COMPARATIVE STUDY OF SPECTRAL EFFICIENCY ANALYSIS IN MIMO COMMUNICATIONS

KRISHNA PATTETI[a1], ANIL KUMAR TIPPARTI[b] AND KISHAN RAO KALITKAR[c]

[a]Department of Electronics and Communication Engineering, S. R. Engineering College, Warangal, Telangana, India
[b]Department of Electronics and Communication Engineering, M. V. S. R. Engineering College, Hyderabad, Telangana, India
[c]Department of Electronics and Communication Engineering, Sreenidhi Institute Technology & Sciences, Hyderabad, Telangana, India

ABSTRACT

Higher data rates and area throughput is required in future wireless cellular networks, since the global demand for wireless data traffic is continuously growing. These goals can be achieved without the need for more bandwidth or additional base stations antennas if the spectral efficiency (bit/s/Hz/) is improved. This paper, discuss the fundamental channel capacity analysis, bandwidth and importance and impact of the various factor of SE in SISO to massive MIMO communications systems.

KEYWORDS: Channel Capacity Analysis, MIMO, SNR and SE.

The amount of data carried by mobile networks continues to increase as growing numbers of users demand more data-rich and on-demand content. Multiple-input Multiple-output (MIMO) systems has been provides high data rate and a wide variety of applications such as IEEE 802.11, High Speed Packet Access (HSPA), Third Generation partnership projects Long Term Evolution (3GPP-LTE) and 5G telecommunications systems. Recent advances in wireless cellular communication systems have contributed to the design of multi-user scenarios with MIMO communication.

The next generation of cellular wireless communication systems (5G) should support a large range of applications such as low latency communication. This requires a more flexible assignment of the channel bandwidth and time frequency resources. Massive MIMO system play vital role for achieving these requirements of next generation communication systems.

Massive MIMO promises order of magnitude spectral efficiency (SE) gains by employing hundreds or even more antennas at the BS to spatially multiplexing(SM) tens of UEs. Major requirement to achieve SE and array gain enables high energy efficiency (EE) is the availability of accurate channel state information (CSI). The Massive MIMO system is economically feasible, low cost per antenna and broadband system must significantly less than in current systems.

This paper provides an insight importance and impact of the various factor of SE in SISO to massive MIMO communications systems. We firstly present some of the main aspects of the channel capacity analysis of SISO, MIMO, SU-MIMO and Multiuser MIMO communication. Finally, we introduce linear precoding techniques which could be exploited SE of multi-user MIMO systems in order to improve the system performance with suppress inter-user interference.

CHANNEL CAPACITY ANALYSIS

In this part, we present the channel capacity of SISO and MIMO systems. This helps to reveal the potential capacity gain of MIMO system and to understand the influence of various system parameters on the channel capacity.

SISO System Chapacity

According to Shannon [Tse and Viswanath, 2005] the capacity of a communication channel is the maximum bit rate for which arbitrarily small error probability can be achieved. The achievable capacity of AWGN channel in SISO is given as

$$C_{awgn} = B_w \log_2\left(1 + SNR\right) \qquad (1)$$

Where channel bandwidth is B_w.

For fading channels, no single definition of capacity can be applicable in all scenarios. Several notions of capacity are developed to form a systematic view of performance limits of fading channels. These various capacity measures reveal the different resources available in fading channels: power, diversity and degrees of freedom [Tse and Viswanath, 2005].

With only channel state information at receiver (CSIR), the transmitter sends the information data over all available frequency bandwidth including deep fading frequencies. Further, we define two types channel capacity such as ergodic and outage capacities [Goldsmith, 2005 & Choudhury and Gibson, 2007]. Then the ergodic capacity is defined as [2]

$$C_{awgn} = \int_0^\infty B_w \log_2\left(1 + \gamma\right) p\left(\gamma\right) d\gamma \qquad (2)$$

Where γ is the instantaneous SNR at the receiver, the probability density function (PDF) of γ is $p\left(\gamma\right)$. The ergodic capacity measures the average of the instantaneous capacity.

On the other hand, outage capacity applies to slow fading channels where the instantaneous SNR is assumed to be constant for a large number of symbols. Unlike the ergodic capacity scenario where the data needs to be correctly received over all fading states, the outage capacity fixes a higher transmission rate in admitting some data loss in deep fading frequencies. Specifically, the transmitter fixes a minimum received

---

[1]Corresponding author

SNR γ_{min}. When the received SNR is below γ_{min} the received symbols cannot be correctly decoded and the receiver declares an outage. The probability of outage is $p_{out} = p\left(\gamma < \gamma_{min}\right)$.

The average rate correctly received over many transmission bursts is

$$C_{out} = \left(1 - p_{out}\right) B_w \log_2\left(1 + \gamma_{min}\right) \qquad (3)$$

We note that the value γ_{min} is typically a design parameter based on the required outage probability. The average rate correctly received C_{out} can be maximized by finding the optimal γ_{min}.

SU-MIMO System Capacity

Single user MIMO system has a BS with multiple antennas communicates with a single user terminal (UT) having multiple antennas. For SU-MIMO systems, the transmission is carried out between one transmitter and one receiver through M transmits antennas and N receives antennas. Assuming flat fading channel, the channel response can be written as a matrix $h \in {}^{M \times N}$ with the element $h_{m,n}$ corresponding to the flat fading coefficient of the link between the mth transmit antenna and the nth receive antenna. Exploit the antenna diversity when each transmits and receives antennas pair transmits the same information [Zheng and Tse, 2003]. In this case, each antenna pair can be considered as an additional signal path. The receiver side receives multiple independently faded copies of the information, which helps to confront the channel fading and enhance the transmission quality. Antenna diversity can be utilized at the transmitter and/or the receiver [Love and Heath, 2003]. Receive antenna diversity systems intelligently combine the multiple received copies to achieve a higher average receive SNR [Love and Heath, 2003].

A classical combing technique is maximum-ratio combining (MRC) [William, 1974], where the signals from the received antenna elements are weighted such that the SNR of their sum is maximized. Transmit antenna diversity is more difficult to obtain, the channel-dependent beamforming techniques (with CSIT required) or the channel-independent space-time coding techniques can be used. Particularly, for the case where CSIT and CSIR are both available, the maximum ratio transmission (MRT) for SU-MIMO systems, this maximum ratio algorithm uses in multiple antennas at both transmitter and receiver, provides optimum performance of the MIMO system can be obtain using transmit and receive diversity [Titus, 1999].

The system capacity can be defined according to MIMO diversity is given as

$$C = B_w \log_2\left(1 + \frac{1}{N} \sum_{p=1}^{N} \sum_{q=1}^{N} \left| \sum_{m=1}^{M} h_{m,p} h_{m,p}^* \right| SNR\right) \quad (4)$$

In the case where the transmission links are mutually orthogonal, i.e, $\forall p \neq q$,

$$\left| \sum_{m=1}^{M} h_{m,p} h_{m,p}^* \right| = 0$$

The system capacity takes the smallest value

$$C = B_w \log_2\left(1 + \frac{1}{N} \sum_{p=1}^{N} \sum_{q=1}^{N} \sum_{m=1}^{M} \left| h_{m,n} \right|^2 SNR\right) \quad (5)$$

In the case where the transmission links are fully correlated, i.e. i.e, $\forall p \neq q$,

$$\left| \sum_{m=1}^{M} h_{m,p} h_{m,p}^* \right| = \sum_{m=1}^{M} \left| h_{m,q} \right|^2 \text{ the system}$$

capacity takes on the largest value

$$C = B_w \log_2\left(1 + \frac{1}{N} \sum_{p=1}^{N} \sum_{q=1}^{N} \sum_{m=1}^{M} \left| h_{m,q} \right|^2 SNR\right) \quad (6)$$

On the other hand, when the transmission links are considered independent from each other, they can be used to transmit different information, and form multiple parallel spatial channels [22]. In this case, the system capacity can be enhanced thanks to the spatial multiplexing gain. When in high SNR regime, assuming CSIR and i.i.d. Rayleigh-faded gains between each antenna pair, the MIMO system channel capacity is

$$C = \hat{M}.B_w \log_2\left(SNR\right) + O\left(1\right) \qquad (7)$$

Where $\hat{M} = \min\left\{M, N\right\}$. Hence the theoretical MIMO channel capacity is multiplied comparing to that of a SISO system.

In Figure 1 shows that, the capacity versus number of transmit antennas of Multiuser MIMO System with Single antenna UEs. Also in figure 1 illustrated that for a fixed curve, system capacity grows with the number of transmit antennas increases, and the growth slows when the number of transmit antennas equal to receiver antennas. It can be concluded from the results, in the next generation wireless communication networks such as WLAN which could serve a large number of users and increase throughput, there are advantages of applying massive antennas.

Multiuser MIMO System Capacity

Multi-user MIMO system BS with multiple antennas is communicates with multiple user terminals (UT) each having one or multiple antennas [Shariati et.al., 2014].

There are many reasons why multi-user MIMO is the most scalable and attractive solution [Gesbert

et.al., 2007]. Firstly, the wavelength is 5-30 cm in the frequency range of cellular communication (1-6 GHz). This limits the number of antennas that can be deployed in a compact user terminal for point-to-point MIMO, while one can have almost any number of spatially separated single-antenna terminals in multi-user MIMO.

This is an important distinction since the number of simultaneous data streams that can be separated by MIMO processing equals the minimum of the number of transmit and receive antennas. Secondly, the wireless propagation channel to a user terminal is likely to have only a few dominating paths, which limits the ability to convey multiple parallel data streams to a terminal in point-to-point MIMO. The corresponding restriction on multi-user MIMO is that the users need to be, say, a few meters apart to have sufficiently different channel characteristics, which is a very loose restriction that is true in most practical scenarios. Thirdly, advanced signal processing is needed at the terminals in point-to-point MIMO to detect the multiple data streams, while each terminal in multi-user MIMO only needs to detect a single data stream.
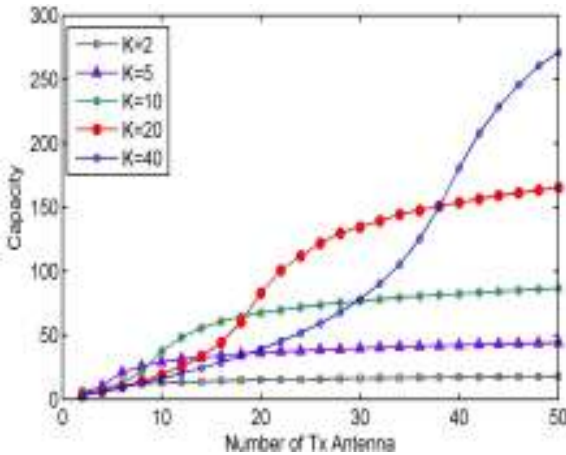

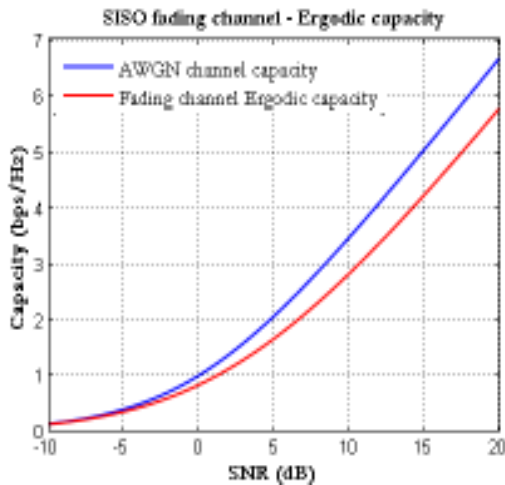**Figure 1: System Capacity of MIMO with number of Transmit Antennas**

Figure 2: Ergodic Capacity of a SISO system over a Rayleigh fading channel

The multi-user MIMO system consists of a BS with M antennas that serves K single-antenna terminal, in this system $\min(M,K)$ represents the maximal number of data streams that can be simultaneously transmitted in the cell, while still being separable in the spatial domain. The number $\min(M,K)$ is referred to as the multiplexing gain of a multi-user MIMO system is shown in Figure3 schematic illustration.
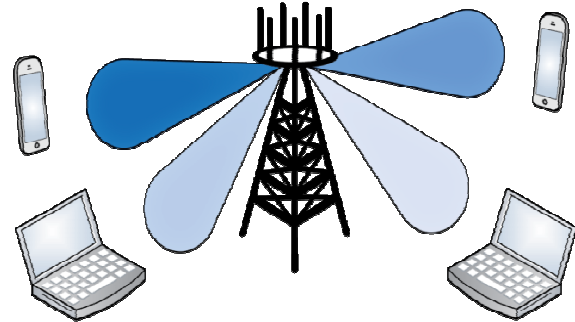

Figure 3: Multi-user MIMO system, where the BS is equipped with M antennas and serves K user terminals simultaneously

SPECTRAL EFFICIECNY OF MIMO COMMUNICATIONS

SE of SISO

The SE of single-input single-output (SISO) communication channel, from a single-antenna transmitter to a single-antenna receiver is upper bounded by the Shannon capacity, which has been expressed as the $\log_2$ (1+SNR) bit/s/Hz for additive white Gaussian noise (AWGN) channels. The SISO capacity is thus a logarithmic function of the signal-to-noise ratio (SNR). To improve SE, we need to increase the SNR, which corresponds to increasing the power of the transmitted signal.

For example, suppose that a system which has operates at 2 bit/s/Hz and we would like to double its SE to 4 bit/s/Hz and then corresponds to improving the SNR by a factor 5, from 3 to 15. The next doubling of the SE from 4 to 8 bit/s/Hz requires another 17 times more transmitted signal power. The SE expression has been described in logarithmic function, concludes that to increase the transmit power exponentially fast to achieve a linearly increase in the SE of the SISO channel. Therefore, this is clearly a very inefficient and non-scalable method to improve the SE and also this approach breaks down when there are interfering transmissions in other cells that scale their transmit powers in the same manner. Hence, we need to identify another process to improve the SE of wireless cellular networks.

The base station (BS) in a wireless cellular network simultaneously serves a multiple user equipments (UE).Traditionally the time-frequency resource blocks have been divided into resource blocks and only one of the UEs was active per each block. These active UEs can receive a single data stream with

an SE quantified as $\log_2\left(1+\dfrac{S}{N}\right)$. The efficient way to increase the SE of a cellular network is to have multiple parallel data transmissions. If the G is parallel and independent data transmission then sum SE becomes $G\log_2\left(1+\dfrac{S}{N}\right)$, where G is multiplicative pre-log factor. The parallel data transmission can implemented with the use of multiple antennas at transceiver ends.

SE of Mulituser MIMO

The BS multiplexes one data stream per user in the downlink and receives one stream per user in the uplink. The BS uses its antennas to direct each signal towards its desired receiver in the downlink, and to separate the multiple signals received in the uplink. If the terminal is equipped with multiple antennas, it is often beneficial to use these extra antennas to mitigate interference and improve the SNR rather than sending multiple data streams [Bjornson et.al., 2013].

Multiuser MIMO transmission capacity achieved based upon non linear signal processing techniques such as, the dirty-paper coding (DPC) scheme that achieves the downlink capacity and the successive interference cancelation (SIC) scheme that achieves the uplink capacity. The inter-user interference needs to be suppressed in DPC and SIC schemes, by interference-aware transmit processing and receive processing techniques to achieve the optimal performance. These non linear processing schemes naturally require extensive computations and accurate CSI, because otherwise the attempts to subtract interference cause more harm than good. The linear processing scheme called zero-forcing (ZF), which attempts to suppress all interference.

Figure 4 shows the average sum SE, as a function of M, achieved by sum capacity-achieving non-linear processing and a simplified linear processing scheme called zero-forcing (ZF), which attempts to suppress all interference.

The results are representative for both uplink and downlink transmissions. This simulation shows that the non-linear processing greatly outperforms linear ZF when $M \approx K$. The operating point M=K makes particular sense from a multiplexing perspective since the multiplexing gain $\min(M,K)$ does not improve if we let M increase for a fixed K. Nevertheless, Figure 4 shows that there are other reasons to consider M > K; the capacity increases and the performance with linear ZF processing approaches the capacity. Already at M = 20 (i.e., M=K = 2) there is only a small gap between optimal non-linear processing and linear ZF. In fact, both schemes also approach the upper curve in Figure 4 which represents the upper bound where the interference between the users is neglected. This shows that we can basically serve all the K users as if each one of them was alone in the cell. The sum capacity is compared with the performance of linear ZF processing

and the upper bound when neglecting all interference. The results are representative for both uplink and downlink.

Nevertheless, the suboptimal ZF curve in Figure 4 was generated without any complicated optimization, thus showing that the optimal linear processing obtained in [Bjornson et.al., 2012] can only bring noticable gains over simple ZF for $M \approx K$, which is the regime where we have learnt not to operate.

SE of Massive MIMO

The amount of data carried by mobile and cellular wireless networks continues to increase as growing numbers of users demand more data rich and on-demand content. The new 5G telecommunications systems will address this issue partly through the use of Massive MIMO.
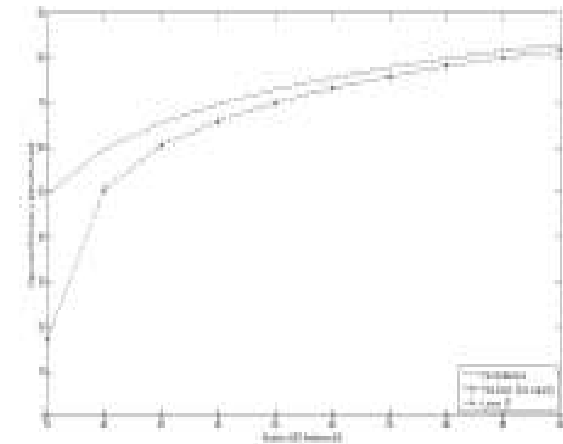
Figure 4: Average spectral efficiency in a multi-user MIMO system with K = 10 users and varying number of BS antennas. Each user has an average SNR of 5 dB and the channels are Rayleigh fading.

Massive MIMO is a form of MU-MIMO that comprises many base station (BS) antennas as comparison with standard MIMO. Massive MIMO systems the BS is equipped with tens or hundreds of low-power antennas and serves tens of UE simultaneously in the same time frequency resources.

Large number of antennas uses in Massive MIMO system to achieve increased throughput, reliability, spectral and energy efficiency. To achieve these high performance goals and its practical application has been limited due to the underlying signal processing complexity such as multi user detection and pre-processing techniques.

The area throughput of a wireless/cellular network is measured in bit/s/km[2] and can be expressed as

Area throughput (bit/s/km[2]) = Bandwidth (Hz) ×Cell density (cells/km[2]) ×Spectral efficiency (bit/s/Hz/cell)

For example, the cellular (terrestrial personal communications system in [12]) technology High Speed Packet Access (HSPA) has approximately 1 bps/Hz of average spectral efficiency in a deployed network [13]. Thus, with a downlink radio carrier of 10 MHz, 10 MHz ×1bps/Hz = 10 Mbps of aggregate throughput would be available for users. Ignoring some minor scheduling overhead, this amount of capacity translates to a single user with a continuous download speed of 10 Mbps or 10 users each with 1 Mbps.

The improvements in area throughput in previous network generations have greatly resulted from cell densification and allocation of more bandwidth. In urban environments, where contemporary networks are facing the highest traffic demands, cellular networks are nowadays deployed with a few hundred meters inter-site distances and wireless local area networks (WLANs) are available almost everywhere. Further cell densification is certainly possible, but it appears that we are reaching a saturation point. Moreover, the most valuable frequency bands are below 6 GHz because these frequencies can provide good network coverage and service quality, while higher bands might only work well under short-range line-of-sight conditions. In a typical country like Sweden, the cellular and WLAN technologies have in total been allocated more than 1 GHz of bandwidth in the interval below 6 GHz and thus we cannot expect any major bandwidth improvements either.

In contrast, the SE has not seen any major improvements in previous network generations. Hence, it might be a factor that can be greatly improved in the future and possibly become the primary way to achieve high area throughput in 5G networks. In this paper, we describe the rationale of the physical layer technology Massive MIMO, which provides the means to improve the SE of future networks by one or two orders of magnitude.

The 128 BS antennas managed to communication with 22 UE 256 QAM modulations scheme used on the same time-frequency resource. The corresponding spectral efficiency (SE) is 145.6 bits/s/Hz on single 20 MHz radio channel. SE is 71 bits/s/Hz achieved if ARIES array system uses 96 BS antennas will be serve 24 UEs and same system communicate with 12 UEs the corresponding SE is 79.4 bits/s/Hz, sum rate throughput of 1.59Gbit/s in a 20MHz channel.

The academic literature and researchers Massive MIMO system operates at a carrier frequency of 3.5GHz and supports simultaneous wireless connectivity to up to 12 single antenna UEs. Each UE shares a common 20 MHz radio channel. The complex DSP algorithms has been used the individual data streams in the spatial domain. Therefore Massive MIMO has been improving the SE greatly. With SE usually measured the sum SE of the transmission of individual cell in cellular network.

CONCLUSION

This paper has study and investigated the user channel capacity of SISO to Massive MIMO system, system capacity grows with the number of transmit antennas increases, and the growth slows when the number of transmit antennas equal to receiver antennas. Importance and impact of the system parameter factor of SE in SISO to massive MIMO communications systems, linear precoding techniques which could be exploited SE of multi-user MIMO systems in order to improve the system performance with suppress inter-user interference

REFERENCES

Tse D. and Viswanath P., 2005. Fundamentals of wireless communication. Cambridge university press.

Goldsmith A., 2005. Wireless communications. Cambridge university press.

Choudhury S. and Gibson J.D., 2007. Ergodic capacity, outage capacity, and information transmission over rayleigh fading channels. In Proceedings of the Information Theory and Applications Workshop.

Zheng L. and Tse D.N.C., 2003. Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels. Information Theory, IEEE Transactions on, **49**(5):1073–1096.

Love D.J. and Heath R.W., 2003. Equal gain transmission in multiple-input multiple-output wireless systems. Communications, IEEE Transactions on, **51**(7):1102–1110.

William C. Jakes, 1974. Mobile microwave communication.

Titus KY Lo, 1999. Maximum ratio transmission. In Communications, 1999. ICC'99. 1999 IEEE International Conference on, **2**:1310–1314.

Bjornson E., Kountouris M., Bengtsson M. and Ottersten B., 2013. Receive combining vs. Multi stream multiplexing in downlink systems with multi-antenna users. IEEE Trans. Signal Process, **61**(13):3431–3446.

Bjornson E., Zheng G., Bengtsson M. and Ottersten B., 2012. Robust monotonic optimization framework for multicell MISO systems. IEEE Trans. Signal Process, **60**(5):2508–2523.

Gesbert D., Kountouris M., Heath R., Chae C.B. and Salzer T., 2007. Shifting the MIMO paradigm IEEE Signal Process. Mag., **24**(5):36–46.

Shariati N., Bj¨ornson E., Bengtsson M. and Debbah M., 2014. Low-complexity polynomial channel estimation in large-scale MIMO with arbitrary statistics. IEEE J. Sel. Topics Signal Process, **8**(5):815–830.

Federal Communications Commission Technological Advisory Council, Sharing Work Group, "Spectrum Efficiency Metrics," Sep. 2011.

Rysavy Research, "Mobile Broadband Explosion, The 3GPP Wireless Evolution," 4G Americas, Aug. 2013.