A Pilot-based Beam-Tracking Technique for OFDM-based Millimeter-Wave Cellular Systems

Yeong Jun Kim[1] and Yong Soo Cho[2]
[1]LG Electronics, [2]School of Electrical and Electronics Engineering, Chung-Ang University, Seoul, Korea

***Abstract*—A pilot-based beam-tracking technique is proposed for OFDM-based millimeter-wave cellular systems. In order to track the variations in the angle of departure (AoD) and angle of arrival (AoA), an antenna array is configured into two different subarrays which allow us to estimate AoD/AoA based on the phase difference between the two subarrays in the received signals. A pilot sequence is designed such that it can distinguish between different subarrays and track a beam for a mobile station in multi-cell multi-user environments.**

Keywords*— *Pilot-based, beam tracking, OFDM, millimeter-wave, cellular system

I. INTRODUCTION

Beam-training operation in millimeter-wave (mmWave) cellular systems is necessary to find the best pair among all possible beam pairs for maximum beamforming efficiency. The beam training operation requires significant network resources because the receiver (Rx) beam sweep needs to be performed at the mobile station (MS) for each transmitter (Tx) beam to measure the SNR of every Tx-Rx beam pair. The SNR measurement must be performed for all neighboring base stations (BSs) [1]. However, the beam alignment can be easily destroyed by even small variations in the device's position due to rotation and displacement. Although the beam-training technique can resolve such problems, it will consume significant network resources if beam-training is performed whenever the received signal experiences a power loss.

In this paper, a pilot-based beam-tracking technique for OFDM-based mmWave cellular systems using subarray structures is proposed. To track the variations in AoD/AoA, an antenna array is configured into two different subarrays that form a beam in the same direction. The subarray structure is designed such that it allows us to estimate the AoD/AoA based on the phase difference between two subarrays in the received signals. The signals transmitted from different subarrays are distinguished by assigning different pilot sequences to subarrays because it is not possible to distinguish two different signals with the signals received from different subarrays. In addition, the information on cell ID (CID) and beam ID (BID) is transmitted on the pilot sequence in order that beam-tracking can be performed for an MS in multi-cell multi-user environments.

II. PROPOSED BEAM-TRACKING TECHNIQUE

Fig. 1 shows the concept of the proposed beam-tracking technique for OFDM-based mmWave cellular systems when the proposed method is applied. In the proposed technique, Subarray 0 is connected to the first ADC/DAC path and Subarray 1 is connected to the second ADC/DAC path. It is assumed that a uniform linear array (ULA) is used at both the BS and MS, and a Tx beam with the BID *b* is formed at the BS in direction of a target MS. It is further assumed that the number of elements in the antenna arrays at the BS and MS are N_{Tx} and N_{Rx}, respectively. On the Tx side, Subarrays 0 and 1 are constructed using antenna elements from 0 to $N_{Tx}-2$ and 1 to $N_{Tx}-1$, respectively. Subarrays on the Rx side are formed in the same manner. Thus, the number of elements in each subarray at BS and MS are $N_{Tx}-1$ and $N_{Rx}-1$, respectively. Subarrays 0 and 1 on the Tx and Rx sides have $N_{Tx}-2$ and $N_{Rx}-2$ overlapping elements, respectively. Note that the (*a*+1)-th element in Subarray 0 experiences the same phase as the *a*-th element in Subarray 1. Owing to the overlapping structure, it is difficult to distinguish difference between signals (of the Tx's Subarrays 0 and 1) using the signals received from the Rx's Subarrays 0 and 1. To distinguish difference between signals from the Tx's Subarrays 0 and 1, different pilot sequences are assigned to the Tx's subarrays, and the signals received from the Rx's Subarrays 0 and 1 are passed through two different ADC paths.

In the paper, variables "*x*" and "*X*" are used to represent the time domain and frequency domain signals, respectively. Also, boldfaces, **x** and **X**, are used to represent the vector and matrix, respectively, all composed of frequency domain signals. Then, the signal $[\mathbf{x}_b^{r,m_{Tx}}]_k$ $(=X_b^{r,m_{Tx}}(k))$ at the input (N point IFFT) of the OFDM system in the BS can be represented by

$$[\mathbf{x}_b^{r,m_{Tx}}]_k = \begin{cases} [\mathbf{s}_b^{r,m_{Tx}}]_{n_{k_P}} = [\mathbf{s}_b^r]_{n_{k_P}} e^{-j2\pi m_{Tx}\omega n_{k_P}/N_S}, & k \in \{k_P\} \\ [\tilde{\mathbf{s}}_b^r]_{n_{k_D}} & k \in \{k_D\} \end{cases}, \quad (1)$$

where $[\mathbf{s}_b^r]_{n_{k_P}} = \mathrm{e}^{-j\pi\{r n_{k_P}(n_{k_P}+1)+2bBn_{k_P}\}/N_S}$, $B = \lfloor N_S / N_B \rfloor$, $0 \le n_{k_P} < N_S$, $0 \le n_{k_D} < N - N_S$, $0 \le k < N$, and $\{k_P\} = \{k_D\}^c$.

Here, m_{Tx}, k_P, k_D, $\mathbf{s}_b^r$, and $\tilde{\mathbf{s}}_b^r$ denote the index of subarray at the BS, index of pilot subcarrier, index of data subcarrier, pilot sequence, and data symbol, respectively. $[\mathbf{s}_b^r]_{n_{k_P}}$ and $[\tilde{\mathbf{s}}_b^r]_{n_{k_D}}$ denote the n_{k_P}-th element and the n_{k_D}-th element of

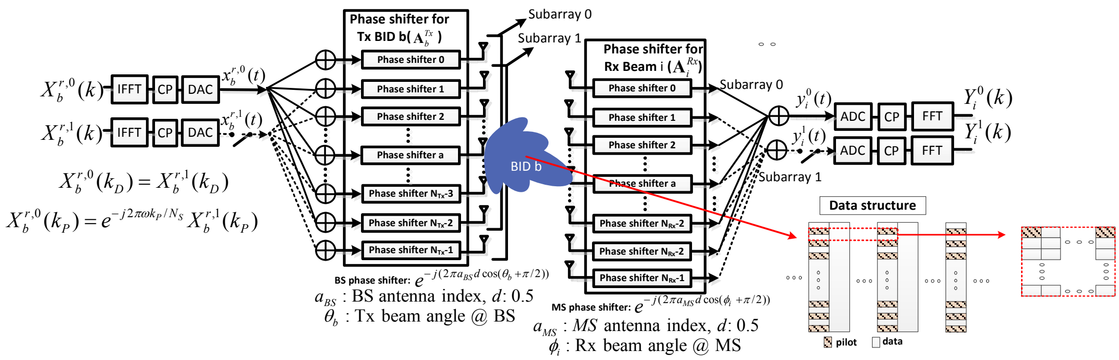

Fig. 1. Concept of proposed beam-tracking technique for OFDM-based mmWave cellular systems with subarray structure.

each vector. In addition, r, b, B, N_S, and N_B are the root index of the Zadoff–Chu sequence, BID, phase rotation parameter (for BID identification), length of pilot sequence, and number of BIDs, respectively. Further, ω denotes the phase rotation factor to distinguish pilot sequences transmitted from different subarrays. The pilot sequence $\mathbf{s}_b^r$ can be viewed as a combination of a Zadoff–Chu and a polyphase sequence. Here, the pilot sequence is generated by mapping the CID to the root index of the Zadoff–Chu sequence and the BID to the index of the polyphase sequence. Note that the pilot sequence needs to carry the CID and BID in order to be detected in multi-cell multi-user environments. If the pilot sequence carries only BID information, it will be impossible to determine by which cell it has been transmitted. When N_S is a prime number, the correlation value between the pilot sequences $\mathbf{s}_b^r$ with the same CID but different BIDs becomes zero. Further, the normalized correlation value between the pilot sequences $\mathbf{s}_b^r$ with different CIDs becomes $1/\sqrt{N_S}$ [2][3].

The subarray gain of a Tx beam with BID b at the BS in Fig. 1 is given by

$$\eta^{m_{Tx}}_{\theta_b,\theta_{BS}} = e^{j2\pi m_{Tx} d\Theta_{\theta_b,\theta_{BS}}} e^{j\pi d(N_{Tx}-2)\Theta_{\theta_b,\theta_{BS}}} (\sin(\pi d\Theta_{\theta_b,\theta_{BS}}))^{-1} \times \sin(\pi(N_{Tx}-1)d\Theta_{\theta_b,\theta_{BS}}),\ m_{Tx}=0 \text{ or } 1 \tag{2}$$

where $\Theta_{\theta_b,\theta_{BS}} = \cos(\theta_b+\pi/2)-\cos(\theta_{BS}+\pi/2)$.

Here, θ_b and θ_{BS} denote the Tx beam direction (angle) of BID b and AoD from the BS with a reference angle ($\theta_b = 0$) in the direction of MS, respectively. The subarray gain of the i-th Rx beam at the MS is given by

$$\mu^{m_{Rx}}_{\phi_i,\phi_{MS}} = e^{j2\pi m_{Rx} d\Phi_{\phi_i,\phi_{MS}}} e^{j\pi d(N_{Tx}-2)\Phi_{\phi_i,\phi_{MS}}} (\sin(\pi d\Phi_{\phi_i,\phi_{MS}}))^{-1} \times \sin(\pi(N_{Tx}-1)d\Phi_{\phi_i,\phi_{MS}}),\ m_{Rx}=0 \text{ or } 1, \tag{3}$$

where $\Phi_{\phi_i,\phi_{MS}} = \cos(\phi_i+\pi/2)-\cos(\phi_{MS}+\pi/2)$.

Here, m_{Rx}, ϕ_i, and ϕ_{MS} denote the subarray index (0 or 1) in the MS, direction (angle) of the i-th Rx beam, and AoA at the MS with the reference angle ($\phi_i = 0$), respectively. The signal received by the i-th Rx beam with the m_{Rx}-th subarray is represented in the frequency domain as

$$\begin{aligned}\mathbf{y}_i^{m_{Rx}} &= \sum_{m_{Tx}=0}^{1}\sum_{l=0}^{L_h-1} h_l\, \mu^{m_{Rx}}_{\phi_i,\phi_{MS,l}}\, \eta^{m_{Tx}}_{\theta_b,\theta_{BS,l}}\, \tilde{\mathbf{x}}^{r,m_{Tx}}_{b,l} + \mathbf{w}_i^{m_{Rx}} \\ &= \sum_{l=0}^{L_h-1} h_l\, \tilde{\mathbf{X}}^r_{b,l}\, \boldsymbol{\varepsilon}^{i,m_{Rx}}_{b,l} + \mathbf{w}_i^{m_{Rx}},\ m_{Rx}=0 \text{ or } 1,\end{aligned} \tag{4}$$

where $\tilde{\mathbf{X}}^r_{b,l} = \mathbf{E}_N^{\Delta_l}\mathbf{X}_b^r = [\tilde{\mathbf{x}}^{r,0}_{b,l}\ \tilde{\mathbf{x}}^{r,1}_{b,l}]$, $\mathbf{X}_b^r = [\mathbf{x}_b^{r,0}\ \mathbf{x}_b^{r,1}]$, $\boldsymbol{\eta}_{\theta_b,\theta_{BS,l}} = [\eta^0_{\theta_b,\theta_{BS,l}}\ \eta^1_{\theta_b,\theta_{BS,l}}]^T$, $\boldsymbol{\varepsilon}^{i,m_{Rx}}_{b,l} = \mu^{m_{Rx}}_{\phi_i,\phi_{MS,l}}\boldsymbol{\eta}_{\theta_b,\theta_{BS,l}}$, $[\mathbf{E}_N^{\Delta_l}]_{k,k} = [\mathbf{e}_N^{\Delta_l}]_k = e^{-j2\pi\Delta_l k/N}$ and $[\mathbf{E}_N^{\Delta_l}]_{k_0,k_1\neq k_0} = 0$.

Here, $[\mathbf{E}_N^{\Delta_l}]_{k_0,k_1}$ denotes the element in the k_0-*th* row and k_1-*th* column in $\mathbf{E}_N^{\Delta_l}$. $\mathbf{E}_N^{\Delta_l}$ is an $N\times N$ matrix accounting for the phase rotation caused by the delay of the l-th path (Δ_l). In $\mathbf{E}_N^{\Delta_l}$, the diagonal terms are $e^{-j2\pi\Delta_l k/N}$ and off-diagonal terms are zero. $\mathbf{X}_b^r$ is a matrix composed of pilot signals of two subarrays in the BS. Further, h_l, L_h, and $\mathbf{w}$ are the l-th tap component of channel impulse response, length of channel impulse response, and AWGN noise vector, respectively. Thus, $\tilde{\mathbf{X}}^r_{b,l}$ can be viewed as a modified version of $\mathbf{X}_b^r$ considering the delay effect of the l-th path. The parameters $\theta_{BS,l}$ and $\phi_{MS,l}$ are AoD and AoA of the l-th tap of the channel, respectively.

Next, the proposed beam-tracking technique is described. Here, it is assumed that a Tx beam with the BID equal to b is formed in the direction of a single user and the user receives the signal through the i-th Rx beam. Although the beam-tracking algorithm is derived for the case of a single user in this paper, the algorithm can be easily extended for multiple users in a multi-cell environment because CID and BID corresponding to the beam can be uniquely identified from the pilot sequence. The data symbols $\tilde{\mathbf{s}}_b^r$ in $\mathbf{x}_b^r$ are assumed to be zero for notational simplicity.

When an MS is operated in tracking mode, pilot sequences and Δ can be assumed to be known to the MS. In practice, Δ can be estimated by the conventional path delay estimation technique. The gain $\mu_{\phi_i,\phi_{MS}}$ of the i-th Rx beam at the MS can be assumed constant because the Rx beam is fixed during pilot-reception. Using the phase difference between subarray 0 and subarray 1 at the BS, the estimate of $\Theta_{\theta_b,\theta_{BS}}$ can be obtained as follows:

$$\hat{\Theta}_{\theta_b,\theta_{BS}} = -\frac{1}{2\pi d}\angle\sum_{m_{Rx}=0}^{1}(\mathbf{y}_i^{m_{Rx}})^H\,\tilde{\mathbf{x}}_b^{r,0}(\tilde{\mathbf{x}}_b^{r,1})^H\,\mathbf{y}_i^{m_{Rx}} \qquad (5)$$

Then, $\Phi_{\phi_i,\phi_{MS}}$ can be estimated as follows:

$$\hat{\Phi}_{\phi_i,\phi_{MS}} = (2\pi d)^{-1}\angle\hat{g}_b^{i,1}(\hat{g}_b^{i,0})^{*} \qquad (6)$$

where $\hat{g}_b^{i,m_{Rx}} = (\tilde{\mathbf{X}}_b^r\tilde{\boldsymbol{\eta}}_{\theta_b,\theta_{BS}})^H\,\mathbf{y}_i^{m_{Rx}}\{(\tilde{\mathbf{X}}_b^r\tilde{\boldsymbol{\eta}}_{\theta_b,\theta_{BS}})^H\,\tilde{\mathbf{X}}_b^r\tilde{\boldsymbol{\eta}}_{\theta_b,\theta_{BS}}\}^{-1}$.

Finally, the estimates of AoD and AoA can be obtained as

$$\hat{\theta}_{BS} = \cos^{-1}(\hat{\Theta}_{\theta_b,\theta_{BS}} + \cos(\theta_b + \pi/2)) - \pi/2, \qquad (7)$$

$$\hat{\phi}_{MS} = \cos^{-1}(\hat{\Phi}_{\phi_i,\phi_{MS}} + \cos(\phi_i + \pi/2)) - \pi/2. \qquad (8)$$

III. SIMULATION

In this section, the performance of the proposed beam-tracking techniques is evaluated by computer simulations. The number of antenna elements (N_{Tx} , N_{Rx}), and parameters related to the pilot sequence generation (N_S , B , r , b , ω) are set to (16, 8), and (479, 59, 11, 6, 29), respectively. A ULA antenna configuration is assumed at BS and MS. The number of subcarriers is 2048. The pilots are transmitted with every fourth symbol in the time domain, and allocated with every fourth subcarrier in the frequency domain. Rician fading channel with K = 10 dB is considered.

Fig. 2 shows the AoD/AoA tracking performance. The AoD/AoA of the LoS path varies by Δ_T/Δ_R for every symbol transmission. Thus, the AoD/AoA difference between adjacent pilot symbols is $4\Delta_T/4\Delta_R$. The SNR is set to −24 dB and three different values of Δ_T are used: 0°, 0.01°, and 0.005°. Δ_R is set to $-\Delta_T$. In Fig. 2, markers represent the correct AoD/AoA values, and lines through the markers represent the results when the proposed tracking techniques are used. Here, the black and blank markers represent AoD and AoA tracking, respectively. As can be seen in Fig. 2, the beam-tracking results are in good agreement with the correct AoD/AoA values for all values of Δ_T and Δ_R.

IV. CONCLUSION

In this paper, a pilot-based beam-tracking technique for OFDM-based mmWave cellular systems is proposed using subarray structures. The proposed technique is shown to provide a good AoD/AoA tracking performance when the MS moves under a Rician fading environment. Since the proposed technique does not require a separate beam-training period, it can be applied to mobile MSs or high-speed vehicles which require fast beam tracking.

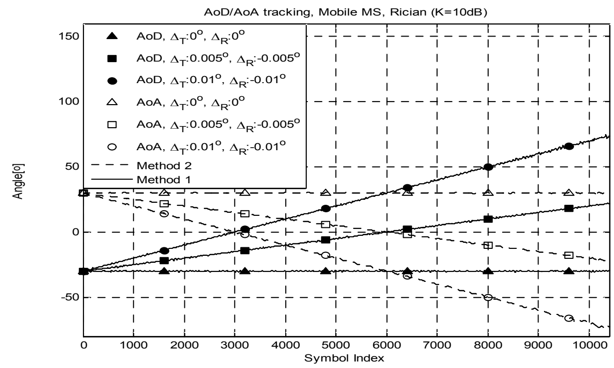

Fig. 2. AoD/AoA tracking performance under Rician fading environment.

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