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Massive MIMO Channel Characterization and Modeling: The Present and the Future

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Abstract

One of the technologies aimed to provide large increase in data rate, enhanced spectral efficiency, transmit power efficiency, high sum rates, and increase link reliability for the fifth generation network (5G) is the massive multiple input multiple output (MIMO) antenna system. The projected benefits of massive MIMO depend on the propagation environment. However, due to the non wide-sense stationarity properties of massive MIMO, small scale characterization (SSC) is not enough for modeling its propagation channel as the spatial domain is also required. Giving consideration to the dynamic adaptation of the elevation angles which is not captured in 2D channel models will open up new possibilities for 3D beamforming which will introduce considerable performance gains for 5G network capacity enhancement. In this paper therefore, we review the various non wide-sense stationary channel parameters for characterizing massive MIMO channel particularly in the 3D plane and their methods of measurement, All through the discussion, we identified outstanding research challenges in these areas and their future directions.

Keywords: 5G, Antenna array, Channel measurement, Channel model, massive MIMO.

NOMENCLATURE

5G:	Fifth Generation
AAoA:	Azimuth Angle of Arrival
AAoD:	Azimuth Angle of Departure
COST 2100:	Cooperation in Science and Technology 2100
CSI:	Channel State Information
EAoA:	Elevation Angle of Arrival
EAoD:	Elevation Angle of Departure
	LTE-A: Long Term Evolution Advance
MF:	Matched Filter
MIMO:	Multiple-Input Multiple-Output
MMSE:	Minimum Mean Square Error
SAGE:	Space-Alternating Generalized Expectation-maximization
SNR:	Signal to Noise ratio
SSC:	Small Scale Characterization
TDD:	Time Division Duplexing
VNA:	Vector Network Analyzer
WINNER11:	Wireless World Initiative New Radio 11
WSS:	Wide-Sense stationary
WSSUS:	Wide-Sense Stationary and Uncorrelated scatterer
ZF:	Zero Forcing

INTRODUCTION

In large scale or massive MU-MIMO, tens or hundreds of antennas at the BS concurrently serve fewer numbers of users in the same time-frequency resource. According to [1, 2], as the number of BS antennas in an massive MIMO approaches a very large number, the effect of uncorrelated noise, small-scale fading and the required transmitted energy/bit tends to zero, thermal noise is averaged out and the system is largely restricted by interfering symbols from other transmitters. Also, simple linear signal processing approaches like the zero forcing (ZF) and the matched filter (MF) pre-coding/detection can be used to achieve these advantages. Other advantages or benefits of massive MIMO include reduced latency, large spectral efficiencies, simplification of the MAC layer, the use of low powered inexpensive components, cell edge performance improvement as well as robustness to intentional jamming [3]. The performance of MIMO systems generally depend on the propagation environment and the properties of the antenna arrays. [4] According to [5, 6], it is therefore essential for massive MIMO operation to obtain channel state information (CSI) at the BS for full achievement of its benefits. In spite of its many advantages which have presented very encouraging unique feat based on theoretical studies, many questions are yet to be answered in the practical application of massive MIMO. In theoretical massive MIMO with transmit antennas N_T approaching infinity, independent and identically distributed (i.i.d) Rayleigh channels are always assumed and this assumption gives us an interference free transmission with optimal performance using linear pre-coding and near optimal detection schemes as earlier enumerated. However, the number of antennas cannot tend to infinity neither is propagation channels hardly i.i.d Rayleigh in real propagation environment [5, 7, 8]. Thus we need to carry out real propagation environment channel measurement to ascertain what can be harness from massive MIMO practically while massive MIMO channel characterization for high speed train, crowded scenarios and hotspot environment are highly sort research areas.

Unlike in conventional MIMO, massive MIMO antenna array are arranged in a large spatial format making the small scale characterization (SSC) assumptions inapplicable, as a result of this, the propagation channel parameters such as the Azimuth angle of arrival (AAoA), Azimuth angle of departure (AAoD), birth/death processes of multipath clusters etc as observed by the different antenna elements making the array fluctuate due to their spatial displacement leading to the non-stationarity property of massive MIMO channels [9]. Massive MIMO channel non-stationarity properties have been investigated in the literature. For example in [10, 11, 12] where measurements at 2-8GHz, 1GHz and 5.6GHz frequency bands were performed using the virtual linear array and the virtual 2D array for both LOS and NLOS scenarios using antenna array up to 128 elements where parameters such as the rms delay spread, cluster number, power delay profile and the k-factor were studied.

According to [9, 13, 14, 15] the non-stationarity property of massive MIMO arises as a result of the smaller than Rayleigh distance connecting some clusters and the antenna array when the number of antenna is large leading to the non applicability of the far-field propagation assumption, therefore the wavefront that is expected to be plane become spherical causing variations in AAoAs, AAoDs etc of multipath signals along the array. Also the closer two antennas in an array is the more common clusters they share [9] given rise to two sets of clusters, those wholly visible to the entire array and those that are visible to a part of the array elements only as a result of their shapes, direction, sizes etc otherwise called partially visible clusters. According to the work in [14] massive MIMO channel capacity is increased by the non-stationarity behaviour of partially visible clusters eliciting interest in research work in spatially non-stationarity of massive MIMO.

Channel propagation models are employed to predict the radio signal propagation characteristics within the wireless environment of a particular geographical location for efficient network planning, coverage and deployment. The use of suitable channel propagation models is critical not only for the performance assessment of diverse candidate 5G technologies, but also for the advancement of new algorithms and products exploiting the large scale antenna system [12]. These models which could be deterministic, stochastic or empirical channel models are required to be only as complex as necessary and can thus neglect propagation effects that do not have considerable impact on the system performance [8] therefore each model is limited to the parameters that characterize them. Wide-sense stationarity and uncorrelated scattering (WSSUS) stochastic process, where -WSS- means that the mean and variance of the distribution are independent of time and -US- means that the path gains resulting from various delays are uncorrelated, and based on these assumptions we characterize the channel by second order statistics with the channel statistics believed to be stationary (does not change) in time and frequency within a specific period during which the statistics can be used for channel estimation, data detection etc purposes [16]. According to [17], WSSUS are not sufficient for MIMO channels anymore as the spatial domain characterization is also required particularly for massive MIMO where we have the effect of non-stationarity property playing out. Such effects include variation in the directions of arrival of signals at different parts of the array as well as variation in the average received energy at each antenna [14]. Since we have the phenomenon of near-field and non-WSS effects in massive MIMO as against conventional MIMO, therefore WINNER II and COST 2100 which are state of the art MIMO channel models and other such MIMO channels models [8, 18] which fail to capture these features are unsuitable for direct use as massive MIMO channel models [19]. Again, massive MIMO is expected to play a key role in the architecture of the new 5G network, including network backhauling in ultra-dense heterogeneous network environment as well as 3D beamforming for users in elevated high-rise positions. This will require characterization of multipath channel parameters in the elevation plane as against the current 2D model where characterization were done in the Azimuth plane. In the establishment of 2D models, estimates of the channel multipath component (MPC) parameters are extracted with the aid of parameter estimation algorithms such as the Space-Alternating Generalized Expectation-maximization (SAGE) procedure and the RiMAX technique [9] where the constant channel or stationary channel is assumed in the Azimuth plane. Since it is not possible to use these channel models in the large scale antenna array MIMO scenarios with satisfactory accuracy, channel sounding for massive MIMO channel characterization is therefore required.

The remainder of this paper is structured as follows. In section II we review channel characteristics of massive MIMO system, while section III investigate various measurable non-WSS channel parameters and their evaluation metrics as well as the challenges and future direction for MIMO channel measurements, while in section IV various MIMO channel models are studied, including extension to 3D models. Challenges and future direction for massive MIMO channel modeling were also considered. Finally we conclude the paper in section V.

MASSIVE MIMO CHANNEL UNIQUENESS

A) Favorable Propagation Condition and Channel Hardening

In massive MIMO systems, a favorable propagation condition is assumed where "favorable" propagation is interpreted as a sufficiently complex scattering environment such that as the BS antennas increases, user channels become pair wise orthogonal which is as a result of the asymptotic of random matrix theory setting in with many consequences as effects that were random previously, begins to appear deterministic such as, the allocation of the singular values of the propagation channel matrix which tends towards a deterministic function. Another important condition is the channel hardening phenomenon where tall/wide matrices begin to be very well conditioned. As the antenna array size become large, some matrix operations such as inversions can be achieve faster, by the use of series expansion methods (this is what makes linear algorithms like ZF and MMSE which requires matrix inversion operation to be near optimal in performance) [4].

These two major characteristics of massive MIMO can be expressed mathematically as:

Favourable propagation condition: ensure users channel vector orthogonality which eliminate co-channel interference and reduce the effect of small scale fading as $M \rightarrow \infty$

$$(\mathbf{h}_i^H \mathbf{h}_j) = \{0, i, j = 1, 2\ldots.., k, \text{ and } i\ j\} \text{ and}$$

$$(\mathbf{h}_i^H \mathbf{h}_i) = \{\|\mathbf{h}_k\|^2 \neq 0, k = 1, 2,\ldots..K\}$$

We also say that the channel offers asymptotically favorable propagation if

$$\frac{1}{M}(\mathbf{h}_k^H \mathbf{h}_j) \rightarrow \mathbf{0} \text{ as } M \rightarrow \infty$$

where $k \neq j$ and M is the BS transmit antenna.

Channel hardening; in which the off-diagonal components of the channel gain matrix become progressively more weaker with respect to the diagonal components as the size of the channel gain matrix increases [20] that is as the transmitter antenna size increases making matrix inversion operation simpler and the use of linear detector optimal.

$$(1/M)\|\mathbf{h}_k\|^2 = (1/M)\mathrm{tr}(R) \rightarrow 0$$

$$M \rightarrow \infty$$

Those two observable occurrences in massive MIMO channel are key properties of the radio channel exploited in achieving Massive MIMO benefits.

B) Non Wide-Sense Stationarity (Non-WSS) and Near Field Effect

According to [14], the complex random sequence h_k is wide sense stationary (WSS) if its expectation $E[h_k]$ is a constant that does not depend on k, neither the covariance $\rho kl = E[h^*_k h_l]$ depend on the values of k and l but exclusively on k−l, otherwise it is not WSS. The difference between Massive MIMO channels and the conventional MIMO channels is that the massive MIMO antennas are widely distributed in a large spatial region that makes the small scale characterization (SSC) assumptions inapplicable. The SSC is based on the wide-sense stationarity and uncorrelated scatterers for characterizing radio channels where the channel statistics are believed to be stationary in time and frequency within a coherent period. Resulting from the above, the propagation paths parameters observed through various antennas in the massive MIMO array fluctuate due to the spatial displacement of these antennas, here various base station antennas detect diverse groups of clusters at dissimilar time slots, which is described as the cluster birth and death process [12]. The channel exhibit spatial non-stationarity [9], see figure 1 below where cluster 1 is visible to the upper antenna array elements while cluster 4 and 5 are visible to the lower last antenna element. It is therefore necessary to determine and estimate the non-WSS channel parameters and investigate their influence on the performance of massive MIMO.

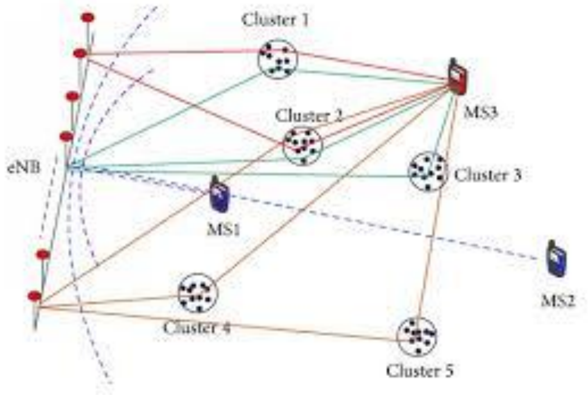

Figure 1: Near-field effect and the non-WSS phenomenon [12]

Again, as the number of antenna array increases to a large figure with several antenna elements, the space between the transmitter, receiver and or a cluster can become less than the Rayleigh distance given as $2D^2/\lambda$ (where D is the antenna array dimension and λ is the carrier wavelength), and the far-field and plane wavefront assumptions for SSC no longer holds for massive MIMO. See figure 2 below.

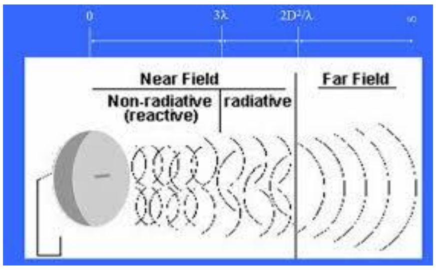

Figure 2: Near Field effect and the Plane-wave Assumption

As the channel condition number or the distance from favorable propagation is used as a measurable metric for favorable propagation condition, the non-stationarity property of massive MIMO channel can be measured by a MIMO correlation matrix based metric. Called the correlation matrix distance (CMD), it estimate the distance between the correlation matrices measured at various times to describe how strong the spatial formation of the channel has changed [21, 22]. This was used to measure and demonstrate the variation in the direction of arrival (DoA) in [21]. With a value ranging from 0 to 1, the CMD was used in [22] to investigate the non-WSS property of the channel gain while the non-WSSUS for vehicular channel was characterized in [23] at the speed of 90km/hr using 5GHz center frequency and 240MHz bandwidth. [24] highlighted some challenges with the use of CMD as a measuring metric for non-stationarity in MIMO system and proposed two new metrics called the normalized correlation matrix distance (NCMD) and the distance between equi-dimentional subspaces (DES) algorithm.

NON-WSS CHANNEL PARAMETERS AND EVALUATION METRICS

Channel measurements refer to as “channel sounding”, is carried out to describe or characterize the physical properties of a wireless channel where the measured data is collected using an equipment called channel sounder. In channel sounding, electromagnetic waves are transmitted to excite (or sound) the channel and the channel output are recorded at the receiver. Different sounding methods are used depending on whether the channel of interest is narrowband or wideband, SISO or MIMO channels. In the case of MIMO channels, the channel impulse responses (CIRs) between all combinations of the transmit and receive antenna branches are recorded. Here three different types of array architectures can be used which are : a) real-array, where each antenna element has its own Radio Frequency (RF) chain such that they can transmit or receive concurrently. However, the main difficulties here are the cost and calibration procedure which are expensive and complex, b) switched array architecture, where there is only one RF chain for all transmit and receive branches. Therefore only one antenna transmit and only one receive at a time. This architecture has a number of advantages including low cost and low complexity. Also, antenna arrays of any size can be used at both link ends, where the maximum size of the array is a function of coherence bandwidth and the speed of the RF switch [25], finally c) virtual arrays, where there is but one antenna element connected to a single RF chain at both link end, such that the antennas are electronically moved to predefined locations and the channel is thus sounded one after the other for each location. The main disadvantage of this architecture is that it allows very limited temporal variations in the channel. From above, we see that the switched array architecture is frequently the most suitable one for MIMO measurements in fast fluctuating, time-variant channels.

Determining the statistical properties of the channel require that sounding be done either in the time realm or in the frequency realm. The time-variant channel impulse response (CIR) h(t,τ) for the time realm/domain measurements are obtained at the receiver by exciting the channel with intermittent pulses on a PN-sequence at the transmitter. In the case of the frequency realm measurements, the time-variant channel transfer function H(t,f) can be obtained through sounding the channel with chirp-like multi-tone signals. The channel sounding of the time-invariant and band-limited channels can be done as long as the channel is sampled at least at the Nyquist rate. However, for the channel sounding of time-variant channels, it must to be ascertained that the channel fulfills a two-dimensional Nyquist criterion [25].

All channel sounders measures $h(t,\tau)$ or its equivalent. For multiple antenna systems, the channel impulse response of the radio channel from each of the transmit antenna elements to each of the receive antenna elements is represented as:

$$h_{i,m} = \left(r_{TX}^{(i)}, r_{RX}^{(m)}\right) = \sum_{l} h_l\left(r_{TX}^{(1)}, r_{RX}^{(1)}, T_l, \Omega_l, \psi_l\right) \tilde{G}_{TX}(\Omega_l)\tilde{G}_{RX}(\psi_l) \exp\left(j\left\langle k(\Omega_l), (r_{TX}^{(i)} - r_{TX}^{(1)})\right\rangle\right) exp\left(j\left\langle k(\psi_l), (r_{RX}^{(m)} - r_{RX}^{(1)})\right\rangle\right)$$

Where:

K Is the wave vector

< > denote the inner product

Ğ Is the complex antenna pattern

$\boldsymbol{r_{TX}}$ Is the location of the transmitter

$\boldsymbol{r}_{RX}$ Is the location of the receiver

Ω Is the Direction of Departure (DoD) containing both the Azimuth and the Elevation angles

Ψ Is the direction of Arrival (DoA) containing both the azimuth and the Elevation angle

τ Is the delay

A) Channel Condition Number (k)

In determining the degree of favorable propagation of a channel, the channel condition number is used. This evaluation metric is the singular value spreads of channel matrices, where on performing singular value decomposition (SVD) of the K×M normalized channel matrix denoted by H, we have

$$H = U\Sigma V^H$$

where U and V are unitary matrices that contains the left and right singular vectors, we obtain the singular values $\sigma_1,\sigma_2,...,\sigma_k$

on the diagonal of the matrix Σ. The singular value spread is the ratio

$$\kappa = \frac{\max \sigma_i}{\min \sigma_i}$$

κ contains information about how orthogonal the user channel vectors are and when κ = 1, all user vectors are orthogonal to each other. In this case, all users can be served simultaneously without inter-user interference. The value of κ gets large when user orthogonality is poor. If κ→∞, it means that some user vectors are aligned [8]. The condition number of the channel can be used to investigate the MIMO channel capacity under various circumstances and to explore the MIMO beamforming performance. When compared with correlation coefficient [21, 22], a metric used for evaluating the orthogonality of channel vectors of two users, the channel condition number is better suitable in reflecting the channel harden phenomenon and the orthogonality of multi-user channel vectors. [12].

B) Distance from Favorable Propagation

According to Erik Larsson and Thomas Marzetta in [26], the channel condition number is not good enough as a metric for favorable propagation condition whenever the various channel vector's norms are not equal, a situation that plays out in practice when the UEs have different locations. In [4, 8, 27] favorable propagation in massive MIMO was discussed, where the channel matrix condition number was used as a metric for measuring how favorable the channel is. The channels in those papers were considered only as i.i.d. Rayleigh fading. However, in practice, due to the situations where the UEs have different locations, [26] says the norms of the channels are not identical and as such the condition number is not a good metric for whether or not we have favorable propagation, rather it proposed the "distance from favorable propagation" measure, (Δc), explaining it as the relative difference between the sum-capacity and the utmost capacity achieved under favorable propagation condition.

In the uplink of a single cell central antenna system, where K single antenna terminals simultaneously and independently transmit data to the base station having M antennas, figure 3 below. If the terminals transmit K symbols x_1, x_2…….x_k where $E[|x_k|^2] = 1$, then the M x 1 received vector at the BS is written as;

$$y = \sqrt{\rho}\sum_{k=1}^{k} g_k\, x_k + n$$

$$= \sqrt{\rho}\, G\, x + n$$

Where $x = [x_1, x_2, \ldots\ldots x_k]^T$ and $G = [g_1, g_2, \ldots\ldots g_k]$ is our channel vector linking the k[th] terminal and the base station. n is the i.i.d $C\sim N(0,1)$ random variable noise vector and ρ is the normalized transmit signal to noise ratio (SNR). Here g_k include the effects of large-scale fading and small-scale fading i.e. h_k^m , β_k and $g_k^m = \sqrt{\beta_k}\, h_k^m$ where k = 1, 2…., K and m = 1, 2…., M

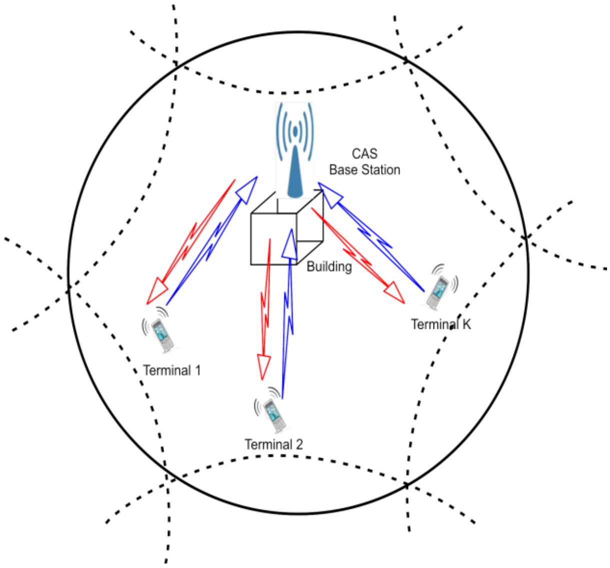

Figure 3: Mobile cellular network with a CAS configuration.

The sum capacity of the system with channel state information at the base station is given by;

$$C = \log_2 (1 + \rho G^H G)$$

Using Hadamard inequality.

$$C = \log_2|1+\rho G^H G| \le \log_2\left(\prod_{k=1}^{k} |1 + \rho G^H G|_{k,k}\right)$$

$$= \sum_{k=1}^{k} \log_2(|1+\rho G^H G|_{k,k}) \quad \ldots.1$$

$$= \sum_{k=1}^{k} \log_2(1+\rho\, ||g_k||^2) \quad \ldots\ldots2$$

Under favorable propagation $G^H G$ is diagonal as off-diagonal element → 0 and diagonal elements becomes $||g_k||^2$ thus equation 1 become equation 2. When $\{g_k\}$ have different norms or $\{\beta_k\}$ are different, [26] says we cannot use the condition number to measure how favorable propagation is, rather we use the distance from favorable propagation which is defined as the relative gap between the capacity C obtained by this propagation and the upper bound in equation (2): Thus distance from favorable propagation Δc is given as

$$\Delta c = \frac{\sum_{k=1}^{k} \log_2 (1+ \rho\, ||g_k||^2) - \log_2|1+ \rho G^H G|}{\log_2|1+ \rho G^H G|}$$

C) Coherence Bandwidth, Delay Spread and Doppler Spread Variations

One of the important parameters of propagation channel is the coherence bandwidth which is a measure of the frequency selectivity of the channel. The coherence bandwidth is proportional to the inverse of the root mean squared (rms) delay spread and is bounded by $W_C \cong 1/T_d$ (where W_C is the coherence bandwidth and T_d is the multipath spread) [25, 28, 29]. Different signals travelling through different paths in a time-dispersive multipath propagation channel arrives at the receiver at different times causing what is termed "Delay Spread" which is proportional to the length of the multipath which in turn is a function of the size and topology of the propagation environment as well as the position of objects or scatterers around the transmitter and receiver [29]. Therefore delay spread T_d can be define as the disparity in propagation time between the shortest path and the longest path [28] using paths with significant energy only.

$$T_d = \max| \boldsymbol{\tau}_i(t) - \boldsymbol{\tau}_j(t) |$$

The delay spread can also be expressed as the root mean squared value, where it is the standard deviation value of the delay of reflections weighted proportionally to the energy of the reflected waves, it is a measure of the different delays in the channel. Also due to the motion of the transmitter/receiver or scatterers, frequency and time induced selective fading that can be characterized by the rms delay and Doppler spread respectively occurs in a propagation channel [25, 29]

D) Angles of Arrival and Departure

In the conventional two dimensional (2D) fading channel measurement, the characterization of the spatial domain channel parameters with the antenna array modeled as a linear array focuses on the horizontal direction where we have angle of arrival (AoA), angle of departure (AoD) and the power angle spectrum (PAS) which have a substantial influence on the level of multiplexing and diversity gain in massive MIMO systems [30]. These are called the Azimuth angles of arrival and departure (AAoA, AAoD) to distinguish them from the 3D parameters of Elevation angles of arrival and departure (EAoA, EAoD). The four parameters were derived in [31] while widespread measurement was carried out in [9, 32] where the CIRs obtained based on the raw data fed into the space-alternating generalized expectation maximization algorithm (SAGE) were used to calculate and get the channel parameters of k-factor, composite channel rms delay, AAoA, EAoA, AAoD, EAoD, polarization matrix, clusters number and the Doppler shift.

E) Cluster Birth and Death Process

Due to the non-WSS property of the massive MIMO antenna array, various antenna elements of the array at the base station may see different groups of clusters at various time instants as the clusters appear and disappear. This is described as the birth-death phenomenon [12], thus a particular cluster may not at all times be visible to all the antenna elements of an massive MIMO array [33]. In a non-stationary time-variant scenario, all multipath components (MPCs) exist over a particular time period and then disappears which is due mainly to the movement of the Tx, Rx and the moving scatterers. This behaviour is suitably described by the discrete Markov process [31]. This birth-death process can also occur in the spatial domain rather than the time domain when we consider massive MIMO due to the spatial arrangement of the antenna array as described earlier above, where the evolution of clusters represent the spatial variation of the massive MIMO channel during the movement of the mobile station where the power of various clusters varies with some of them appearing or disappearing. Based on the birth-death process, the evolution of clusters can be simulated and the cluster number can be measured in LOS and NLOS condition as done in [34]. Both [9, 34] investigated the cluster birth and death process and measured the cluster number in LOS and NLOS conditions. According to [14], the non-WSS caused by the cluster partial visibility as it appears and disappears leads to increment in the channel capacity of massive MIMO, motivating the research interest in massive MIMO.

F) Other Channel Characteristics

Channel measurement in real propagation environment have been done in [2, 10, 11, 13, 35] and [36-40] for massive MIMO system to identify the basic properties of MIMO channels. While [40] is a flexible 100 antennas test bed for investigating massive MIMO in the uplink mode for four users using 20MHz bandwidth where the synchronization capabilities of the base station RF frontends were verified achieving 384 Gbps of data in the transmit and receive directions, also low latency of 500µs was achieved. [10] Using a 2-8GHz frequency band investigated cluster influence on the delay spread and coherence bandwidth of the channel, also the authors in [12] proposed the channel condition number as a metric for the measurement of both the channel correlation and channel hardening properties of massive MIMO. The paper also presented a general framework for large scale antenna array system channel modeling using a home-built channel sounder operating at 5.6GHz center frequency and 200MHz bandwidth, a vertical polarized Omni-directional antenna are used at the transmitter as well as the receiver. The authors in [38] compared the measured channels with i.i.d entries in terms of their capacity sum rates with linear precoders using 2.6GHz frequency with 20MHz bandwidth, they also studied the spatial orthogonality among channel vectors using the correlation coefficient as well as the inverse condition number as measurement metric, at different measurement positions.

The table below show the different related works and their channel parameters of interest, type of antenna array employed as well as the center frequency of operation.

Table 1: Various related works on channel measurements

		V-ULA [37]	**V-2D [12]**	**V-Cylinder [38]**	**Planar [19]**	**V-ULA [39]**	**V-ULA + Cylinder [40]**	**Planar [35]**	**ULA [10]**	**V-ULA +LPA [11]**
	Operating Freq (Ghz)	2.6	5.6	2.6	2.4	2.6	2.6	3.7	2- 8	1.0
1	Condition number			✓						
2	Spatial Correlation	✓								✓
3	K-Factor	✓								✓
4	Angular Power Spectrum	✓								
5	Eigenvalve Distribution	✓								
6	Channel gain	✓								
7	Inverse condition number		✓							
8	RMS delay spread		✓			✓				✓
9	Capacity			✓	✓	✓	✓			
10	Sum rates			✓	✓	✓	✓			
11	Correlation coefficient			✓						
12	Singular value spreads						✓			
13	Mutual couplings							✓		
14	Signal constellation points							✓		
15	Channels response								✓	
16	Cluster number								✓	
17	Angle spread								✓	
18	Delay spread								✓	
19	Angle PDF								✓	
20	PDP (power delay profile)								✓	
21	Average power									✓
22	Coherence bandwidth									✓
23	Mean delay									✓
24	Beam forming APS									✓

G) Challenges of Massive MIMO Channel Measurements

The major challenge of massive MIMO channel measurement is the fluctuating nature of the non-WSS parameters which oscillate both in the array axis and time axis thus requiring a very huge number of channel measurements to be done to capture the parameters. This is time consuming both on the field and during data analysis. It is also noticed that these parameters behave differently to different types of antenna array such as the uniform linear array, the planar array or the cylindrical array etc, therefore the employment of various types of antenna array in the measurement campaign increases the time and resources required. This is why a single measurement hardly captures all the parameters and most current measurements make use of the uniform linear arrays due to its relatively low complexity.

H) Future Direction for Massive MIMO Channel Measurements

Though there are measurement campaigns carried out to investigate the cluster appearance and disappearance including AoA, EAoA, AoD and EAoD shift in the literature [9, 12, 30, 31, 32], more work still need to be done in the investigation of birth and death rates of partially visible clusters and their effects on the channel capacity of massive MIMO system. Most of the above works are in the 2D plane but [30, 31, 32, 34, 41] carried out investigations in the 3D elevation domain of large scale antenna systems which require more investigation in the literature. [30] Stated that using 3D multiuser massive MIMO at the BS can improve the system capacity beyond what 2D antenna array can offer where the signal will transmit in the 3D space with angle distribution in both horizontal and vertical plane. Therefore, the impact of receiver location within a high-rise building should be studied and this is still an open research problem to be investigated according to [19]

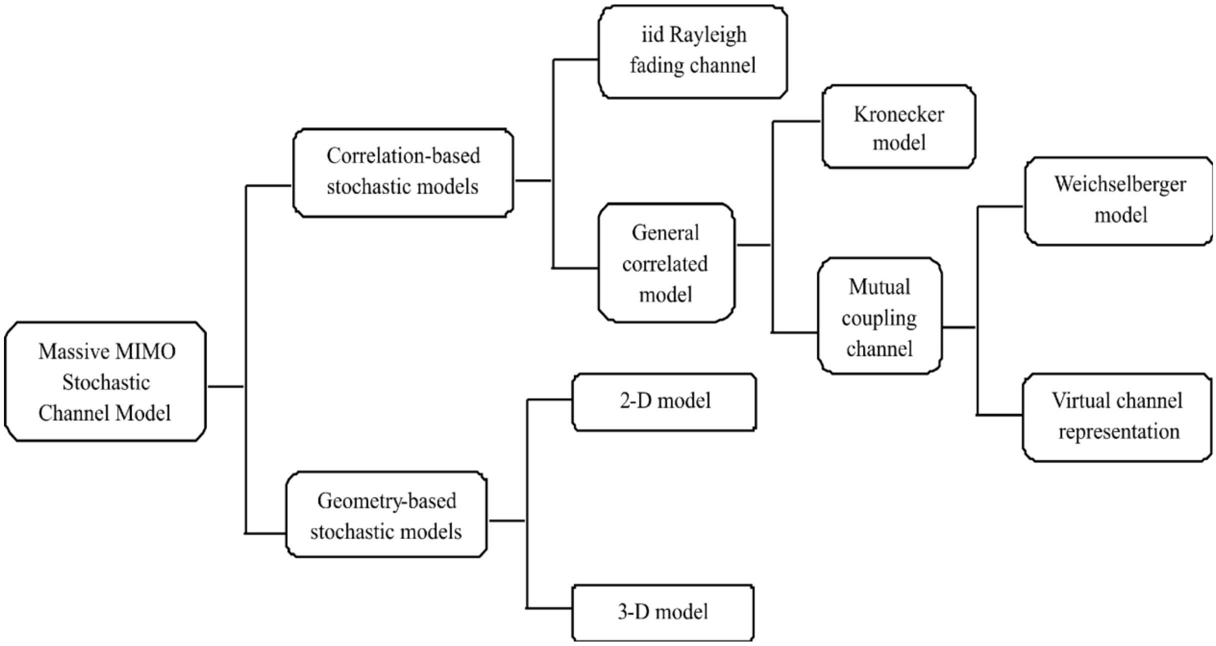

Figure 4: Different MIMO Channel Models

VARIOUS MIMO CHANNEL MODELS

There are different types of MIMO channel models classified into two broad groups namely the correlation based stochastic models (CBSM) and the geometry based stochastic models (GBSM) as depicted in figure 4 below. The CBSMs are mainly used for evaluating hypothetical capacity and performance of MIMO systems simply due to their lesser complexity but with lower accuracy and is therefore inadequate in modeling the non-WSS occurrence nor the sphere-shaped wave result as earlier enumerated. On the other hand, GBSM models are more accurate though with higher computational complexity. The best channel model type for practical massive MIMO is thus the GBSM and this section will concentrate on the GBSM model.

A) Geometry Based Stochastic Models (GBSM)

There are two categories of the GBSM modeling method called the two dimensional (2D) channel model which propagate beam on the 2D plane as we have in the linear array system while the second category is the three dimensional (3D) channel model which propagate beams on the 3D plane as we have in the spherical, rectangular and the cylindrical array [42]. In the current state of the art 2D channel models like the 3GPP Spatial Channel Model (SCM), World Wireless Initiative New Radio (WINNER), as well as the COST 2100, the azimuth angles only are used to describe the propagation paths while the elevation angle of the antenna is fixed at π/2, however, in the elevation, we have a considerable component of energy been radiated there, therefore using the azimuth alone to characterize the propagation paths is not a true representation of the environment. Again, fixing the angle of elevation of the antenna at π/2 means that the degrees of freedom of the channel in the elevation are not taken advantage of [43].

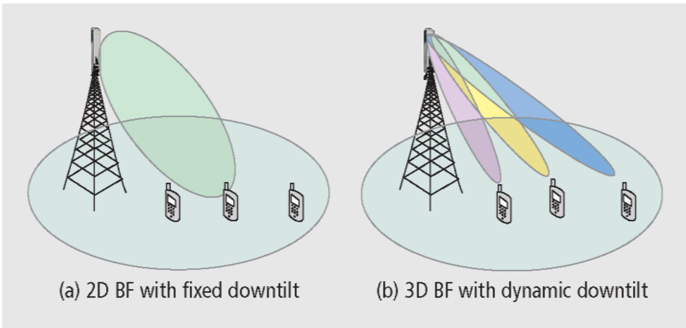

Figure 5: 2D and 3D Beamforming

When analyzing cross-correlation among antennas with diverse 3D patterns, 3D model components becomes of great importance, where if we consider the radiation arriving in the azimuth plane alone will produce inaccurate results. Thus modifying the 2D channel model to incorporate the elevation plane based on the elevation statistics is of importance consideration. [44]. Considering the dynamic adaptation of the elevation angles will unlock new potentials for 3D beamforming which will introduce considerable performance gains. See figure 5 above. Thus the expansion of the current 2D channel models to incorporate the 3D scenarios must take into cognizance the elevation angles of the propagation paths [43].

Meanwhile, [45] classified the GBSM channel models into the WINNER-type which include the 3GPP spatial channel model (SCM), the extended-SCM, WINNER, WINNER 11, WINNER+ and the QuaDRiGA model whose main feature is based on the measurement of the AoAs and AoDs as a reflection of the definition of the scatterers while the second group is called the COST-type which include COST 2100 etc whose main feature is based on the physical position of the scatterers in the visible region (VR). This classification is done simply because nearly all current channel models are 2D.

WINNER/IMT-Advance

The earlier parameterization of this model was done in the 2D plane which describe both the indoor, outdoor and the indoor-to-outdoor scenarios. This model which is based on a huge measurement campaign generated its channel realizations by plane wave superimposition with some distinguishing parameters on the assumption that every antenna element undergo the same large scale parameters fluctuations which may not be valid for massive MIMO systems. Small scale parameters considered are AoA, AoD, propagation delay and power. The WINNER 11/+ model is a 3D extension of the 2D model and the main 3D channel parameters considered are geometric polarization, shadow fading, Ricean K-factor, Delay spread, AoA, AoD, EAoA, EAoD [36, 12, 46], it should be noted however that this 3D extension depend to a large extend on theoretical literature rather than on channel propagation measurements [36] and thus real life measurements are needed for verification, including the elevation characteristics of the antenna array and the cross-correlation matrix of the large-scale fading parameters. This means that we cannot directly apply this 3D model in realistic scenarios without physical measurements campaigns.

COST 2100 Model

The COST 2100 model support non-WSS by modeling clusters and their respective visibility regions (VR) where the visibility region specifies the probability for a cluster being visible by a UE such that if a UE comes within the VR of a cluster, the UE signal propagates through that cluster [9, 46]. This way it is obvious that close UEs will likely partially observe similar clusters and therefore have comparable angular characteristics. The VRs are characterized for UE side only and not for the BS side in the current COST 2100 model because one of the major reasons for time and spatial variations in the channel is the UE movement where antennas with small arrays are deployed at the BS. On the other hand, for massive MIMO with large scale antenna arrays, a spatially variant channel is also noticed at the base station antenna arrays and this is not currently supported in the COST 2100 model. Therefore, more effort is needed by researchers to extend the idea of cluster VRs regions to the base station side for large scale arrays in massive MIMO systems [12]. See table 2 below for WINNER type and COST type model characteristics.

Table 2: COST-type and WINNER-type GBSM comparison

S/N	COST-TYPE	WINNER-TYPE
1	Defined the clusters by their physical position based on the visible region associated with each [12, 45]	Defined the clusters by their AoA and AoD based on plane wave approximations which does not hold for massive MIMO and thus need to model for spherical wave [12, 45, 43]
2	Difficult to extract MPC parameters using measurement [45]	Does not support multiuser consistency since channels are generated independently for each user without considering user correlation thus failing to harness the mutual orthogonality effect making WINNER type over optimistic in performance
3	Visibility regions (VR) used at the UE side only however due to large antenna array at the BS, VR at the BS also need to be characterized	Extension to 3D for beamforming needed in 3D 5G massive MIMO system [43, 30]
4	Extension to 3D for beamforming needed in 3D 5G massive MIMO system [43, 30]	

B) 3D Massive MIMO Channel Model

The 2D channel models follows a stochastic modeling technique in which, statistical parameters such as delay spread, AoA and AoD etc are used to describe the propagation paths [43], where 2D plane is assumed for the location of scatterers, transmit and receive antennas as well as the reflectors. Various MIMO transmission techniques such as beamforming, spatial multiplexing, precoding and multi-user MIMO etc are therefore by this assumption limited to the azimuth dimension where the elevation angle of the antenna bore-sight is fixed at a value of $\pi/2$.

However, as shown by several works [43, 30, 47], there is a considerable part of energy that is emitted in the elevation, therefore characterizing the transmission paths in the azimuth without the elevation is not a true interpretation of the situation. Again, if we assume the angle of elevation of the antenna bore-sight to be fixed means that in the elevation, the channel's degrees of freedom are not being exploited. However, in order to appraise techniques such as vertical sectorization in which a narrow elevation beam is directed to each vertical segment as shown below in figure 6, or in a situation where we need to evaluate a UE specific elevation beamforming, a 3D channel model will be needed.

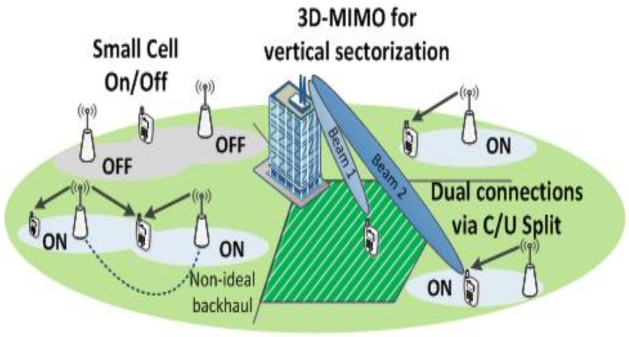

Figure 6: 3D MIMO for vertical sectorization

In the 5G architecture where deployment of massive MIMO in urban macro cells located outdoor is expected to be used for HetNet traffic backhauling as well as connecting with building mounted large scale antenna arrays for traffic evacuation from indoor access points (since 80% users are indoor and 20% outdoor), this typical usage scenarios will require elevation beamforming as well as full dimension MIMO (FD-MIMO) for which a 3D model is essential [48]. The opportunity to tilt the transmit beam angle in the full 3D space will enhance the overall system throughput and interference management particularly in situations where the users are spread in a 3D space with different and identifiable elevation. Another potential use of the 3D model is in the extension of spatial multiplexing from 2D MIMO to the 3D MIMO application [49] where channel state information at the transmitter which is UE specific is required. Spatial multiplexing is used to enhance system throughput performance. All the above potentials of 3D MIMO techniques requires and call for 3D MIMO channel measurements and modeling.

In the process of providing a 3D channel model, it is necessary to measure 3D components, this is followed by raw data post-processing and finally data analysis and channel modeling, [49]. 3D channel modeling has been discussed in [44, 47, 50]. In [47] a composite 2D and 3D channel model and channel coefficient were defined and used to evaluate the system ergodic channel capacity. The composite channel model sensitivity to different azimuth and elevation power distributions were then discussed while [44, 50] basically compared the 2D and 3D models with greater emphasis on the 3D model and its characteristics.

The 3D MIMO channel measurement and modeling is yet in its infancy as a result of the elevated requisite on the measurement apparatus. Recent 3D MIMO measurement campaigns paid attention to channel parameters relating to the elevation e.g. (EAoD), (EAoA), distribution of the delay spread (DS), distribution of the angle spread (AS) etc [49, 51, 52], however, their effect on other critical parameters such as polarization, Doppler, power delay profile, time variation, and stationarity are yet to receive adequate attention [53]. This is due to the fact that the collection of accurate 3D spatial information requires specially designed Tx and Rx antennas.

C) Challenges and Future Direction for Massive MIMO Channel Model

A lot of work has been done and advancement made in channel models required for massive MIMO, however, many issues are yet unresolved. A major technology in the emerging 5G network is the millimeter wave communication that is able to combine its huge bandwidth (≥ 1 GHZ) with massive MIMO for compensating for the large path loss and atmospheric absorptions at mmWave frequencies using huge beamforming gain which has been proposed for HetNet backhauling in 5G network. However, because the time domain resolution in mmWave channels is very high (1ns), even the IMT-A channel model supporting 5ns time domain resolution still fall short of the requirement of mmWave channels, therefore, a massive MIMO channel model having improved time resolution is of critical research interest for 5G development. [19]. WINNER 11/+ as well as the IMT-Advanced channel models were designed for frequency range below 6GHz. Since 5G network is expected to cover frequency ranges from 380MHz up to 86GHz, channel models suitable for 5G applications should cover this frequency ranges, however, due to limited availability of channel sounders researchers make use of some "snapshots" from the ranges which are measured while the gap is filled with software simulations and interpolations [46]. Finally, majority of the literature evaluate the elevation angles at the UE, with not many paying attention to the BS side [52]. It is necessary to characterize the elevation angle at the BS side as well.

CONCLUSION

Massive MIMO will play a crucial role in the deployment of future 5G mobile communication as greater spectral and energy efficiency could be enabled. More importantly, since massive MIMO is suggested as the dominant technology to provide wireless high speed and high data rate in the gigabits per seconds for backhauling various heterogonous networks to be deployed in 5G network, therefore measurement based channel models for massive MIMO are critical and important for the system design and network planning. We have therefore reviewed here the various critical measurements both in the 2D and 3D plane as well as the extensions required in the current state of the art models to meet the requirement for the application of massive MIMO in the expected 5G network.

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