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LETTER

Wideband THz Beam Tracking Based on Integrated Sensing and Communication System

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SUMMARY Terahertz (THz) Integrated sensing and communication (ISAC) is viewed as one of the most promising technologies for future 6G wireless communications, which can simultaneously enable data transmission at terabits-per-second (Tbps) rates and millimeter-level accurate sensing. To meet the communication requirements of high-mobility users, an efficient beam tracking method is crucial. However, existing beam tracking methods have a high beam training overhead and cannot cope with the severe performance loss caused by the beam split effect under the wideband system. In this letter, we propose a wideband THz beam tracking method based on the ISAC system, which introduces the time-delay network in the precoding to cope with the challenge of the beam split effect and reduce the beam training overhead with the aid of radar sensing. Simulation results show that the method can achieve near-optimal sum-rate performance with only little beam overhead compared to conventional methods.

key words: *THz communication, ISAC, wideband beam tracking.*

1. Introduction

THz ISAC technology is able to significantly improve spectrum and energy efficiency and reduce hardware and signaling costs by sharing frequency bands, hardware and signal processing modules [1].

In THz communication, the precoding approach helps to resolve the severe path loss problem. Nevertheless, the traditional hybrid precoding structure in narrowband systems cannot apply to the wideband THz systems. Due to the wide bandwidth and substantial number of antennas in wideband THz communication, the beam split effect will lead to a severe achievable sum-rate loss. To address this problem, [2] proposed a delay-phase precoding structure, which realizes the frequency-dependent analog beamforming by introducing a time-delay network as a new precoding layer to mitigate the beam split effect.

To realize the delay-phase precoding, accurate channel state information is crucial. Conventionally, channel estimation is a common method by sweeping all the candidate beam pairs to find the beam pair with the strongest channel gain [3]. While this scheme is unacceptable in high-mobility scenarios, which would result in considerable communication overhead and latency. With the development of ISAC technology makes up for this shortcoming. By integrating radar sensing aided beam alignment, we can improve the target angular tracking accuracy, reduce the specific pilots needed in the downlink transmission and replace the uplink feedback with radar echo signals [4].

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A efficient wideband beam tracking method is needed to ensure the stability of the communication link while improving the localization accuracy in high-mobility scenarios. The existing methods [5] and [6] rely on modeling user mobility. The user states and beam directions are estimated by the radar sensing technology, and an extended Kalman filter (EKF) method is adopted to realize the predicted beam tracking. Additionally, [7] searched for the optimal beam direction among a beam codebook through exhausted training. To reduce the large amount of training overhead required, [8] proposed a predicted beam tracking method using a hierarchical codebook. However, these methods can only achieve acceptable performance in narrowband systems. In wideband THz systems, it will suffer a severe performance loss due to the beam split effect. Therefore, realizing a low overhead and efficient beam tracking method in wideband THz systems is an important challenge to be tackled.

To tackle this challenge, we propose a novel beam tracking method in this letter. The main idea is to employ the delay-phase precoding structure within the ISAC system, which is suitable for the THz wideband system. This method is essential to eliminate the severe performance loss caused by the beam split effect in wideband THz systems. Compared to the traditional methods, the proposed method requires less beam training overhead and achieves better beam tracking performance.

Notation: Italicized font, lower-case and upper-case boldface letters denote scalars, vectors and matrices, respectively; $(\cdot)^T$, $(\cdot)^H$ denote the transpose and conjugate transpose of a matrix, respectively; The term $\mathrm{blkdiag}(\cdot)$ denotes the block diagonalization operator; $\mathcal{CN}(a, \sigma)$ denotes the Gaussian distribution with mean a and covariance σ. $\mathcal{U}(a, b)$ denotes the uniform distribution between a and b.

2. System Model

In this letter, we consider a wideband THz communication scenario as shown in Fig. 1. The road-side unit (RSU) is equipped with a massive MIMO uniform linear array (ULA) serves vehicles on the road, while simultaneously performing radar sensing. The ULA consists of N_T transmit antennas and a separate array of N_R receive antennas. We note that the delay-phase precoding structure is employed in the transmit array, where N_{RF} RF chains are full-connected to all the N_T antennas via K_{TD} time-delayers (TDs), where $K_{TD} << N_{RF} << N_T$. To communicate with the RSU, each vehicle is assumed to have N_{UE} antennas ULA on both sides.

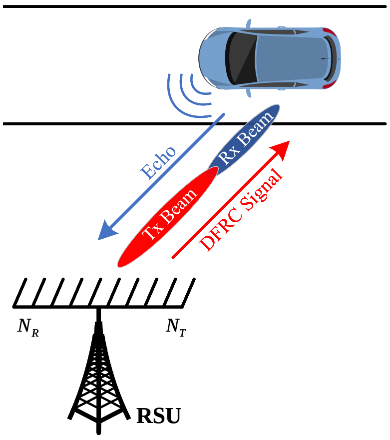


Fig. 1 Communication scenario model.

For brevity, it is assumed that the vehicle moves along a single-lane straight road parallel to the RSU array. We denote the distance, the angle and the speed of the k-th vehicle at the n-th instant relative to the RSU array by $d_{k,n}$, $\phi_{k,n}$ and $v_{k,n}$, respectively. Since the vehicle moves along the direction parallel with the RSU, the angle of the RSU relative to the k-th vehicle is also $\phi_{k,n}$.

2.1 Radar Measurement Model

At the n-th instant, the RSU serves K vehicles over the downlink by using the orthogonal frequency division multiplexing (OFDM) with M subcarriers and radar sensing signals. The complex multi-beam signal $\mathbf{s}_n(t)$ denoted as $\mathbf{s}_n(t) = [s_{1,n}(t), \ldots, s_{K,n}(t)]^T \in \mathbb{C}^{K\times 1}$. The beamformed signals $\widetilde{\mathbf{s}}_n(t)$ transmitted by the RSU can be formulated as

$$\widetilde{\mathbf{s}}_n(t) = \mathbf{F}_n \mathbf{s}_n(t), \tag{1}$$

where $\mathbf{F}_n \in \mathbb{C}^{N_T\times K}$ is the transmit beamforming matrix. The reflected echoes received at the RSU can be given as:

$$\mathbf{r}_n(t) = \sum_{k=1}^{K} \sqrt{p_{k,n}}\beta_{k,n} e^{j2\pi\mu_{k,n}t}\mathbf{b}(\phi_{k,m})\mathbf{a}^{\mathrm{H}}(\phi_{k,m}) \widetilde{\mathbf{s}}_n(t-\tau_{k,n}) + \mathbf{z}_r(t), \tag{2}$$

where $p_{k,n}$ is the transmit power at the k-th beam and n-th instant, $\beta_{k,n}$, $\mu_{k,n}$ and $\tau_{k,n}$ denote the reflection coeffcient, the Doppler frequency and the delay of path for the k-th vehicle, $\mathbf{z}_r \in \mathbb{C}^{N_R\times 1}$ denotes the zero-mean Gaussian noise with variance of σ^2. $\mathbf{a}(\phi)$ and $\mathbf{b}(\phi)$ are transmit and receive beam steering vectors of the antenna array, which are expressed as

$$\mathbf{a}(\phi) = \sqrt{\frac{1}{N_T}}[1, e^{j\pi\widehat{\phi}_{k,m}}, \cdots, e^{j\pi(N_T-1)\widehat{\phi}_{k,m}}]^T, \tag{3}$$

$$\mathbf{b}(\phi) = \sqrt{\frac{1}{N_R}}[1, e^{j\pi\widehat{\phi}_{k,m}}, \cdots, e^{j\pi(N_R-1)\widehat{\phi}_{k,m}}]^T, \tag{4}$$

where the angle of arrival/departure (AoA/AoD) $\widehat{\phi}_{k,m}$ at the n-th instant satisfy $\widehat{\phi}_{k,m} = \frac{2d}{c} f_m cos\theta_k$, d is the antenna spacing usually set as $d = \lambda_c/2 = f_c/2c$ with λ_c denoting the wavelength at the central frequency f_c and c being the speed of light. For simplicity, we use $\cos\phi_{\mathrm{k}} \approx \phi_{\mathrm{k}} \in [-1, 1]$ to represent the user physical direction range.

In the THz communication, the beams at different subcarriers can be seen asymptotically orthogonal and the inter-beam interference can be omitted. Therefore, the reflected echoes from different vehicles will not interfere with each other, the RSU can process each echo signal individually. For the k-th vehicle, by performing radar-matched filtering on each echo signal to obtain the estimation of delay $\tau_{k,n}$ and Doppler frequency $\mu_{k,n}$, from which we can obtain the motion parameters of vehicles, which are given as

$$\tau_{k,n} = \frac{2d_{k,n}}{c} + z_\tau, \tag{5}$$

$$\mu_{k,n} = \frac{2v_{k,n}cos\phi_{k,m}f_c}{c} + z_f, \tag{6}$$

where z_τ and z_f are the measurement Gaussian noise following the distribution $\mathcal{CN}(0, \sigma_\tau^2)$ and $\mathcal{CN}(0, \sigma_f^2)$.

2.2 THz Communication Model

A wideband ray-based channel model is considered for the THz communication [9]. The downlink channel of the k-th vehicle at the m-th subcarrier can be denoted as:

$$\mathbf{h}_{k,m} = \sum_{l=1}^{L} g_{k,m}^l e^{-j2\pi\tau_k^l f_m}\mathbf{u}(\phi_{k,m}^l)\mathbf{a}^H(\phi_{k,m}^l), \tag{7}$$

where $g_{k,m}^l$ is the frequency-dependent path gain at subcarrier m and τ_k^l is the path delay of the l-path for k-th vehicle, L denotes the number of resolvable paths, f_m follows $f_m = f_c + \frac{B}{M}(m-1-\frac{M-1}{2})$ is the frequency of the m-th subcarrier, $\mathbf{u}(\phi) \in \mathbb{C}^{N_{UE}\times 1}$ denotes the steering vector in the vehicles, which is defined similarly to (3) and (4).

Since THz communication heavily relies on line-of-sight (LoS) path, the non-LoS (NLoS) paths are considered as the noise. Therefore, we consider the communication with the vehicle through the LoS channel, the received signal at the m-th subcarrier by the k-th vehicle is denoted as:

$$\mathbf{y}_{k,m}(t) = \mathbf{h}_{k,m}^1 \mathbf{w}_{UE}\widetilde{\mathbf{s}}_n(t-\tau_{k,n}) + \mathbf{z}_c(t) \tag{8}$$

$\mathbf{w}_{UE}$ denotes the receive beamforming in the vehicles, $\mathbf{z}_c$ is Gaussian noise following distribution $\mathcal{CN}(0, \sigma_c^2)$. Assuming the transmitted signal $\mathbf{s}_n(t)$ has unit power, the received signal-to-interference-noise ratio (SINR) is expressed as

$$\mathrm{SINR}_{k,m} = \frac{|\mathbf{h}_k^H \mathbf{F}_m \mathbf{D}_{m,[:,k]}|^2}{\sum_{k'\neq k}^{K} |\mathbf{h}_k^H \mathbf{F}_m \mathbf{D}_{m,[:,k']}|^2 + \sigma_c^2}, \tag{9}$$

where $\mathbf{D}_m \in \mathbb{C}^{K\times K}$ is the digital precoder designed by the zero-forcing (ZF) method. The achievable sum-rate of all K vehicles in the data transmission period can be given as

$$R = \sum_{k=1}^{K}\sum_{m=1}^{M} \log_2(1 + \mathrm{SINR}_{k,m}). \tag{10}$$

Algorithm 1 Proposed wideband THz beam tracking method

Input:initial state $\phi_{k,n}$, $\tau_{k,n}$, $\mu_{k,n}$; The number of TDs K_{TD}; The number of subcarriers M; Beam tracking overhead T;
Output: Physical directions $\phi_{k,n+1}$

1. **for** $n \in 1, 2, \ldots, N$ **do**
2. Estimate $\phi_{k,n}$, $\tau_{k,n}$, and $\mu_{k,n}$ from radar echoes
3. Determine the target physical direction set **s**
4. Design the analog beamforming $\mathbf{F}_n$
5. **for** $t \in 1, 2, \ldots, T$ **do**
6. Perform wideband beam tracking procedure
7. **end for**
8. Determine the beam pairs with the largest SNR
9. Return the physical direction $\phi_{k,n+1}$
10. **end for**

3. The proposed method

In this letter, we propose a wideband THz beam tracking method to solve the problems of the high beam training overhead required for tracking and severe beam spilt effect in the wideband THz systems. In the multi-vehicle communication, The beams generated by the RSU need to be associated with the corresponding vehicle. However, since the reflected echoes cannot contain ID information in the ISAC system. We consider the Euclidean distance-based scheme as [5] to associate the reflected echoes with the vehicle IDs.

The idea of the proposed method can be briefly described: Firstly, the method is initialized by letting the RSU estimate the motion trajectory by inferring initial parameters angle $\phi_{k,n}$, delay $\tau_{k,n}$ and Doppler $\mu_{k,n}$ from the reflected echoes. We assume the angular variation range in a specific slot is limited. The RSU can estimate the possible angular variation range of physical direction as α_k for the k-th vehicle. This α_k can be obtained by the estimated motion trajectory in advance [5]. Then, the candidate angular tracking range can be given as $[\phi_{k,n} - \alpha_k, \phi_{k,n} + \alpha_k]$. Secondly, the transmit analog beamforming matrix $\mathbf{F}_{k,m}$ is designed based on the initial parameters. The proposed method using delay-phase precoding structure can generate beams aligned with multiple physical directions of this angular tracking range simultaneously. We denote the beam training overhead as T,i.e., the number of time slots used for beam tracking. Next, the wideband beam tracking procedure will be carried out for T time slots until the whole angular tracking range is tracked. After T time slots, the physical direction $\phi_{k,n+1}$ at the next instant will be found corresponding to the largest received signal power. Finally, the RSU generates beams aligned with the physical direction $\phi_{k,n+1}$ to provide service to the vehicle.

The specific procedure of the proposed beam tracking method is prensented in **Algorithm 1**. The steps are as follows: At first, we donate the physical direction of the k-th vehicle at the n-th instant as $\phi^{(0)}_{k,n}$. To cover the candidate angualr tracking range in T time slots, The physical direction tracked in each slot satisfies $\phi^{(t)}_{k,n} = \phi^{(0)}_{k,n} - \alpha_k + (2t-1)\frac{\alpha_k}{T}$. $\phi^{(t)}_{k,m,n}$ denotes the physical direction will be tracked at the m-th subcarrier in the t-th time slot as:

$$\phi^{(t)}_{k,m,n} = \phi^{(t)}_{k,n} + (1-\xi_1)\frac{\alpha_k}{T} + \frac{2\xi_M \xi_1 (\xi_m - 1)}{\xi_m(\xi_m - \xi_1)T}\alpha_k, \quad (11)$$

where $\xi_m = f_m/f_c$ is the relative frequency compared with the central frequency f_c. Then, All the physical directions based on the angular tracking range will be tracked in T time slots. The target physical direction tracked in each time slot can be combined as a target physical direction set $\mathbf{s}^{i+1}_k$.

$$\mathbf{s}^{i+1}_k = [\phi^{(1)}_{k,1,i}, \phi^{(1)}_{k,2,i}, \ldots, \phi^{(1)}_{k,M,i}, \ldots, \phi^{(T)}_{k,M,i}], \quad (12)$$

After determining the target physical direction set. The RSU formulates the analog beamforming $\mathbf{F}^{(t)}_{k,m}$, which contains the phase shifts $\phi^{(t)}_k$ and time delays $\mathbf{t}^{(t)}_k$ provided by the phase shifters (PSs) and TDs. where ϕ^t_k and $\mathbf{t}^{(t)}_k$ are calculated as:

$$\phi^{(t)}_k = \phi^{(t)}_{k,n} + (1-\xi_1)\frac{\alpha_k}{T}, \quad (13)$$

$$\mathbf{t}^{(t)}_k = -\frac{P}{2f_c}(\phi^{(t)}_k + \frac{2\xi_M \xi_1 \alpha_k}{(\xi_m - \xi_1)T})\mathbf{p}(K_{TD}). \quad (14)$$

where $\mathbf{p}(K_{TD})$ is defined as $\mathbf{p}(K_{TD}) = [0, 1, \ldots, K_{TD}-1]^T$. As proved in [10], when satisfying (13) and (14), the beams over different subcarrier frequencies can align with the target physical direction set. The analog beamforing $\mathbf{F}^{(t)}_{k,m}$ is designed by the $P = N_T/K_{TD}$ PSs connected to RF chains through K_{TD} TDs, which contains the phase shifts provided by PSs satisfies $\mathbf{F}^{(t)}_k = \text{blkdiag}([a_{k,1}, a_{k,2}, \ldots, a_{k,K}]) \in \mathbb{C}^{N \times K_{TD}}$ and the time delays provided by TDs satisfies $\mathbf{F}^{(t)}_m = \text{blkdiag}([e^{-j2\pi f_m t_1}, e^{-j2\pi f_m t_2}, \ldots, e^{-j2\pi f_m t_K}]) \in \mathbb{C}^{K_{TD}K \times K}$. Therefore, the beamforming vector $\mathbf{f}^{(t)}_{k,m}$ in the t-th time slot is calculated as

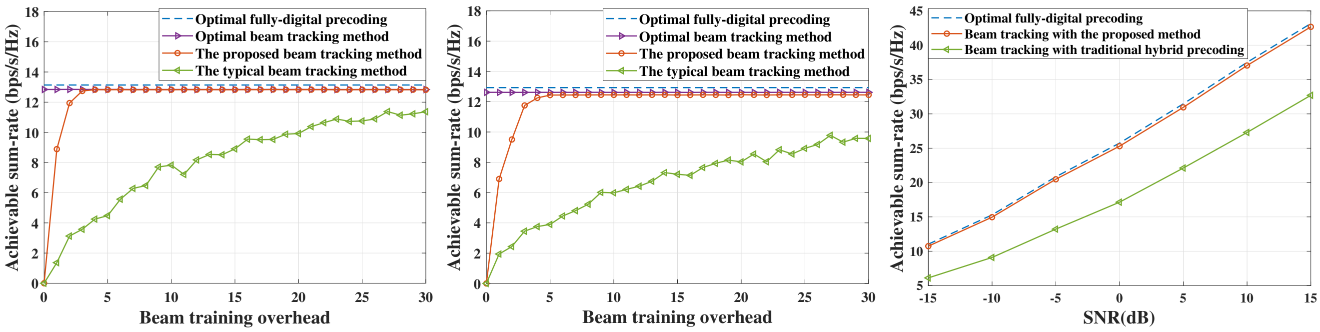
$$\mathbf{f}^{(t)}_{k,m} = \mathbf{F}^{(t)}_k e^{-j2\pi f_m \mathbf{t}^{(t)}_k}. \quad (15)$$

After determining the analog beamforming $\mathbf{F}^{(t)}_{k,m}$, the RSU transmits beams by using $\mathbf{F}^{(t)}_{k,m}$ to track k-th vehicle in T time slots, traversing the target physical directions set $\mathbf{s}^{i+1}_k$. Finally, the physical direction $\phi_{k,n+1}$ in the next instant can be obtained by finding the beam pairs with the largest SNR.

4. Simulation results

In this section, we give simulation results to show the performance of the proposed wideband beam tracking scheme. The parameters of the simulation are set as: $N_T = 256, M = 128, N_{RF} = 4, K_{TD} = 16, f_c = 300$ GHz and $B = 10$ GHz. We assume the transmit power as $p_k = 1$ and path gain of the LoS path as $g_{k,m} = 1$ without loss of generality. The physical directions of vehicles $\phi_{k,m}$ are randomly generated by the distribution following $\mathcal{U}(-1, 1)$, and the angular variation range α_k of vehicles' physical directions follows $\mathcal{U}(0, \alpha_k)$.

In Fig. 2, we compare the achievable sum-rate performance against the beam training overhead T, where the



(a) $\alpha_k = 0.2$ (b) $\alpha_k = 0.4$ (c) $T = 5$, $\alpha_k = 0.2$

Fig. 2 The achievable sum-rate performance against the beam training overhead. The angular variation range set as (a) $\alpha_k = 0.2$ (b) $\alpha_k = 0.4$, (c) The achievable sum-rate performance under different SNR.

three methods are compared to the proposed method as: the optimal fully-digital minimum mean square error (MMSE) precoding [11], beam tracking [12] with the perfect physical directions, and the typical beam tracking method [13]. Depending on different angular variation ranges α_k, the required minimum training overhead to achieve the near-optimal achievable sum-rate performance is different. It can be observed from Fig. 2(a) and Fig. 2(b). When $\alpha_k = 0.2$, the minimum training overhead is $T = 2$, which is much smaller than the typical beam tracking method $T = 30$. When $\alpha_k = 0.4$ the minimum training overhead is large to $T = 3$. Although the larger angular variation range requires more beam training overhead, the proposed method can still reduce the training overhead by almost 90%. The superior performance is mainly because the ISAC-aided beam tracking method can reduce the specific pilots for channel estimation and the employed delay-phase precoding can compensate for the severe performance loss caused by the beam split effect.

Fig. 2(c) depict the performance curves of the proposed method under different SNR. Some system parameters are set as $N_{UE} = 4, \alpha_k = 0.2, T = 5$. The optimal fully-digital MMSE precoding and the typical beam tracking method are depicted for a comparison. It is observed that the proposed method can achieve the near-optimal achievable sum-rate. In contrast, the typical beam tracking method suffers from a severe sum-rate performance loss when using traditional hybrid precoding structure. The results can vertify the effectiveness of the proposed method in wideband THz systems.

5. Conclusion

In this letter, we propose a wideband THz beam tracking method based on the ISAC system to solve the problems of large beam training overhead and the severe beam split effect of the typical beam tracking method in the wideband THz system. The proposed method can use a very low training overhead to achieve more accurate angular tracking accuracy and improve achievable sum-rate performance. The simulation results validate that the proposed method is significantly better than the typical beam tracking method, which can achieve near-optimal sum-rate performance.

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