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Concept of Joint Fast Beam Search and Synchronization Scheme using Fast Beam Steering

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***Abstract*—This report proposes a fast beam search which is completed within a single synchronization signal block (SSB). Massive Multiple-Input Multiple-Output (Massive MIMO) with multiple antenna elements can enhance antenna gain by beamforming to specific user equipment (UE). However, the beam search requires a number of beam candidates which incurs non-negligible latency and degrades beam tracking capability. Fast beam steering is realized in the vertical domain by our previously proposed antenna equipped with fast phase shifter. The horizontal beam is set for each SSB to be transmitted, and only the vertical beam direction is switched by a fast phase shifter within that SSB to determine its direction. Computer simulations verifies that the proposed beam search scheme can determine the horizontal and vertical beams corresponding to the UE's location while reducing the number of SSBs relative to the number of beams.**

***Index Terms*—Massive MIMO, fast beam steering, beam search, fast phase shifter**

I. Introduction

In mobile communications, the fifth-generation mobile communication system (5G) has been launched, and the sixth-generation mobile communication system (6G) has begun to be considered [1], [2]. In addition to high-speed and large-capacity communications, various use cases are being considered for 5G, including highly reliable and low-latency communications and multi-terminal connectivity. Each use case has different technique requirements, and elemental technologies suitable for each have been considered. In 6G, new requirements such as expanded coverage, low power consumption, and low cost have been added. In addition, the demand for wireless communications has continued to increase year after year since 2010, when smartphones began to spread. In reference [4], it is predicted that the amount of data used by one smartphone per month will exceed 19 GB in 2023 and continue to increase after that. Although studies are underway to realize various use cases, it will be necessary to realize high-speed, high-capacity communication technology to meet the ever-increasing communication demand.

Massive Multiple-Input Multiple-Output (Massive MIMO), in which the base station (BS) has a huge number of antennas, has been considered as one of the technologies to realize high-speed and high-capacity wireless communications [5], [6]. Massive MIMO can provide the beamforming gain to the desired user equipment (UE) and is continuously considered an essential technology in 6G [7]. Massive MIMO performs precoding to prevent radio interference between multiple UEs or streams [8], [9]. Although extended sptial multiplexing performance can be achieved using fully digital signal processing, computation complexity becomes an inevitable issue. Hybrid beamforming is being considered to reduce the computational complexity by combining analog and digital processing [10], [11]. Furthermore, the use of Butler matrices is being considered to simplify the power feed circuit [13].

To maximize beamforming gain, the UE needs to designate the appropriate beam provided by BS. BS needs to determine the beam direction to the UE especially at the initial connection state since there is no prior information [14]. The BS sweeps the beam in each direction to the extent available, and the UE selects the desirable beam direction that maximizes reception gain. In beam search, reference signal or synchronization signal block (SSB) is transmitted for each beam. UE measures the received power and feedback the determined optimal beam ID. In the case of using the Butler matrix, the number of available beam direction corresponds to the number of elements; the beam search time is proportional to the number of beams. SSB placement for beam search is specified in [15]. Case B configuration specifies a maximum of eight beams. It takes four frames to transmit eight SSBs, which is defined as one cycle. On the other hand, Case D specifies a maximum of 64 beams which requires 38 frames to complete one cycle. The beam search period is extended as the number of beams increases. Therefore, challenge is defined as reducing the beam search duration which is increased as the number of array antenna is enlaged as well as the number of beams increases.

Hierarchical beam search, in which initial beam steering is performed with a wide beamwidth and a narrow beamwidth is searched based on the results, has been considered a scheme to reduce the beam search time. [16], [17]. However, as the number of UEs increases, the UE placement becomes uniform, so sufficient reduction cannot be achieved. A scheme to estimate beams from UE positions has also been considered [18], [19]. At the time of initial connection, it is necessary to transmit position information for each UE, which increases the control overhead.

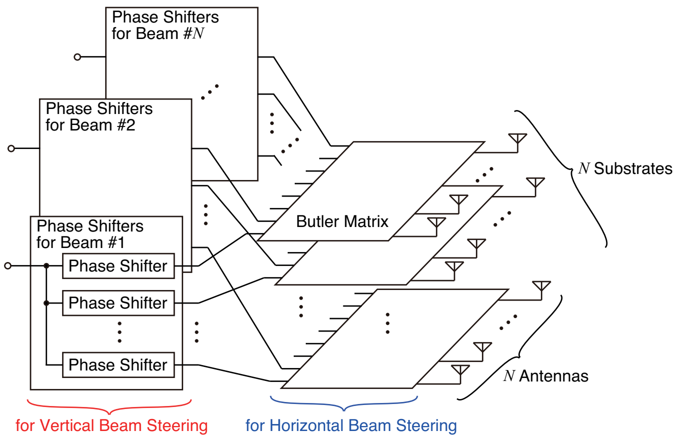


Fig. 1. Block diagram of proposed beam search scheme.

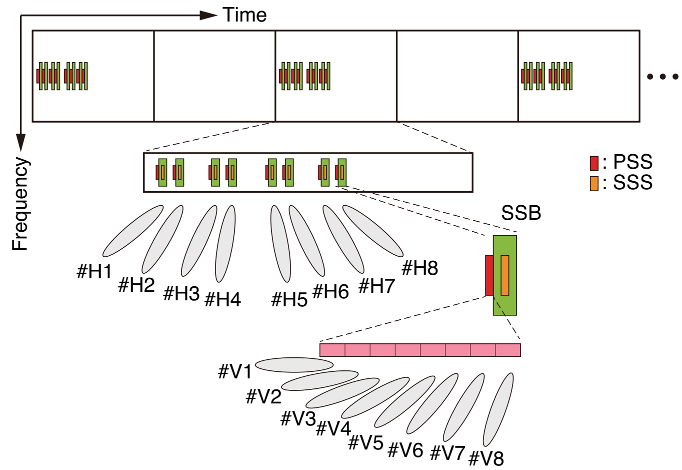


Fig. 2. SSB placement and beam steering.

This letter proposes a novel beam search scheme using fast beam steering to reduce the overhead required for beam sweeping. A phase shifter capable of fast switching in the order of nanoseconds has been proposed [20]. This letter assumes a phased array antenna with fast beam switching using this phase shifter. The proposed scheme performs beam steering only at high speed within a single SSB. The proposed beam search scheme can reduce the beam search period by searching multiple beams in a single SSB instead of searching for one beam in one SSB as in the conventional scheme. In the case of a two-dimensional array antenna with $N \times N$, the beam search time can be reduced to $1/N$ by fast beam steering in one dimension. Computer simulation results evaluate the characteristics of the proposed scheme.

II. Proposed Beam Search Scheme with Fast Beam Steering

First, let us describe the configuration used in the beam search scheme with fast beam steering. The proposed configuration of $N \times N$ array antennas is shown in Fig. 1. The $N \times N$ array antenna consists of a one-dimensional patch array antenna, a Butler matrix, and a variable phase shifter. The patch array antenna and the butler matrix are mounted on the same substrate, stacking N substrates. These substrates are connected to a variable phase shifter set with N variable phase shifters. A phase shifter is used, which can switch phases discretely and rapidly within a single symbol [20]. The input signals of the beams corresponding to each horizontal direction are split into N branches, and each is input to a variable phase shifter. The outputs of the variable phase shifters are input to the same port of the Butler matrix on each substrate. This allows the horizontal beam to be formed according to the input port of the Butler matrix and the vertical beam to be formed by the variable phase shifter.

Next, let us describe the beam search procedure. Fig. 2 shows the configuration of the SSB for $N \times N$ beams and examples of horizontal and vertical beam steering configurations. This example shows for $N = 8$. There are N SSBs corresponding to N types of horizontal beams, each transmitting at a different time. The SSBs are assumed to be those specified in [15]. Each SSB transmits using a different horizontal beam. The same synchronization signal is transmitted repeatedly with N SSBs as one period. The UE assumes that the correspondence between SSBs and horizontal beams is known. The horizontal beam is searched for by measuring the Reference Signal Received Power (RSRP) using the secondary synchronization signal (SSS) in the SSB as before, and the horizontal beam with the largest RSRP is selected. A high-speed phase shifter searches for the vertical beam within a single SSB. Vertical beam steering is performed in N steps within one symbol time of the primary synchronization signal (PSS) in the SSB. Specifically, the PSS is divided into N segments, and each is transmitted using a different vertical beam. The UE uses the PSS to detect the cell ID and symbol start timing. After timing synchronization, the PSS is divided into N segments in the time domain, the point with the maximum power is detected, and the corresponding vertical beam is selected. Perform the same vertical beam steering for each SSB and perform the same vertical beam detection for all SSBs. From the detection results of N SSBs, the beam with the highest number of selections is selected as the vertical beam. Although beam steering in the PSS degrades time synchronization accuracy, the accuracy can be maintained by using the demodulation reference signal (DMRS) in the SSBs for channel demodulation. As described above, N^2 vertical and horizontal beam searches can be performed in N SSB segments, thus reducing the search time to $1/N$.

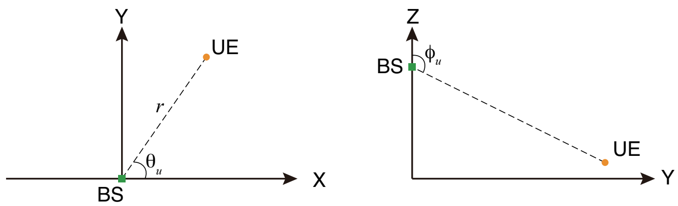
III. Computer Simulations

A. Simulation Conditions

The computer simulation results evaluate the feasibility of the proposed scheme. Table I lists the simulation parameters. The center frequency was set to 4.5 GHz, and the signal bandwidth to 100 MHz. A 64-element (8×8) two-dimensional patch array antenna was used, and eight types of horizontal beams (33°, 53°, 69°, 83°, 97°, 111°, 127°, 147°). The

TABLE I
SIMULATION CONDITIONS

Center frequency	4.5 GHz
Bandwidth	100 MHz
SSB settings	Case B [15]
No. of SSB	8
No. of Tx antennas	64 (8×8)
No. of Rx antennas	1
Transmission power	25 dBm
Feeder loss	3 dB
Tx antenna gain	6 dBi/Anteanna
Rx antenna gain	0 dBi
Horizontal beam direction (°)	33, 53, 69, 83, 97, 111, 127, 147
Vertical beam direction (°)	90, 100, 110, 120, 130, 140, 150, 160
Noise power	−174 dBm/Hz
Noise figure	9 dB
Antenna height of BS	40 m
Antenna height of UE	1.5 m



(a) Top view (b) Side view

Fig. 3. UE placement.

SSB setup is based on Case B of [15], where eight SSBs correspond to eight different horizontal beams, and the SSBs are transmitted at other times. Vertically, eight types of beams are formed every 10° from 90° to 160° using variable phase shifters. The PSS is divided into eight beams in the time domain, and the vertical beams are switched for transmission. For SSB other than PSS, beams of 90° were used. The BS antenna height was set to 40 m, and the UE antenna height to 1.5 m. Polarization of antennas was not considered. The simulation was assumed to be an additive white Gaussian noise (AWGN) channel for line-of-sight communication.

B. Cell ID Detection Performance

First, the cell ID detection characteristics when the proposed method is used are evaluated. Fig. 3 shows the placement of BS and UE. When the BS is placed at the origin, the UE is separated from r in the horizontal plane, and the direction is θ_u from the X-axis. The distances between BS and UE are $r = 100, 200, 300, 400$ m. The directions are set to $\theta_u = 76°$, which is the mid direction of beams 3 and 4 in the horizontal plane, and $\theta_u = 83°$, which is the front direction of beam 4. The number of candidate cell IDs is set to five, and cell IDs are detected. The evaluation is based on the correct detection rate of cell IDs when each SSB is received.

TABLE II
CELL ID DETECTION RATE

r	θ_u	Beam index for horizontal beam steering 1	2	3	4	5	6	7	8
100	76°	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
200	76°	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
300	76°	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
400	76°	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
100	83°	1.00	0.99	0.11	1.00	0.01	1.00	0.00	1.00
200	83°	1.00	0.54	1.00	1.00	0.92	0.04	0.79	1.00
300	83°	1.00	0.48	1.00	1.00	0.85	0.99	1.00	1.00
400	83°	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00

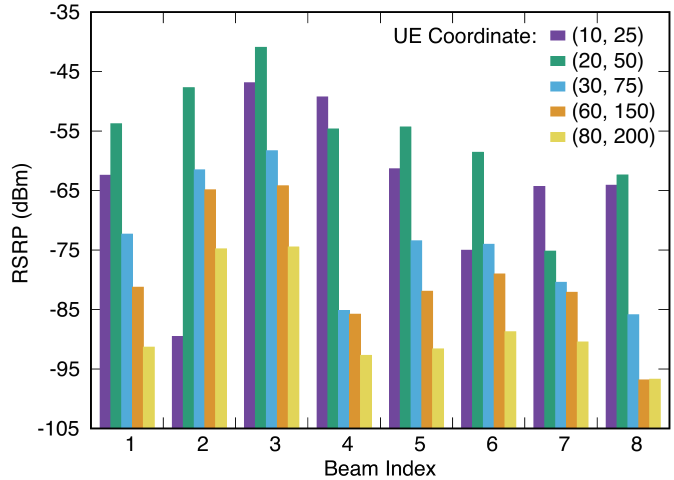


Fig. 4. RSRP characteristics for every horizontal beams.

Table II lists the correct detection rate of cell IDs using the proposed method. In $\theta_u = 76°$, the cell IDs are successfully detected in all beams, although the received power fluctuates within a symbol due to fast beam steering in the PSS. The 76° direction is in the main beam for beams 3 and 4 and in the side lobes for beams other than 3 and 4. This is because the Signal-to-Noise Power ratio (SNR) can be ensured. On the other hand, in the case of $\theta_u = 83°$ with beam 4 direction, the cell ID detection rate is degraded except for beams 1, 4, and 8. The 83° direction is null except for beam 4 and degrades the SNR. Lower SNR increases the probability of timing detection errors and degrades the detection performance. However, cell IDs are successfully detected in beams 1 and 8. This is because the beams are more angled than the frontal direction (33° and 147°), and thus nulls are not formed sufficiently. The horizontal and vertical beams were detected correctly in the present results. The simulation results show that cell IDs cannot be detected correctly for beams with insufficient SNR, but the correct cell IDs can be detected by selecting cell IDs for beams with a certain amount of received power.

C. Beam Detection Performance

Next, the beam detection characteristics are evaluated. In this simulation, time synchronization is assumed to be perfect. The UEs were placed horizontally in the 69° direction (beam 3) at four locations (in meters): $(x, y) = (10, 25), (20, 50), (30, 75), (60, 150), (80, 200)$. Let us evaluate the horizontal beam detection performance. Fig. 4 shows the RSRPs for each horizontal beam at each location. It can be seen that the RSRP of beam 3 is the largest at any position

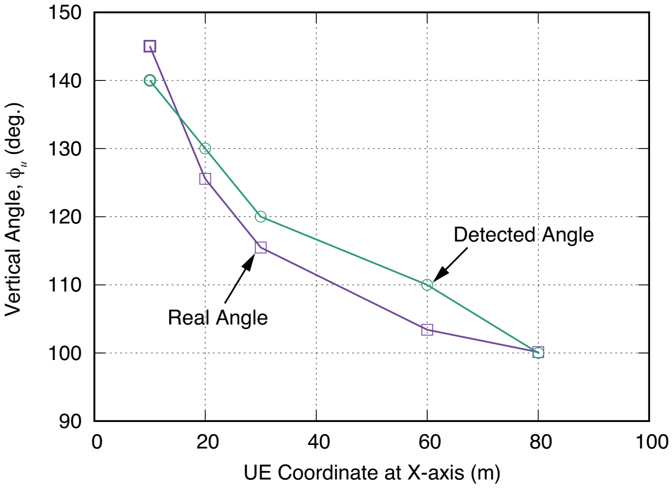


Fig. 5. Detected vertical angle using proposed scheme.

of the UE, indicating that the horizontal beam can be detected correctly. The difference from the adjacent beam 2 is smaller at the position where the UE is $x \geq 60$ m. Let us show the characteristics of vertical beam detection. The vertical beam search results are shown in Fig. 5. For comparison, the actual vertical angle θ_u calculated from the UE position is also shown. As the distance between the BS and the UE increases, θ_u becomes smaller. The results show that the searched beam angle follows the position of the UE. The maximum error is $7°$, but since the angular resolution in the vertical direction is $10°$, this is not a problem for the vertical beam steering used in this study.

IV. Conclusions

To reduce the beam search time in Massive MIMO, which increases as the number of candidate beams increases, a beam search scheme using fast beam steering is proposed. The proposed beam search scheme performs fast beam steering using a fast phase shifter in a single SSB and reduces the number of signals required for beam search by using the SSB to search for beams. Computer simulations show that the proposed beam search method can select horizontal and vertical beams corresponding to the position of the UE while reducing the number of SSBs relative to the number of beams.

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References

[1] T. Nakamura, "5G Evolution and 6G," *VLSI-DAT 2020*, pp. 1–1, Sep. 2020.
[2] Ericsson, "Ever-present intelligent communication," White paper, Nov. 2020.
[3] NTT DOCOMO, "6G White paper," Nov. 2022.
[4] Ericsson, "Ericsson mobility report," Nov. 2022.
[5] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3590—3600, November 2010.
[6] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.
[7] Z. Xiao, Z. Han, A. Nallanathan, O. A. Dobre, B. Clerckx, J. Choi, C. He, and W. Tong, "Antenna array enabled space/air/ground communications and networking for 6G," *IEEE JSAC*, vol. 40, no. 10, pp. 2773–2804, Oct. 2022.
[8] T. Obara, S. Suyama, J. Shen, and Y. Okumura, "Joint fixed beamforming and eigenmode precoding for super high bit rate massive MIMO systems using higher frequency bands," *PIMRC 2014*, pp. 607–611, June 2014.
[9] V. Crâşmariu, M. Arvinte, A. Enescu, and S. Ciochină, "Performance analysis of the Singular Value Decomposition with block-diagonalization precoding in multi-user Massive MIMO systems," *ISETC 2016*, pp. 71–74, Dec. 2016.
[10] F. Sohrabi and W. Yu, "Hybrid digital and analog beamforming design for large-scale antenna arrays," *IEEE J. Sel. Top. Signal Process.*, vol. 10, no. 3, pp. 501–513, Apr. 2016.
[11] H. Miyazaki, S. Suyama, T. Okuyama, J. Mashino, and Y. Okumura, "User selection and rank adaptation for multi-user Massive MIMO with hybrid beamforming," *IEEE VTC-Fall 2017*, Sep. 2017.
[12] S. Kim, S. Yoon, Y. Lee, and H. shin, "A miniaturized Butler matrix based switched beamforming antenna system in a two-layer hybrid stackup substrate for 5G applications," *Electronics*, vol. 8, no. 11, Oct. 2019.
[13] H. So, T. Kaho, Y. Yamamoto, M. Suga, Y. Takahashi, Y. Shirato, and N. Kita, "Staircase array antenna with stacked butler matrix for concurrent multi-beams," *IEEE Access*, vol. 11, pp. 76638–76646, Aug. 2023.
[14] D. Wang, Z. Mei, H. Zhang, and H. Li, "A novel PSS timing synchronization algorithm for cell search in 5G NR system," *IEEE Access*, vol. 9, pp. 5870–5880, Jan. 2021.
[15] 3GPP TS 38.211 (V17.0.0), "NR; Physical channels and modulation," Jan. 2022.
[16] L. Zhou and Y. Ohashi, "Efficient codebook-based MIMO beamforming for millimeter-wave WLANs," in Proc. *PIMRC 2012*, pp. 1885–1889, Sep. 2012.
[17] V. Desai, L. Krzymien, P. Sartori, W. Xiao, A. Soong, and A. Alkhateeb, "Initial beamforming for mmWave communications," *ACSSC 2014*, pp. 1926-1930, Nov. 2014.
[18] R. E. Rezagah, H. Shimodaira, G. K. Tran, K. Sakaguchi, and S. Nanba, "Cell discovery in 5G HetNets using location-based cell selection," *CSCN 2015*, pp. 137–142, Oct. 2015.
[19] I. Filippini, V. Sciancalepore, F. Devoti, and A. Capone, "Fast cell discovery in mm-wave 5G networks with context information," *IEEE TMC*, vol. 17, no. 7, pp. 1538–1552, July 2018.
[20] R. Imanishi and H. Nosaka, "Vector sum phase shifter using phase control linearization technique," *APMC 2022*, pp. 704–706, Dec. 2022.