2D Discrete Cosine Transform Based Channel Estimation for Single User Millimeter Wave Communication System

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Abstract—Channel estimation is a very challenging problem in millimeter wave communication system. With its sparse nature, millimeter wave channel has strong path loss and severe scattering effects. The higher operating frequency and larger bandwidth enables large number of antenna elements packed in single antenna array for hybrid beamforming architecture. The channel degradation and RF chains less than propagation path to estimate the channel parameters is an open problem. Previously, channel estimation approach like 2D-Discrete Fourier transform results with complex valued, even for real data. A related transform, the 2D discrete cosine transform (DCT), does not have this problem. It is also possible to use 2D- DCT for filtering using a slightly different form of convolution called symmetric convolution. In this paper, we propose a 2D DCT based channel estimation method for millimeter wave systems with the transmitter and receiver equipped with less number of RF chains than the number of antenna elements. A training sequence is used to setup the analog and digital beamformers to probe the channel. A prefilter technique using 2D-DCT is applied to the received training samples. This exploits the sparse nature of the millimeter wave channel and improves the effective SNR at the receiver using the energy compaction property. Proposed channel estimation method is justified using the estimation of angle of arrival (AOA), angle of departure (AOD), path gain, spectral efficiency and bit error rate. Numerical results show that the proposed 2D-DCT based channel estimation method improves effective SNR than the 2D-DFT method at the receiver chain.

Index Terms—Millimeterwave, Channel estimation, angle of arrival (AOA), angle of departure (AOD), Discrete Cosine Transform, Average SNR, Spectral Efficiency and BER

I. Introduction

The user demand for increasing data throughput due to the frequent usage of internet TV, video call services etc in sub 6GHz will be reaching its limit in few years [1]. Early experiment on generation and detection of millimeter waves was undertaken 100 years ago by Bose [2]. Hence, Millimeter-wave spectrum with frequencies in the range of 3–300 GHz can potentially provide the bandwidth required for mobile broadband applications for the next few decades and beyond. Also millimeter wave propagation channel characteristics are not similar to sub 6-GHz band. Extensive propagation measurement campaigns at 28 GHz and 38 GHz were conducted to gain insight on angle of arrival (AOA), angle of departure (AOD), root mean square (RMS) delay spread, path loss, and building penetration and reflection characteristics for the design of future mm-Wave cellular systems [5].

It also includes the evaluation on suitability of millimeter wave frequencies. Due to the narrow beam width of millimeter broadband (MMB) transmissions, the interference among MMB base stations is a lot smaller than traditional cellular systems, and the coverage of neighboring base stations significantly overlap [4].Detailed study on path loss measurements for various propagation models are found in [7]-[8].

Other factor that make 5G mere possible is “Internet of Things” comprised of billions of miscellaneous devices, and the increasing integration of past and current cellular and WiFi standards to provide a ubiquitous high-rate, low-latency experience e for network users. [6, 14]Due to the variation in the mmWave channel, the signal processing algorithms too become complex in applied theory. Sub 6GHz bands transceivers are either analog or digital beamforming. But the transceiver architecture is quite different. It includes both analog and digital beamforming termed as hybrid beamforming [10], [11], [20]. It imposes hardware constraints such as modulo phase shifters, nonlinearity problems, less number of RF chains compared to antenna elements etc. Channel estimation is one of the challenging signal processing problems in millimeter wave communication [19]. A strategy exploiting the channel sparsity with less number of RF chains are necessary. Large scope of signal processing techniques beings applied to improve mmWave communication systems are due to (i) mmWave devices with wider bandwidth promises to provide high capacity gain, (ii) high path loss channel characteristics (iii) directional beamforming.

Compressive sensing approach is proposed to estimate the wireless channel in millimeter wave incorporating the Hierarchical codebook method to reduce the feedback overhead by exploiting the channel sparsity, However it has the exhaustive searching strategy to choose the codebook beamforming vector and long training sequence for better channel estimation [9]. Another method in compressed sensing is estimate the channel with 1-bit analog to digital converters. Its shows that among Expectation and Maximization (EM) algorithm and generalized approximate message passing (GAMP) algorithm, GAMP can reduce mean squared error in the

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important low and medium SNR regions [13]. Two stage compressive sensing based channel estimation performs better with one stage feedback overhead compared to other adaptive compressive sensing based channel estimation schemes [15]. Angular domain channel model proposed uses the sampling theory and linear space to analyze the physical propagation channel to reduce the gap exist in the real channel [3].

2D-Discrete Fourier transform based channel estimation shows improvement even in the low signal to noise ratio (SNR) conditions [12]. Alternatively Discrete Cosine Transform (DCT) based transceivers works as a prefilter to make the channel impulse response to symmetric improves the estimation of MIMO channel parameters [16]. Outdoor urban scenarios channel model uses sectorized beamforming in the millimeter wave channel compensates the large path-loss at mmWave range and study how channel statistics, namely, delay spread and angle spread, are influenced by employing different beam widths. [17]. A short training sequence to estimate the channel parameters based on the two-dimensional discrete Fourier transform method improves the average SNR at the receiver [18].

Hierarchical codebook design for channel estimation in millimeter-wave (mmWave) communications with a hybrid precoding structure shows the improvement in spectral efficiency[21].CBP- based dictionary offers substantially higher estimation accuracy and greater spectral efficiency than the grid-based counterpart but require less computational effort compared with existing algorithms [22].

The accuracy of channel estimation parameters relies on quantization errors, ADC and phase shifter resolutions too [23]. DBF-based millimeter- wave MIMO transceiver architecture is a promising solution. [24]. Angular domain sparsity is exploited in the DOA estimation and path gain estimation using 2D DFT based channel estimation method. [25]. In this paper, fully connected hybrid beamforming architecture providing full beamforming gain for each RF chain is considered for single user MIMO (SU-MIMO) channel estimation. Exploiting the high energy compaction in 2D- Discrete Cosine Transform, it is proposed to estimate the channel parameters like path gain, Angle of Arrival (AoA), Angle of Departure (AoD) and average SNR. This method gives better SNR improvement when estimating the channel's parameters at mmWave frequencies. We compared the performance of proposed method with 2D-DFT channel estimation algorithm by NDFT samples, Γ_{AWGN} values. Numerical solution for proposed channel estimation techniques in MMW gives good performance differentiate with 2D-DFT channel estimation method.

Notation: W is a matrix, a is a vector and a is a scalar, W^{-1} is an inverse matrix, W^T transpose matrix, W^H is a conjugate (Hermitian) transpose matrix, and $\|W\|$ is a Forbenius norm. Block diagonal matrix of given elements are $diag[.,.,...]$, ∘Hadamard product. Mean vector is x and covariance matrix, $\sigma^2 I$ is denoted by CN(x, $\sigma^2 I$) where I_N the identity matrix of size number of receiving antennas.

II. Proposed Methodology

In Section III Millimeter wave System model and Channel Model are discussed. Section IV Problem formulation for millimeter wave channel estimation is highlighted. Section V followed with proposed 2D –DCT channel estimation Method. Section VI discusses the estimated analog beamformer and combiner.

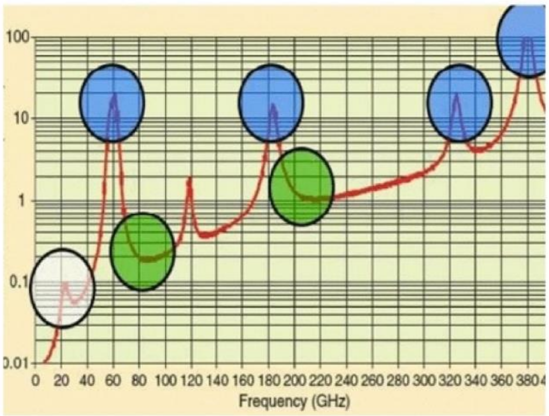

Fig. 1. Atmospheric absorption of electromagnetic waves [7–8]

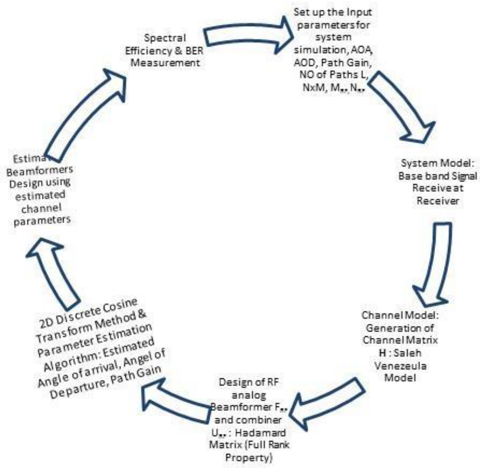

Fig. 2. Proposed methodology

III. System and Channel Model

A. System Model

Consider the symbol x send from M number of transmitter side antennas to N no of receiver side antennas. The transmitter consists of M_{RF} RF chains ($M_{RF} \le M$) and receiver consists of N_{RF} RF chains ($N_{RF} \le N$). The BS (Base Station) or transmitter is expected to apply a $M_{RF} \times 1$ complex valued vector $M_{RF} \times 1$ Complex valued to digital beamformer f_{BB}

followed by an $M \times M_{RF}$ RF analog beamformer F_{RF}. Similarly, the MS (Mobile Station) or receiver is assumed to apply a $N_{RF} \times 1$ Complex valued vector to digital combiner u_{BB} followed by an $N \times N_{RF}$ RF analog combiner U_{RF}. The F_{RF} and U_{RF} are defined with unitary magnitude and arbitrary phase. The single user MMW system with fully connected hybrid analog digital beamforming has shown Fig. 1. Let as assume x be a symbol transmitted from the base station to the mobile station. Let the training symbol x applied to the digital precoder f_{BB} is given by baseband symbol x_{BB}. The baseband symbol vector is given by

$$x_{BB} = f_{BB} \times x \tag{1}$$

The baseband symbol vector transmitted through the RF beamformer F_{RF} is given by

$$x_{RF} = F_{RF} \times x_{BB} \tag{2}$$

The transmitted signal vector received at the receiver analog RF combiner is expressed as

$$y_{RF} = (H \times x_{RF}) + n \tag{3}$$

where H is the MIMO channel matrix (Saleh-Valenzuela Model) and n is the thermal noise vector. Received signal at the baseband combiner is given by

$$y_{BB} = U_{RF}^{H}(H \times F_{RF} \times x_{BB} + n) \tag{4}$$

in which the thermal noise is $n \sim CN\left(0_{Nx1}, \sigma_n^2 I_N\right)$ with variance σ_n^2 and mean is Zero, The signal vector processed at detection point is given by

$$y = U^{H}{}_{BB} \times y_{BB} \tag{5}$$

i.e., $$y = U_{BB}^{H}.U_{RF}^{H}\left(H \times F_{RF} \times x_{BB} + n\right) \tag{6}$$

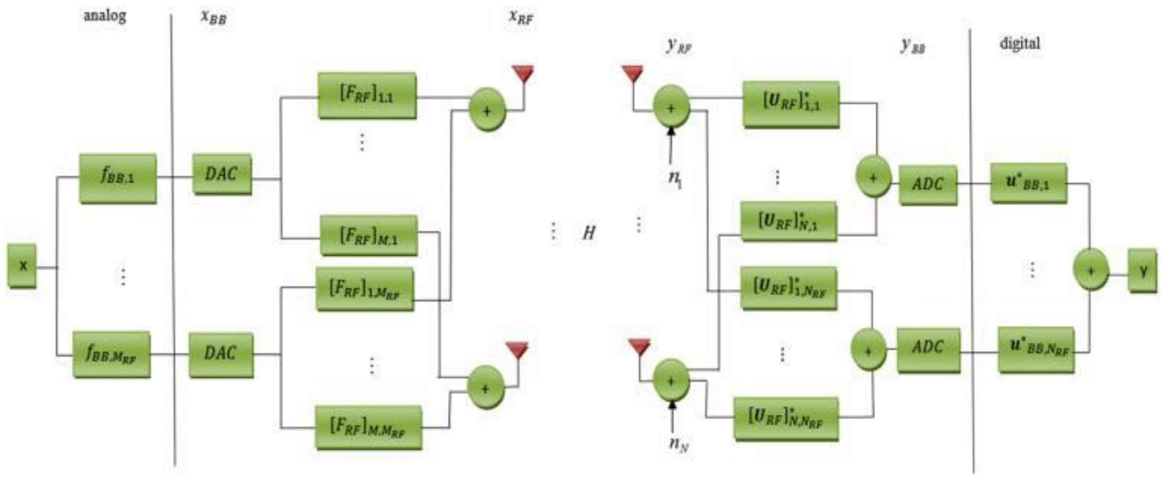

Fig. 3. Fully connected Hybrid beamforming architecture

B. Channel Model

Consider auniform linear array (ULA) with N elements and inter-element spacing D. As the millimeter wave channel undergo scattering problem, Saleh-Valenzuela or Geometry channel model preferred for experimenting the propagation channel characteristics. Also for the chosen N-element ULA, the steering response column vector can be written as

$$a(\phi) = \left[1 \quad e^{j\beta D \sin\phi} \quad . \quad . \quad e^{j\beta(N-1)D\sin\phi}\right]^{T} \tag{7}$$

where, $\beta = 2\pi/\lambda$, λ is the carrier wavelength, D is the distance between the antenna elements. L is the number of paths and ϕ denotes the angle of arrival (departure) rays in the azimuth plane. The path gain of the l-th ray is denoted with $g_l \sim CN(0,1)$ zero mean and unit variance, ϕ_l^r is the angle of arrival and ϕ_l^t the angle of departure. H denotes $N \times M$ channel matrix with L scatterer's uses the geometric channel model. Each scattering path is assumed to give single path between transmitter and receiver. The $N \times M$ MIMO channel Matrix is represented as

$$H = \frac{1}{\sqrt{L}} A_r H_g A_t^H \tag{8}$$

where the transmit and receive steering vectors are given by

$$A_t = \left[a_t\left(\phi_1^t\right) \quad a_t\left(\phi_2^t\right) \quad . \quad .. \quad .. \quad .. \quad a_t\left(\phi_L^t\right)\right] \tag{9}$$

$$A_r = \left[a_r\left(\phi_1^r\right) \quad a_r\left(\phi_2^r\right) \quad . \quad .. \quad .. \quad .. \quad a_r\left(\phi_L^r\right)\right] \tag{10}$$

and the H_g is the diagonal path gain matrix with the $g_1 \ldots g_L$ are the L^{th} path gain diagonal elements expressed as

$$H_g = diag\left(g_1, . \quad . \quad . \quad . \quad g_L\right) \tag{11}$$

It's noted that the H is very large matrix depends on number antennas in terms of hundreds of columns and rows with 2L real phases and L complex gains, where L is usually much smaller than the number of antennas[12] . Also the estimate angle of departure and angle of arrival in beamspace method and CS method from channel

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model (8) is not the real physical angle, but only provide an approximation of the quantized angle with limited resolution. If σ_x^2 is the power of x as each term in (8) has unitary power, the average SNR for each antenna [12] is given by

$$\Gamma_{AWGN} = \frac{\sigma_x^2}{\sigma_n^2} \tag{12}$$

Under the power constraint the TX side $\|F_{RF} f_{BB}\|^2 = 1$

For a given channel matrix, assuming $\|U_{RF} u_{BB}\|^2 = 1$, and then we can define the SNR detection at a point as

$$\gamma = \frac{\Gamma}{\Gamma_{AWGN}} = \left|u_{BB}^H U_{RF}^H H F_{RF} f_{BB}\right|^2 \tag{13}$$

The improvement of Γ with respect to Γ_{AWGN}, defined as (12), is given by

$$\gamma = \frac{\Gamma}{\Gamma_{AWGN}} = \left|u_{BB}^H U_{RF}^H H F_{RF} f_{BB}\right|^2 \tag{14}$$

And by averaging γ with respect to H, we denote

$$\bar{\gamma} = E_H[\gamma]$$

IV. Problem Formulation

Millimeter wave channel exhibits clustered path propagation characterized with the Saleh Venezeula Channel Model. Existing 2D DFT Method [12], [3] exploits the sparse nature of the channel by oversampling of received signals at the antenna element. Also 2D DFT is applied sub-matrices size of $M_{RF} \times N_{RF}$ of channel H matrix. The analog design beamformer and combiner matrix are obtained using the equations (12) in [3].Also related equation (13-16) in [12]. Hence the analog beamformer F_{RF} and analog combiner U_{RF} are of full rank matrix. Hence the base band signal at the receiver is given by (17) in [12].

$$y_{BB}^{(p,q,m)} = \left(U_{RF}^{p}\right)^H \left(H F_{RF}^{(q)} x_{BB}^{(m)} + n^m\right) \tag{15}$$

Supplying the Hadamard matrix for analog beamformer and combiner equation (15) is deduced to

$$y_{BB}^{(p,q,m)} = \bar{U}_{RF}^{H} \left(\tilde{H}^{(p,q)} \bar{F}_{RF}\, x_{BB}^{m} + \bar{n}^{(m)} \right) \tag{16}$$

with m=0,1,2, 3, 4, 5, ….. M_{RF}-1, and where $\bar{n}^{m} = [n^{(m)}]_{pN_{RF}:(p+1)N_{RF}-1)}$

The deduced estimated channel is given by [12] is given by

$$\tilde{H}^{(p,q)} = \sqrt{M_{RF}} \left(\bar{U}_{RF}^{H}\right)^{-1} Y_{BB}^{(p,q)} \left(\left(\bar{F}_{RF}\right)^{-1}\right) \tag{17}$$

with $N_D \leq N$and $M_D \leq M$, are two integers chosen with respect to the length N_{TS} of the training vectors.

$$\hat{\tilde{H}}^{(p,q)} = \bar{H}^{(p,q)} + \tilde{n} \tag{18}$$

$\bar{F}_{RF}$ and $\bar{U}_{RF}$is denoted by Hadamard matrix to ensure the full rank characteristics. This assures the noise is still white with variance σ_n^2 *and*

$$\bar{n} = \sqrt{M_{RF}} \begin{bmatrix} \bar{n}^{(0)} & . & . & \bar{n}^{(M_{RF}-1)} \end{bmatrix} \tag{19}$$

Equation (17) and (10) is the estimated channel matrix. and noise vector. Now to estimate the channel parameters like angle of arrival, angle of departure and path gain, 2D DFT method [3, 12] was studied. As this transformation results with complex valued even for real valued data. Alternate transform 2D DCT doesn't have this problem. In the following section, 2D DCT base channel estimation is detailed.

V. Proposed 2D-DCT Channel Estimation Method

In this section, we will discuss about the 2D DCT based Channel estimations method.

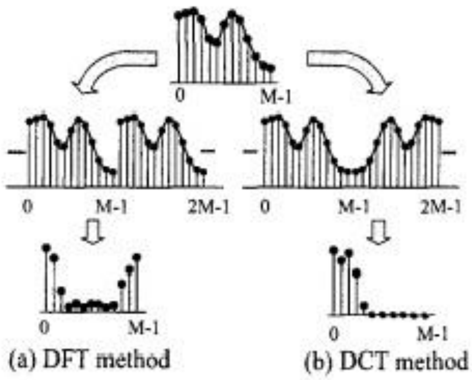

Fig. 4. Comparison between DFT and DCT Method

The Discrete Cosine Transform (DCT) is well known as one of the orthogonal transform functions as the same as DFT. Fig. 2 shows the difference of DFT and DCT methods. The DFT method processes N samples data assuming that these data is repeated at every N samples as shown in Fig. 4 (a). Therefore, if the both end of data is discontinuous, the higher order component will be appeared after performing DFT. On the other hand, the DCT method can be considered as the conventional DFT method, which processes 2N point's data as shown in Fig. 4 (b). Since the both end of data is always continuous in the DCT, the lower order of components will be dominated in the transform domain signal after converted by DCT. The proposed DCT-based channel estimation method employs the above feature of DCT and the fact that the time domain impulse response of multi-path fading is only existed during the guard interval.

The 2D Discrete Cosine Transform (DCT) is given by

$$W_{(k,i)} = DCT\left(\tilde{H}\right)_{n,m} \tag{20}$$

This is equal to,

$$W_{(k,i)} = \frac{1}{N} c_k c_i \sum_{m=0}^{N_{DCT}-1} \sum_{n=0}^{N_{DCT}-1} \left[\hat{\tilde{H}}\right]_{n,m} \cos\left[\frac{\pi(2m+1)k}{2N_{DCT}}\right] \cos\left[\frac{\pi(2n+1)i}{2N_{DCT}}\right] \quad (21)$$

For k,i=1,2,..., $N_{DCT} - 1$. where N_{DCT} is a row and column vector and the harmonic coefficients are given by

$$c_k = \begin{cases} \frac{1}{\sqrt{M}} & k = 0 \\ \sqrt{\frac{2}{M}} & 1 \le k \le N_{DCT} - 1 \end{cases} \quad (21a)$$

and

$$c_l = \begin{cases} \frac{1}{\sqrt{M}} & l = 0 \\ \sqrt{\frac{2}{M}} & 1 \le l \le N_{DCT} - 1 \end{cases} \quad (21b)$$

The proposed channel estimation procedure is detailed in the Fig. 5. Fig. 6 shows the cancellation algorithm [12] applied to estimate the channel parameters like angle of arrival (AOA), angle of departure (AOD) and channel path Gain. The size of the channel matrix H is very larger. The 2D-DCT can be applied to sub-matrix as mentioned in (12) to extract the channel parameters. The estimate of parameters by using $N_D \times M_D$ sub matrix is given by

$$\tilde{H} = [H]_{0:N_D-1, 0:M_D-1} \quad (22)$$

With $N_D \le N$ and $M_D \le M$, are two integers chosen with respect to the length N_{TS} of the training vectors. This assures the noise is still white with variance σ_n^2. To extract the path parameters AoA (ϕ_l^t), AoD (ϕ_l^r) and path gain (g_l), evaluate the 2D-DCT of $\hat{\tilde{H}}$ on $N_{DFT} \times N_{DFT}$ samples, If N_{DCT} is larger enough such

$$\theta_l^{(t)} = -2\pi\left(\frac{i_l}{N_{DCT}}\right) \quad (23a)$$

$$\theta_l^{(r)} = -2\pi\left(\frac{k_l}{N_{DCT}}\right) \quad (23b)$$

For convenience, the 2D-DCT-based channel estimation method is presented as follows:

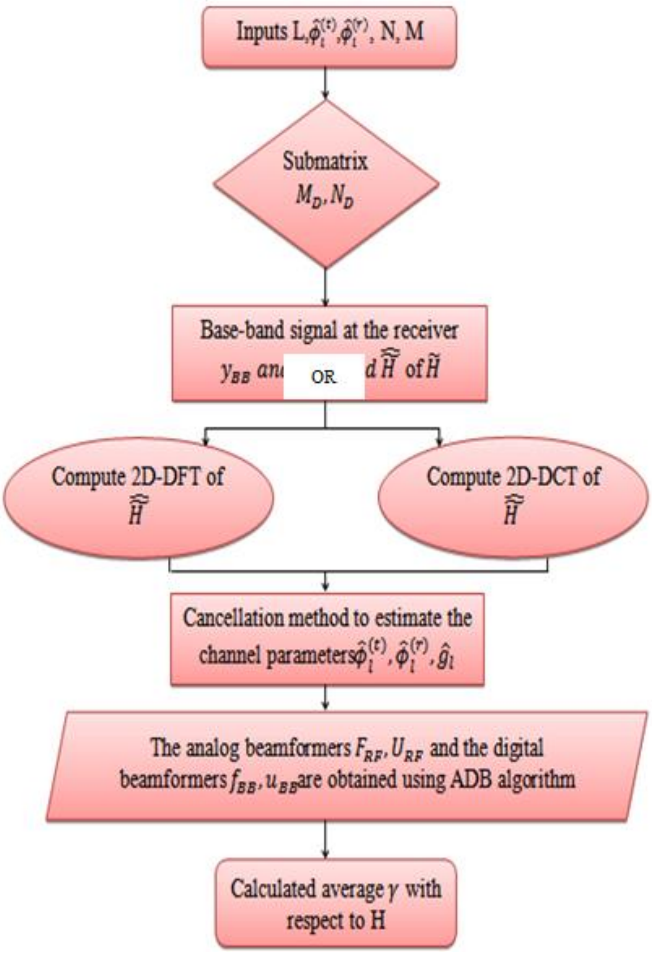

Fig.5. 2D-DCT based channel estimation

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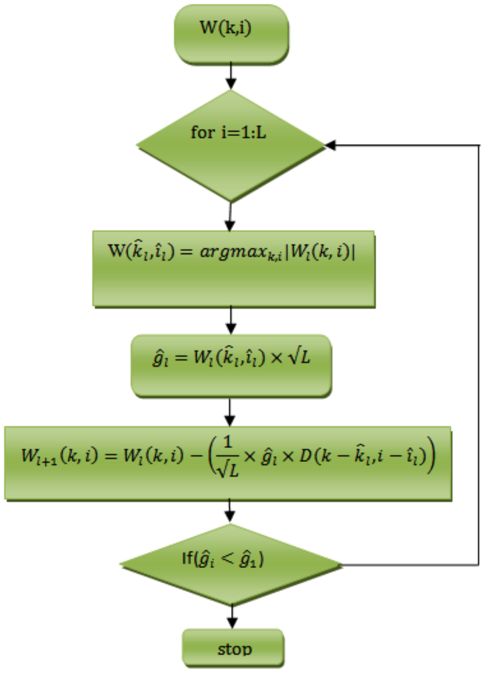

Fig. 6. Cancellation algorithm [12]

D(k,i), k,i=0,1,.., N_{DCT} is the 2D-DCT of the $N_D \times M_D$ ones matrix on $N_{DCT} \times N_{DCT}$ samples. From eqn. (8) and (13) can rewrite,

$$W(k,i) = \frac{1}{\sqrt{L}} \sum_{l=1}^{L} g_1 \times D(k-k_i, i-i_l) + N(k,i) \tag{24}$$

To obtain the channel parameters of various modes from W(k,i), the cancellation algorithm [12] used as outlined in Fig. 6. The algorithm terminated when $|\hat{g}_i|$ turns out to me much smaller than $|\hat{g}_1|$. |.Its indexed is noted as $\hat{\imath}_l$ and $\hat{k}_l$

From $\hat{\imath}_l$ and $\hat{k}_l$ now can obtain $\hat{\phi}_l^t$ and $\hat{\phi}_l^r$.

$$\hat{\phi}_l^t = \sin^{-1}\left(-\frac{2\pi\hat{i}_l}{\beta D N_{DCT}}\right) \tag{25a}$$

$$\hat{\phi}_l^r = \sin^{-1}\left(-\frac{2\pi\hat{k}_l}{\beta D N_{DCT}}\right) \tag{25b}$$

VI. Beamformer Design

Analog Digital Beamforming algorithm used to calculate the baseband digital beamformer f_{BB} and baseband analog combiner u_{BB} as in [13] shown in Fig. 7. The problem to designing precoder is,

$$\left(f_{BB}, u_{BB}\right) = \arg\max_{f,u} \left|u_{BB}^H U_{RF}^H G F_{RF} f_{BB}\right|^2 \tag{26}$$

Consider a base station has 2D-DCT based channel estimation approach; here we design hybrid beamformer to maximize the spectral efficiency expressed as

$$R = lb\left|I_{N_s} + \frac{\rho}{N_s} R_n^{-1} W_{BB}^H W_{RF}^H H F_{RF} F_{BB} F_{BB}^H F_{RF} H^H W_{RF} W_{BB}\right| \tag{27}$$

Also $R_n = \sigma^2 W_{BB}^H W_{RF}^H W_{RF} W_{BB}$ is the noise covariance matrix after combining. The estimated angle of arrival, angle of departure and path gain is used in the measurement of G matrix RF beamformer and combiner.

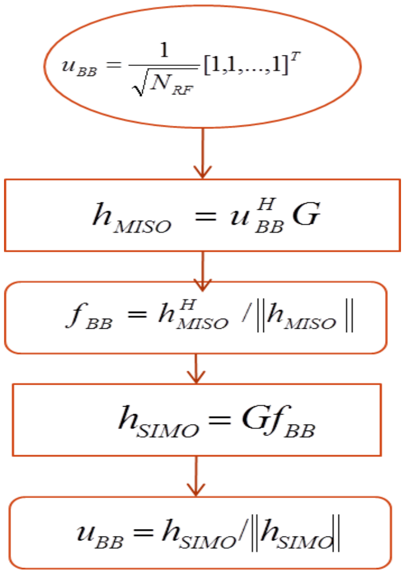

Fig 7. Analog digital beamforming

VII. Simulation Results and Discussion

In this section we evaluate the performance of the proposed channel estimate in a typical 60 GHz channel with L = 3 rays. The antenna elements are separated by a distance $\lambda/2$. The angle of arrival and angle of departure are random between -90^0 to +90^0. The performance is measured using the average SNR γ.

Channel model chosen is the Saleh Venezeula Model. Number of RF chains must be equal to Number of training symbols. Here $M_{RF}=N_{RF}=4$. Sampling points chosen are 64, 128, 256, 512, 1024 Samples. Numbers of Antenna elements chosen at the transmitter and receiver are 16, 32, 64, 128, 256, and 512. Analog beamformers and combiner are full rank matrices.

TABLE I. Channel Path Parameters Estimation

Case No	AOA/ AOD	Angular Inputs (in deg)	Estimated AOA and AOD	
			2D-DFT (in deg)	2D-DCT (in deg)
Case I	$\phi_l^{(t)}$	[-60 -55 -70]	[-58.40 -58.79 -60.67]	[-58.58 -59.01 -61.01]
Case II	$\phi_l^{(r)}$	[60 125 55]	[57.68 123.04 59.54]	[57.38 126.82 57.69]

Several Cases are studied by tossing up different angle of arrival and angle of departure scenario. Table I presents the case I and case II experiments and corresponding estimated channel parameters are listed. Fig. 8 shows the average SNR improvement γ versus the

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number of antennas M = N with N_{DFT} = 128, M_D = M_{RF} = N_D = N_{RF}= 2 (N_{TS} = 2), and four values of Γ_{AWGN} .

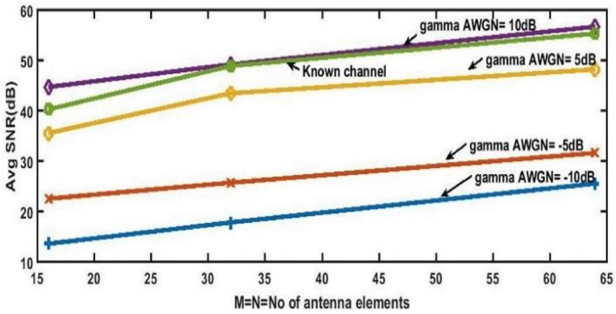

Fig 8. 2DFT Method: Average SNR (dB) Vs No of antenna elements

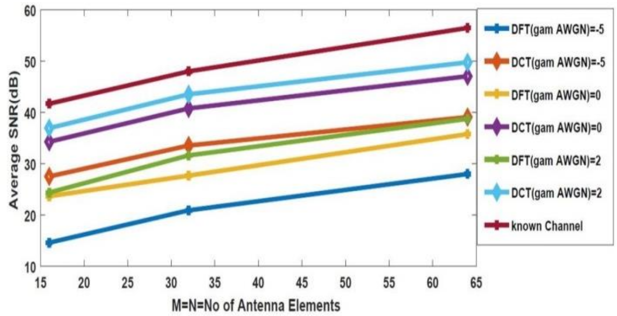

Fig 9. 2DFT Vs 2D DCT Method: Average SNR (dB) Vs No of antenna elements.

Fig. 9 shows the average SNR improvement γ versus the number of antennas M = N with N_{DFT} = 128, N_{DCT}=128 M_D = M_{RF} = N_D = N_{RF}= 2 (N_{TS} = 2), and four values Γ_{AWGN} .

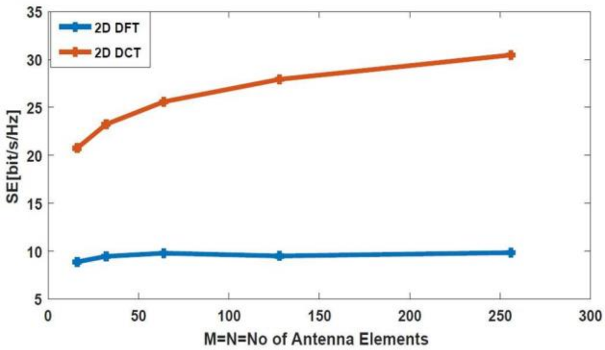

Fig. 10. Spectral efficiency Vs No of elements

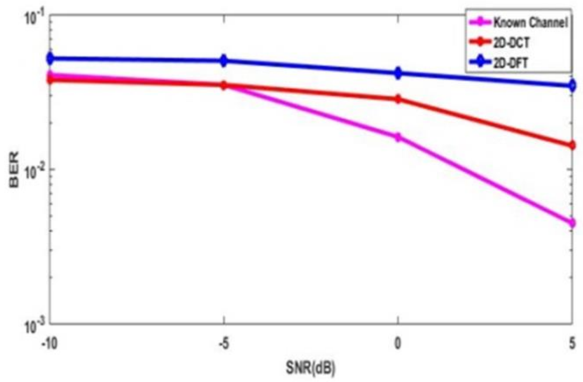

Fig. 11. Bit Error Rate Vs SNR (dB)

Fig. 10. show the spectral efficiency improvement varying with antenna elements. The proposed 2D DCT based method gives twice larger spectral efficiency than the 2D DFT counterpart with respect different number of antenna elements with N_{DFT}=N_{DCT}=256.

Fig 11. show the bit error rate improvement with varying signal to noise ratio.

VIII. Conclusion and Future Directions

In this work, we estimated the channel parameters of the MMW channel by using 2D-DCT by cancellation and analog digital precoding algorithm of the received training sequence. We observed the system performance is closer the known channel with low SNR scenario. The proposed method of channel estimate has high energy compaction even in the low SNR region which makes better than the 2D-DFT approach.

Conflict of Interest

"The authors declare no conflict of interest".

Author Contributions

S. Merlin Gilbert Raj[1], G. Josemin Bala[2], and M.L Merlin Sajini[3].

S. Merlin Gilbert Raj[1] designed the 2D –DCT based channel estimation method, performed the Matlab simulation, analyzed the results and co-wrote the paper. G. Josemin Bala[2] supervised the research. M.L Merlin Sajini[3] co-wrote the paper. All authors had approved the final version.

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