# A Comprehensive Review on Channel Estimation Methods for Millimeter Wave MIMO Systems

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**Abstract.** The major requirements of fifth-generation (5G) cellular networks and further are low latency and great speed of data transmission. One such way to fulfill these requirements is to make use of 5G enabling technology called Millimeter-wave (mmWave) communication. The cellular systems relying on this technology can function with higher data transfer rate up to gbps due to the availability of large band width. A very high transceiver intricacy is required exorbitantly in the case of conventional MIMO methods whereas digital precoding/conjoining is generally accomplished at baseband with single radio frequency (RF) sequence and a single ADC per antenna in case of traditional MIMO systems. So an all-digital processing approach is prohibitive owing to the high price and power depletion of RF chains and ADCs at frequencies of mmWave. This appraisal primarily aims at offering a complete analysis of channel approximation techniques accompanied with various diversified millimeter wave scheme. Consequently, in terms of their corresponding aids and inadequacies a comparison is also provided among prevailing resolutions.

**Keywords:** Millimeter-wave communications · 5G cellular systems · Massive MIMO · Hybrid architecture · Channel estimation · Beamforming · Compressive sensing

## 1 Introduction and Background

Technology has emerged all its way to the next level with the upbringing of various evolving applications like AR, VR, MR, holography projection, high definition videos, smart cities, industrial IoT, connected cars and many more. The high ended technologies mention above need to link devices immensely and they need to transmit the data with high speed and also more data need to be exchanged between devices. So we go for a fifth generation technology in which the user data rate is increased by a factor of 10–100 (up to 10 Gigabps), latency is reduced by factor 10, connectivity density is increased by 10 when compared to 4G, and also to decrease the price and power intake [1]. Owing to this immensely growing ultimatum for data congestion and enormous connectivity and


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in addition the inadequacy in the sub-6 GHz radio spectrum, investigators are attempting to put forward innovative elucidations. These are primarily centered either on making the network busy or on developing extra bands of frequency or on employing the novel schemes of signal processing.

In terms of employing several bands, the millimeter wave frequency in between the range of 30 Giga Hertz and 300 Giga Hertz (i.e. range of 1–10 mm wave lengths), and the vast underutilized bandwidth in these bands will let the wireless systems to handle massive increases in capacity ultimatum as the employed bandwidth increases. Because of this reason, mmWave communications play a superior role in fifth and further peers of cellular networks [2].

The basic challenge with the mm Wave communication systems is that they have a difficulty of large path loss of free space when related to the ones of sub-6 Giga Hertz although their bandwidth is striking. Adding to that, in some mm Wave bands, a significant attenuation is witnessed due to atmospheric changes, and extreme weather conditions like the effects of rain and snow. Consequently, in such cases, the mm Wave communications may be appropriate only for indoor applications i.e., very close distance communications since it is unsafe to broadcast over a small distance of meters. For outdoor mobile communications, by either raising the power of transmission or by employing high-gain, high-directional antennas, one can overcome this difficulty and owing to this, a better range of transmission is expected.

The high transmission power is possible by facilitating constricted steering beams in mm Wave systems, since the transmission power is always restricted by conventions. A lot much gain is essential in the desirable direction and lesser gain in the undesirable region. These can be accomplished by allowing the transmitter and the receiver to direct towards each other. Signal processing technique such as beam forming is employed to attain the requisite high directivity, which is possible by taking the number of antennas in each antenna group at the sender and receiver ends huge. This method is enabled by the lesser mm Wave signal wave length of which makes it feasible to hold together more antennas while overcome maintaining the size of the array small.

One more feature of millimeter wave structure design emanates from the unfeasibility to straight away smear the outmoded digital transceiver designs, which is engaged in sub-6 Giga Hertz, straight to the millimeter wave structures since there is large power intake of mm Wave RF chains. In order to solve this problem, of late, some novel personalized multiple-input-multiple-output (MIMO) structural designs i.e. *Totally-analog fusion* and *few bit Analog to Digital Converters (ADC)* designs were recommended. Whichever architecture is implemented, the goal is to reduce the total amount of power consumed by minimizes the Radio Frequency chains count or the power consumed per unit.

Channel estimation is the most essential part of any telecommunication structure as it is very much required for augmenting the performance of the link. But because of the multifaceted architecture of transceiver, massive number of antennas and large misused bandwidth, attaining Channel State Information (CSI) is quite a bit challenge predominant in millimeter wave systems. The main intention of this appraisal is to put forward a complete general idea of the prevailing channel estimation techniques for millimeter wave systems. Each method of estimation is analyzed and provided with the appropriate level of particulars in a clear and crisp manner. Also a reasonable assessment among them is carried out by a measure of structural design and performance.

In the current study, many diverse prevailing research works were considered and different assumptions were made to them. They are with regard to the: i) Type of data transmission (simplex or half duplex or full duplex), ii) Number of users of the system (whether single or many), iii) Dimensions of channel estimation (2D or 3D), iv)Type of the channel (frequency selective or not), v) mode of the channel for implementation.

**Table 1.** Review of millimeter wave Communications System existing Surveys.

| Coverage and Access | [3] |
|---|---|
| Channel Estimation Technique | [3, 4] |
| Channel Measurement Technique | [3, 4, 6] |
| Channel Modeling Technique | [3, 4] |
| Cross-Layer Design | [4, 7] |
| Technical Potentials and Key Challenges | [2, 3] |
| MIMO system Architecture | [3, 5] |
| Performance Analysis | [5] |
| Propagation Characteristics of channel | [2, 5, 6] |
| Standardization | [4, 7] |

Table 1 illustrates an examination of some attributes associated with mmWave systems and the appraisals in which respective area was fundamentally gone through.

## 2 Characteristics of mmWave Communications

For applications like radar and dedicated communication, mmWave communications have been utilized previously. Later, IEEE has developed certain standards such as IEEE 802.15.3c [9] for wireless PAN's, IEEE 802.11ad [10] for wireless LAN's and Wireless HD [11] for wireless HDMI in the last decade. Of late, the mobile link exploration communal has paid much attention to sub-100 GHz structures functioning in the bands of 28, 38, 71 and 81 GHz, where as the band over 100 GHz has only been explored by a limited latest article [12]. At mmWave frequencies, the propagation characteristics distinct from those of a standard sub 6 GHz system.

### A. *Propagation Characteristics*

The free space path loss is a significant characteristic of propagation where a clear comparison is made between sub-6 GHz and mm Wave systems and it is given by the following expression.

$$PL_{FS} \propto \frac{d^n}{\lambda^2} \tag{1}$$

where *FS* stands for free space and *n* is the path loss coefficient, which is usually equivalent to 2. But, in certain circumstances of the cellular networks and indoor routines *n* is smaller than 2. In some cases such as in the course of extreme weather conditions while propagation, the value of the path loss coefficient could come near the value of 6 [14], λ is the wavelength and *d* is the separation distance between the transmitter and receiver [15]. An analysis is made in terms of distance of transmission, antenna array, propagation environment between microwave broadcast in the 1.8 Giga Hertz Global System for Mobile (GSM) Communication band and mmWave propagation in the 73 Giga Hertz bands was compared, and found an additional loss of 32 dB.

Path loss includes the reduction in strength of mm Wave signals which are caused due to atmospheric changes principally by $O_2$ and water vapor absorption, along with the scattering effects of the rain. The atmospheric attenuation is proportional to the operating frequency. At 60 and 120 GHz, atmospheric oxygen absorption is very severe, while water vapour absorption is generally very strong at 180 GHz [16].

### B. *Technical Potential*

Owing to the high bandwidth efficiency and shorter wavelengths, the 5G cellular technology gives the mm Wave Communication systems the front face. Of course there are a few characteristics of mmWave channel which were quite a bit challenging, but they can be over written because of the presence of some benefits.

*Large Bandwidth:* Concentration restricted alone on the profoundly engaged traditional sub-6 Giga Hertz frequency bands doesn't serve the purpose of achieving very high speeds of data. This high data rates can be attained by providing a very large bandwidth. So the large number of mmWave bands is made available to achieve enormous data exchange in spite of low spectral proficiency [17].

*Short Wavelength:* Antennas with high directivity can be employed for overcoming the problem of shorter wavelengths finally resulting in the free space path loss. This can be overcome by spending on antenna arrays and methods of beamforming. Narrower beams involve higher antenna count in the array which is attuned with mmWave structures.

## III. *Technologies that enable*

Millimeter Wave communications tools is enabled by other techniques like massive MIMO, signal processing and advancements in circuit plan and amalgamation.
*Massive MIMO:* It is a most essential method for improving the capacity of cellular networks. Massive MIMO employs a large number of antennas at base stations and mobile terminals. So far the traditional sub-6 GHz systems have made use of this Massive MIMO, and so it is as well very much important for mmWave structures where more amount of directivity is obligatory [18]. Due to the availability of higher frequency bands, antenna arrays were designed with a more number of antennas.

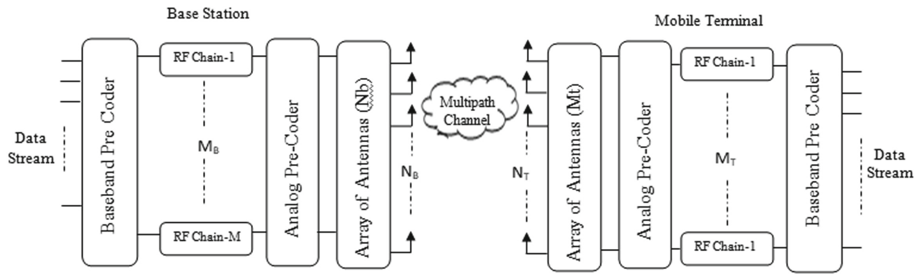


**Fig. 1.** Overall mmWave transceiver system architecture.

*Enhanced Signal Processing Techniques:* The problem with the traditional MIMO systems is that they are made totally digital and a single RF chain is made available to each antenna. Due to this the difficulties such as high enactment cost and high energy in take arise [19, 20]. Certainly, it has been demonstrated that Radio Frequency constituents can ingest up to 70 percent of the whole transceiver power intake [21]. So instead of going after the completely digitalized one, quite a few mmWave hybrid designs were put forward.

## 3 Massive MIMO for Millimeter Wave Systems

For millimeter wave communication systems, more number of antennas must be used, both at the transmitter and receiving ends. As per the previous exploration carried out, it is recommended that the base station have to be possessed with 32 to 256 antennas and the mobile terminal with 4 to 16 antennas [22].

The overall design of hybrid mm Wave transceiver is depicted by means of a block diagram displayed in Fig. 1. Without loss of generality, a Base Station which is constructed with number of Radio Frequency chains ($M_B$) and a number of antennas ($N_B$) then ($M_B < N_B$) is expected to fortified with $M_T$ Radio Frequency chains and $N_T$ antennas ($M_T < N_T$) so as to interchange some blocks of data [5]. In general, the count of Radio Frequency chains at base stations is more than that of mobile terminals. The same design might be drawn-out to several numbers of handlers. However, here, a point-to-point transmission is considered.

The hybrid design's baseband digital processing and analogue circuit work together to generate beams for the sender or/and receiver. In disparity by the outmode overall-digital design that would not contemplate an analog circuit beforehand the Radio Frequency chains at the sender and contemplates a single Radio Frequency chain per every antenna, i.e. $M_B = N_B$ and $M_T = N_T$ [3]. Because of the problems mentioned above, nowadays a complete digital design is sidestepped in millimeter wave communication system design. In the place of that novel hybrid designs were proposed so as to make the massive MIMO system achievable. The awareness is to lessen the total power intake and the total amount needed out which can be made possible by diminishing the count of Radio Frequency chains and the resolution of the Analog to Digital (ADC) Converters.

*Hybrid Style:* The hybrid design characterizes a negotiation between an entirely digital structural design (with the same number of antennas and Radio Frequency chains) and a completely analogue design (where only single Radio Frequency chain is utilized). Both analogue and digital domains are used for precoding (at transmitter side) and combining (at the receiver side). The aim is to make utilization of a dimension compact pre-coder/combiner with a very less count of Radio Frequency chains while still banking on complete-size analog pre-coder/combiner. This hybrid architecture has enhanced the performance in terms of reduction in the RF chain count but the results are shown to be not very much enhanced from complete digital design [8].

*mmWave MIMO Channel Modeling:* Physical modeling and analytical modeling are the two different types of mmWave channel architectures. The physical models are centered on the electromagnetic properties of signal broadcast between arrays of antennas matching to transmitter and receiver. They are an excellent choice for mmWave MIMO channels because they can effectively redirect to the measured parameters and are well-known. The latter one i.e., the analytical models on the other hand, are more suitable for the development of algorithm and for scrutinizing the system.

**Table 2.** Techniques for estimating channel in hybrid architecture systems

| Reference paper | Method | No. of Users | Up Link/Down Link | Description |
|---|---|---|---|---|
| Alkhateeb et al. [23] | Divide and conquer approach | Single | Down Link | Orthogonal Matching Pursuit, Least Square Estimation |
| He et al. [25] | Mode by mode approach | Single | Up Link/Down Link | Non Line of Sight channel based on the Time Division Duplexing correlation statistics |
| Lee et al. [24] | Open loop system | Single | Not specified | Orthogonal Matching Pursuit, MG-OMP, LSE |
| Schniter et al. [26] | Aperture shaping | Not specified | Not specified | Least Absolute Shrinkage and Selection Operator, LMMSE |

(*continued*)

**Table 2.** (*continued*)

| Reference paper | Method | No. of Users | Up Link/Down Link | Description |
|---|---|---|---|---|
| Payami et al. [27] | Ping pong approach | Single | Not specified | The amount of multi-path components has no effect on the training time |
| Peng et al. [29] | Antenna Array with Virtual Elements | Single | UpLink | The angular estimate resolution is improved using a CS-based approach |
| Kokshoorn et al. [28] | Overlapped beam patterns | Single | Not specified | MRC, used to track fast changing channels |
| Montagner et al. [30] | 2D Discrete Fourier Transform | Single | Not specified | DFT, iterative cancellation method |
| Mendezrial et al. [31] | Switches | Single | Down Link | Orthogonal Matching Pursuit, M-OMP |
| Han et al. [32] | Two stage asymmetric | Multi | Down Link | Exhaustive search, Compressive Sensing |
| Park et al. [33] | Spatial covariance Technique | Single | Up Link | Orthogonal Matching Pursuit, S-OMP, C-OMP, Dynamic Simultaneous -OMP, Dynamic Covariance OMP |
| Guo et al. [34] | Dimension Deficient | Single | UpLink | CoSaMP, it reduce the accidental errors |

The channel model communicates the NTX NB composite matrix HDL of the Narrowband Down Link (DL) channel is expressed as,

$$H_{DL} = \sqrt{\frac{N_B N_T}{L\alpha_{PL,DL}}} \sum_{l=1}^{L} \alpha_{l,DL} a_T(\theta_{l,T}, \varphi_{l,T}) a_B^H(\theta_{l,B}, \varphi_{l,B}), \quad (2)$$

where L represents path count between the Base Station (BS) and Mobile Terminal (MT), $(\theta_{l,T}, \Phi_{l,T})$ are the azimuth angles of arrival and elevation angles of arrival (AoA) and $(\theta_{l,B}, \Phi_{l,B})$ are the azimuth angles of departure and elevation angles of departure

(AoD), $\alpha_{PL,DL}$ is the regular value of the path-loss, $\alpha_{l,DL}$ is the complex increase of gain of the $1^{th}$ track in the Down Link channel. The Eq. (2) ought to be revised to signify the D-delay down link channel exemplary because of the reason that the channel is frequency-discerning when the structure is extended to wide range of frequencies.

Henceforth the equation is produced as:

$$H_{DL} = \sqrt{\frac{N_B N_T}{L\alpha_{PL,DL}}} \sum_{l=1}^{L} \alpha_{l,DL} p_B(dT_s - \tau_l)\ldots$$
$$a_T(\theta_{l,T}, \varphi_{l,T}) a_B^H(\theta_{l,B}, \varphi_{l,B}), \quad (3)$$

At the Base Station, Where $p_B(.)$ is a combination of the pulse shaping filter and other filters responses.

## 4 Techniques for Estimating Channels in Hybrid Architecture Systems

Taking into consideration the previously mentioned restraints, a few channel approximation approaches by way of this hybrid design have been suggested. These approaches, along with others, are detailed below, and they are given in Table 2 with t corresponding references. Many of the proposals undertake a narrowband constant frequency mmWave channel prototype. Various techniques for mm wave channel estimation with hybrid architectures are presented in this section.

*Divide and Conquer Approach:* In this method, [23] a low-intricacy algorithm has been proposed called adaptive channel estimation for mmWave channel. For this approach, more and less number of antenna arrays and RF units are employed at both the sides of Base Station and Mobile Terminal respectively. The approximation procedure is separated into several phases. The Angle of Arrivals/Angle of Departures angular values are parted into K non-overlaid angular sub-slots at each stage, and K beam patterns are employed to direct the pilot signal and syndicate the signal at the destination. As a result, each beam arrangement at the sender is joined with K beam structures at the receiver, requiring $K^2$ time slots for each stage to span all possible transmit-receive beam pattern combinations. The authors constructed and offered a predetermined codebook that contains the beam patterns. Evaluating the amounts of the $K^2$acknowledged signals is then used to decide or surmount the subsequent Angle of Arrivals / Angle of Departures sub-range for the following stage.

*Ping-pong Approaches:* This algorithm customs ping-pong iterations. In order to attain the channel parameters, this algorithm entails an intricacy of $O(KL^2 N_B log_K(N_G/L))$, wherefrom an even network of N$G$ points, the parameters AoAs and AoDs are acquired. Two-phase procedure for estimation of channel with a single-user (SU) is presented in [27] and in addition a codebook design which is analogous to that in [23] is also developed. The procedure is categorized by a dual phase handshaking amidst the sender and the receiver.

*Overlapped Beam Patterns Technique:* In [28] by making use of a conception of making an approximation on the beam patterns that are overlapped, a fast channel estimation algorithm is put forward. When compared to [23], this idea lessens the time turns desirable to approximate the channel by $K^2/\log_2^2(K+1)$ with a minor deprivation in performance. This minor deterioration can be tolerated when tracking rapidly changing channels is essential.

*Open-loop Approach:* In [24] proposed an open-loop channel approximation method that does not require a feedback loop. The procedure is grounded on CS methods and is recommended for an SU mmWave structure. Just like various channel approximation procedures, the researchers employed the Orthogonal Matching Pursuit and least squares estimation algorithm (LSE) practices to accomplish the approximation of the Angle of Arrivals/Angle of Departures increase in power correspondingly.

*Mode-by-Mode Method:* A different structure was proposed in [25] in order to assess a time basely correlated Non Line of Sight (NLOS) in mmWave MIMO channel. To effectively trail the channel disparities, the authors former changed the parametric channel structure into a progression time basely correlated MIMO channel model. The structure is established on TDD correlation statistics and investigates the channel's reciprocity. The mode by mode technique, a suggested procedure, updates each column of the analog pre-coder and combiner.

*Aperture Shaping Technique:* In [26], The aim of augmenting the sparseness of the virtual MIMO channel have recommended a procedure labeled as aperture shaping. Concisely, shaping of aperture is implemented by smearing a constant gain value at individual antennas at either ends of the Transmitter and Receiver. The shaping coefficients are augmented to get the most out of the signal-to-interference ratio. Adding to that, to further uncover the channel sparsity, They used a millimeter Wave system, which employs modulation and demodulation practices established on Fast Fourier transforms (FFT).

*Antenna Array in Virtual Element Approach:* The authors in [29] suggested a novel idea, which outspreads the actual antenna groups at individually the sender and receiver to a different one by affixing some $A\upsilon$ virtual antennas without changing the physical array, based on the same assumptions as in [23]. The goal of AAVE is to progress the angular approximation resolution by adding simulated antennas to the existent of physical antennas at either sides of the Base Station (BS) and Mobile Terminal (MT).

*2D DFT Approach:* In [30], Millimeter Wave channel approximation technique relied on the Discrete Fourier Transform in two dimensional was offered. The approximation of the channel considerations is made by means of the iterative dissolution technique. In detail, the method after withdrawing the earlier estimated parameters in each iteration, samples are used in Discrete Fourier Transform (DFT) to examine the channel parameters for each path.

*Switches Approach:* In order to lessen price, intricacy and power intake, particularly at Mobile Terminals where these parameters are essential, in [31], the authors projected an innovative hybrid design for a Down Link Single User Millimeter Wave system by means of switches as a substitute for phase shifters.

*Asymmetric Two Stage Approach:* An unbalanced channel estimate procedure for a Down Link multi user Millimeter Wave system was suggested in [32]. As the name suggests it is a dual stage procedure namely, a comprehensive search phase, subsequently a CS approximation phase. During the former phase, the Base Station directs the training signals which points in all directions to the Mobile Terminals which in turn explore in comprehensive routine for the finest conjoining vectors to discover the Angle of Arrival. In the latter phase, CS approximation is done.

*The Spatial Covariance Method:* In [33], channel approximation algorithm scentered on assessing the three-dimensional covariance for a Time Division Duplexing Up Link Single User Millimeter Wave channel were offered. The researchers planned to evaluate the channel covariance straight without guesstimating the channel clearly whereas in two stage approach, first channel need to be approximated and followed by that finding out channel covariance need to be done.

*Over Complete Dictionary Method:* In [34] proposes an additional channel approximation approach for a fully-connected Up Link Single User mmWave system The number of Radio Frequency chains is significantly less than the number of antennas, and as a result, the signal at the receiver stage does not contain all of the Channel State Information, which the authors referred to as the measurement deficient that causes the channel approximation difficulty.

## 5 Conclusion

An overview of current channel estimate approaches for massive MIMO communication systems using mmWave is provided in this survey. First, the system architecture and channel characteristics that must be considered were explained. After that, we examined the performance of various channel estimate approaches in order to have a thorough understanding of each. This technique was used on millimeter Wave system architectures, specifically the hybrid design.

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