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Research Article

Precoding, Pilot Contamination and CSI Acquisition in Massive MIMO Systems: State of Art and Research Trends

Swapnaja Deshpande[1], †Mona Aggarwal[1], Swaran Ahuja[1], Mohit Dayal[2], Pooja Sabherwal[1]

[1]Swapnaja Deshpande, Mona Aggarwal, Swaran Ahuja, Pooja Sabherwal are with the deptt of Electrical, Electronics and Communication Engineering, North Cap University, Sector 23 A, Gurgaon, Haryana, India-122017. (e-mail: deshpande.swapnaja@gmail.com, monaaggarwal@ncuindia.edu, swaranahuja@ncuindia.edu, pooja@ncuindia.edu)
[2] Mohit Dayal with the deptt of Information Technology, Bharati Vidyapeeth's College of Engineering, New Delhi-110063. . (e-mail: mohitdayal.md@gmail.com)
† Corresponding Author: monaaggarwal@ncuindia.edu

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Wireless communication is becoming increasingly important for micro economic indicators as the contribution of mobile broadband penetration to gross domestic product (GDP) growth is clearly established now. Developments in wireless technology like high bandwidth, low latency, resilience and reliability are further going to propel the economy. As we advance to long term evolution (LTE),5G, beyond 5G and 6G, massive multiple input multiple output (MIMO) systems become an integral part of technology development for addressing higher bandwidth requirements. With ultra-mobile broadband requirements of Industry 4.0 Internet of Things (IoT) applications, importance of 5G, beyond 5G, and 6G and hence massive MIMO systems becomes even more pressing. This paper presents a comprehensive review of three aspects precoding, pilot contamination and channel state acquisition of massive MIMO networks, its advancements and challenges while moving towards 6G wireless communication network. The paper highlights the paradigm shift brought by future wireless generation, characterized by enhanced energy efficiency, spectral efficiency, massive device connectivity, and higher frequency bands. The paper also explores its role in augmenting overall network performance via advanced techniques for signal processing. Considering the commercialization trajectory of MIMO technology and its integration into modern telecommunications, the paper highlights the ongoing research directions and future potential of massive MIMO networks gathering aspiring demands of 5G, beyond 5G and 6G wireless networks.

Keywords: Multiple Input Multiple Output (MIMO); Pilot Contamination (PC); Channel State Information (CSI); Energy Efficiency; Spectral Efficiency; Quality of Service (QoS)

1. INTRODUCTION

Requirement across industries is driving bandwidth and latency demands on cellular network as they are getting digitally transformed [1]. Industries need various IoT applications of massive and critical nature to rest on reliable and resilient, high speed cellular network i.e. 5G, beyond 5G and 6G [2,3]. Bandwidth efficiency, energy efficiency (EE), quality of service (QoS) become critical matrices of performance of such future networks whose evolution will be guided by industrial requirements emanating from Industry 4.0. As per various marketing research firms and study reports, per capital usage of mobile data is projected to grow many folds owing to change in consumer behavior and high-speed network availability. Current wireless networks, therefore, need to evolve to the new data centric requirements of industry and consumers, e.g. autonomous cars, vehicle to vehicle or vehicle to infrastructure communication, 4K-8K video streaming, robotics, smart manufacturing etc. Therefore. the cosmos of wireless communication has undergone an evolving journey, over several generations of technologies, each characterizing a momentous leap in capability, efficiency, and application. This evolutionary path has led us to the brink of the 5G, beyond 5G [4] and upcoming 6G

[5], a radical stage in wireless communication that promises exceptional speeds, reliability, and connectivity. The onset of 5G technology is certain to reconsider the outlook of digital communication, generating too many opportunities for industries and services. The transition to 5G is characterized by enhanced spectral efficiency, higher frequency bands, lower latency, and the ability to connect a massive number of devices jointly. 5G is a network specially designed to cover wide range of applications such as autonomous vehicles, Internet of Things (IoT) [6], smart cities, augmented reality (AR) virtual reality (VR), and much more. Due to enhanced capabilities of 5G networks, various industries such as automotive, healthcare manufacturing etc. are at great benefit.

One of the key technologies that supports the 5G architecture is Massive Multiple Input Multiple Output (MIMO). Massive MIMO system has a large number of base station (BS) antennas (M>>K>>1), where M is number of antennas at the BS and K is number of users, eliminating small scale fading, interference and noise and serves large number of users by utilizing available radio spectrum, thereby increasing overall SE [7,8,9]. This technology provides increase in capacity by utilizing available radio spectrum, which makes it more important element for 5G in achieving the required high data rates and low latency promised by 5G. Massive MIMO can enhance signal quality and system capacity, by exploiting techniques like beamforming and spatial multiplexing, making it a pivotal component for the success of 5G, beyond 5G and 6G networks. Thus, massive MIMO system approach is gaining importance as it offers exceedingly high bandwidth solution with no major power & interference overheads, thus, providing ultra-high throughputs. The wireless communication industry estimates increase in network capacity by 2000× until 2030; to meet the exponentially increasing demand for network traffic. Thus, one of the major concerns of wireless communication technology is to find a meeting ground between tremendous demand of network capacity at one hand and, constant spectrum availability on the other. We can augment network capacity multi fold by increasing cell density; SE and by utilizing more frequency spectrum. If we consider SE as a way to go, then massive MIMO system appears as a promising candidate for future wireless communication.

The concept of massive MIMO system is shown in Fig 1 where with increase in the number of antennas at the BS, uncorrelated noise and small-scale fading vanishes. In massive MIMO system, it is assumed that number of antennas at the BS must be significantly larger than the number of users, providing larger degrees of freedom which is then utilized to suppress interference [10], which is one of its potentials. Effective algorithms are required to make such systems practically feasible. Another potential of massive MIMO system is its increased energy efficiency (EE) as compared to single antenna system [11]. With the advent of massive MIMO system, we can scale down transmit power required by single antenna unit at the BS, which makes it a future candidate for green communication [12,13]. According to [14] we can deploy very large number of antennas with much low power for activation. We can achieve massive MIMO system performance without any loss even if we scale down transmit power and make it inversely proportional to square root of number of BS antennas [15]. The radiated power in massive MIMO system decreases with increase in the number of antennas at BS and it is in the range 10-100 mW. Due to this, it is possible to design massive MIMO system using low power transceivers instead of conventional high-power equipment. Thus, massive MIMO system as a technology provides higher data rates, improved link reliability, larger coverage and increased EE, thereby attracting many researchers. Most of the benefits, challenges and limitations of massive MIMO are inked down in the literature [16].

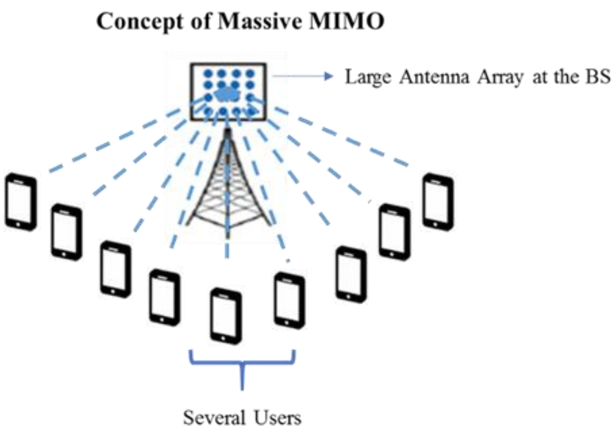

Figure 1. Concept of Massive MIMO

1.1 Paper Organization

The remainder of this paper is organized as follows: Section 2 below illustrates overview and potential of massive MIMO systems. Performance enhancement of massive MIMO systems can be achieved through effectively selecting precoding schemes, PC schemes and CSI acquisition techniques. Section 3 elaborates concept and various schemes of precoding. Section 4 describes concept and various schemes of PC. The concept and various schemes of CSI acquisition are discussed in Section 5. Application landscape is highlighted in section 6 and section 7 discusses future research areas of massive MIMO systems. Finally, last section 9 deals with the conclusion of the survey paper.

2. MASSIVE MIMO SYSTEM: AN OVERVIEW

Massive MIMO system is a multiuser MIMO technique which is better than conventional MIMO in terms of SE, EE, reliability and interference mitigation capacity. Considering antenna configuration of massive MIMO, system can be categorized into non-cooperative single cell/ multi-cell and cooperative single cell/ multi-cell massive MIMO system. In non-cooperative communication, BS is not concerned with the CSI of other cells whereas, in cooperative communication, BS knows CSI of other cells also. Non-cooperative massive MIMO system is further divided MIMO system into multi-cell, multi-user massive MIMO system as shown in the Fig 2 and point-to-point massive as shown in Fig 3.

In multi-cell, multi-user massive MIMO system, number of BS antennas is large as compared to the number of active mobile station (MS) antennas as depicted in Fig.2. Such antenna configuration will facilitate high receiver diversity gain resulting in suppression of multi-user interference (MUI) and noise. In point to point massive MIMO system, receiver and transmitter are equipped with large number of receiver and transmitter antennas as depicted in Fig.3. With large number of receiver and transmitter antennas, the channel becomes more and more deterministic. The diagonal elements grow larger as compared to off-diagonal elements which is called as "Channel Hardening (CH)". CH will facilitate simpler detection with enhanced performance.

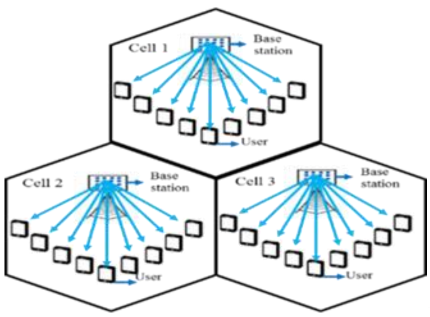

Figure 2. Multi-cell, Multi-user massive MIMO System

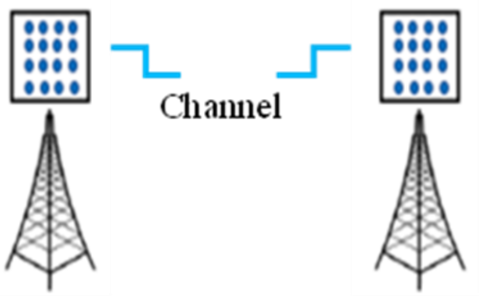

Figure 3. Point to Point massive MIMO System

Thus, by virtue of a large number of transmitter antennas, performance enhancement is achieved as discussed in literature [9,16]. But, the performance of non-cooperative system is limited by pilot contamination (PC) [16]. Therefore, further enhancements are achieved using cooperative communication [17]. Thus, cooperative multi-cell multi-user massive MIMO system is categorized into centralized and decentralized systems shown in Fig 4 and Fig 5 respectively.

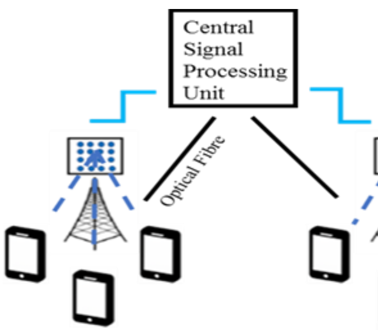

Figure 4. Centralized Massive MIMO System

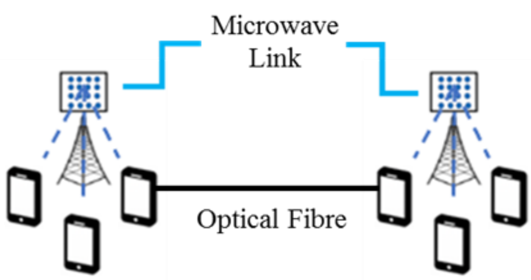

Figure 5. Distributed Massive MIMO System

By centralizing or by distributed approach, interference is further reduced to an acceptable level. In both systems, different BSs of adjacent cells of a particular area are connected with the help of microwave links or with high-capacity optical fiber. Thus, cooperative communication results in reduced interference but at the cost of increased backhaul traffic. These networks are also called as network MIMO. There are various advantages of massive MIMO which are discussed below in detail.

Array Gain Enrichment: With large number of antennas, massive MIMO system will provide more degrees of freedom thereby increasing signal to noise ratio (SNR) of the system as compared to single antenna system. Thus, this increase in power gain is array gain. Thus, large array gain can be achieved with massive MIMO system resulting from increase in SNR. For all linear schemes SNR increases with increase in value of M, resulting in large array gain. Thus, massive MIMO system can achieve large spectral efficiency by exploiting large array gain. Spectral efficiencies Obtained is ten times higher than that in the conventional MIMO technology [4].

Energy Efficiency: The massive MIMO systems are more energy-efficient. The transmit power is significantly reduced with increase in the number of transmit antennas. Thus, the throughput could be increased without increasing the transmit power. Massive MIMO systems have the ability to maximize the data rates by reducing the transmitted power 1000 times below conventional MIMO.

Capacity Enrichment: The capacity of multiuser-MIMO scales linearly with min (M, K). If M is increased keeping K fixed, then array gain achieved will increase significantly with reduction in inter user interference. Thus, network capacity of massive MIMO system is increased.

Inter User Interference Attenuation: When $M \rightarrow \infty$, user channel becomes orthogonal thereby supressing inter user interference.

Simpler Precoding and Detection: Simple linear schemes will give optimal DPC performance. Hence, we can design a massive MIMO system with linear precoding and detection scheme.

Hardware Cost Optimization: In massive MIMO system, use of large number of antennas, will lead to suppression of fading, noise and hardware imperfections which facilitate low power components. Massive MIMO system is efficient even in case of failure of few antenna elements. We can transmit signals with very low peak to average power ratio (PAR) or with constant envelope (CE) with the advent of massive MIMO system thereby facilitating cheap low power components. Thus, due to all, aforementioned advantages it is possible to build an inexpensive massive MIMO system.

Low Latency: Low latency wireless links can be built with massive MIMO system due to cancellation of fading effect.

Enhanced Security: Massive MIMO systems are more robust to internal jamming, hackers, and static intruders, which poses a serious cyber security threat. With the help of large number of antennas, we can cancel the signals from intentional jammers. Thus, enhanced security is obtained with massive MIMO systems.

Channel Hardening: CH is a process in which off-diagonal elements vary very slowly as compared to diagonal elements of propagation channel matrix in massive MIMO system. Due to channel hardening, small scale fading disappears i.e. signal to interference and noise ratio (SINR) at the receiver will not vary with small scale fading coefficients, thereby giving stable output at the receiver. Another advantage of channel hardening is that resource allocation is to be done only when large scale fading occurs in the channel. Another advantage is that we get more stable precoders and detectors.

Beamforming: Beamforming for massive MIMO system can be analog or digital. Digital beamforming is linear precoding in which received signal strength of the intended user obtained is very high on the other hand, in analog beamforming, directional narrower beams for intended user can be obtained with significant separation between user signals but, performance of analog beamforming is limited by the number of orthogonal beams used and radio frequency (RF) chains deployed. With large number of antennas in massive MIMO system, array calibration is required for analog beamforming, which is complex, however, it is not required in digital beamforming. Digital beamforming is flexible and hardware friendly therefore, we consider it for massive MIMO system over the analog one.

User tracking: A massive MIMO system can point narrow signal beams to the users; making reliable and accurate user tracking when required. user tracking become more reliable and accurate.

Reliability: Due to high diversity gain, obtained with massive MIMO systems link reliability increases to a greater extent. All above mentioned advantages of massive MIMO are listed below in table 1.

Table 1: Massive MIMO Benefits

Sr No	Massive MIMO Potential
1	Array Gain Enrichment
2	Capacity Enrichment
3	Inter User Interference Attenuation
4	Simpler Precoding and Detection
5	Hardware Cost Optimization
6	Low Latency
7	Robustness
8	Channel Hardening
9	Beamforming
10	Accurate User Tracking
11	Enhanced Security
12	Energy Efficiency
13	Spectral Efficiency
14	Increased Link Reliability

With large number of antennas in massive MIMO systems, there are various signal processing challenges. Few of them, i.e.; precoding, channel estimation and pilot contamination are discussed in details below.

3. PRECODING

One of the main technologies in massive MIMO systems is precoding, which plays important role in eliminating the effects of interference and fading, thereby increasing the throughput and capacity, when the number of antennas approaches infinity. Precoding is done at the BS to mitigate inter user interference. The BS will design a precoder in such a way to maximize the gain and minimize the interference by using CSI. CSI is an essential factor while designing a precoder. So, with the advent of precoder we can suppress inter user interference and thus increase in the network sum rate of the system. Precoding methods are divided into linear and non-linear methods. Linear precoders are ZF, MF, Block Diagonalization (BD) and MMSE. Non-linear precoders are DPC, Tomlinson Harashima Precoding (TH) and Vector Perturbation (VP). Non-linear precoders are very complex but achieve optimal sum rate capacity as compared to linear ones. If we consider MIMO system, then DPC will give optimal performance at the cost of increase complexity. For DPC implementation, complete channel gain at the transmitter side is required. In massive MIMO system, with many antennas at the BS, the channels between users and BSs become orthogonal which is mandatory to realize interference free transmission. Thus, linear precoding schemes will give near optimal performance in massive MIMO systems. The linear and non-linear precoding methods are discussed below in details.

3.1 Linear Precoding

Consider linear precoding, with transmit vector as

$$T = W\sqrt{P}x \quad (1)$$

Where, W is precoding matrix, P is power allocated to different users (K), x is the transmit signal for K users. While precoding, W is designed in such a way to cancel interference and maximize SNR of the system. considering sum power constraint $E\{\|T\|^2\} = 1$, we have

$$Tr\{PW^H W\} = 1 \qquad (2)$$

Thus, power normalisation factor γ can be defined as

$$\gamma = Tr\{PW^H W\} \qquad (3)$$

Linear precoding considering total radiated power constraint and per-antenna power constraint is studied in [18,19]. Precoders under total radiated power constraint will emit signal with high peak to average power (PAR) ratio which is not desired. To tackle high PAR signal, higher back off is required which results in degradation of power efficiency of amplifiers. So, precoders with low PAR signals are desired. Massive MIMO with low PAR precoders is investigated in the literature [20,21]. Linear precoding schemes [30] for massive MIMO DL system can give optimal DPC capacity performance with a smaller number of BS antenna. Approximately, 98% of DPC capacity is obtained with linear precoding schemes with 20 BS antennas. When channel correlation is high, capacity of DPC and MMSE is equal to that of single user transmission rate and capacity of ZF is zero. When channel correlation becomes zero, sum rates of ZF and MMSE precoders becomes equal to DPC capacity. Zero channel correlation indicates orthogonal user channels, due to which linear precoding schemes like ZF, MMSE give near optimal DPC capacity performance. Comparison of three linear precoders and two non- linear precoders is done in [22] for single carrier and orthogonal frequency division multiplexing (OFDM) transmission scheme.

A. Zero Forcing (ZF)

It is a precoding technique which aims to mitigate interference by transmitting multipath signals meant for intended user and adding up destructively to zero for other users. It results in interference cancellation but at the cost of reduced signal strength of the intended user. This technique gives optimal performance for high SNR scenario. The ZF precoding matrix is given as:

$$W_{ZF} = H^{\dagger} \qquad (4)$$

Where $H^{\dagger} = H^H (HH^H)^{-1}$ is the pseudoinverse of the channel matrix H and $(HH^H)^{-1}$ is Gram Matrix. Let us examine sum power constraint for ZF precoder which is given as,

$$\sum_{l=1}^{K} P_{ZF,l} \, [(HH^H)^{-1}]_{l,l} = 1 \qquad (5)$$

Wherein, $P_{ZF,l}$ is the l-th diagonal element of P_{ZF}. Power requirement for user signals is governed by channel condition. If channel vectors are orthogonal i.e. Gram matrix is diagonal, then transmit power is fully utilised by intended user. But if channel vectors are not orthogonal i.e. Gram matrix is not diagonal, then more power is required for nulling and thus limited power for intended user. This will result in reduced receiver signal strength which is a drawback of ZF precoder.

If M>>K, then SINR of ZF precoder is given as:

$$SINR_{ZF} = P_d \left(\frac{M-K}{K}\right) \qquad (6)$$

Where, P_d is the DL power

ZF and maximum ratio transmission (MRT) linear precoders are compared and analyzed for single cell DL massive MIMO system [23,24] in terms of maximum achievable data rate and transmit power. Comparative analysis reveals better performance of ZF than MRT. ZF precoding [25,26] gives higher power efficiency and higher data rates for single cell scenario. ZF precoder is used for simplifying large matrix inversion, reducing total power consumption, facilitating user distribution thereby enhancing network sum rate of the system and used for EE and SE enhancements. These aspects are discussed below.

B. Large Matrix Inversion

DL precoding involves complex large matrix inversion, to alleviate this complexity a novel method based on Neuman series expansion is used in [27]. In this new method, full matrices are converted into multiplication of diagonal matrices by hollow matrices. So, DL massive MIMO with ZF precoding along with above method results in reduced complexity and avoiding delay in high mobility scenario. Another fast matrix inversion method [28] with reduced complexity, based on Neuman series is introduced for massive MIMO system with ZF precoding. The basic concept of Neuman series for fast matrix inversion is illustrated in [29]. Higher complexity of matrix inversion is simplified by Neumann series expansion in [30]. Less complex Neumann series version is utilized for DL ZF multiuser massive MIMO system. There are different algorithms for calculating exact large matrix inversion such as QR-Givens Rotation [31], QR-Gram Schmidt, Gauss-Jordan, but Neumann series is desired one for inversion purpose. Comparison of QR-Gram Schmidt and Neumann series expansion in terms of number of mathematical operations and the energy associated with the calculations is also discussed in [30]. Symmetric successive over relaxation method (SSOR) [32] outperforms Neumann based precoding and truncated polynomial expansion precoding and resulting in near optimal performance with relatively small number of iterations.

C. Conjugate gradient (CG)

CG based precoding is proposed in [33] to reduce the computational complexity of Neumann Series. In CG based precoding, SINR is directly calculated using CG algorithm and thus, do not require large matrix inversion, resulting in simplicity of precoding design.

D. Power Consumption

In wireless communication, focus is on reducing BS Power consumption. With increase in wireless traffic, it is very important to design a BS with minimized power consumption, as it consumes 80% of power. An attempt to reduce power consumption while maintaining QoS is done in literature [34,35,36,37] considering small scale fading environment. But, the impact of small-scale fading is negligible in massive MIMO system [38]. Power allocation problem for massive MIMO system is addressed in [39]. Power allocation and user association is jointly optimized in [40] which results in improved sum rate of the network. Multicell massive MIMO DL system is considered, where power consumption is minimized using non-coherent joint transmission with MRT and ZF precoding.

E. User Distribution

The impact of non-uniform user distribution on system performance of DL massive MIMO system is given in [41] using ZF precoder. In [42,43,44] distance between user and BS is assumed to be deterministic but randomness of user location is very important for area SE analysis. In literature, Probability Density Function (PDF) [45,46] model and Poisson Point Process (PPP) [47] models are used to determine the randomness of user location, so, we studied center intensive user distribution and edge intensive user distribution for maximum achievable sum rate and EE of massive MIMO System. It is observed that center intensive user distribution outperforms edge intensive user distribution in terms of maximum achievable sum rate of the system.

F. Energy Efficiency and Spectral Efficiency

EE and SE of large antenna array are much higher than that of small antenna array [9]. Analysis is done using maximum ratio combining (MRC) and ZF precoding. ZF is better than MRC due to its ability to suppress intracell interference. But, in multicell scenario, ZF is not able to suppress intracell interference completely.

EE (bits/Joule) = SE (sum rate in bits/channel)/ Transmit Power (Joules/ Channel)

Increase in SE results in increased transmit power thus decrease in EE. So, generally there is trade-off between SE and EE. Energy efficient hybrid precoding and minimum RF chain (EEHP-MRFC) algorithm is proposed in [48] for 5G wireless system employing large number of antennas at the BS which outperforms conventional ZF precoding algorithm. Critical number of antennae searching (CNOAS) and user equipment number optimization (UENO) algorithms are introduced in [49] for maximizing energy efficiency of 5G system. Energy efficiency of massive MIMO system is studied in literature [50-52].

EE and SE of signal to leakage and noise ratio (SLNR) precoding scheme for massive MIMO system is analyzed in [53]. SLNR precoding scheme is used to balance desired signal power and a leakage (interference) power. SLNR precoding scheme gives same performance as MMSE precoding scheme while considering equal power allocation (EPA). Signal to leakage and noise precoding scheme (SLNR-PS) [54] with optimal power allocation (OPA) gives better results as compared to SLNR-PS with EPA.

G. Matched-filtering

MF precoding is also referred as MRT aims at nulling inter user interference and maximizes SNR of intended user. The MF precoding matrix is given as

$$W_{MF} = H^H \quad (7)$$

For an arbitrary P_{MF}. The SINR for MF precoder is given as

$$SINR_{MF} = \frac{P_d M}{K(P_d+1)} \quad (8)$$

Due to its capability of maximizing SNR of intended user, it is preferred for noise-limited scenario. MF precoding gives optimal performance for low SNR scenario, since at high SNR its performance is limited by interference. DL massive MIMO system with MRT precoding scheme is analyzed [55] considering a large-scale fading channel. Due to large number of antennas, large scale fading is very dominant in massive MIMO system [56]. But, in [57] large scale fading factor is neglected. It is found that there is large impact of large-scale fading factor on SE considering both perfect and improper CSI. Also, reduction in SE due to large scale fading factor with imperfect CSI is minimal. Performance parameters, i.e. SE, EE and reliability of a DL massive MIMO System are analyzed in [58] using MRT precoding and considering CSI delay. If CSI delay is increased, then system performance deteriorates. SE is directly proportional to user terminals (UTs) but, at the cost of system reliability.

Maximum ratio combining (MRC) and ZF precoders for multicell massive MIMO DL system are studied in [59] with pilot contamination. The system is observed under two different scenarios i.e. DL with pilot and DL without pilot. When M is small, beam forming gain of MRC outperforms interference suppression capability of ZF and vice versa. ZF excels MRC at low cross cell interference level. As cross cell interference level increases, both MRC and ZF show the same performance.

Phase noise degradation of DL massive MIMO is studied in [60] with ZF and MRT linear precoders. Greater robustness is shown by MRT as compared to ZF precoder in terms of phase noise degradation. But achievable rate per user is lower in case of MRT precoder. Phase noise degradation for ZF and MRT precoders is independent of large number of transmit antennas M.

User interference and outage probability is analyzed in [61] for single cell multi-user massive MIMO system with MF precoding. In most of the cases performance evaluation of massive MIMO system is done by calculating network sum rate of the system. Outage probability analysis of massive MIMO system is also an important aspect for evaluating user experience. With large number of users in massive MIMO systems, the SINR degrades which results in large outage probability. This will highly degrade the performance of massive MIMO system so; it is very important to analyze outage probability thereby achieving required massive MIMO gains. In wireless communication system, certain amount of signal called threshold is required for acceptable communication performance. If signal level drops below this threshold signal, then user will experience outage, so, during the fade period, user experiences signal outage. Outage analysis for massive MIMO system is given in [62,63] but [64,65,66] do not provide any useful information for analysis of multiuser MIMO. So, in [67] outage probability and user interference analysis of multi-user DL massive MIMO system is considered with MF precoding. The signal outage probability can be calculated easily if probability distribution i.e. pdf of fading is known. The computational complexity increases if fading is related with multiple interfering signals. Herein, outage probability is calculated by using pdf of user interference power.

H. Minimum Mean Squared Error

MMSE precoder gives trade-off between signal efficiency and interference suppression. It is suitable for entire SNR range. In MMSE precoder, estimated noise covariance at the receiver is feedback to the transmitter. The MMSE precoding matrix is given as

$$W_{MMSE} = H^H(HH^H + \alpha I)^{-1} \qquad (9)$$

Where, α is a regularization parameter resulting from minimizing MSE. MMSE is also known as regularized zero forcing (RZF) precoder. It is designed by considering measured user noise power and transmit power available at the BS. When $\alpha = 0$, MMSE precoder will act as ZF precoder and when $\alpha = \infty$, it will act as MF precoder. For the entire range i.e. $0 -$

∞ MMSE will give optimal performance then ZF and MF, due to its lower MSE then ZF and MF. It has the advantage of reducing Power required for interference reduction then ZF.

Degree of freedom (DOF) provided by massive MIMO can be exploited to suppress interference and increase SE. Therefore, massive MIMO is coupled with device to device (D2D) underlay cellular network in [64] forming D2D underlay massive MIMO system. A novel time division duplexing (TDD) scheme is used for CSI acquisition from the BS to D2D and interference aware MMSE precoder is used to suppress cellular to D2D interference. Recently, MMSE Precoder for DL Massive MIMO is proposed in [68] where, MSE of users is minimized under 1-bit constraint.

I. Regularized and Phase Zero Forcing Precoder (RZF and P-ZF)

SINR analysis for RZF, ZF and MF precoders is done in [65] considering phase noise for massive MIMO system. CSI quality of massive MIMO system is directly proportional to phase noise. When phase noise increases, quality of CSI acquired at the BS gets degraded. SINR of all precoders decreases with increase in number of oscillators. With a greater number of oscillators, interference power increases and signal power decreases. For MF precoder, interference power is independent of the phase noise. SINR performance of RZF is better than ZF and MF when phase noise is considered. ZF is better than MF when phase noise is less at the BS. MF is better than ZF when phase noise is severe for low SNR region. [40] reveals that for EE, MF is preferred and for SE, ZF precoder is preferred.

Comparison of linear precoders Eigen beam forming (BF) and RZF for multicell multiuser TDD massive MIMO system are studied. Results show that RZF gives same performance as that of BF with reduced number of antennas per user terminals. RZF precoding for multiuser DL massive MIMO [66] is utilized for maximum EE. Performance parameter i.e. SE of massive MIMO system is analyzed using MR, ZF and phase zero forcing (P-ZF) precoding for both DL and uplink (UL) configuration [67]. Impact of user scheduling and resource allocation on SE is also analyzed. Maximum SE per user is given by PZF, but MR shows poor performance per user. But, as far as user scheduling is considered, MR gives better performance than P-ZF. If per cell SE is considered, then, ZF gives best performance. P-ZF is only required under stringent intercell interference scenario. The impact of CSI acquisition on SE is discussed in literature [7,17,69].

J. Truncated Polynomial Expansion (TPE)

Herein Cayley -Hamilton theorem is utilized which states that, the inverse of large matrix say B of dimension S can be written as

$$B^{-1} = \frac{(-1)^{S-1}}{det(B)} \sum_{e=0}^{S-1} \alpha_e B^e \quad (10)$$

Where, α_e are the coefficients of the characteristic polynomial.

Inversion of large matrix in regularized ZF is becoming complex with large number of antennas in massive MIMO system. Matrix operation in RZF has cubic complexity in min (M, K) [70] while, MRT has square complexity [71]. To address this issue, TPE based precoder is evaluated in [72,73]. TPE enables balancing of precoding complexity and system throughput via different truncation orders. In TPE, inverse of Hermitian matrix is expressed as a matrix polynomial. Thus, TPE based precoders are less complex and give better performance in terms of throughput.

K. Block Diagonalization

Block diagonalization is a linear precoding technique preferred for users with multiple antennas. BD precoding mitigates interference from other user signals and inter-antenna interference of each user is cancelled by different signal detection techniques employed at the receiver end.

In massive MIMO system, cell edge user performance is improved by using a new method of Soft Pilot Reuse (SPR) [74]. SPR is used along with multicell BD (MBD) precoding which improves UL and DL rates for edge users. SPR scheme significantly eliminates PC and enhances QoS of the massive MIMO system. MBD precoding eliminates inter cell interference (ICI) and thus improves average DL cell throughput.

Low complexity hybrid BD precoding for DL multiuser massive MIMO is proposed in [75] which gives near optimal performance like conventional BD precoding.

Precoding scheme such as BD, regularized BD (RBD), Generalized ZF Channel Inversion and Generalized MMSE Channel Inversion can be used for multiple antenna users. BD precoding outperforms RBD in high SNR regime [76,77].

Therefore, BD and BD space time block code (STBC) precoders are evaluated in [78] for massive MIMO DL system. Capacity performance of BD precoding outperforms BD-STBC for both cases of perfect and imperfect CSI.

L. Hybrid Precoding (HBP)

Digital beam forming for massive MIMO system is very expensive with increased power consumption. To address above issue, hybrid beam forming is proposed where precoder is divided into digital baseband precoder and RF analogue precoder. Architecture of massive MIMO system with hybrid precoding and beamforming is explained in fig 7.

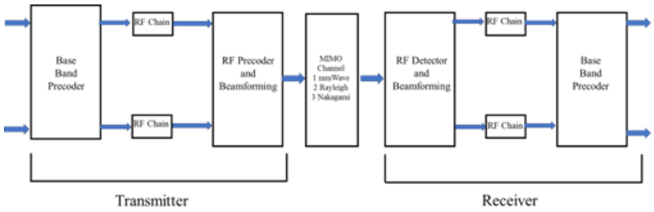

Figure 7. Hybrid Precoding and Beamforming

Thus, low computational complexity, low implementation cost, reduced feedback overhead, are some of the advantages of hybrid precoding discussed in [79].

M. Constant Envelope Precoding (CEP)

Practical implementation of massive MIMO system is very difficult and faces many problems such as high RF chain cost, and high peak to average power ratio (PAPR). With M no antennas, M RF chains and linear power amplifiers (PAs) are required which results in costly hardware. Therefore, research is going on to reduce requirement of RF chains enabling low cost implementation. Due to high PAPR, expensive linear PAs are required to cancel out-of-band radiations and signal distortions. Therefore, research is going on to invent new transmission schemes which result in low PAPR transmit signals, thereby enabling low cost implementation of massive MIMO BSs. Thus, to deal with aforesaid issues, CEP which has low PAPR is used, enabling energy efficient implementation of massive MIMO. Implementation of cost effective and energy efficient large antenna arrays in massive MIMO system is a big challenge. For cost effective implementation, non-linear highly efficient power amplifiers must be used in DL massive MIMO system. Input signal must lie in the linear region of the non-linear PA transfer characteristics curve to avoid non-linear PA distortion. Therefore, input signal with high PAPR must be scaled down in amplitude to achieve required results. With CEP, the input signals are obtained with low PAPR and thus improved power amplifier (PA) efficiency. CEP scheme for frequency flat multiuser massive MIMO is proposed in [80]. A new precoding scheme based on CEP using phased shift keying modulation for MU-MIMO DL is explained in [81] wherein, MUI is used to increase SINR ratio at the receiver. The proposed precoding scheme outperforms conventional precoding scheme. CEP technique for single user scenario is explained in [82] while for MU-MIMO is explained in [83]. In [82,83] transmitted signals have constant amplitude thereby facilitating low-cost PAs. In [84] MIMO precoder is divided into RF precoder and baseband precoder, enabling low-cost implementation of massive MIMO systems. The RF precoder gives array gain and baseband precoder gives spatial multiplexing gain of massive MIMO system. Manifold advantages of two stage CEP are low -cost implementation, reduced number of RF chains, enabling non-linear PAs at the base station, reduced CSI signaling overhead, and no need of OFDM to combat frequency selective fading as it is done by two stage-CE precoder.

A precoder based on Approximate Message Passing (AMP) is used for multi user massive MIMO system [85] which significantly suppresses MUI and enables hardware friendly implementation. With AMP precoders, we can use cheap, highly power efficient amplifiers at the BS. AMP precoding is proved to be better than CE and Annulus Constraint (AC) from computational complexity and average running time point of view.

N. Two Stage Precoding

The two-tier precoding scheme, is useful in alleviating basic implementation problems of massive MIMO systems such as huge pilot symbols, large number of RF chains, requirement of real time global CSI and high computational complexity. In two-tier precoding, outer precoder is used to mitigate intercell and inter cluster interference and inner precoder is used for spatial multiplexing of inter cluster users. Two stage precoding schemes is discussed in [86] in which precoder is divided into baseband precoder and RF precoder, with limited RF chains and reduced CSI signaling overhead.

O. Other Precoding Methods

Subspace constrained precoding is used in [87], for FDD massive MIMO system. Herein, precoder is divided into inner precoder (for spatial multiplexing gain) and transmit subspace control matrix (for inter cell interference (ICI) mitigation). Due to large antenna array in massive MIMO system, channel vectors of each users are usually concentrated in a subspace with much smaller dimension then M, which motivates the idea of having subspace constrained precoding. FDD mode of duplexing is used to obtained real time CSIT.

Omnidirectional precoding (OP) for public channels is introduced in [88] for massive MIMO system. OP results in several advantages such as increase in network sum rate, increase in diversity order and decrease in outage probability thereby enhancing the performance of the system. It also retains the PAPR of transmitted signal after precoding. OP is done with the advantage of reduced pilot overhead.

A turbo-Tabu-Search (TS) beam forming method for mm Wave massive MIMO is introduced in [89] with low surge in complexity and near optimal performance. TS based precoding is used for best results.

Precoding is an important factor to achieve optimal performance of massive MIMO system. For precoding, CSI is important and accurate CSI is required at the transmitter. For CSI acquisition at the transmitter, TDD and FDD are used, but, TDD system is limited by pilot contamination and FDD system is limited by feedback channel. To overcome above limitation, the concept of code book which is generally, precoding matrices has emerged. Code book is known to the transmitter and receiver, the receiver will select optimal precoding matrix from code book according to available CSI and inform the same to the transmitter with the help of feedback channel. This method will enhance the performance of massive MIMO system. So, code book is designed for uniform rectangular array deployment of massive MIMO system. Code book is designed in such a way to support multiple users in different scenarios, there are many code books in literature such as Grassmannian Packing [90], Vector Quantization Codebook [91], Kerdock Codebook [92]. The proposed codebook results in better channel coverage and good achievable sum rate than other kinds of codebooks.

Channel Inversion (CI) and Channel Correlation Rotation (CR) [93] linear precoding for massive MIMO system is explored in [94], considering spatial correlation and mutual coupling effects of antenna deployment.

3.2 Non-Linear Precoding

As mentioned earlier, there are two types of signal precoders for massive MIMO systems: linear precoders and non-linear precoders. The non- linear precoders are complex but with the advantage of providing higher precoding accuracy as compared to linear precoders. This section deals different types of non-linear

precoders, and its related advantages and disadvantages.

3.21 Dirty Paper Coding (DPC)

The DPC algorithm was referred by Costa in 1983, according to which the capacity of the theoretical channel can be obtained if the interference at the transmitter side is known. With the advent of DPC, interference is suppressed by subtracting known interferences before transmission. DPC can be implemented only if prior channel gain information is available at the transmitter side.

The concept of UL-DL rate balancing is given in [95] for FDD based massive MIMO system. In UL-DL rate balancing, unused UL capacity is used for CSI feedback thereby increasing DL capacity. Dirty paper coding and ZF precoding is considered for the analysis.

3.22 Tomlinson Harashima Precoding

Tomlinson and Harashima have proposed THP algorithm in [96]. This algorithm is an equalization process to abrogate inter symbol interference (ISI). In spite of few disadvantages like complexity and performance loss as compared to linear precoders, it has an advantage of avoiding noise amplification. In THP, DPC is combined with symmetric modulo operation. THP was initially introduced to reduce peak or average power in the decision feedback equalizer (DFE).

3.23 Vector Perturbation Precoding

It is a generalized form of THP algorithm proposed in [97]. It offers low complexity, near-capacity performance and standardizes inversion process to exploit perturbed input data, which is then precoded by front end precoder. The perturbed input vector aims to mitigate inter user interference (IUI). The literature [98] successfully utilizes vector-perturbation (VP) precoding to convey simultaneously information and energy in multiple-user multiple-input single-output (MU-MISO) downlink channel.

3.24 Least Square Error (LSE)

LSE is a non-linear precoder, wherein, signals to be transmitted are selected from a predefined set [99]. LSE precoder will facilitate use of efficient hardware and increase power efficiency for massive MIMO system

TABLE 2: Developing trajectory of linear and non-linear precoding techniques for massive MIMO system

Precoding Algorithm	**Features**
ZF Precoding [23,24,25,26]	1.Eliminates IUI 2.Performs better then MRT in terms of data rate. 3.Excellent performance in interference - limited system, and single cell scenario. 4.It amplifies noise which is not desirable.
Neuman Series -based Precoding [27,28,29,30]	1.Reduced computational complexity when M/N ratio is large. 2. Easy hardware implementation 3. Simplified large matrix inversion 4. Convergence rate is slow
Symmetric Successive Over Relaxation Method [32]	1.Reduced complexity of matrix inversion. 2. Better than Neumann series and TPE 3. Relevant for fast time varying systems
Conjugate gradient-based Precoding [33]	1. Simpler then Neuman series, since large matrix inversion is not required
MRC and ZF Precoder for minimizing power consumption [34,35,36,37,38,39,40]	1.ZF Outperforms MRC at low cross cell interference 2. Phase noise effect is less on MRT then ZF
Precoding considering user distribution [41-47]	1.Center intensive user distribution outperforms edge intensive user distribution in terms of achievable sum rate and EE.
Energy efficient hybrid precoding and minimum RF chain (EEHP-MRFC) algorithm [48]	1.Outperforms conventional ZF precoding algorithm.
Critical number of antennae searching (CNOAS) and user equipment number optimization (UENO) algorithms [49]	1.Maximizing EE for 5G system.
Energy Efficient Precoding [50,51,52]	1.Maximizing EE.
SLNR Precoding Scheme (Signal to leakage and Noise ratio) [53,54]	1. Balance desired signal power and interference power 2. SLNR-OPA gives better performance then SLNR-EPA
Matched-Filtering (MF) Precoding [55-67]	1.Maximizes SNR of intended user 2. Preferred for noise limited scenario

	3.Optimal performance for low SNR scenario 4. At high SNR, performance is limited by interference. 5. Provides trade-off between performance and complexity 6. Robust against ZF in terms of phase noise degradation 7. Unable to eliminate IUI.
Minimum Mean Squared Error (MMSE) Precoder [68]	1.Provides trade-off between signal efficiency and interference suppression 2. Suitable for entire SNR range. 3. Gives optimal performance then ZF and MF 4. Reduces power required for interference suppression. 5. It mitigates IUI 6. It considers the effect of noise.
Regularized Zero Forcing Precoder (RZF) [65]	1. SINR performance of RZF is better than ZF and MF when phase noise is considered. 2. Utilized for maximum EE.
Phase Zero Forcing Precoder (P-ZF) [66,69]	1. P-ZF is only required under stringent intercell interference scenario.
Truncated Polynomial Expansion (TPE) [72,73]	1. TPE enables balancing of precoding complexity and system throughput via different truncation orders 2. Inverse of Hermitian matrix is expressed as a matrix polynomial 3. Less complex then RZF and MRT 4. Gives better performance in terms of throughput.
Block Diagonalization (BD) [74-78]	1. Preferred for users with multiple antennas 2. Mitigates interference from other user signals 3. Eliminates inter cell interference (ICI) and thus improves average cell throughput. 4. Improves UL and DL rates for edge users. 5.Capacity performance of BD precoding outperforms BD-STBC for both cases of perfect and imperfect CSI.
Hybrid Precoding (HBP) [79]	1.Low computational complexity 2. Low implementation cost 3.Reduced feedback overhead
Constant Envelope Precoding (CEP)[80-84]	1.Low peak to average power ratio (PAPR) 2.Enabling energy efficient implementation of massive MIMO. 3. Low-cost implementation, 4. Reduced number of RF chains, enabling non-linear PAs at the base station, 5. Reduced CSI signaling overhead 6. No need of OFDM to combat frequency selective fading

Approximate Message Passing (AMP) Precoder [85]	1. Significantly suppresses MUI 2. Enables hardware friendly implementation 3.we can use cheap, highly power efficient amplifiers at the BS 4. AMP precoding is proved to be better than CE and Annulus Constraint (AC) from computational complexity and average running time point of view.
Two Stage Precoding [86]	1. Limited RF chains 2. Reduced pilot symbols and CSI signaling overhead. 3.Outer precoder is used to mitigate intercell and inter cluster interference 4. Inner precoder is used for spatial multiplexing of inter cluster users
Subspace constrained precoding [87]	1. Provides spatial multiplexing gain 2. Mitigates inter cell interference (ICI) 3.Channel vectors of each users are concentrated in a subspace with much smaller dimension then M.
Omnidirectional precoding (OP) [88]	1.Increase in network sum rate 2. Increase in diversity order 3.Decrease in outage probability thereby enhancing the performance of the system. 4. It also retains the PAPR of transmitted signal after precoding. 5. OP is done with the advantage of reduced pilot overhead
Tabu-Search (TS) beam forming Precoding [89]	1.Low surge in complexity 2. Near optimal performance
Codebook Based Precoder [90,91,92]	1. Enhanced Performance 2. Support multiple users in different scenarios
Channel Inversion (CI) and Channel Correlation Rotation (CR) Precoding [93,94]	1.Considers spatial correlation 2.Considers mutual coupling effects of antenna deployment.
Dirty Paper Coding (DPC) [95]	1. Provides best performance than all other linear and non-linear precoding techniques 2. Provides system capacity, which is equal to system capacity without interference 3. Interference free output is obtained by mitigating known interference at the transmitter side. 4. Computationally complex for massive MIMO systems.
Tomlinson Harashima Precoding [96]	1.This algorithm is an equalization process to abrogate inter symbol interference (ISI). 2. Avoids noise amplification. 3. In THP, DPC is combined with symmetric modulo operation.

	4. Reduce peak or average power in the decision feedback equalizer (DFE). 5.Disadvantages like complexity and performance loss as compared to linear precoders.
Vector Perturbation Precoding [97,98]	1. Generalized form of THP algorithm 2. Offers low complexity 3. Provides near-capacity performance 4.Standardizes inversion process to exploit perturbed input data. 5.The perturbed input vector aims to mitigate inter user interference (IUI) 6. Expensive and sensitive to CSI inaccuracies
Least Square Error (LSE) Precoding	1.Signals to be transmitted are selected from a predefined set 2.Facilitates use of efficient hardware and increase power efficiency for massive MIMO system.

4. PILOT CONTAMINATION

The main reasons of PC are, reuse of non-orthogonal pilot sequences, hardware impairments, and non-reciprocal transceivers [100]. For a multi-cell scenario, if there are 'Z' no. of cells and 'K' no of users in a cell, then orthogonal pilot sequences required for data transmission will be K X Z, which is not feasible owing to short coherence time. So, generally non-orthogonal pilot sequences are considered for data transmission. Due to assumption of frequency reuse factor of 1, pilot signals get contaminated by intercell interference leading to so called pilot contamination. Due to PC, performance of massive MIMO system will not grow even if there are large number of antennas at the BS. So, to reap full benefits of massive MIMO systems, research is ongoing to introduce new techniques to combat pilot contamination. Hardware impairment results into distortion of received signal from the transmitted ones, as a result, channel estimation accuracy gets impacted which leads to PC. Considering Hardware Impairment, analysis of massive MIMO system is given in literature [101]. Amplifiers of transceivers must be ideal to exploit channel reciprocity in TDD system. But, practically, it is not feasible to exploit channel reciprocity due to off-set residual frequencies, thus, UL and DL channels are not reciprocal resulting into inaccurate CSI leading to PC.

4.1 PC Mitigation Techniques

There are various methods in literature for assigning pilot sequences to users to minimize PC. One method is to use same set of orthogonal pilot sequences in all cells. Due to such pilot assignment, users with same pilot sequence from neighboring cell will interfere with each other. Consider Fig 8 as a depiction of PC. In Figure 8, it is shown that estimated channel vector of UE 1 in Cell 1 is linear combination of channel vectors of UE 1 from Cell 2 and Cell 3. Due to inaccurate channel estimation (CE), performance of massive MIMO system will be scaled down significantly. PC severely affects the performance of massive MIMO system and hence is studied in [102] for different scenarios. A single cell precoding [103] and multi cell precoding [104,105] is considered to eliminate PC. Hermitian Precoding [106] also significantly reduces PC. The performance of massive MIMO system using MF and MMSE precoder is given in [107] considering PC. Herein, system is analyzed by keeping the ratio of number of BSs antennas to number of UEs fixed and assuming infinite number of BS antennas. SINR of the system is shown to be impacted by PC.

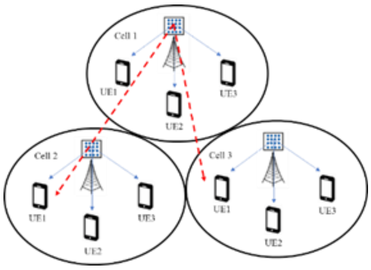

Figure 8. Pilot Contamination Effect

Covariance information is exploited in [108] wherein, covariance of desired user and that of interfering user traverse independent subspaces thereby eliminating PC. Also, UEs [108,109] with mutually non-overlapping angle of arrival (AoA) do not interfere with each other. Thus, covariance aided CE methods give better performance in terms of UL and DL SINR and better reduction in intercell interference. But, as given in [110], massive MIMO covariance-based CE methods are practically not feasible.

Another approach to mitigate PC is given in literature [111] which is use of time shifted pilot. This method will give better results as long as user transmission is done in non-overlapping time. But, with the advent of heterogenous networks it is difficult to maintain user transmission in non-overlapping time. A PC scheme [110] reduces PC but at the cost of higher training overhead. To decrease the overhead, new PC Precoding (PCP)is used in which, BS will compute precoding matrices as per the slow fading coefficients. Enhanced version of PCP is large-scale fading precoding (LSFP) and large-scale fading decoding is utilized for massive MIMO system. Subspace based CE techniques [112] are very efficient due to the requirement of a smaller number of pilot symbols. Eigen Value Decomposition (EVD) based method for CE will not give desired performance because channel vectors between UEs and BSs are not orthogonal as number of BS antennas go to infinity. Enhanced version of EVD is given in [113], where it is combined with iterative least square with projection algorithm. EVD based methods perform better than conventional pilot-based techniques. SVD based method [17] in which signal subspace is separated from interference subspace. Semi blind method to mitigate PC [114] in which cell cooperation is not required i.e. channel information of all cells is not required. Semi blind method is efficient than pilot-based method, asynchronous protocol-based method and SVD based method.

As far as desired channels are evident than all interfering/ noisy channels, blind methods [115] give optimal performance. Subspace CE with maximum-a-posteriori (MAP) approach given by Neumann in [116] gives better performance than blind methods however, with increased complexity. Multicell cooperation is also used to mitigate PC, however, number of antennas [117] fuel information exchange among the BSs. A Bayesian CE method [14, 9] utilizes covariance information of users to mitigate PC completely under specific conditions. Power allocation using game theory and coordinated tilt adaptation (CTA) in [118] is used to mitigate PC. Antenna down tilting is an efficient beam forming method in 3D MIMO system by which network sum rate of the system is increased by reducing ICI. For fast CE, Diagonal jacket-based estimation method with iterative least square projection is given in [119].

Smart pilot assignment scheme is discussed in [120] where pilot Signals are intelligently allocated to users with the focus on minimizing pilot contamination to improve SE. Another low complexity algorithm based on Smart Pilot Assignment is given in [121]. In short, smart pilot schemes are very simple giving desired results by smartly allocating pilot signals across cells. Angle of Arrival-Based Assignment Scheme is introduced in [122] where, pilot assignment is done considering angle of arrival of pilot signals, focussing primarily on spectral efficiency and contamination-free estimation. It has lower complexity as compared to smart pilot assignment [120]. But due to loss of performance in uplink, another version is introduced in [123] Which uses deep reinforcement learning along angle of arrival- based pilot allocation scheme. In [124] a soft pilot reuse scheme is proposed for multicell massive-MIMO system. In this scheme, users are differentiated as cell-centre and cell-edge users. Pilot symbols are assigned to cell-edge users in such a way so as to mitigate PC. It is observed that this scheme significantly eliminates PC as compared to conventional methods and improves QoS for edge users. But due significant pilot overhead, SE of the system is affected adversely and to tackle this issue soft pilot and soft frequency reuse technique is used in [125]. With the advent of this new technique higher spectral efficiencies can be obtained as shown by results. Graph Colouring-based pilot Assignment Scheme is introduced in literature [126] considering unidirectional interference, and Bidirectional interference is considered in [127,128,129]. Graph coloring technique optimizes the efficient use of limited pilot signal resources. It aims at maximizing SE of the system with reduced complexity. In [130], the authors proposed Rate-splitting multiple access

(RSMA) in a single cell massive MIMO network. RSMA is a new technology designed for future 6G physical layer transmission for mitigating interference caused by PC. RSMA technology mitigates pilot contamination thereby improving SE, especially with imperfect CSI at the transmitter. Thus, RSMA is robust to imperfect CSI resulting in performance enhancement in multi-user MIMO networks. RSMA for coherent cell-free networks is studied in [131] While both coherent and non-coherent data transmission for cell-free networks is studied in [132]. Superimposed Pilots Based Interference Mitigation is explained in [133], where pilot symbols do not require dedicated space for transmission and are embedded within data symbols. Such a scheme provides reduction in signalling overhead thereby increasing system performance. Another superimposed pilot framework for massive-MIMO systems is introduced in [134] targeting reduction in signalling overhead.

4.2 Open Issues in PC

Till now we have covered several PC mitigation techniques. All the proposed PC schemes in literature are based on certain assumptions but, it is very important to exploit dynamic properties of channel to meet requirements of real-life scenario. With large antenna arrays it is very challenging to obtain accurate CSI at the BS due to backhaul latency. The performance of all PC schemes depends on accuracy of CSI. All pilot-based schemes discussed so far will require training overheads which result in decrease in SE. This is because channel bandwidth is wasted due to overhead occupancy. A PC scheme in [110] also results in high overhead occupancy thereby decreasing SE. SE of a massive MIMO system can be increased by using sub space-based CE methods, in such methods, negligible overhead is required. However, in [135] EVD based CE method requires additional technique for identifying Eigen vectors of respective users. As far as deployment scenario is concerned, most of the literature is focused on symmetrical distribution of users. But practically, study of random user distribution is required. Again, assumption of uncorrelated channel models will not give optimal results, study of channel correlation is required. In massive MIMO system, channels are not i.i.d. [14] resulting in performance degradation of systems. So, to analyze the effect of PC, channel correlation, large scale fading coefficient [136], random user distribution must be considered to have real picture of a dynamic system [35,17]. While designing PC schemes, it must be cost effective and computationally simpler. The parameters such as cost effectiveness and computational simplicity must be tested using realistic channel models. In most of the TDD systems discussed so far, channel reciprocity is considered but practically UL and DL channels are not exactly inverse of each other due to hardware impairments. To overcome above issue, calibration schemes are used in literature [137] which gives realistic approach to pilot mitigation in massive MIMO system.

4.3 Broader Perspective

PC techniques are mostly related to homogenous networks according to literature survey, but it is very important to consider PC technique for multi-tier heterogenous networks [138,139]. Existing PC mitigation techniques are not useful for multi-tier heterogenous networks due to various factors such as transmission power, user distribution etc. So, future research is going on to investigate new PC schemes for multi-tier heterogenous networks. SE of massive MIMO system can be increased with the use of In Band Full Duplex (IBFD) communication mode [140,141] which is new research area. IBFD offers several advantages over TDD and FDD as given in literature [142]. IBFD is considered as a key technology for the upcoming wireless network [143,144]. IBFD massive MIMO system becomes more complex due to interference that exists in massive MIMO and self-interference from IBFD. In IBFD communication mode, transmission and reception is simultaneous over same frequency band at same time.

TABLE 3: Developing Trajectory of Pilot Contamination Mitigation Techniques

Pilot Contamination Mitigation techniques	Performance
Single cell Precoding (SCP) considering PC [103]	1.SCP outperform ZF
Multi cell Precoding (MCP)Considering PC [104,105]	1.MCP outperforms ZF
Hermitian Precoding [106]	1.Significantly reduces PC
MF and MMSE precoder considering PC [107]	1.SINR analysis is affected by PC
Covariance aided method [108,109,110]	1.High overhead
Time shifted pilots [111]	1.Not suited for Het Net

Subspace based CE [112]	1.Efficient due to less requirement of pilot symbols
Enhanced version of EVD based CE [113]	1.Performance better then pilot based methods
Semi-blind method [114]	1.Outperforms pilot based, asynchronous protocol and SVD base methods.
Blind Method [115]	1.Optimal performance
Subspace CE with (MAP) approach [116]	1.Better then blind method
Multi cell cooperation [117]	1.Combat PC with increased overhead
Power allocation using game theory and coordinated tilt adaptation [118]	1.Along with PC mitigation, significant increase in network sum rate
Diagonal jacket-based estimation approach [119]	1.For fast CE
Smart Pilot assignment for PC [120,121]	1. Maximize the minimum SINR via pilot Assignment 2. Maximizing SE through optimal pilot assignment
Angle of Arrival-Based Pilot Assignment Scheme [122,123]	1. Decrease complexity with only a slight SE Variance 2. Suboptimal pilot allocation via reinforcement learning
Soft pilot reuse scheme [124,125]	1. QoS improvement through soft pilot reuse 2. Maximizing SE via soft pilot and frequency reuse
Graph Coloring-based pilot Assignment Scheme [126-129]	1.Mitigate pilot contamination via pilot assignment 2.Optimizing pilot assignment using Weighted Graphs 3.Mitigating pilot contamination and enabling scalability in massive MIMO
Rate-splitting multiple access (RSMA) [130,131,132]	1. Improve channel estimation through rate Splitting and enhances SE.
Superimposed Pilots Based Interference Mitigation [133,134]	1. Improved channel estimation and network performance via superimposed pilots

5. CSI ACQUISITIONS

For massive MIMO precoding and detection, CSI at the BS is required. CSI at the BS can be obtained using FDD or TDD i.e. Feedback or Channel Reciprocity respectively. However, in massive MIMO system, TDD is more efficient to acquire timely CSI as channel reciprocity feature is inherent to it, which is nothing but the forward channel being a transpose of reverse channel by definition [96]. In TDD, UEs and BSs share the same frequency band for transmission. UEs send UL data signals and pilot sequences to BSs. Then CSI at the BS is estimated using pilot sequences. According to available CSI, BS will detect UL data and generate precoding matrices for DL data transmission. In TDD, training overhead required is directly proportional to number of UEs making it feasible for massive MIMO system.

However, in massive MIMO system, FDD [145,146] is used to acquire timely CSI through feedback loop. In FDD, DL and UL frequencies are different, due to which feedback is necessary for CSI acquisition in DL. In FDD DL, first all BSs will send pilot signal to all UEs, thus, training overheads required will be directly proportional to number of antennas, which will make it practically infeasible to be used for massive MIMO system [147]. Then, UEs will send CSI information to BSs. BSs will send pre-coded data with the help of precoding matrices to all UEs and time required for DL data transmission is directly proportional to the number of BS antennas. Now let us assume that channel coherence interval support 200 complex symbols for transmission. Then for 200 BS antennas, whole coherence interval is utilized for DL pilot transmission leaving no space for data transmission. This problem is addressed using TDD. But practically, majority network providers currently are dealing with FDD architecture making FDD for massive MIMO system a future research topic.

In massive MIMO system, TDD over FDD is preferred due to its advantages of low overhead and simplicity in channel estimation. Ideally, users from different cells should employ orthogonal pilot sequences. But, number of orthogonal pilot sequences is limited due to limited coherence time and bandwidth. This will result in a smaller number of users served by the system which is not desired. So, to meet the demand of increasing number of users, non-orthogonal pilot sequences are used, but the CSI quality at the BS is impacted causing pilot contamination.

5.2 CSI Estimation Techniques

CSI estimation techniques for massive MIMO systems are designed to minimized training overhead in TDD system. There are several TDD and FDD methods in literature for CSI acquisition and performance of massive MIMO w.r.t. to TDD and FDD is illustrated in literature [148]. CSI acquisition using FDD is a major challenge posed by massive MIMO system. It is practically difficult to predict number of pilot sequences required to achieve desired CSI quality. This problem is addressed in [149] wherein a close-loop pilot and CSIT feedback resource adaptation framework is used for MU- massive MIMO FDD system. The proposed scheme has several advantages compared to non-adaptive compressive CSIT estimation schemes. With conventional CE schemes, the training overhead for CSIT signaling scales linearly with number of antennas. So, in massive MIMO system, training overhead will be large for large number of antennas. There are several methods [150,151] wherein, CSI signaling overhead is reduced significantly for FDD massive MIMO system. Compressive sensing (CS) based CE methods [152-155] are also used with reduced signaling overhead. CS based quasi signal independent K-singular vector decomposition (KSVD) dictionary is used for CSI acquisition [93]. With the advent of proposed method, feedback load is reduced. KSVD dictionary has the ability to convert signal into sparse form. CS based techniques are also discussed in [156]. Like KSVD, several dictionaries like DCT (Discrete Cosine Transform) and Kahrunen-Loeve Transform (KLT) [156] are discussed along with their disadvantages. FDD massive MIMO system in [157] exploits partial support information to reduce training overhead. A low complexity scheme [158] for space constraint massive MIMO system is introduced which exploits inter antenna correlation thereby relaxing CSI. This will reduce the number of RF chains required thus reducing computational complexity and increasing EE. Space constraint deployment of large antenna arrays is given in literature [159,160]. CSI acquisition based on multipath extraction approach offers several advantages such as reduced feedback overhead etc. In [161] sparsifying based compression method is used for spatially correlated massive MIMO system resulting in decreased overhead. A CSI estimation scheme [162] for massive MIMO OFDM system utilizes novel pilot design and unitary feedback matrix. It allows CSI estimation from limited number of Long-Term Frames (LTFs). Due to proposed scheme, number of LTFs are inversely proportional to number of transmit antennas. A new technique of joint-angle-delay subspace for massive MIMO OFDM system is introduced in [163] for CE. An overview of low rank approaches for CSI acquisition is discussed in [164]. A distributed MMSE algorithm for CE is proposed in massive MIMO OFDM [165] system which relies on coordination among BS antennas.

A channel estimator for multi-cell massive-MIMO TDD system is presented in [166], which is based on the use of Zadoff-Chu (ZC) pilot sequence. The proposed estimator was found to be more efficient than MMSE estimator. Another channel estimation algorithm, which provides high SE is proposed in [167] based on statistical channel information and contaminated CSI. The channel estimation scheme based on assigning specific orthogonal variable spreading factor (OVSF) code is proposed in [168] which provides interference-free downlink transmission and enhanced sum-rate performance by mitigating pilot contamination. Least square channel estimation method (LSCE) is proposed in [169] for OFDM massive MIMO systems. The performance of the proposed system is improved in terms of Bit Error Rate. Authors in [170], proposed a channel estimation scheme which exploits spatial correlation using factor analysis. The proposed scheme mitigates pilot contamination and noise interference at the same time resulting in enhanced system performance. Uniform rectangular array (URA) based channel estimation is introduced in literature [171]. Another channel estimation method based on compressed sensing is discussed in [172] which provides enhanced performance in terms of sum rate and reduced pilot length. LS estimation technique combined with deep neural network is given in [173]. The proposed scheme easily handles pilot contamination, co-channel interference compared to traditional methods. A semi-blind channel estimator based on space-alternating generalized expectation-maximization (SAGE) is proposed in [174]. The proposed channel estimation method is divided into two stages. The proposed algorithm has enhanced the SE and improved the CSI accuracy of massive MIMO systems.

TABLE 4: Milestones in the Development of CSI Acquisition Techniques

Channel Estimation Schemes	Performance
Closed loop pilot and adaptive CSIT f/b resource framework [149]	Proposed scheme outperforms non-Adaptive, compressive CSIT estimation schemes
Channel quantization schemes for CE [150,151]	CE with reduced CSI signalling overhead
CS-based CE schemes [152-155]	Reduced feedback load
DCT and KLT dictionary for CSI acquisition [156]	Provides optimal sparse representation of signal
Compressed CSI acquisition through partial support system information [157]	Result in reduced training overhead
Inter-antenna correlation is exploited for relaxing CSI [158]	Reduced computational complexity and increased EE
Sparsifying based compression method [161]	Reduced overhead
A joint angle-delay subspace-based CE method [162]	CE with increased efficiency
A novel pilot design for CSI estimation [163]	Prevent the no. of LTFs to increase with no. of BS antenna
ZC sequences and minimum-variance unbiased estimator (MVUE) method [166]	More efficient than MMSE estimator
CE based on statistical channel information and contaminated CSI [167]	Provides high SE
CE based on assigning specific orthogonal variable spreading factor (OVSF) code [168]	Provides interference-free downlink transmission and enhanced sum-rate performance by mitigating pilot contamination
Least square channel estimation method (LSCE) [169]	Performance of the proposed system is improved in terms of Bit Error Rate.
exploits spatial correlation using factor analysis. [170]	Enhanced system performance
Uniform rectangular array (URA) based CE [171]	Enhanced system performance
Compressed sensing -based CE [172]	Enhanced performance in terms of sum rate and reduced pilot length.
LS estimation technique combined with deep neural network [173]	Easily handles pilot contamination, co-channel interference compared to traditional methods.
Semi-blind channel estimator based on space-alternating generalized expectation-maximization (SAGE) [174]	Enhanced the SE and improved the CSI accuracy

6. APPLICATION LANDSCAPE

As telecom network is evolving into its next generation and user requirements mature, need of massive MIMO is increasingly felt for want of various applications which could well be served by massive MIMO system through both homogenous and heterogenous network configurations. Under homogenous networks, primarily adaptive beamforming, sectorization with angular beamforming and distributed antenna array with large scale cooperation schemes are used to serve various application requirements. In adaptive beam forming system throughput enhancement could be obtained by suppressing spatial interference and 3D adaptive beamforming takes a precedence over 2D due to its efficient utilization of radio resources in spatial domain. In sectorization, angular beamforming is used to divide cells into different sector in a way to reduce interference among sectors to improve number of users served with high multiplexing gain. Distributed antenna arrays [175,176,177] give better coverage as against co-located and utilizes effective bandwidth in presence of interfering scenarios therefore, researchers are investigating different architectures with distributed antenna deployment with effective large-scale cooperation scheme to reduce intra-cell interference.

Heterogenous networks consist of macro and small cells in large number to utilize available bandwidth effectively, however, it can further be enhanced if micros / small cells are served over wireless backhaul using massive MIMO as against fixed backhaul [178]. Small cells with massive MIMO can serve high rise buildings very well from coverage and capacity perspective. Small cells can change dimension [179,180] considering user position thus helping achieve traffic balance between macros and micros. Het-Nets also become imperative as we approach 5G rollouts and IoT applications, as network slicing towards enterprises to serve defined applications will call for dedicated network resource allocation for ensuring service throughput, latency and quality leaning on the advantages of massive MIMO system, evolved packet core (EPC) and software defined network (SDN). Enterprises are driven by virtualization requirements when it comes to cloud-based information technology (IT) systems, automated and artificial intelligence (AI) driven operational processes and business model digitalization, thus, putting pressure on serving network connectivity layers also to be software defined and reconfigurable. These advancements are a part of 5G offering based on Massive MIMO advantages.

New wireless access technology is also emerging in which thin electromagnetic panels of very large physical dimensions which can transmit and receive electromagnetic signals are used. Such concept is largely known as- Extremely Large Aperture massive MIMO [181] or Extra-large Scale massive MIMO or Large Intelligent Surfaces [182]. Such panels will increase performance of the system by providing reliable low latency communication. These panels have a unique capability of capturing complete 3D ultra-high-resolution snapshot of the environment.

7. FUTURISTIC RESEARCH AREAS

Apart from massive MIMO potentials, practical implementation of massive MIMO system requires much more efforts. While implementing such system, there are certain challenges and open issues which need to be addressed in the near future. some of the challenges and futuristic research areas are discussed below:

7.1 Advanced Signal Processing

Large amount of baseband data produced by massive MIMO system must be processed in real time. For real time data, fast and distributed coherent signal processing is required which is the future research direction.

7.2 Low-cost Hardware considering Hardware Impairment

Building massive MIMO system is a challenge which requires low- cost hardware. Manufacturing with low- cost components will result in large number of hardware impairments i.e. I/Q imbalance, phase noise degradation and non-linearities of cheap hardware components. Such hardware impairments will degrade the system performance. So, to deal with hardware impairments, new physical layer transmission schemes and new network architectures must be invented [183]. Similarly, there is much scope to invent new receiver algorithms to tackle phase noise degradation of the system.

7.3 Power Consumption

Power consumption is an important aspect while analyzing future wireless communication networks. In most of the literature review, power consumption of PAs is considered but total power consumption including circuit power and radiated power must be considered, while implementing massive MIMO system, thus going one step forward towards green communication. Thus, the system must be designed in such a way so that with minimum power consumption, required EE of the system is achieved. With massive MIMO system, we can scale down radiated power, although by maintaining its potential to drastically increase data rates. But, designing of massive MIMO system hardware considering trade-off between total power consumption and EE [184] is a difficult task and a new research direction.

7.4 Channel Modelling

Realistic channel models for massive MIMO system depicting effects of antenna arrangement is also a new research direction. New channel model which can be used to model channel correlation must be investigated.

7.5 Scalable Low-Cost Scheduling Algorithm

Cost effective scalable scheduling algorithms which will facilitate massive MIMO system array is an area for further development.

7.6 Reciprocity Calibration in TDD Mode

Reciprocity calibration requires development while designing massive MIMO system in TDD mode. New effective algorithms which take care of calibration is a new research direction [185].

7.7 Effective Receiver Algorithms

Cost-effective receiver algorithms considering dimensionality reduction plays an important part in massive MIMO system devices. New receiver algorithms considering non-linear interference capabilities is a promising research direction, facilitating low- cost detectors.

7.8 Smart Information Exchange

Strategies must be investigated to reduce delay incurred while exchange in information.

7.9 Antenna Array Configuration

The impact of antenna array configuration will be seen on diversity gain, array gain, multiplexing gain and channel properties. So, antenna arrays must be employed carefully by considering physical area constraint maintaining required gains of the system. Overall, in near future new physical layer transmission schemes and networking architectures must be investigated.

7.10 Cell-free massive MIMO

It is a potential technology for 5G communication which provides good service to all users uniformly. In cell-free massive MIMO technology, single antenna users are served by various distributed access points (APs) [186] and can be easily implemented using simple linear processing techniques. The disadvantage of this technology is its higher power consumption due to numerous APs. This issue is considered in literature [187] wherein, EE is maximized from green friendliness viewpoint. The performance of cell free massive MIMO is improved significantly w.r.t. conventional small cell topologies and a future research direction.

7.11 Massive MIMO for Internet of Things

The paper this far has discussed use of massive MIMO for emerging 5G systems; a thorough research is done highlighting the benefits of massive MIMO for broadband communication related applications, however, IoT (Internet of Things) angle of massive MIMO is overlooked to a large extent. Application area of massive MIMO for IoT enablement is recently being mulled over in research corridors. Let's briefly discuss how massive MIMO could be a significant component of IoT applications in ensuing paragraphs.

Data traffic in 5G system is broadly categorized as – 'human type' & 'machine type' of traffic. Machine type traffic emanates from IoT applications to a large degree. 5G new radio network supports three types of communications- URLLC (Ultra Reliable Low Latency Communication), eMBB (extended Mobile Broadband Communication) and mMTC (massive Machine Type Communication).

eMBB is a 'human type' data traffic but, URLLC and MMTC comes from 'machine type' data traffic. Examples of eMBB are high speed wireless broadband access on mobile phones or ultra-high-quality video streaming or VR (Virtual Reality) or AR (Augmented Reality).

URLLC is also called as Mission Critical IoT. Basic requirement of URLLC is highly reliable and low-latent IoT connection which is provided by large no of spatial Degree of Freedom (DoF) offered by massive MIMO. Such type of communication will require small data packets to be transmitted with very high reliability ranging between 99.999% to 99.999999% [188] leaving virtually no room for any error as the dependent application is ultra-critical.

Attributed to two properties CH and Favorable Propagation (FP) [189] of massive MIMO, it is very useful for URLLC. Due to CH; massive multi antenna pre and post processing; transforms the channel into almost deterministic quantities and channel does not get affected by small scale fading variations. Due to large number of spatial DoF, CH and FP properties of massive MIMO, efficient spatial separation of devices is obtained in URLLC. Efficient use of large no of DoFs is dependent on channel estimation process which is time consuming in massive MIMO. So, for low latency URLLC application, shortening of channel estimation is required and can be obtained using second order statistics. Imperfect channel estimation affects inter-user-interference, so, to handle complexity of channel estimation process in massive MIMO, TDD is preferred which relies only on reciprocity of UL and DL channels. URLLC thus comes handy to safety systems, wireless industrial robots, autonomous vehicles, tactile internet, and immersive VR with haptic feedback.

mMTC provides service to large number of machine type devices out of which it is assumed that only a certain number of devices are active at a given time, any massive deployment of connected devices falls into the category of mMTC, where devices are mainly sensors, used to gather information of environment, manufacturing, energy, agriculture, transport etc. While considering mMTC, two parameters of performance evaluation i.e. SE, and EE must be considered. It is very difficult to obtain desired SE of mMTC due to overhead of transmitting messages from large set of devices. EE at the device side, is thus severely affected, since mMTC devices are battery operated sensors so, energy consumption of devices is more due to collision occurring in the access. Basic requirement of mMTC is activity detection and decoding of data packets, collision resolution [191,192], wide area low- rate coverage. mMTC traffic is sporadic and unpredictable in nature. mMTC devices transmit in an uncoordinated way, whenever they have data to transmit. So, the main problem is how to detect that activity and successfully decode the data from a maximal number of transmitting mMTC devices within a limited bandwidth. With large spatial multiplexing capability and favorable propagation of massive MIMO, activity between large devices is easily detected i.e. multiuser detection (MUD). Along with detection, large antenna array will easily decode the data packets for desired destination, the array gain of massive MIMO will boost SNR thereby providing extended coverage capability. Thus, use of massive MIMO for MMTC will provide activity detection and decoding, collision resolution and wide area coverage capability.

Apart from above advantages, massive MIMO will also support network slicing [193], for heterogenous services of 5G. Slicing means to allocate orthogonal radio resources to eMBB, mMTC and URLLC. Now, allocating orthogonal radio resources to eMBB, mMTC, URLLC is very difficult due to their different characteristics, posing a major challenge. With multi-antenna processing capability of massive MIMO, separation of different data traffic services will be easier thereby making network slicing easier too.

TABLE 5: Futuristic Research Areas

Sr No	Futuristic Research Areas	Prerequisites
1	Advance Signal Processing	Fast and distributed coherence signal processing of real time data
2	Low-cost hardware, considering impairment constraints	Physical layer transmission schemes for cost optimization
3	Power consumption	Algorithms to optimize power consumption
4	Channel Modelling	Realistic channel models considering channel correlation, spherical and cylindrical antenna arrays
5	Scheduling low-cost algorithm	Cost effective scheduling algorithms to achieve economies of scale
6	Reciprocity calibration in TDD mode	Effective algorithms for meticulous calibration in TDD mode

7	Effective receiver algorithm	Receiver algorithm considering sub-linear interference capabilities
8	Smart information exchange	Information exchange with optimized latency
9	Antenna Array Configuration	Efficient antenna array deployment techniques.
10	Cell-Free massive MIMO	Low power distributed Aps
11	Massive MIMO for IoTs	Large Antenna Array

8. CONCLUSION

Massive MIMO is considered to be one of the crucial technologies for the next generation of wireless systems i.e. 5G, beyond 5G and 6G, providing high SE and EE, while pilot contamination, precoding and channel estimation remains a significant challenge. Three signal processing challenges i.e. precoding, pilot contamination and channel estimation are discussed in this survey paper and referred to as various streams of study been undertaken by global researchers. This paper has inked down important features of the linear and non-linear precoding schemes along with their comparison. Linear precoders are simpler and hence plays important role while considering transmitter side in spite of few disadvantages. Non-linear precoders are highly complex but they provide satisfactory performance and hence are important and discussed in depth. Pilot contamination causes interference and impacts adversely on system SE. This paper briefly discusses various mitigation strategies with the aim of reducing interference and enhancing SE. This paper, also provide a systematic mapping study on the state-of the- art research efforts of channel estimation issues of massive MIMO system. Thus, it is evident that massive MIMO remains a critical field of future research in evolution of mobile communication technology as it evolves from LTE to LTE Advance to 5G,beyond 5G and 6G. The benefits of Massive MIMO technology should translate the very nature of telecommunication industry by making it mitochondria of IoT bearer. The paper is expected to be a road map for researchers in this field. Future research may explore machine learning for precoding, pilot contamination and channel estimation.

9. GLOSSARY

3D-MIMO	3 Dimensional MIMO
ACP	Annulus Constraint Precoding
AHP	Adaptive Hybrid Precoding
AI	Artificial Intelligence
AMP	Approximate Message Passing
AOA	Angle of Arrival
APs	Access points
BC	Broadcast
BS	Base Station
BD	Block Diagonalization
CAEs	Calibration Errors
CE	Channel Estimation
CEP	Constant Envelope Precoding
CG	Conjugate Gradient
CI	Channel Inversion
CNOAS	Critical Number of Antenna Searching
CR	Channel Correlation

C-RAN	Cloud – Radio Access Network
CS	Compressive Sensing
CSI	Channel State Information
CSI-RS	Channel State Information-Reference Signal
CSIT	Channel State Information at the Transmitter
CTA	Coordinated Tilt Adaptation
DCS	Distributed control system
DCT	Discrete Cosine Transform
DFE	Decision Feedback Equalizer
DFT	Discrete Fourier Transform
D-MM	Distributed Massive MIMO
DL	Downlink
DPC	Dirty Paper Coding
DOF	Degree of Freedom
EE	Energy Efficiency
EEHP-MRFC	Energy Efficient Hybrid Precoding-Minimum Number of RF Chains
eMBB	extended Mobile Broad Band
EPA	Equal Power Allocation
EPC	Evolved Packet Core
EVD	Eigen Value Decomposition
FDD	Frequency Division Duplexing
FLC	Fast Linear Convolution
FPGA	Field Programmable Gate Array
FSF	Frequency Selective Fading
GD	Gradient Descent
GTS	Greedy Taboo Search
Het-Nets	Heterogenous Networks
HP	Hybrid Precoding
IBFD	In-band Full Duplexing
ICI	Intercell Interference
IoT	Internet of Things
KLT	Kahrunen-Loeve Transform
KSVD	K-Singular Vector Decomposition
LJTP	Local Joint Transmission Precoding
LSE	Least Square Error
LSFP	Large Scale Fading Precoding
LTFs	Long Term Frames

MAP	Maximum A Posteriori
MMSE	Minimum Mean Square Error
mMTC	massive Machine Type of Communication
MUI	Multi-User Interference
MU-MM	Multi-User Massive MIMO
MRC	Maximum Ratio Combining
OFDM	Orthogonal Frequency Division Multiplexing
OP	Omnidirectional Precoding
OPA	Optimal Power Allocation
PAPAR	Peak to Average Power Ratio
PAs	Power Amplifiers
PC	Pilot Contamination
PCP	Pilot Contamination Precoding
PDF	Probability Density Function
PPP	Poisson Point Process
PZF	Phase Zero Forcing
RBD	Regularized Block Diagonalization
RF	Radio Frequency
RMT	Random Matrix Theory
SDN	Software Defined Networks
SE	Spectral Efficiency
SINR	Signal to Interference Noise Ratio
SLNR	Signal to Leakage Noise Ratio
SLNR-PS	SLNR Precoding Scheme
SPR	Soft Pilot Reuse
SSOR	Successive Symmetric Over relaxation
STBC	Space Time Block Codes
SVD	Singular Value Decomposition
TDD	Time Division Duplexing
TDVP	Time Domain Vector Perturbation
TPE	Truncated Polynomial Expansion
TS	Tabu Search
UE	User Equipment
UENO	User equipment number optimization
UL	Uplink
URA	Uniform Resource Allocation
URLLC	Ultra Reliable Low Latency Communication

ZF Zero Forcing

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