



Beam Tracking based on Delay Phase Precoding Technique in THz mMIMO Systems

V.Nikitha¹, G.Vigneshwar², A.Akanksha³, S.Tejaswini⁴, E.Saisri⁵, Sammaiah Thurpati⁶.

^{1,2,3,4,5}B.Tech Final Year ECE Students, Jyothishmathi Institute of Technology and Science, Karimnagar, Telangana, 505481.

⁶Associate Professor, Department of ECE, Jyothishmathi Institute of Technology and Science, Karimnagar, Telangana, 505481

Abstract: A promising technique for the next 6G network is terahertz (THz) communication. To reduce the severe attenuation and excessive power utilization, massive MIMO (mMIMO) accomplished by hybrid precoding has been broadly used for THz. However, frequency independent phase shifters as to be the typical hybrid precoding architecture cannot survive to the beam split effect into THz mMIMO effected by the high number of antennas and bandwidth. A full bandwidth array gain loss is caused by the beam split effect. In this paper, the beam split effect causes a considerable performance loss in beam tracking algorithms developed for narrowband with the typical hybrid precoding. To alleviate this problem, a DPP (delay phase precoding) facing THz massive MIMO was recently developed. We verify the beam tracking system to easily manage the angular coverage of frequency based beams through bandwidth. By analysing the array gain loss generated through beam split effect in terahertz mMIMO systems, the severity of the problem may be shown and quantified. We use a beam tracking method suggest to track numerous users physical directions at the concurrent in always lot to generate many beams. The suggested beam track can concurrently track many user physical directions by utilizing numerous frequency based beams generated through radio-frequency chains. The analysis exhibits that the suggested system can attain the sum rate performance with short beam training and considerably reduce the array gain the loss effected through beam split effect. We suggest TTD (true time delayer) to recognize frequency based phase shifters on appreciating the idea of Delay Phase Precoding.

Keywords: massive MIMO, Beam tracking, Hybrid precoding.

I. INTRODUCTION

Terahertz (THz) communication is considered a promising technology for future 6G wireless communications. It offers a bandwidth of tens of GHz, enabling high data rates [1-2]. However, THz signals face significant path loss due to their very high frequency. To overcome this, mMIMO technology. However, the hybrid precoding structure commonly used in massive MIMO systems is insufficient to handle the beam split effect generated by the narrow bandwidth and high number of antennas in THz mMIMO systems [3-4]. The beams can't align with the specify target user in a specific direction, leading to a loss in array gain and a

decrease in achievable sum-rate. To address this issue, various precoding structures have been proposed, including the use of time-delayers such as TTD array, array-of-subarray structure, and delay-phase precoding.[5],[6],[7].

THz communications are currently limited to small-scale applications due to the significant path loss bottleneck. The THz band is utilized in various cutting-edge applications[7]. nevertheless, path loss often poses challenges for THz signals. For example, at 0. THz, a path loss of 110 dB/100 m can occur, making it difficult to achieve desired coverage. Fortunately, the use of a precoding strategy can address the path loss issue without the need to increase transmitter power. This technique allows for the generation of narrow beams with high antenna array gain, effectively mitigating the impact of severe path loss[8].

Due to the extremely short wavelength of the THz band signal, THz communication requires the use of large-scale antenna arrays. In 6G wireless networks, THz precoding is an essential technology used to minimize the loss of THz signals during transmission. However, the unique properties of THz signals present new challenges for 6G precoding methods, particularly when compared to existing hybrid precoding architecture. In the current hybrid precoding architecture, the beams are linked to the spatial directions of the channel route in the analog beamform. Yet, the spatial directions are at various sub carrier frequencies for the wide band mmWave systems. The analog beamformer is valued by frequency independent PSs because it corrects for the apparent array gain loss[9-10]. To arrange through the outcome as beam squint, some systems have been suggested in mmWave mMIMO systems[11],[12].

A. Prior Work:

In the hybrid precoding system, the analog beamform will outcomes in directed beams that both achieve maximum array gain and are connected to the directions of the channel link components[8]. Narrowband systems perform well with an analog beamformer. Several approaches has suggested to mmWave mMIMO[9]–[12]. In [9], [10], the array gain loss and the beams squint is not considerable, therefore these methods[8]–[10] are active for enhancing the rate performance.

Owing to the THz transmissions have a broader bandwidth and require a greater number of antennas, beams at various sub carriers will split into fully divided physical directions. Which presents a significant difficulty for THz communications since it is the primary distinction among the mmWave and mMIMO THz system. This shows that only beams at the centre frequency are capable of achieving significant array gain. The beam split effect will cause an attainable rate deterioration, with the achievable rate gain in THz mMIMO systems benefiting from the increased bandwidth. The many antennas used in the current works[11] might, however, result in excessive power consumption, particularly for precoding, which transmits several data streams.

B. Our Contribution

Wideband systems with the conventional hybrid precoding structure experience performance abasement required to the beam split effect. We present beam tracking algorithms for these systems. The beam split

effect should cause no performance loss, and narrowband systems should compensate for it. The following is a brief summary of the paper's resources.

The beam tracking approach is demonstrated using the coverage of such beams may be compliantly tracked to attain a necessary arrange using an extensive arrangement of time delays. We may construct numerous beams concurrently with only one RF chain using this technology for dynamically managing angular coverage.\

We present a solution to the wide band beam tracking problem on the beam tracking mechanism. In the proposed method, several frequency dependent beam track several user directions in each period. After tracking the whole variation range of the user's directions, the BS may calculate the optimal beam based on the signal power acquired by the user.

II. SYSTEM MODEL

The wideband THz multi-user mMIMO system is considered. The Base Station use N-antennas to serve K single-antenna users over a band width B, and OFDM with M subcarriers is employed.

A. Channel model

We explore the beam-based channel model in wideband terahertz channel. The channel $h_{k,m} \in \mathbb{C}^{N \times 1}$ of user K at sub carrier m, indicating to

$$h_{k,m} = \sum_{l=0}^{L-1} \beta_{k,m}^l a_N(\psi_{k,m}^l), \quad 1$$

where $\beta_{k,m}^l = g_{k,m}^l e^{-j2\pi\tau_{k,m}^l f_m}$ with $g_{k,m}^l, \tau_{k,m}^l$ indicating is the time delay of the l-th path, and f_m is the frequency of sub-carrier m agreeable $f_m = f_c + \frac{B}{M}(m-1-(M-1))$. Beam selection algorithms are almost ideal because THz communication rely on the LoS path due to the significant path loss[17]. Each user in the beam selections supplied by a beam that is pointed in the same physical direction because of the ultra-wide bandwidth and a large number of antennas. This effect is called the beam split effect. The beam f_k will be aligned with the physical direction $\theta_{k,m}$ at subcarrier m as

$$\theta_{k,m} = (f_c / f_m) \theta_k^0, \quad 2$$

Where $\zeta_m = f_c / f_m$. It is clear from (2) that f_k may point to frequency-dependent physical directions at different subcarriers. Therefore, as shown in Fig. The typical hybrid precoding structure will experience a significant attainable sum-rate loss as a result[16].

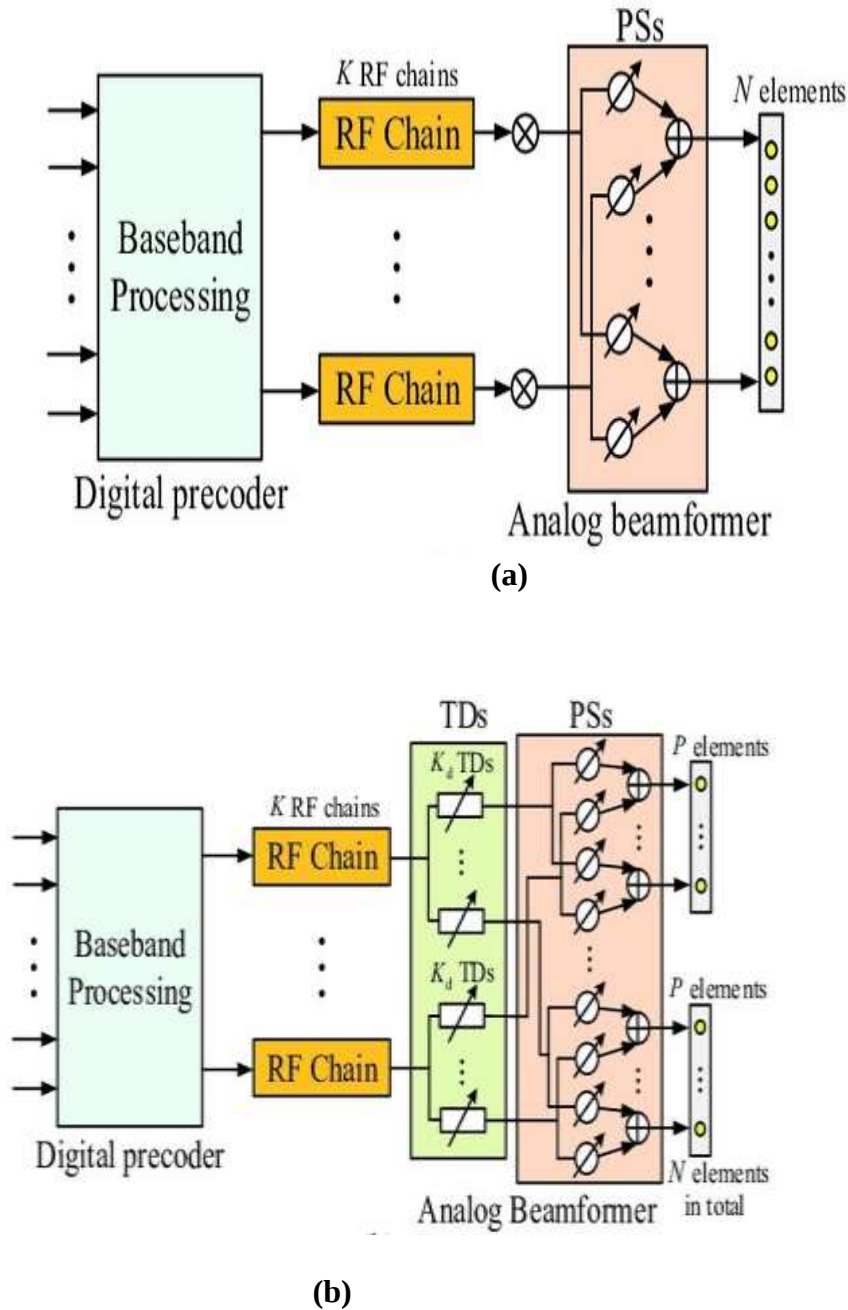


Fig 1: (a) Hybrid precoding structure; (b) Delay phase precoding structure[16].

III. DELAY-PHASE PRECODING FOR THz MASSIVE MIMO

A terahertz massive MIMO system utilizes a conventional hybrid precoding technique. However, Analog Beamforming and Spatially sparse precoding methods have certain limitations. To address these drawbacks, we propose a new technique called DPP (Digital Precoding with Time-Delay). In this study, we examine a THz mMIMO system that incorporates conventional hybrid precoding. The Base Station (BS) is equipped with an array of N_t antennas, and the RF chain is represented by N_{RF} . Each user is provided with N_r

antennas, and N_s data streams are transmitted simultaneously (where $N_s = iN_r$, $i \leq iN_{RF}$, and $i \ll iN_t$). In order to achieve consistent wideband transmission, we employ orthogonal frequency division multiplexing with M subcarriers[19,20]. Additionally, we introduce a TD (time-delay) between the traditional analog beamform and the digital precoder. Every RF chain being sub connected to K TD components, which are in turn sub connections to $P = \frac{N_T}{K}$ conventional frequency independent PS. As a result, the m^{th} subcarrier of signal received may be written as

$$y_m = \sqrt{\rho} H_m^H A D_m S_m + n_m \quad 3$$

Where $H_m \in \mathbb{C}^{N_t \times N_r}$ denotes the channel at the m^{th} subcarrier, $A \in \mathbb{C}^{N_t \times N_{RF}}$ is the analog beamforming provided by the frequency based PSs. D_m is the the precoder at the m -th sub carrier and $n_m \in \mathbb{C}^{N_s \times 1}$ is additive white Gaussian noise (AWGN) at the m -th sub carrier .

$$h_{n_t, n_r} = \sum_{l=1}^L g_l \delta(t - T_l - (n_r - 1) \frac{d}{c} \sin \tilde{\phi}_l - (n_t - 1) \frac{d}{c} \sin \tilde{\theta}_l), \quad 4$$

Where L is the paths, g_l and T_l denotes the path gain and path delay of the l^{th} path, $\tilde{\theta}_l, \tilde{\phi}_l$

$\tilde{\phi}_l \in [-\pi/2, \pi/2]$ are the frequency independent directions of the l^{th} path at the BS

A. Beam split effect

As illustrated in Fig.2, the effect of beam split occur when the array gain is harshly degraded[13]

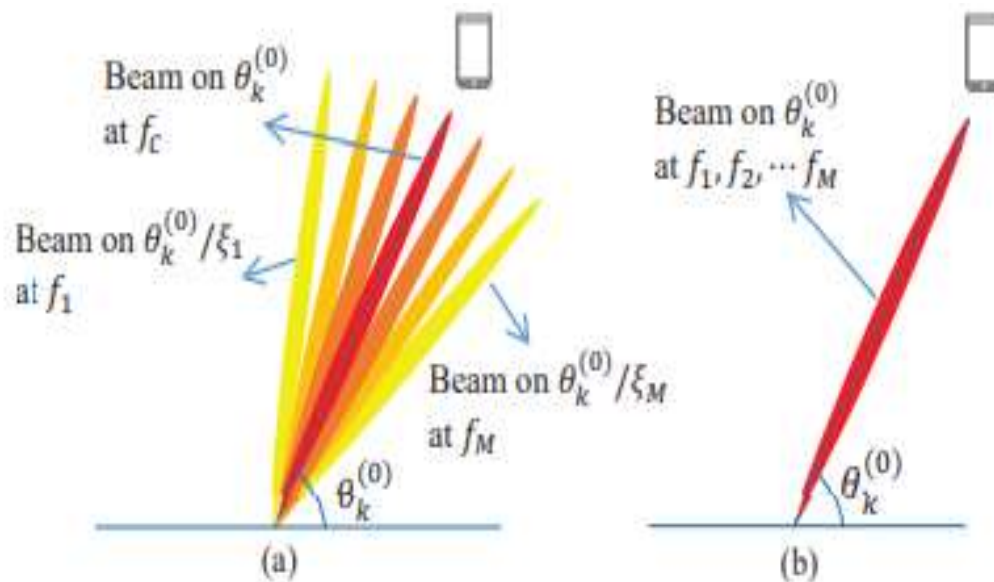


Fig 2. (a) Beam Split effect; (b) Beams generated by the DPP.

We start with l^{th} path component, which has a spatial direction $\theta_{l,m}$ in THz m MIMO channel without loss of generalization. Typically $a_l = A_{:,l}$, is used to generate a beam on the l -th path's spatial direction at f_c and $a_l = f_t(\theta_{l,c})$

$$|\eta(a_l, \theta_{l,c})| = |f_t(\theta_{l,c})^H a_l| = |f_t(\theta_{l,c})^H f_t(\theta_{l,c})| = 1 \quad 5$$

Narrowband systems demonstrate the highest array gain within their bandwidth, f_m and f_c should not be overlooked. Consequently, the path components exhibit different spatial directions at various subcarriers.

$$\theta_{l,m} = \frac{f_m}{f_c} \theta_{l,c} = \xi_m \theta_{l,c} \quad 6$$

Where $\xi_m = \frac{f_m}{f_c}$ is the comparative frequency. In THz communications, Based on the problem given above, we suggest a new precoding method for the DPP.

B. True-time-delayers based DPP

The frequency-independent beam shape produced by the PSs in the traditional hybrid precoding design would suffer substantial array gain loss as a result of the beam split effect. We'll suggest a precoding architecture called DPP in this subsection to address this issue. Fig. 1 illustrates the comparison with the hybrid precoding architecture.

We investigate the l -th channel route component without losing generality. We now use the frequency $a_{l,m}$ instead of the frequency-independent a_l to indicate the analog beamform vector created through the Delay Phase Precoding, because the TD network can give frequency based phase shifts. The frequency based analog beamform vector $a_{l,m}$, for example, may be written as

$$a_{l,m} = \text{blkdiag}([\bar{a}_{l,1}, \bar{a}_{l,2}, \dots, \bar{a}_{l,K}]) P_{l,m} \quad 7$$

Where $\bar{a}_{l,k} \in \mathbb{C}^{P \times 1}$, $k = 1, 2, 3, \dots, K$ represents the analog beamform vector concluded through PSs connected to the k -th Time Delay elements.

The user may then be covered by the beams across the whole bandwidth, resulting in a gain for the array that is close to ideal. First, we will employ frequency based PS to build a beam pointed in the desired physical direction to fulfill this design objective. θ_l at all M sub-carriers in order to compensate for the substantial array gain loss caused by the beam split effect.

$$[\bar{a}_{l,1}^T, \bar{a}_{l,2}^T, \dots, \bar{a}_{l,K}^T] = f_t(\theta_l) \quad 8$$

Then, we use frequency dependence for the direction which the beams $[\bar{a}_{l,1}^T, \bar{a}_{l,2}^T, \dots, \bar{a}_{l,K}^T] = f_t(\theta_l)$ is arranged from $\theta_{l,m}$ to θ_l . In particular, due to the frequency based phase shifts $-2f_m t_{l,k} = -(K-1)\beta_{l,m}$ with $k=1, 2, \dots, K$, $P_{l,m}$ satisfies

$$P_{l,m[k]} = [1, e^{-j\pi\beta_{l,m}}, e^{-j2\pi\beta_{l,m}}, \dots, e^{-j\pi(K-1)\beta_{l,m}}]^T, \quad 9$$

To obtain the almost ideal array gain across the full bandwidth, we developed a DPP design, and a new Time Delay network is interposed among the PS network and the RF chains as.

We have proposed DPP architecture ,a new TD network is presented among the PS network and the RF chains in the hybrid precoding to afford the near optimal array gain over the fully wide bandwidth.

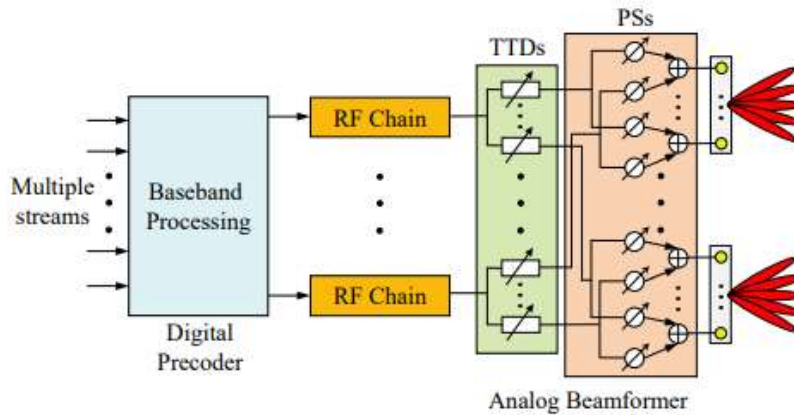


Fig.3:The proposed TTD-DPP structure.

Therefore, the received signal y_m at the m -th sub carrier in(3) can be denoted as

$$y_m = \sqrt{\rho} H_m^H A_u A_m^{TTD} D_m s_m + n_m \quad (10)$$

$A_u \in \mathbb{C}^{N_t \times N_{RF}}$ is the analog beamformer with the formation as

$$A_u = [A_{u,1}, A_{u,2}, \dots, A_{u,N_{RF}}] \quad (11)$$

Where $A_{u,l} = \text{blkdiag}([\bar{a}_{l,1}, \bar{a}_{l,2}, \dots, \bar{a}_{l,K}])$ indicates the analog beamform and $A_m^{TTD} \in \mathbb{C}^{K N_{RF} \times N_{RF}}$ is the frequency based phase shifts fulfilled by the TTD network, which satisfies the following conditions

$$A_m^{TTD} = \text{blkdiag}([e^{-j2\pi f_m t_1}, e^{-j2\pi f_m t_2}, \dots, e^{-j2\pi f_m t_{N_{RF}}}]) \quad (12)$$

Algorithm1:HybridprecodingforTTD-DPP

Inputs: Spatial directions $\theta_{l,c}$, channel H_m ;

Outputs: $F_{RF_g} F_{BB_m} A_m^{TD}$;

1: for $l \in \{1, 2, \dots, N_{RF}\}$ do

2: Generate $F_{RF_{u,l}}$ by $[\tilde{a}_{l,1}, \tilde{a}_{l,2}, \dots, \tilde{a}_{l,K}]^T = f_t(\theta_{l,c})$;

3: $s_l = -\frac{P\theta_{l,c}}{2}$;

4: $t_{l,i} = \begin{cases} (K-1-i)[s_l]T_c, \theta_{l,c} > 0 \\ i[s_l]T_c, \theta_{l,c} \leq 0 \end{cases}$;

5: $t_{l,i} = [t_{l,1}, t_{l,2}, \dots, t_{l,K}]$;

6: end for

```

7:  $F_{RF_u} = [F_{RF_{u,1}}, F_{RF_{u,2}}, \dots, F_{RF_{u,N_{RF}}}]$ ;
8: for  $m \in \{1, 2, \dots, M\}$  do
9:  $A_m^{TD} = \text{blkdiag}([e^{-j2\pi f_m t_1}, e^{-j2\pi f_m t_2}, \dots, e^{-j2\pi f_m t_{N_{RF}}}] )$ ;
10:  $H_{m,eq} = H_m^H F_{RF_u} A_m^{TD}$ ;
11:  $F_{BB_m} = \mu V_{m,eq,[:,1:N_{RF}]}, H_{m,eq} = U_{m,eq} \sum_{m,eq} V_{m,eq}^H$ ;
12: end for
13: return  $F_{RF_u}, F_{BB_m}$  and  $A_m^{TD}$ .

```

C. Beam Tracking Scheme Using DPP

The beam codebook generates the prospective beam matched with a certain directions for each codeword. For beam tracking, BS delivers training pilot sequences to every user at various times using distinct code words from the codebook[19]. The beamforming vector for the following frame is then chosen from the codeword with the highest received power.

The frame of the k^{th} user is to physical direction is indicated by $\theta_{k,i}^{(0)}$. In general, the angle tracking range may be reduced using information about the user's movement. The method of the standard beam tracking method in[19] utilising the Delay Phase Precoding may be expressed as

$$\theta_{k,i}^{-(t)} = \theta_{k,i}^{(0)} - \alpha + (2t-1) \frac{\alpha}{T} \quad 13$$

In physical directions of the $\theta_{k,i}^{-(t)}$, $t = 1, 2, \dots, T$ can covering the tracking ranges $[\theta_{k,i}^{(0)} - \alpha, \theta_{k,i}^{(0)} + \alpha]$. Then, the BS sends pilot sequence with the beam aligned to the physical direction $\theta_{k,i}^{-(t)}$ to the k -th user in the t -th time slot.

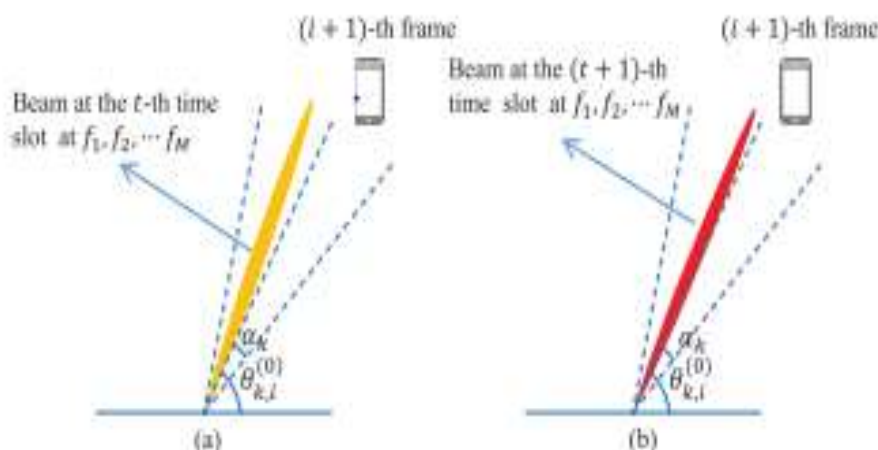


Fig.4.The typical beam tracking scheme [19] adapted to the DPP structure: (a) the beams generated by the DPP structure at the t -th time slot; (b) the beams generated by the DPP structure at the $(t + 1)^{\text{th}}$ time slot

The Algorithm 2 is Beam's tracking method to find the physical directions of users $\theta_{k,i}^{(0)}$ for all K users $k = 1, 2, \dots, K$. At 1st, the user that will be tracking in the t -th time slot are calculated in steps 1 and 2, where $\theta_{k,i, \text{cen}}^{-(t)}$ indicates the central direction that will be tracking at the m -th subcarrier in the t -th time slot as

$$\theta_{k,i}^{-(t)} = \theta_{k,i, \text{cen}}^{-(t)} + (1 - \zeta_1) \frac{\alpha}{T} + \frac{2\zeta_m \zeta_1 (\zeta_m - 1)}{\zeta_m (\zeta_M - \zeta_1) T} \alpha \quad 14$$

In step 3, a target direction set ψ_k^{i+1} is created by combining all probable users directions that will be monitored throughout T time intervals. To ensure that the whole angle tracking range will be explored, the target direction set is tracked in T time slots once it has been constructed. In the t -th time slot, beams that cover the t -th fraction of tracking range $[\theta_{k,i+1}^{(0)} - \alpha + \frac{(2t-2)\alpha}{T}, \theta_{k,i+1}^{(0)} - \alpha + \frac{2t\alpha}{T}]$ are caused by the DPP structure in steps 5–9.

$$\theta_k^t = \theta_{k,i, \text{cen}}^{-(t)} + (1 - \zeta_1) \frac{\alpha}{T} \quad 15$$

$$s_k^t = \frac{P}{2} \left(\phi_k^t + \frac{2\zeta_M \zeta_1 \alpha}{(\zeta_M - \zeta_1) T} \right) \quad 16$$

Then, in step 7 and 8, when ϕ_k^t and s_k^t satisfy (15) and (16). The beams generated by $f_{k,m}^t = A_k^{s,t} e^{-j2\pi f_m t_k^t}$, $m = 1, 2, \dots, M$ which is corresponding to the target users directions in ψ_k^{i+1} . Based on $A_k^{s,t}$ and t_k^t , the t -th time slot A_m^t of the analog beamform is calculated in steps 8 and 9.

In step 10, A_m^t is the analog beamformer as calculated, the Base Station transmits training pilot sequence. The pilot sequences of the received signal for K users $Y_{m,t} \in \mathbb{C}^{K \times Q}$ at subcarrier m can be indicated as

$$Y_{m,t} = k_m H_m A_m^t Q_m^t + N^t \quad 17$$

where $Q_m^t = [q_{1,m}^t, q_{2,m}^t, \dots, q_{K,m}^t]^H$ denotes the pilot sequences of all K users

Inputs:

Physical directions $\theta_{k,i}^0$; Variation range of user physical direction α ; The number of pilots in each time slot Q ;

Outputs:

$$1: \theta_{k,i,cen}^{-(t)} = \theta_{k,i}^{(0)} - \alpha + \frac{(2t-1)\alpha}{T}$$

$$2: \theta_{k,i,m}^{-(t)} = \theta_{k,i,cen}^{-(t)}(1-\zeta_1)\frac{\alpha}{T} + \frac{2\zeta_m\zeta_1(\zeta_m-1)}{\zeta_m(\zeta_m-\zeta_1)}\frac{\alpha}{T}$$

$$3: \psi_k^{i+1} = [\theta_{k,1,i}^{-(1)}, \theta_{k,2,i}^{-(1)}, \dots, \theta_{k,M,i}^{-(1)}, \theta_{k,1,i}^{-(2)}, \theta_{k,2,i}^{-(2)}, \dots, \theta_{k,M,i}^{-(T)}]$$

4: for $t \in \{1, 2, \dots, T\}$ do

$$5: \phi_k^t = \theta_{k,i,cen}^{-t} + (1-\zeta_1)\frac{\alpha}{T}$$

$$6: s_k^t = -\frac{P}{2}(\phi_k^t + \frac{2\zeta_m\zeta_1\alpha}{(\zeta_m-\zeta_1)T})$$

$$7: A_k^{s,t} = \text{diag}(a_p(\phi_k^t)e^{j\pi(P\phi_k^t+2s_k^t)})$$

$$8: f_{k,m}^t = A_k^{s,t}e^{j2\pi f_m}$$

$$9: A_m^t = [f_{1,m}^t, f_{2,m}^t, \dots, f_{K,m}^t]$$

$$10: Y_{m,t} = k_m H_m A_m^t Q_m^t + N^t$$

11: end for

$$12: (t_k, m_k) = \arg \max_{t \in \{1, 2, \dots, T\}, m \in \{1, 2, \dots, M\}} \|Y_{m,t,[k,:]} q_{k,m}^t\|$$

$$13: \theta_{k,i+1}^0 = \psi_k^{t+1}$$

$$14: \text{return } \theta_{k,i+1}^0$$

IV. Simulation & Results:

The performance of different precoding approaches is demonstrated in this section using numerical simulations. The system parameters are shown in Table 1. We analyze the rate performance of DPP, Hybrid Precoding, and Analog Beamforming for $L=4$ and $L=16$ in Figures 5 and 6. The proposed DPP outperforms the other approaches, achieving over 96% performance compared to the benchmark, as depicted in the graph.

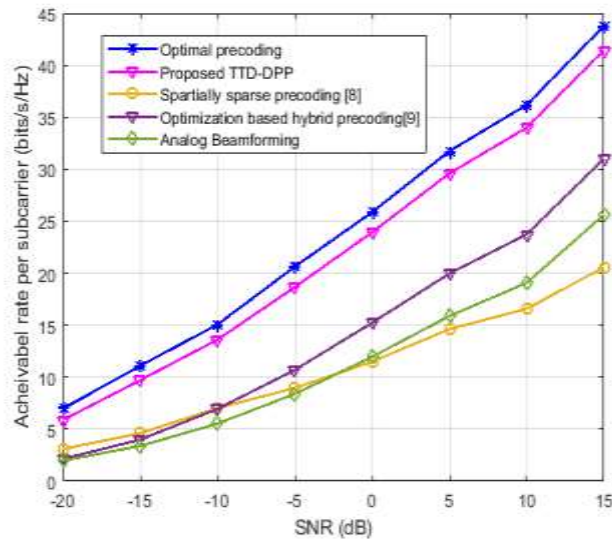


Fig 5: SE versus SNR for different PNRs (L=4)

When $N_s=4$, Fig. 5 and 6 compare the performance of the suggested TTD-DPP and various hybrid precoding methods in terms of the average attainable rate. The spatially sparse precoding in [8], the attainable rate optimisation [9], and the analogue beamforming [12] are examples of existing solutions. We can clearly observe in Figs. 5 and 6 that the beam split effect causes a rate loss of about 50% for the spatially sparse precoding [8]. While the attainable rate loss generated by the beam split effect can be substantially alleviated by the analogue beamforming [12] and achievable rate optimization [9] developed for mm-wave mMIMO systems.

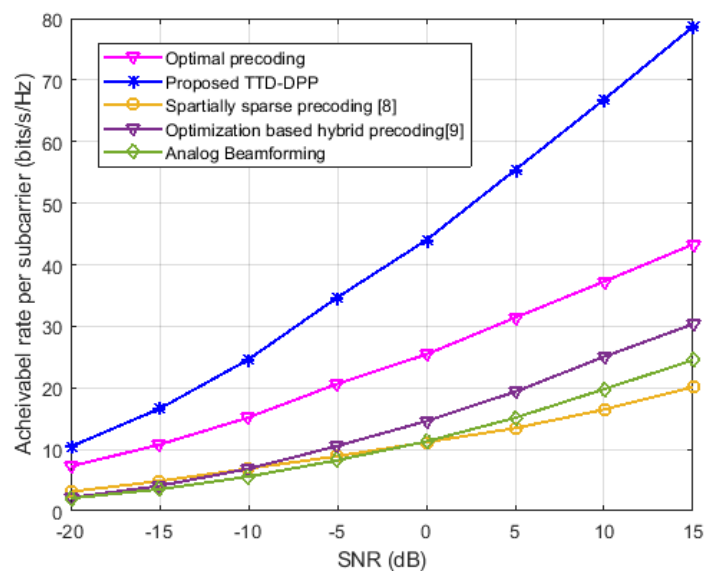


Figure 6: SE versus SNR for different PNRs (L=16)

Fig.7 gives where $N_s=4$, the performance of the average achievable rate K , $SNR=10dB$, to illustrate the outcome of the no. of TTDs K on the proposed TTD-DPP are considered. That the recompense for array gain losses effected within the beam split examine the whole total bandwidth. Observe from Fig. 7 that the

performance of the achievable rate for the suggested TTD-DPP improves as K rises and reaches the almost ideal possible rate at K=16.

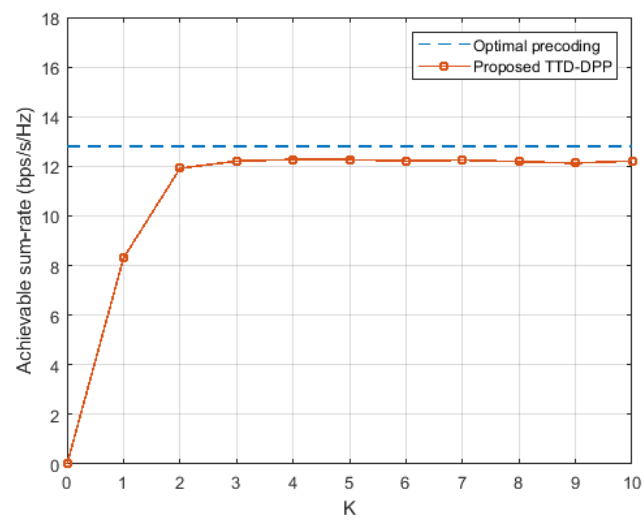


Fig 7: Achievable rate performance versus the No. of TTD's K

Table I:Simulation Parameters for Precoding Techniques

The no. of the BS's antennas(N_t)	256
The no. of the user antennas(N_r)	1,2,4
The no. of channel paths(L)	4,16
The central frequency(f_c)	0.1THz
Bandwidth(B)	30GHz
No. of the subcarriers(M)	128
No. of RFchains(N_{RF})	4
No. of TD elements(K)	16
Physical directions paths($\bar{\theta}_l, \bar{\phi}_l$)	$u[\pi / 2, \pi / 2]$
Transmission SNR(ρ/σ^2)	-20-15dB

In Figure 8, we show the sum-rate performance versus the no. of beam tracked time slot T with k user, the best fully digital Zero Forcing precoding [14], beam selection with suitable physical directions [17] and selection of the beam to the situated on the physical direction tracked by the traditional beam schemes [19] that uses a DPP structure. Physical directions are chosen for the beam using a hybrid precoding structure[8]. We can see from Fig. 8 that the suggested beam tracking system may be used to take advantage of the beam choice to attain near-optimal possible sum-rate with minimal training overhead.

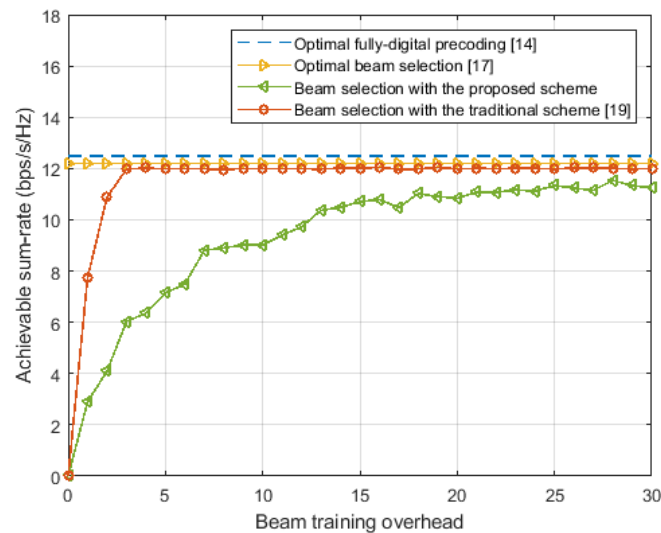


Fig 8: Achievable sum-rate vs beam training overhead

V. Conclusion:

In this research, we have addressed the problem of wideband beam tracing in THz-mMIMO systems and first demonstrated that the beam tracking mechanism can dynamically regulate the angular coverage of the rays caused by the Dealy Phase Precoding, i.e, unlike conventional methods the frequency dependent beams can usually be caused by the RF chain, the suggested approach uses several frequency based beams caused by a single RF chains to track various directions of the user simultaneously, which is achieved by dynamically changing the beam-splitting effect. Compared with the various beam-tracked methods, the suggested method can perfectly tracking the user's mobility with a decreased beams-training overhead of about 95%, as shown by theoretical values and simulation results. Moreover, in the physical directions covered by the proposed approach, the recommended ray tracing method can achieve about 99% of the achievable sum rate, which makes the desirable for massive THz MIMO systems.

REFERENCES:

- [1] C. Liu, W. Feng, Y. Chen, C.-X. Wang, and N. Ge, "Cell-free satellite-UAV networks for 6G wide-area Internet of Things," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 4, pp. 1116–1131, Apr. 2021, doi: 10.1109/JSAC.2020.3018837.
- [2] Y. Zhao, G. Yu, and H. Xu, "6G mobile communication networks: Vision, challenges, and key technologies," *Sci. China Inf. Sci.*, vol. 49, no. 8, pp. 963–987, Aug. 2019, doi: 10.1360/N112019-00033.
- [3] I. F. Akyildiz, C. Han, and S. Nie, "Combating the distance problem in the millimeter wave and terahertz frequency bands," *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 102–108, Jun. 2018, doi: 10.1109/MCOM.2018.1700928.
- [4] L. Yan, C. Han, and J. Yuan, "Hybrid precoding for 6G terahertz communications: Performance evaluation and open problems," in *Proc. 2nd 6G Wireless Summit (6G SUMMIT)*, Mar. 2020, pp. 17–20.

- [5] C. Han, J. M. Jornet, and I. Akyildiz, “Ultra-massive MIMO channel modeling for graphene-enabled terahertz-band communications,” in Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring), Jun. 2018, pp. 3–6.
 - [6] J. Chen, W. Feng, J. Xing, P. Yang, G. E. Sobelman, D. Lin, and S. Li, “Hybrid beamforming/combining for millimeter wave MIMO: A machine learning approach,” IEEE Trans. Veh. Technol., vol. 69, no. 10, pp. 11353–11368, Dec. 2020, doi: 10.1109/TVT.2020.3009746.
 - [7] Z. Wei, D. W. K. Ng, and J. Yuan, “NOMA for hybrid mmWave communication systems with beam width control,” IEEE J. Sel. Topics Signal Process., vol. 13, no. 3, pp. 567–583, Jun. 2019, doi: 10.1109/JSTSP.2019.2901593
 - [8] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, “Spatially sparse precoding in millimeter wave MIMO systems,” IEEE Trans. Wireless Commun., vol. 13, no. 3, pp. 1499–1513, Mar. 2014.
 - [9] S. Park, A. Alkhateeb, and R. W. Heath, “Dynamic subarrays for hybrid precoding in wideband mmwave MIMO systems,” IEEE Trans. Wireless Commun., vol. 16, no. 5, pp. 2907–2920, May 2017.
 - [10] L. Kong, S. Han, and C. Yang, “Hybrid precoding with rate and coverage constraints for wideband massive MIMO systems,” IEEE Trans. Wireless Commun., vol. 17, no. 7, pp. 4634–4647, Jul. 2018.
 - [11] M. Cai, K. Gao, D. Nie, B. Hochwald, J. N. Laneman, H. Huang, and K. Liu, “Effect of wideband beam squint on codebook design in phasedarray wireless systems,” in Proc. IEEE GLOBECOM 2016, Dec. 2016, pp. 1–6.
 - [12] X. Liu and D. Qiao, “Space-time block coding-based beamforming for beam squint compensation,” IEEE Wireless Commun. Lett., vol. 8, no. 1, pp. 241–244, Feb. 2019
 - [13] B. Wang, F. Gao, S. Jin, H. Lin, G. Y. Li, S. Sun, and T. S. Rappaport, “Spatial-wideband effect in massive MIMO with application in mmwave systems,” IEEE Commun. Mag., vol. 56, no. 12, pp. 134–141, Dec. 2018.
 - [14] D. Tse and P. Viswanath, Fundamentals of Wireless Communication. Cambridge, U.K.: Cambridge Univ. Press, 2005.
 - [15] R. W. Heath, N. Gonzalez-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, “An overview of signal processing techniques for millimeter wave MIMO systems,” IEEE J. Sel. Top. Signal Process., vol. 10, no. 3, pp. 436–453, Apr. 2016.
 - [16] J. Tan and L. Dai, “Delay-phase precoding for THz massive MIMO with beam split,” in Proc. IEEE Global Commun. Conf. (GLOBECOM), Dec. 2019, pp. 1–6.
- Our contribution'Wideband Beam Tracking in THz Massive MIMO Systems'
- [17] A. Ali, N. Gonzalez-Prelcic, and R. W. Heath, Jr., “Millimeter wave beam-selection using out-of-band spatial information,” IEEE Trans. Wireless Commun., vol. 17, no. 2, pp. 1038–1052, Feb. 2018.graph
 - [18] X. Gao, L. Dai, S. Han, C. L. I, and R. W. Heath, “Energy-efficient hybrid analog and digital precoding for mmwave MIMO systems with large antenna arrays,” IEEE J. Sel. Areas Commun., vol. 34, no. 4, pp. 998–1009, Apr. 2016.
 - [19]. PHY/MAC Complete Proposal Specification (TGad D0.1), document IEEE 802.11-10/0433r2, 2010.graph

[20]. C. Wang, L. Ma, R. Li, T. S. Durrani, and H. Zhang, “Exploring trajectory prediction through machine learning methods,” IEEE Access, vol. 7, pp. 101441–101452, Jul. 2019.