channel matrix on the receiver side, that a well-conditioned channel matrix allows the receiver to recover the distinct signals or important linear combinations of signal effectively [3]. Training processes are required on the receiver by transmitting pilot signals from the transmitter to learn the matrix-valued channel [3].

Although its advantages like higher data transfer rate, Point-to-Point MIMO limits on maximum 8 antennas on both transmitter and receiver side and the reasons are summarized by [3]:

1. Eight data streams may not be supported by propagation environment due to the line-of-sight condition as compact arrays limits data stream to one
2. Proportional amounts of time are required in matrix-valued channel training when number of antennas increase
3. Signal to Interference & Noise Ratio are low on the edge of the cell with low multiplexing gain when applying minimum amount of antennas
4. Independent electronic chains are required on each antenna, result in complicated user equipment
5. Further improving performance requires involved signal processing on base station and user end

4.2 Multi-user MIMO (MU-MIMO)

The introduction of MU-MIMO solves the problems of Point-to-Point MIMO while maintaining its benefits, by splitting the multiple antennas on the user end into multiple users with single antenna and handling multiple users' connection by the same time frequency block [3, 8]. The elimination on the need to equip multiple antennas on the user end reduce the cost and difficulty due to the small size on most user devices [1, 4]. In addition, limitations like degraded channels, line-of-sight condition, and channel correlation do not results in huge impacts on performance in MU-MIMO [1, 4].

However, few limitations and challenges still occur in MU-MIMO and summarized by [4]:

1. Interference when serving multiple users.
2. Perfect Channel State Information (CSI) is required to process the received signals coherently in Base Station, which is impractical in real life situation especially during high mobility.
3. Cost of employment is still expensive as precoding and CSI are required to schedule user in same time-frequency block.

4.3 Massive MIMO

Massive MIMO which also known as Large-Scale MIMO, is the successor of MU-MIMO with the significant change on base station through equipping more than 100 antennas, compared to around 8 antennas in previous two generations of MIMO [9]. The number of antennas installed on the base station is assumed to be far exceed the number of users serving and each user's terminal only include a single antenna [9, 10]. It is achievable by the small wavelengths of mmWave which becomes a part of 5G standard and spectrum ranges from 30 GHz - 300 GHz are used, to reduce the dimensions of antenna and spacing between each antenna significantly, packing many antennas into extremely small from factors on both base station and user end [8, 11].

The advantages of massive MIMO are summarized below:

Offering reliable communication and spectral efficiency – Massive MIMO introduced spatial multiplexing which gains the reliable communication and spectral efficiency by creating higher spatial data stream, throughput, and multiplexing gain through the increasing number of antennas compared to previous generations of MIMO [4, 8, 10].

Energy efficiency – it is achieved by few multiple ways. First, combining the signals from user end coherently with large array of antennas reduce the energy usage for transmission during uplink [4]. Second, during downlink, signals are directly transmitted to the direction where the user terminal located, reducing the power of signals required [4]. Third, doubling the antennas but maintaining the same number of users to be served allows to decrease the transmission power while keeping the same spectral efficiency [4]. Fourth, for user with single antenna, the transmission power can be scaled down proportionally to the number of antennas equipped in base station when perfect CSI is available or square root of the number of antennas when imperfect CSI is the only option [9]. Finally, massive MIMO offers extra range of operation compared to single antenna system when adequate transmission power is available [9].

Low complexity of signal processing – simple linear precoding is employed on uplink and decoding on downlink to remove the effects of interference between users and noise when favorable propagation is available [3, 4].

Low Latency – by utilizing technique like beamforming and having larger option on selecting data streams, signals can be transmitted with better signal-to-noise-ratio and bit rate while pointing to desired direction directly to prevent interference, resulting low latency transmission [12].

Security improvement – passive eavesdropping attacks can be prevented by beamforming and signals from intentional jammers can be cancelled by the large array of antennas with its freedom on transmission degrees [10].

Cost efficiency – by eliminating the coaxial cables connecting between base station components, using cheap milliwatts amplifier and reducing the radiated power 1000 times while maximizing the data rates, the cost efficiency in massive MIMO is much efficient than previous generations [10].

5. How MIMO Works

First, we need to install multiple antennas on a base station. [3] Then, we have multiple terminals such as smartphones, all of which have non-directional, small antenna, with one and only one antenna in each user [3]. With all these setups, the basic MIMO structure is complete.

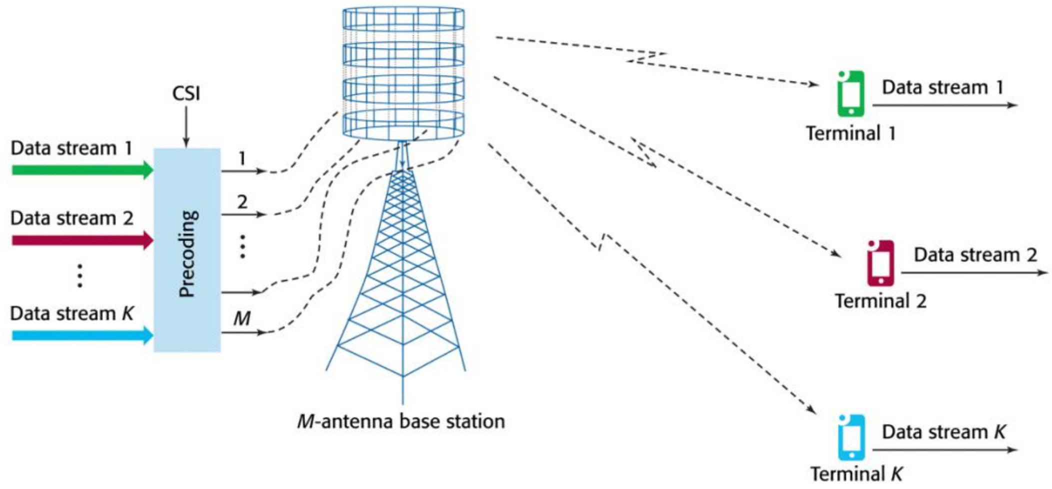

Fig. 4. Downlink [3]

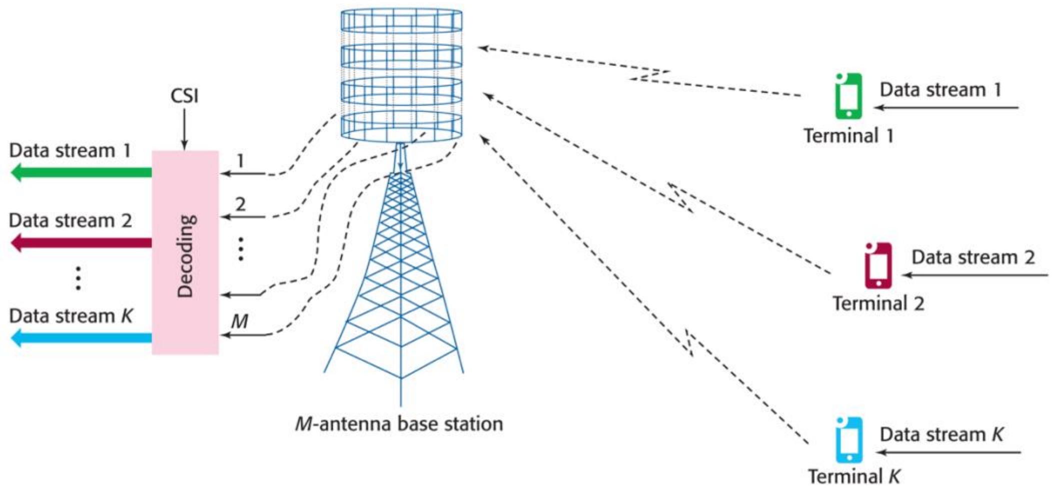

Fig. 5. Uplink [3]

The MIMO main task is to perform downlink and uplink [3]. Downlink transmits data from multiple data streams to the terminals. The data stream is multiplexed (precoded) such that the terminals can receive and only receive the data streams he/she desires [3]. For example, if terminal 1 wants to receive data stream 1 and 2, the MIMO will only give him data stream 1 and 2. For data stream 3 to data stream K, it will be removed, or at least did not cause interference to data stream 1 and 2.

Uplink, on the contrary, transmits data from the terminal(s) to the antenna base station. The antenna base station receives a sum of signals from the terminals and will do multiplexing (decoding), then send them to multiple data streams [3].

Both uplink and downlink utilize a technique called multiplexing which precodes or decodes the signals into different data streams. Modern MIMO such as massive MIMO uses spatial-division multiplexing, meaning different data streams occupy the same frequencies and times through splitting the whole space into cells [3]. Before carrying out multiplexing, the base station's multiplexer needs to know the characteristics of a signal, such as shape, frequencies of a signal, travelling to and from the users and the data stream(s) [3]. This kind of information called channel state information (CSI) [3]. Data streams are transformed into signals for downlink, and summed signals can be mapped into respective data streams.

6. MIMO Components

This section continues section 5 in greater technical detail. The downlink procedure involves two major steps. The first step: beamforming, and the second step: precoding [12].

In the beamforming process, different data streams are transmitted to the base station, and then base station will transform multiple data streams into a single strong beam according to the user [12]. Beamforming stacks the desired signals in a spatial way and rejects the other unrequired signals as interference [12].

The precoding process uses the received beamformed signal and does preprocessing which includes superposition of signals [13]. The superposition process requires knowing the frequency response between the user and the elements of the propagation channels [12]. The precoding is to ensure when sending the signal to the receiver, there is no interference from other devices such that other devices will not receive the wrong signal and the receiver and have the best and strongest signal received [13]. Techniques for doing precoding include linear precoding and dirty-paper-coding [9].

The uplink procedure has 4 steps:

The first step is to perform encoding [12]. The encoding process converts data into symbols and usually MIMO adopts space-time coding [12].

The second step is transmitting pilot and uplink data sequences simultaneously in the same frequency from each user to the base station [12]. The pilot sequences are for estimating CSI in both uplink and downlink [12]. During transmission, the signal will inevitably experience fading, scattering and other signal deficiencies due to long propagation. The CSI needs to accommodate different signal conditions and successfully recognize the signal is sent by whom and establish a complete transmission [12]. It is done by collecting the power of the uplink UL [14].

The third step is when the base station receives the sum of signals from the users and estimates the channel [12]. When the signal is received, the base station measures the actual signal and predicts which channel is sent from [3]. The most common way to perform channel estimation is time division duplex [9, 12] (TDD). TDD is the channel that is periodically estimated from uplink and the estimation results will be applied both in uplink and downlink operations [9, 12]. However, this type of channel estimation brings up pilot contamination [9], this will be further discussed in later sections.

Another rarer form of channel estimation is using Frequency division duplexing (FDD). The uplink and downlink use different frequencies as well as CSIs [12]. The uplink channel estimation is performed by letting user send pilot sequences. While in downlink, the CSI is obtained by transmitting pilot symbols from the base station to all users and then the users respond by sending the estimated CSI to the base stations [9, 12]. The number of base station’s antennas is directly proportional to the time for transmission for downlink [12]. Moreover, if there are more antennas, the complexity of FDD will increase and it might become impossible to resolve [9, 12]. In general, FDD requires more time to setup and train than TDD [3].

The final step is decoding and performing detection operations to generate individual data.

7. Other Applications

Besides becoming a standard component of wireless communication standards like Wi-Fi, 4G and 5G mentioned before, other applications including homogeneous network (HomoNet), heterogeneous network (HetNet), unmanned aerial vehicle (UAV) and wireless sensor network can also benefits from MIMO technology.

For HomoNet which only includes macro-cell deployment, benefits of massive MIMO are summarized by [2]. In the case of multi-layer sectorization which divide a cell into multiple sectors to fulfil the increasing demand on wireless communication, massive MIMO achieves accurate sectorization with less interference by performing horizontal high-selectivity angular beamforming [2]. In addition, for HetNet which include both macro and small cells, massive MIMO is used at the macro-cell radio access nodes for supporting wireless backhauls which is easier to be deployment than the wired backhauls [2].

On the other hand, cell-free massive MIMO which serves users without cell boundaries by utilizing a series of access points controlled from a same CPU with coherent transmission and reception, can assists the communication link for unmanned aerial vehicle (UAV) [15]. UAV which often considered to be used in military, surveillance and monitoring and delivery of medical supplies, can actually act as a flying base station, increasing the network coverages and capacity by continuously updating its location [15]. Cell-free massive MIMO assists UAV to achieve this by offering reliable, low latency and high data rate uplink and downline between access points and user even in bad channel conditions [15].

In wireless sensor network which aims to monitor, measure, and detect physical phenomena like temperature, pressure, and humidity, multiple antennas installed in base station offered by MIMO not only achieves better detection and estimation performance, but also better energy efficiency even when utilizing simple algorithm and limited CSI information [12].

8. Pilot Contamination

This crucial problem in massive MIMO occurs when the reusing same time-frequency of blocks due to the limited frequency spectrum available, resulting cell contamination by pilot signals from users in neighbour cells, which weaken the system performance [4, 12]. Eventually, system fault will be caused if the number of interfering cells increased which the situation cannot be solved by increasing the number of antennas on base station to the infinity [4, 12].

Few methods have been proposed solve or moderate the effect and they are summarized below:

*Channel Estimation Method*s – the essential components directly affects the overall performance of massive MIMO by selecting the best CSI from picking the strongest channel impulse response [10, 12]. Methods like TDD and FDD have be proposed, however, TDD could also be the reason of pilot contamination [9].

Optimum Pilot Reuse Factor Methods – by choosing a frequency reuse factor larger than unity optimized or reducing the number of users utilizing non-orthogonal pilot sequences, however, may only make little difference in general [9, 12].

Pilot Sequence Hopping Methods – randomization is introduced on moving users to a new pilot between time slots, resulting a randomized pilot contamination [12].

Cell Sectoring based Pilot Assignment – by splitting cells into centre and edge region which partly sequences are used by users in neighbouring border, number of serviced user can be reduced to improve the service quality [12].

Besides these methods, techniques like distributing single-cell precoding, detecting Angle of Arrival (AoA) of users, time-shifted pilot methods and cooperative methods which finds the optimum pilot for all base stations, are also proposed to tackle this significant challenges [9, 12].

9. Conclusion

This paper briefly introduced MIMO, a form of communication technology that can improve network throughput without installing additional hardware or expanding the bandwidth. MIMO has gone through different phases including Point-to-Point MIMO, MU-MIMO and today's most popular form: Massive MIMO; all of which performs the basic functions for uplink and downlink, with some variance in channel estimation and encoding techniques. This paper also discusses applications including UAV and HomoNet, limitations such as pilot contamination and its remedies to tackle this problem.

The popularity of massive MIMO is rising due to rapid adoption on 5G and 5G mmWave with its supported devices like smartphones, self-driving vehicles. Currently, there is ongoing research on mmWave regarding the operations in mmWaves, and in real life scenarios [15]. For instance, the channel estimation techniques in mmWaves to allow massive data transfer are a future research direction [15]. In addition, pilot contamination is still a huge topic on MIMO research, as none of the methods can solved the situation perfectly and channel estimation method TDD default method causing the pilot contamination problem.

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