Paper Summary:
An Overview of Massive MIMO: Benefits and Challenges

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***Abstract*— The paper gives a comprehensive overview of massive MIMO wireless communication systems. The paper begins with the advantages of massive MIMO from information theoretic perspective. In the next part, implementation issues related to channel estimation, detection and precoding schemes have been discussed. Special attention has been given to the problem of pilot contamination due to the use of non-orthogonal pilot sequences used by the users in the adjacent cells. The author has also demonstrated how the degrees of freedom provided by massive MIMO imparts more efficient single-carrier transmission. In the last section of the paper, the challenges and opportunities associated with future use of massive MIMO in wireless communication are discussed.**

I. INTRODUCTION

MIMO technology has significantly improved the capacity and reliability of wireless systems. In the recent years, the focus has shifted to massive MIMO from the point-to-point MIMO. Multi-User MIMO (MU-MIMO) is a more practical system, where typically a Base Station with multiple antennas serves a set of many single-antenna users simultaneously. Due to multi-user diversity, the performance of MU-MIMO systems is generally less sensitive to the propagation environment as compared to point-to-point MIMO case. Also, we just have to use expensive equipment at the BS end only and hence it is cheaper.

II. FROM REGULAR TO MASSIVE MIMO

Let's look at the advantages of massive MIMO from information theoretic perspective. Let's begin with the point-to-point MIMO and see how the performace is improved in MU-MIMO systems.

A. Point-to-point MIMO

Let the number of antennas at transmitter and receiver be N_t and N_r respectively. Also consider narrow-band time-invariant channel with constant and deterministic channel matrix $H \,\epsilon\, C^{N_r \times N_t}$. The received signal vector will be:

$$y = \sqrt{\rho} H x + n$$

where, x represents transmit signal vector and n represents noise and interference. Let, $E[||x^2||] = 1$ and the noise be the zero-mean circularly symmetric complex Gaussian with an identity covariance matrix I. Hence, the scalar ρ is the transmit power. Assuming the transmit signals to be i.i.d. Gaussian variables and having perfect receiver side CSI, the instantaneous achievable rate can be written as:

$$C = log_2\, det(I + \frac{\rho}{N_t} H H^H)\ \frac{bits}{s.Hz}$$

After normalizing the propagation coefficients in H as $Tr(HH^H) \approx N_t N_r$, upper and lower bounds can be derived using the Jensen's inequality and can be written as:

$$log_2(1+\rho N_r) \leq C \leq min(N_t, N_r) log_2 \left(1+\frac{\rho max(N_t, N_r)}{N_t}\right)$$

The upper and lower bound in the above equation can be obtained by varying the distribution of singular values of HH^H. The upper bound can be obtained in the limit where all the propagation coefficients in the channel matrix are i.i.d., while the lower bound corresponds to the scenario with line-of-sight (LOS) propagation.

Now, let's see two cases where either N_t or N_r goes to infinity. The following formulas, obtained using the concept of asymptotic orthogonality for the two cases suggest that the upper bound of the above formula can be achieved in both the cases.

1) *Case 1: When $N_t >> N_r$ and $N_t \to \infty$:*

$$C \approx N_r log_2(1+\rho)\ \frac{bits}{s.Hz}$$

2) *Case 2: When $N_r >> N_t$ and $N_r \to \infty$:*

$$C \approx N_t log_2(1+\frac{\rho N_r}{N_t})\ \frac{bits}{s.Hz}$$

Hence, from the above equations, the advantages of equipping the arrays in MIMO link with large number of antennas can be seen clearly. This multiplexing gain disappears in the LOS environments.

B. Multi-User MIMO

Consider a MU-MIMO system with L cells. In each cell there is a BS with N antennas which serves K single-antenna users. The channel coefficient from the k^{th} user in the l^{th} cell to the n^{th} antenna of i^{th} BS can be written in terms of complex small scale fading $g_{i,k,l,n}$ and large scale fading coefficients $d_{i,k,l}$ as follows:

$$h_{i,k,l,n} = g_{i,k,l,n}\sqrt{d_{i,k,l}}$$

Hence the channel matrix for all the K-users in the l^{th} cell to the i^{th} BS can be expressed as:

$$H_{i,l} = \begin{bmatrix} h_{i,1,l,1} & \dots & h_{i,K,l,1} \\ \vdots & \ddots & \\ h_{i,1,l,N} & \dots & h_{i,K,l,N} \end{bmatrix} = G_{i,l} D_{i,l}^{1/2}$$

where,

$$G_{i,l} = \begin{bmatrix} g_{i,1,l,1} & \cdots & g_{i,K,l,1} \\ \vdots & \ddots & \\ g_{i,1,l,N} & \cdots & g_{i,K,l,N} \end{bmatrix}$$

and

$$D_{i,l} = diag(d_{i,1,l}, ..., d_{i,K,l})$$

Let's consider a single-cell MU-MIMO system with a BS, having N antennas, serving K single-antenna users. Hence the achievable rate for uplink and downlink transmission can be written as follows:

1) Uplink: The received signal vector at the BS can be expressed as:

$$y_u = \sqrt{\rho_u} H x_u + n_u$$

where, $y_u \,\epsilon\, C^{N\times 1}$, $x_u \,\epsilon\, C^{K\times 1}$ is the signal vector from all the K users and $H \epsilon C^{N\times K}$ is the uplink channel matrix. The k^{th} element of X_u, i.e. x_k^u denotes the symbol transmitted by k^{th} user with $E[|x_k^u|^2] = 1$. ρ_u denotes the uplink transmit power.

Assuming that the small scale fading coefficients are independent for different users, the column vectors in H will become asymptotically orthogonal as $N \to \infty$. Hence,

$$H^H H = D^{1/2} G^H G D^{1/2} \approx N D^{1/2} I_K D^{1/2} = ND$$

And therefore the overall achievable rate of all users can be written as:

$$\begin{aligned} C &= log_2\, det(I + \rho_u H H^H) \\ &\approx log_2\, det(I + N\rho_u D) \\ &= \sum_{k=1}^{K} log_2\, det(1 + N\rho_u d_k)\, \frac{bits}{s.Hz} \end{aligned} \tag{1}$$

Now, we show that when MF processing is used at the BS, we can achieve the above given capacity. The BS processes the signal vector in the following manner:

$$\begin{aligned} H^H y_u &= H^H(\sqrt{\rho} H x_u + n_u) \\ &\approx N\sqrt{\rho_u} D x_u + H^H n_u \end{aligned}$$

When N grows to ∞, the channel vectors become asymptotically orthogonal and hence H^H will not color the noise. Also, as the D is a diagonal matrix, asymptotically there will be no inter-user interference. Hence, the signal transmission from each user can be treated as as if originating from a SISO channel. Hence from the above equation, the SNR for the k^{th} user is $N\rho_u d_k$. It shows that when N grows to ∞, simple MF processing at the BS can achieve the capacity shown in (2).

2) Downlink: For the downlink transmission, the BS usually has the CSI of all the channels connected to the users, using the uplink pilot transmission. Hence, the BS can perform power allocation and the sum capacity can be given as:

$$\begin{aligned} C &= \max_P log_2\, det(I_N + \rho_d H P H^H) \\ &\approx \max_P log_2\, det(I_K + \rho_d N P D)\, \frac{bits}{s.Hz} \end{aligned} \tag{2}$$

where, P is a positive diagonal matrix with power allocations $(p_1, p_2, ..., p_K)$ as diagonal elements and $\sum p_k = 1$. It can be shown that the above capacity can be achieved using the simple MF precoder at the BS.

Hence, we saw that simple MF precoder/detector can acheive the capacity of MU-MIMO systems when the number of antennas at BS grows to inifnty. We'll soon look at the case when the ratio N/K remains constant as N,K tends to infinity.

C. Channel Estimation And Signal Detection

Let's begin with the channel estimation at BS and then we will proceed to signal detection methods.

1) Channel Estimation: For MIMO systems, in general, we require CSI at BS to precode(detect) in downlink(uplink) transmission. The time or resource required to estimate channels in MIMO systems is proportional to the number of transmit antennas and is independent of the number of receive antennas. TDD is preferred over FDD because in order to estiamte CSI of TDD, we need to separately estimate CSI for both uplink and downlink channels. However, in TDD, we just need to estimate the CSI for uplink channel and then using the assumption of channel reciprocity, we can estimate the CSI of downlink channel easily. However, while estimating the channels using pilot signals sent by the users, we also need to take care of the pilot contamination problem which arises due to non-orthogonality of pilot sequences employed by the user in the neighbouring cells. Besides these, linear MMSE based channel estimation is also used which provides near-optimal performance with low complexity.

2) Signal Detection: Linear signal detectors like MF, ZF and MMSE can asymptotically achieve the capacity as the number of antennas at BS grows large in a massive MIMO system. The MMSE receiver can achieve the same performance as the MF receiver with fewer antennas, especially when there exists inter-cell interference. Apart from linear detection methods, some non-linear detection methods like block iterative generalized decision feedback equalizer (BI-GDFE) are also used. Such non-linear methods can achieve better performance but are more complex than the linear methods. Various complexity reduction schemes have also been proposed in the recent years to reduce the complexity problem in non-linear methods.

D. Precoding

For regualar MIMO systems, non-linear pre-coding methods at the BS, like dirty-paper-coding, vector-perturbation and lattice aided methods have been known to perform better w.r.t. to linear methods however they are complex. But with an increase in the number of antennas at the BS, linear precoders like ZF, MF and MMSE are shown to be near-optimal. Hence, such linear precoding techniques are practically used due to their low complexity.

1) Basic Precoding: ZF and MF are two of the most basic precoding methods. In regularized ZF, the transmit signal at the BS can be expressed as:

$$x_d^{RZF} = \frac{1}{\sqrt{\alpha}} H^*(H^T H^* + \delta I)^{-1} s_d$$

where, $\delta > 0$ is the regularization parameter. The RZF precoder becomes ZF precoder as $\delta \rightarrow 0$ and becomes the MF precoder as $\delta \rightarrow \infty$. It is shown that the ZF precoder outperforms MF in the high spectral efficiency region while MF is better in the low spectral efficiency region. In the scenario when the number of antennas grow very large but the ratio N/K remains constant, ZF precoding achieves an SNR that tends to the optimal SNR for an interference free system with N-K transmit antennas.

2) Multi-Cell Precoding: In multi-cell massive MIMO systems, BSs are designed to cooperate with each other to serve users in different cells. Depending on the overhead of the information exchange among the BSs, there are three scenarios: single-cell processing, coordinated beamforming and network MIMO multi-cell processing. Single-cell processing can avoid the information exchange overhead but it is unable to reduce inter-cell interference. On the contrary, network MIMO provides the best performance but also has the highest information exchange overhead. Coordinated beamforming can obtain a trade-off between performance and the information exchange overhead.

3) Practical Considerations: In practice, to build a large array, the use of non-linear but power efficient radio-frequency front end amplifiers is preferred. Now, in order to avoid signal distortions, the transmit signals are required to have a low peak-to-average-power-ratio (PAPR). Since the computational complexity of precoder increases with the increase in the number of antennas at BS, it becomes necessary for us to use low-complexity precoding methods like ZF and MMSE precoders. Also, some complexity reduction techniques are used in addition, so as to further reduce the complexity of the above methods.

E. Pilot Contamination

For TDD based massive MIMO systems ideally orthogonal pilot sequences are employed for channel estimation. Let $\psi_{k,l} = (\psi_{k,l}^{[1]}, ..., \psi_{k,l}^{[\tau]})$ be the pilot sequence of user k in cell l. The pilot sequence employed by users in the same and adjacent cells must be orthogonal, $\psi_{k,l}^{H} \psi_{j,l'} = \delta(k-j)\delta(l-l')$. For such pilot sequences the base station can obtain uncontaminated estimation of channels because the channel vectors are not correlated to those of other users. However, the number of orthogonal pilot sequences with a given period and bandwidth is limited, which in turn limits the number of users that can be served. So, the estimate of the channel vector to a user becomes correlated with the channel vectors of the users with non-orthogonal pilot sequences. This is pilot contamination.

1) Pilot Contamination Effect: Consider a system with L cells with each cell having K single antenna users and a N antennae BS where N¿¿K. Let us assume all L cells use same set of K pilot sequences represented by τ X K orthogonal matrix $\phi = (\psi_1, \psi_2, ..., \psi_K)$ satisfying $\phi^H \phi = \tau I$. The received signal matrix at i-th BS, $Y_i^p \in C^{NX\tau}$ is given by

$$Y_i^p = \sqrt{\rho_p} \sum_{l=1}^{L} H_{i,l} \phi^T + N_i^p$$

where $H_{i,l} \in C^{NXK}$ is the channel matrix from all K users in the l-th cell to i-th BS. The k-th column of $H_{i,l}$, denoted by $h_{i,k,l}$, is the channel vector from the k-th user in the l-th cell to the i-th BS.N_i^p is the noise matrix at the i-th BS during the pilot transmission phase, whose entries are i.i.d. circular complex Gau ssian random variables with zero-mean and unit variance, and ρ_p is the pilot transmit power.

To estimate the channel, the i-th BS projects it's received signal on ϕ^* to estimate $H_{i,i}$. The resulting channel matrix is

$$\hat{H}_{i,i} = \frac{1}{\sqrt{\rho_p}\tau} Y_i^p \phi^*$$

$$= H_{i,i} + \sum_{l \neq i} H_{i,l} + \frac{1}{\sqrt{\rho_p}\tau} N_i^p \phi^*$$

The k-th column $\hat{h}_{i,k,i}$ of $\hat{H}_{i,i}$ is the estimate of channel vector $h_{i,k,i}$. We can see that $\hat{h}_{i,k,i}$ is a linear combination of the channel vectors $h_{i,k,l}, l = 1, 2, ..., L$ of users in different cells with same pilot sequence. This is called *pilot contamination.*

2) Mitigating Pilot Contamination:

- **Protocol Based Methods**
  One way to reduce the effect is through frequency reuse or reducing the number of served users that use non-orthogonal pilot sequences. But this makes a little difference since fewer users are served simultaneously even though the SINRs for specific users increase. In order to mitigate the pilot contamination, a scheme based on a time-shifted (asynchronous) protocol is proposed in [1][2]. The basic idea is to partition cells into several groups and to use a time-shifted protocol in each group. Let us consider an example with 3 groups. When users from group A_1 transmit pilots the BSs from A_2 transmit downlink data signals. This avoids pilot contamination among users from A_1 and A_2. At the same time the BSs from A_1 have to estimate their channel vectors in the presence of downlink signals transmitted by the BSs from A_2 and A_3. The uplink and downlink SNRs approach the following limits respectively,

$$SINR_{k,i}^u = \frac{d_{i,k,i}^2}{\sum_{j \in A, j \neq i} d_{i,k,j}^2}$$

$$SINR_{k,i}^d = \frac{\frac{d_{i,k,i}^2}{\alpha_{k,i}^2}}{\sum_{j \in A, j \neq i} \frac{d_{i,k,j}^2}{\alpha_{k,l}^2}}$$

From these expressions it is clear that only users from the same group interfere with each other. This leads to better performance. We can further enhance this method by allocating optimized powers $\rho^u_{k,l}$ and $\rho^d_{k,l}$ to uplink and downlink transmissions.

- **Precoding Methods** A precoding matrix at one BS is designed to minimize the sum of the squared error of its own users and interference to the users in all other cells. However the information exchange overhead among the BSs increases with number of antennas. Therefore, these methods are only feasible for MIMO systems whaving limited number of antennas. A PCP(Pilot Contamination Precoding) method is proposed in [3]. PCP is based on two assumptions that the source signals for all users in all cells are accessible at each BS and that large-scale fading coefficients, $d_{i,k,l}$, are accessible to all BSs.
To transmit data to k-th users of all cells, the i-th BS transmits the signal
$$\hat{s}^d_{k,i} = \sum_{l=1}^{L} a_{i,k,l} s^d_{k,l}$$
The coefficients $a_{i,k,l}$ are called PCP coefficients and are functions of large scale fading coefficients $d_{j,k,l}$. If $a_{i,k,l}$ are computed using ZF criterion, it is called ZF-PCP. ZF-PCP theoretically yields infinite SINRs as N$\rightarrow\infty$. But for finite N, SINR is given as
$$SINR^d_{k,l} = \frac{N\rho_d\rho_u\tau \mid \sum_{j=1}^{L} d_{j,k,l}a_{j,k,l} \mid^2}{T_1 + NT_2}$$
where T_1 and T_2 are functions of large scale fading coefficients and PCP coefficients. When the coefficients $a_{i,k,l}$ are optimized to maximize $SNR^d_{k,l}$ this method is called optimal PCP.
- **AOA Based Methods** Under realistic channel models, some users with identical or non-orthogonal pilot sequences may have no interference with each other. According to the multipath channel model, the channel vector from the k-th user in the l-th cell to the i-th BS is
$$h_{i,k,l} = \frac{1}{\Theta}\sum_{\theta=1}^{\Theta} a(\phi)\eta_{i,k,l}$$
where Θ is the number of paths, $\eta_{i,k,l} \sim \mathcal{CN}(0, \sigma^2_{i,k,l})$ where $\sigma^2_{i,k,l}$ is the user's average path loss and $a(\phi)$ is the steering vector which is the function of antenna spacing D,wavelength of the carrier and random angle of arrival(AOA) ϕ with pdf $f(\phi)$ Users with mutually non-overlapping AOA pdf hardly contaminate each other and can be assigned same pilot sequence.
- **Blind Methods** They are based on subspace partitioning. An eigenvalue-decomposition (EVD) based channel estimation wherein it is assumed that channel vectors from different users are orthogonal and they are estimated using statistics of received data. There is also an iterative least square with projection(ILSP) channel estimation method based on joint iterative estimation of the channel vectors and transmitted data. In [4], a blind method is proposed to separate interference subspace from the desired signal subspace, resulting in no pilot contamination.

F. Energy Efficiency

Consider an uplink transmission with K single antenna users, a BS with N antennas where N$\gg$K. The maximum achievable uplink data rate for the k-th user when N$\rightarrow\infty$ with MF detector having perfect CSI at the BS is given by
$$R^u_k \approx \log_2(1 + Nd_k\rho_u) \quad bits/sec/Hz$$
The data rate for a user with transmit power ρ_u through a SISO link with large scale fading coefficient d_k is given by
$$R^{u,SISO}_k \approx \log_2(1 + d_k\rho_u) \quad bits/sec/Hz$$
As can be seen when N is large the performance of a user with transmit power ρ_u/N in the MU-MIMO system with N antennas at the BS is same as a SISO system with transmit power ρ_u without small scale fading. Consequently, the power can be scaled down by N times for one user when perfect CSI is available at the BS. Moreover, the spectral efficiency increases by a factor of K in serving K users simultaneously. For channels with imperfect CSI at BS, the maximum achievable uplink data rate for the k-th user with MF detector as N$\rightarrow\infty$ is given by
$$R^u_{k,I} \approx \log_2(1 + \tau Nd^2_k\rho^2_u) \quad bits/sec/Hz$$
where τ is the length of pilot sequence and the pilot power satisfies $\rho_p = \tau\rho_u$. The rate of a user with transmit power $\rho_u/\sqrt{N}$ in the MU-MIMO system with N BS antennas is same as SISO system with transmit power $\tau d_k\rho^2_u$ without small scale fading. Thus the transmit power of one user can be scaled down by $1/\sqrt{N}$ to get the same performance.

The power scaling law is also valid for multi-cell systems; that is, one user can scale down the transmit power proportional to $1/N$ or $1/\sqrt{N}$ based on perfect and imperfect CSI, respectively, to get the same performance as in the SISO case. Note that this result still holds even with pilot contamination.

Energy efficiency is defined as the ratio of the spectral efficiency and transmit power. With perfect CSI, the energy efficiency decreases as the spectral efficiency increases. With imperfect CSI, in the low transmit power region, energy efficiency increases with the spectral efficiency, while in the high transmit power region, energy efficiency decreases as the spectral efficiency increases. Compared to the MF precoder, ZF can provide better performance in scenarios with high spectral efficiency and low energy efficiency, whereas MF is more suitable for scenarios with high energy efficiency and low spectral efficiency.

When the circuit power is also considered, the question of how to perform antenna selection to improve energy efficiency comes into the picture. It is shown that for a MISO case without CSI, the optimal number of RF chains is about half the maximum number of RF chains that can be supported by the power budget.In broad terms, all antennas should be used if the circuit power can be ignored compared to the transmit power while only a subset of the antennas should be chosen if the circuit power is comparable to the transmit power.

G. Single-Carrier Transmission

There are certain disadvantages to the use of OFDM in massive MIMO systems. They have high PAPR(Peak to Average Power Ratio) which can result in low power amplifier efficiency. A cyclic prefix (CP) is introduced to reduce ISI which further decreases power and spectral efficiency. The computational overhead of calculating DFT for OFDM modulation and demodulation increases with the number of antennas. Thus single carrier transmission is studied which has lower PAPR and can reduce the complexity incurred by DFT.

For a single cell MU-MISO, the downlink channel between the n-th transmit antenna to the k-th user can be modelled as FIR filter with Θ taps. The channel coefficient for tap θ is given by

$$h_{k,n}[\theta] = g_{k,n}[\theta]\sqrt{d_{k,n}[\theta]}$$

Let $x_d[t] \in C^{NX1}$ be the transmit signal vector from BS at time t. The received signal vector at time t combined together for all K users is given by

$$y_d[t] = \sqrt{\rho_d}\sum_{\theta=0}^{\Theta-1} H^T[\theta]x_d[t-\theta] + n_d[t]$$

where $n_d[t] = [n_1^d[t], ..., n_K^d[t]]^T \in C^{KX1}$ is additive white gaussian noise at all users and $H[\theta] = (h_{k,n}[\theta])_{k,n=1}^{K,N}$ is an NXK channel matrix for channel tap θ. The following precoder for suppressing ISI is used

$$x_d[t] = \sqrt{\frac{1}{NK}}\sum_{\theta=0}^{\Theta-1} H^*[\theta]s_d[t+\theta]$$

where $s_d[t]$ is the information symbol vector at time t. It has been shown that multi-user interference and ISI can be efficiently suppressed with low total transmit power to receiver noise ratio, leading to near optimal sum rate performance independent of the channel power delay profile.

H. Challenges and Potentials

1) Basic Issues:

- **Propagation Models** Most existing work on massive MIMO is based on the premise that as the number of antennas grows, the individual user channels are still spatially uncorrelated and their channel vectors asymptotically become pairwise orthogonal under favorable propagation conditions which is hard to justify under many practical situations. The real antenna correlation coefficients are significantly larger than would be expected under i.i.d. channel assumptions. Very highly correlated channel vectors cannot be rendered orthogonal by increasing the number of antennas. So, user scheduling becomes a critical component of massive MIMO systems.
- **TDD and FDD Modes** It is possible to enable FDD mode in massive MIMO systems by designing precoding methods based on partial or no CSI. Another way is to use the idea of compressed sensing to reduce the feedback overhead. At the BS, the antennas are usually correlated when placing so many antennas in a finite area. The correlation among channel responses from different antennas indicates that we do not need CSI for each individual antenna. Instead, the CSI can be compressed first and then only the necessary information is fed back. The BS can reconstruct the CSI according to the received information. In this way, the overhead for CSI feedback can be greatly reduced.
- **Modulation** To construct a BS with such large number of antennas fitted in a finite space, low cost power efficient RF amplifiers are desired. Problems of high PAPR with OFDM can be removed by employing single carrier transmission which does not require equalization at the receiver.
- **Pilot Contamination** As discussed in the above sections, pilot contamination causes directed inter-cell interference which unlike other sources of interferences, grows together with the number of BS antennas and significantly damages the system performance. Various channel estimation, precoding, and cooperation methods have been discussed above to mitigate the effects of pilot contamination.
- **Hardware Impairments** A user side hardware impairment is more critical compared to that at the BS. Work on mutual coupling, hybrid analog/digital beamforming architectures, RF power amplifiers and antenna arrays have shown that these require a great deal of precise and energy efficient hardware implementations.
- **Antenna Arrays** The configuration and deployment of antenna arrays in a 2-D grid or 3-D distributed structure is an important design aspect in massive MIMO systems. The mutual coupling among such compactly placed antennas further affects the performance. The increased hardware and computational costs due to the use of very large antenna arrays should also be considered. An electromagnetic lens antenna(ELA) is proposed that can provide spatial multipath separation and energy focusing functions, which can be used to improve the performance of massive MIMO and reduce its implementation cost.

2) Application Issues:

- **Heterogeneous Networks** In HetNets, low cost small cells are deployed in large numbers and with high density to provide better coverage and increase throughput. The use of massive MIMO in coordination with HetNets in order to provide improved interference management and energy efficiency is an important future research direction.
- **Millimeter Waves** Millimeter waves helps in improving capacity and spectral efficiency by using bands above 30 GHz where the spectrum is less crowded and available

bandwidths are broader. MMW fits well with massive MIMO and HetNets because smaller cell sizes are attractive for operation at MMW frequencies where RF path loss is significantly higher, the shorter wavelength associated with higher frequencies is appealing for massive MIMO designs since the size of the antenna array and associated electronics is reduced, and the large beamforming gain achievable with a very large number of antennas can extend coverage to help overcome the high MMW path loss. There are certain issues in MMW technology too like they are only useful in short range applications and that too with minimum mobility, failing of Rayleigh models in these. But they can provide various advantages to the existing communication system like significant reduction in delay spread, increase in bandwidth, etc which makes them an acitve area of research.

References

[1] F. Fernandes, A. Ashikhmin, and T. L. Marzetta, Inter-cell interfer- ence in noncooperative TDD large scale antenna systems, IEEE J. Sel. Areas Commun., vol. 31, no. 2, pp. 192201, Feb. 2013.

[2] K. Appaiah, A. Ashikhmin, and T. L. Marzetta, Pilot contamination reduction in multi-user TDD systems, in Proc. IEEE Int. Conf. Commun. (ICC), Cape Town, South Africa, May 2010.

[3] A. Ashikhmin and T. Marzetta, Pilot contamination precoding in multicell large scale antenna systems, in Proc. IEEE Int. Symp. Inf. Theory (ISIT), Jul. 2012, pp. 11371141.

[4] R. R. Muller, M. Vehkapera, and L. Cottatellucci, Blind pilot decontamination, in Proc. Int. ITG Workshop on Smart Antennas (WSA), Stuttgart, Mar. 2013.