Hash-based Fast Beam Alignment for 6G Sub-Terahertz MIMO

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***Abstract*—The 6th generation mobile networks require large bandwidth on sub-Terahertz bands to provide more than 100 Gbps throughput. To provide enough beamforming gain to combat the path loss on high-frequency bands, large-scale antenna arrays should be used, which generate narrow and directive beams. It may require hundreds or thousands of beams to cover a cell and introduce challenges for the beam alignment during the initial access stage. As a result, both the overhead and latency of beam sweeping may become unacceptable. We propose the Hash-based beam alignment method to address this problem, including a Hash-based beam transmission scheme for the synchronization signal block (SSB) transmissions and a corresponding UE beam pair selection method. It utilizes multiple transceivers to transmit multiple beams simultaneously, where the beam order follows a pattern generated by a Hash function. Considering UE may only receive discrete SSBs randomly, we design a weighted voting algorithm for UE to fast select the optimal beam pair for the following data transmissions. Simulations demonstrate that the proposed methods can reduce about 50% of the beam alignment latency or find a better beam pair with about 3 dB higher beamforming gain given a limited searching time.**

I. Introduction

The 5th generation of mobile networks (5G) has been widely deployed for commercial utilization, which achieves more than 10 Gbps cell peak throughput. The studies on the 6th generation of mobile networks (6G) have been started aiming at providing more than 100 Gbps peak cell throughput [1]. It may require about 10 GHz bandwidth to provide such high throughput, which is only available on the high-frequency spectrum, i.e., the sub-Terahertz band and above.

One of the significant challenges of communications on high-frequency bands is to cope with the significant path loss of radio propagation with the radio frequency (RF) modules with constrained output power and efficiency. Large-scale antenna arrays are usually used to generate high directional beams with large array gain to compensate for the path loss. However, the high directional beams cause coverage issues, especially for cell discovery and initial access. 5G New Radio (NR) specifies the beam-based operation and beam alignment scheme [2] to solve this problem. For cell discovery and initial access, it uses the beam sweeping mechanism to broadcast the synchronization and system information, named synchronization signal block (SSB). The beam sweeping of SSBs operates on millimeter-wave (mmWave) bands up to 71 GHz. Each SSB is transmitted using a directive beam, and all beams for SSB transmissions cover the whole area of a cell. If user equipment (UE) detects at least one SSB during the cell searching stage, it can access the network and report the index of detected SSB during the access procedure.

The NR beam sweeping enables the exhaustive beam search mechanism that UE can iterate all beam pairs between BS and UE and pick the one with the best signal-to-noise ratio (SNR). Currently, NR specifications support up to 64 SSBs, i.e., 64 beams. These SSBs can be transmitted within 5 ms and result in a reasonable beam search latency. However, when we consider sub-Terahertz systems with large bandwidth, it requires ultra-large arrays for more severe path loss that leads to even narrower beams. For sub-Terahertz, it may require several hundred to thousands of beams to cover a cell. If we reuse the NR beam sweeping mechanism, the number of necessary SSBs will grow linearly with the number of beams that introduces significant overhead to downlink channels. Besides the exhaustive search in current NR systems, a family of beam alignment methods uses hierarchical beam search or two-step beam search to reduce the beam sweeping overhead. It usually uses omnidirectional or wide beams to reduce overhead and search latency. For example, the SSB is transmitted with a limited number of wide beams and UE can access the network with one of them. After the initial access, the beam refinement procedures are necessary for the BS and UE to acquire a high directional gain beam pair for the data transmissions. For sub-Terahertz systems constrained by the SNR, the lower beamforming gain of wide beams introduces severe coverage issues, especially for UE initial access via uplink channels. Other approaches include beam alignment based on compressive sensing technologies [3], [4], which also applies randomized beams with lower gains. Recently, deep learning-based beam alignment has been introduced, which usually requires prior information such as UE location [5] or UE channel state information on other bands [6], [7], and is suitable to be used during the beam refinement after the initial access. Recent work [8] introduced Hash-based beam alignment considering a 60 GHz IEEE 802.11ad network. The access points (APs) with massive beams can be configured to a reception mode with a Hash-based reception beam pattern. The beams are applied with a pseudo-random order by Hash functions and paired randomly with each other. With such a mechanism, the search latency becomes logarithmic to the total number of beam pairs instead of the linear tendency, which significantly reduces the search latency with massive beams. However, for mobile networks, the beam alignment between BS and UE during initial access is conducted via downlink transmissions, which means that the BS that uses massive beams is the transmitter. UEs are in receiving mode without knowing which beams are transmitted in an SSB from the BS. Besides, UEs may start the cell search and beam alignment at any time. They have no information about the frame structure during this stage and can only detect discrete SSBs with enough reception power. These factors restrict the directly using Hash-based beam alignment in mobile networks.

In this paper, we focus on the beam alignment for sub-Terahertz multiple-input multiple-output (MIMO) mobile networks during cell discovery and initial access stages when no prior information about the BS and UE is available to each other. To support the beam alignment with massive beams (hundreds or thousands) and reduce the search latency, we propose a Hash-based beam alignment scheme for mobile systems where the BS usually has a large-scale antenna array. The Hash-based beam sweeping is conducted at the BS side. To notify UEs of the necessary information for the beam pair detection at UE side, we design a Hash function based on a pseudo-stochastic sequence, which depends on both the cell identifications and the time domain locations of SSBs. When a UE successfully decodes an SSB, it can fetch the information on the Hash beam pattern and estimate the optimal beam pair. Considering the characteristics of mobile networks where UEs randomly switch to a frequency point and start the cell detection and beam alignment, we further propose a weighted voting algorithm as a heuristic low complexity algorithm for UE to detect the optimal beam pair. The proposed algorithm can work with the discrete receptions of SSBs without the coordination of the beam alignment procedures with beacon signals as in IEEE 802.11ad networks.

The rest of the paper is organized as follows. Section II introduces the system model and NR beam alignment. Section III describes our proposed Hash-based beam alignment method. Performance evaluations can be find in Section IV. Finally, Section V gives conclusions.

Notations: Vectors (lower case) and matrices (upper case) are presented in boldface. $(\cdot)^{\mathrm{T}}$, $(\cdot)^{\mathrm{H}}$ and $(\cdot)^{-1}$ denote the transpose, conjugate transpose, and inverse, respectively. The convolution operation is denoted as $\otimes$.

II. System Model and NR Beam Alignment Mechanism

We consider a mobile network based on the current 5G NR air interface, which uses the orthogonal frequency division multiplexing (OFDM) waveform and multiplexing scheme [9].

NR systems transmit SSBs for UE synchronization and broadcast of system information such as physical layer cell identifications. One SSB consists of 4 OFDM symbols and occupies 240 subcarriers, and carries the primary synchronization signal (PSS), the secondary synchronization signal (SSS), and the physical broadcast channel (PBCH). The details on SSB format and its transmission opportunities are shown in Fig. 1. The SSBs are transmitted in a group named SSB burst,

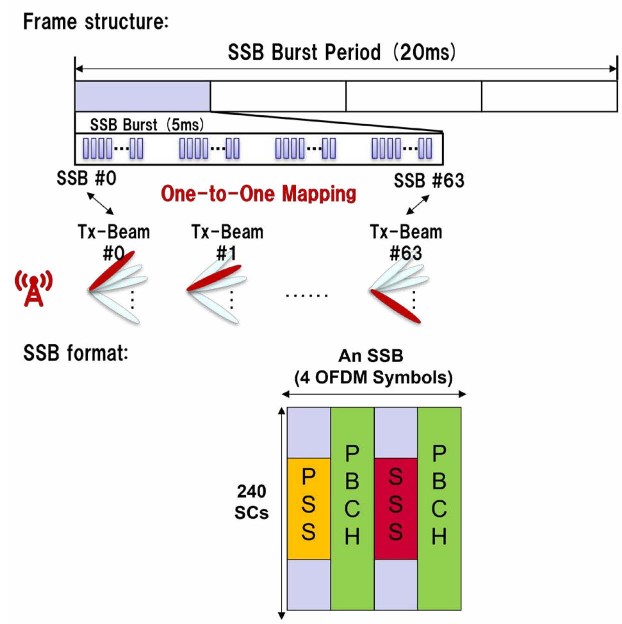

Fig. 1. NR frame structure with SSB transmission scheme and SSB format.

which is typically transmitted in 20 ms period. Each SSB is transmitted with different beams directed to cover different areas of a cell. For BSs operated on mmWave bands, there are up to 64 SSBs candidate positions in each SSB burst with different SSB indexes, which means up to 64 beams can be supported during the synchronization and initial access stages. UEs can select one received SSBs with maximum reception power to access the network after demodulating multiple SSBs successfully.

The SSBs are transmitted with different beams, i.e., pre-coded with different beamforming vectors. Current systems usually use discrete Fourier transformation (DFT)-based beamforming vectors which steer the beam to a direction with horizontal angle ϕ_m and vertical angle θ_m in spherical coordinate for m-th SSB. The beamforming vector for transmitting m-th SSB can be written as,

$$\mathbf{P}_m = \begin{bmatrix} \exp\left(j\frac{2\pi\mathbf{r}_m\cdot\mathbf{d}_1}{\lambda}\right) \\ \exp\left(j\frac{2\pi\mathbf{r}_m\cdot\mathbf{d}_2}{\lambda}\right) \\ \vdots \\ \exp\left(j\frac{2\pi\mathbf{r}_m\cdot\mathbf{d}_{N_t}}{\lambda}\right) \end{bmatrix}, \tag{1}$$

where N_t is the number of antenna elements on the BS, λ is the wavelength, $\mathbf{d}_n$ is the distance vector in the Cartesian coordinate of n-th antenna elements to the reference antenna element. We usually use the first antenna element as the reference one, then we have $\mathbf{d}_1 = [0,0,0]^{\mathrm{T}}$ and the vector for others is relative to the position of $\mathbf{d}_1$. The vector $\mathbf{r}_m$

represents which direction the beam is steered, which is

$$\mathbf{r}_m = \begin{bmatrix} \cos\phi_m \sin\theta_m \\ \sin\phi_m \sin\theta_m \\ \cos\theta \end{bmatrix}. \quad (2)$$

Suppose that the time domain signal of SSB is $s(t)$. The received SSB signal of a UE with N_r antenna element is

$$\mathbf{r}(t) = \mathbf{G}^{\mathrm{H}}\mathbf{H}(t) \otimes \mathbf{P}s(t) + \mathbf{n}(t), \quad (3)$$

where $\mathbf{n}(t)$ is thermal noise of the receiver, $\mathbf{G}$ is the beamforming vector of the receiver with dimension $N_r \times 1$, and $\mathbf{H}(t)$ is the time-spatial domain channel response with dimension $N_r \times N_t$ given time t.

UEs can detect the PSS and SSS, then demodulate the PBCH to fetch the system information as well as the index of SSB received. The reception power of SSB, i.e., reference signal reception power (RSRP) of SSB, can also be measured by UE. Then UE can select the SSB with the highest RSRP and initialize the access request on the resources corresponding to this SSB. This procedure implicitly notifies the BS which beam is selected by UE for the downlink transmissions.

The above model describes the current NR networks on mmWave bands up to 71 GHz, where 64 beams are usually enough to cover a cell. However, the beams become much narrower if we consider the systems on higher frequency bands, such as sub-Terahertz bands from 100 GHz to 300 GHz. Therefore, it requires hundreds or even thousands of beams to cover a cell that cannot be accommodated with current SSB numbers. It is not feasible to simply increase the number of SSBs since the overhead introduced will become unacceptable. Therefore, advanced beam search methods should be considered.

III. Proposed Hash-based Beam Alignment Method

Hash-based beam search [8], which leads to the logarithmic search complexity and latency, is introduced as a beam alignment scheme for 60 GHz IEEE 802.11ad networks, where a beacon can be used as roast synchronization and notify the signal patterns for fine beam alignments, based on which the receiver can detect the optimal beam pair with a Hash-based beam pattern. However, for the beam alignment problem in mobile networks, the BSs usually mount the large-scale array and transmit signals with narrow beams. The BS and UE have no prior information about each other during the initial access stage. UE needs to detect the optimal beam used to access the network only based on the information it received from SSB.

We introduce a Hash-based beam alignment scheme for mobile networks. It utilizes the multiple transceiver units (TXRU) mounted in the BS to transmit multiple beams with a Hash pattern during the transmission of each SSB. To notify the Hash beam pattern to UE, the SSB bursts are grouped to formulate an SSB burst set. Each SSB burst in the SSB burst set is indexed, based on which UEs can derive the beam pattern and use this information to detect the best beam pair.

Since the SSBs are transmitted with different beamforming vectors, only several SSBs reach a UE with enough reception power and can be successfully decoded by the UE. Therefore, a UE can only decode several SSBs discretely. We propose a weighted voting algorithm for UE to select the access beam under such a situation. The votes to a beam are weighted by the reception power measured. For those SSBs detected with high reception power, the weight can be positive, while for those SSBs detected with poor power or those miss detected SSBs, the weight can be negative. For an extreme case, we can also consider one ballot veto for those poor SSBs. With this algorithm, UEs can rapidly eliminate the ambiguity of beam index caused by multiple beam transmissions with the limited number of received SSBs and find the optimal beam pair.

In the sequel, we describe these algorithms in detail.

A. Enhanced SSB Transmission Scheme

Fig. 2 demonstrates an example procedure of SSB transmissions. A BS nowadays usually has several (typically 2 or 4) transceiver units (TXRUs) mounted, which can simultaneously transmit multiple beams during the SSB transmissions without SNR loss. We hash the beams and distribute them on different SSBs to accelerate the UE beam alignments. The UEs in the network may also have one or multiple TXRUs mounted and have multiple beams for the reception. It can also randomly switch the reception beams according to a Hash pattern to accelerate the beam alignment.

The reception Hash beam pattern is an implementation issue of UE and is decided by itself. But the transmission beam pattern should be notified to the UE for the best beam pair detection. To this end, we group multiple SSB bursts to formulate an SSB burst set, where each SSB burst is indexed. The beams transmitted in each SSB are decided by a Hash function where both the SSB index and SSB burst index are the parameters of the functions. The SSB burst index is also transmitted with SSB. To reduce the overhead introduced by the newly added SSB burst index, we consider reusing the existing signaling to carry the SSB burst index. In current NR systems, a system frame number (SFN) with 10 bits is transmitted in the PBCH of SSBs. We extended the usage of SFN and let it denote the SSB burst index as well. Then UEs can obtain the SSB burst index without inserting additional bits into the PBCH.

Without losing generality, we reuse the pseudo-noise (PN) generator specified in [10] to generate the Hash beam pattern. To avoid the beam pattern collision among cells, the PN generator is initialized with cell identifications and generates bit sequence $c(n)$ as specified in [10]. Given SSB burst index L_1 and SSB index L_2, the index of the m-th beam transmitted with this SSB is

$$I(L_1, L_2, m) = \sum_{k=0}^{K-1} 2^k c\left(\left(\left(L_1 L_S + L_2\right) M + m\right) K + k\right), \quad (4)$$

where M is the number of beams used to transmit one SSB, L_S is the number of SSBs in a SSB burst, and K is the bit length of beam index, i.e., the scheme can support up to 2^K beams during initial access stage.

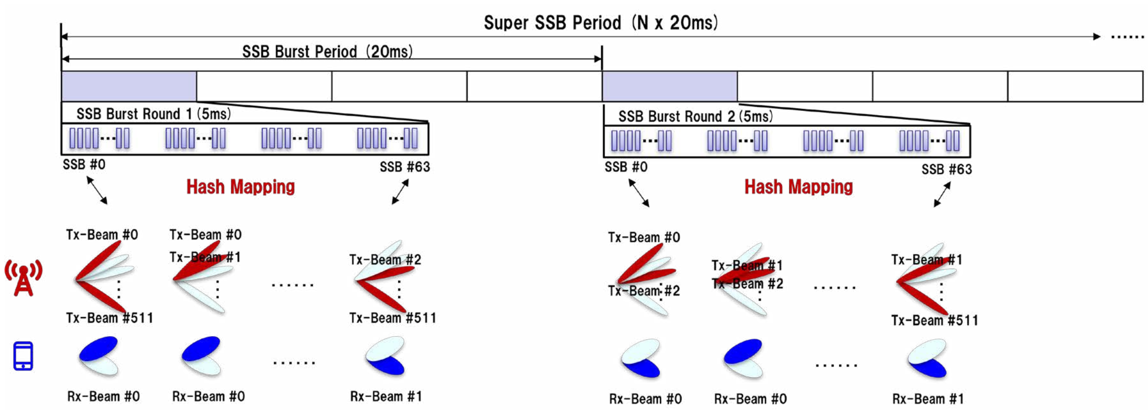

Fig. 2. An example of Hash-based beam sweeping with enhanced SSB transmission schemes

UEs can derive the transmitted beams after correctly detecting the SSBs and demodulating the SSB burst and SSB index. With such information, UE can further derive the best beam pair that will be used to access the network.

B. Enhanced UE Beam Pairing Algorithm

In mobile networks, UEs may start the SSB detection and initial procedure at any time when it has data to transfer. In such conditions with narrow beams on sub-Terahertz bands, UE may receive several discrete SSBs which are randomly located on the time domain. We consider a weighted voting method to accelerate the procedure of UE selecting the optimal beam pair to access the network. When an SSB is received with high reception power, positive weight is used to vote the corresponding beams that are used to transmit this SSB. On the contrary, the SSBs with poor reception power and the miss detected SSBs between any two successfully detected ones will have negative weights. The voting number of corresponding beams will be degraded. For an extreme case, we can consider one ballot veto and then exclude the corresponding beams from the candidates.

The detailed algorithm of UE beam selection is described as follows

- Step 1: UE initializes a table for voting. The columns and rows of the table denote the BS beams and UE beams, respectively. Therefore, each block on the table denotes a BS-UE beam pair.
- Step 2: An SSB is detected and demodulated. UE calculates the indexes of beams used to transmit this SSB.
- Step 3: UE measures the RSRP of this SSB γ_i and compares it with that of the most powerful SSBs received so far (denoted as γ_{Max}). If $\gamma_{Max} - \gamma_i < \eta$, where η is a given threshold, γ_i is used as positive weighted voting and added to all the corresponding beam pairs. Otherwise, $-\gamma_i$ is used as negative weighted voting and added to all the corresponding beam pairs. If one ballot veto is adopted, the corresponding beams are directly removed from the candidate beam pair list. If γ_i is larger than γ_{Max}, γ_{Max} is updated and the voting results are updated correspondingly.

SSB Rx Power Measurement

Tx-Beam #0 + Tx-Beam #511	Tx-Beam #0 + Tx-Beam #1
15 dB	-3 dB

Weighted Voting (e.g., min)

	Tx-Beam #0	Tx-Beam #1	Tx-Beam #511
1st	15 dB		15 dB
2nd	-3 dB	-3 dB	
Total	-3 dB	-3 dB	15 dB

Fig. 3. A toy example of UE weighted voting procedures to detect the optimal beam when the index of the optimal beam is 511.

- Step 4: UE treats SSBs between this one and the last one detected as miss detected SSBs and uses a default negative weight to vote corresponding beams.
- Step 5: UE checks the table and judges whether the voting results can eliminate the ambiguities of the multiple beams from one SSB, say, only one beam from an SSB has high votes and other beams have low votes or are excluded. If so, the algorithm outputs this beam pair. Otherwise, go back to Step 2 for another detected SSB.

Fig. 3 demonstrates a toy example of the proposed algorithms where UE only has one reception beam and the optimal transmission beam is Beam #511. After the first SSB is received, UE votes Beam #0 and Beam #511 with positive weight. At this moment, there are ambiguities among these two beams, and UE has no idea which one should be used. After the second SSB is received with poor RSRP, Beam #0 is excluded based on the RSRP of this SSB. Therefore, Beam #511 is detected as a high gain beam and can be used for the following initial access procedures.

IV. Simulations

The simulation assumptions are listed in Table I. We consider a 300 GHz sub-Terahertz system with 6.4 GHz bandwidth and extend the NR UMi scenario and channel

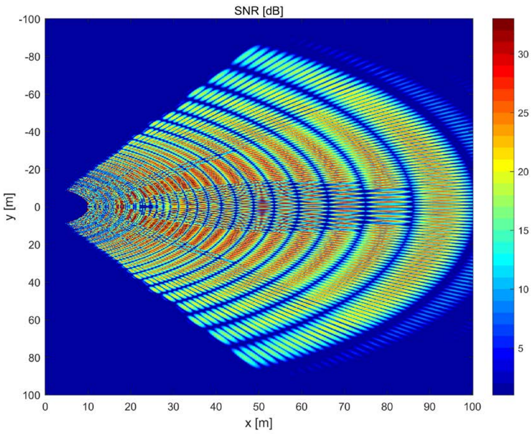

Fig. 4. SNR distribution in the cell with planned 2092 beams.

TABLE I
SIMULATION ASSUMPTIONS

Parameter	Value
Carrier frequency	300 GHz
Bandwidth	6.4 GHz
Subcarrier spacing	1920 kHz
Channel model	NR UMi-LoS [11]
Cell radius	100 m
Cell coverage angle	120°
BS antenna array	4096 (64 × 64)
BS TXRU	4 (2 × 2)
UE antenna array	16 (4 × 4)
UE TXRU	1
BS beam number	2092
UE beam number	4
BS Tx. power	25 dBm
Antenna gain	5 dBi
Noise figure	10 dB

TABLE II
AVERAGE BEAM SEARCH LATENCY AND FAILURE RATIO OF INITIAL ACCESS WITH DIFFERENT BEAM ALIGNMENT SCHEMES

	Exhaustive	Two-step	Proposal
Latency [s]	0.9	0.1	0.4
Failure ratio	29%	71%	6%

model [11] with line-of-sight (LoS) propagation condition to the sub-Terahertz band. The cell covers an area with 100 m radius and 120° angle. To fairly compare the performance, we fixed the SSB transmission overhead for all methods under evaluation, i.e., 64 SSBs are transmitted during a 20 ms period.

We first evaluate the necessary beam number to cover the cell by beam planning under the assumptions in Table I. The object of the beam planning is to provide a unified coverage and enough SNR to support 64-quadrature amplitude modulation (64-QAM) for the majority area of the cell. From the beam planning, it requires 2092 beams to cover the ground area of the cell, which is used for our following simulations. The SNR distribution in the cell with the planned 2092 beams is shown in Fig. 4.

Besides our proposed Hash-based beam alignment scheme, the following beam alignment schemes are evaluated as well for the comparison,

- Exhaustive search: Each SSB is transmitted with one beam. UE needs to iterate all combinations of transmission and reception beams to find the one used for accessing the network. Note that although multiple TXRUs are considered in the BS, one SSB still carries only one beam in the exhaustive search to avoid any ambiguity. Multiple SSB transmission with spatial domain multiplexing is not considered in this paper since it may introduce interferences.
- Two-step search: Each SSB is transmitted with a wide beam, and UE can detect one SSB and then access the network. After UE is connected to the network, UE-specific reference signals can be configured to transmit high-directional beams for beam refinement. In this paper, we only focus on the initial access stage. The latency introduced by UE connection and beam refinement procedures is not counted in simulations. The wide beam for the initial access can be generated by the superposition of narrow beams from multiple TXRUs, which does not affect the beamforming gain, or by designing an analog beamforming vector for the array connected to each TXRU, which degrades the beam gain since the transmission power of each TXRU is constrained. We use the combination of the two methods to generate wider beams in the simulations, i.e., each one of 4 TXRUs transmits a beam that spans $1/4$ width of the target wide beam, and the wide beam is generated by the superposition of these 4 beams.

To study the characteristics of different beam alignment schemes, we evaluated the performance of beam alignment from multiple perspectives. The following performance metrics are used,

- Average beam searching latency, measured from UE starting the beam searching to finding a beam which gain is within the 3 dB margin to the optimal one.
- Receiving SNR of the beam after 1 second from UE starting the beam searching. Because UEs need to search multiple frequency bands during the cell search stage, they will spend limited time for a frequency point and switch to another one. This metric is considered to evaluate the beam quality obtained by different schemes within a given duration.
- Failure ratio of initial access. The ratio that the receiving SNR of the beam after the 1-second search is lower than the necessary SNR for the initial access. In this evaluation, we set a -6 dB beam SNR threshold, which is necessary to support the transmissions with the lowest modulation and coding schemes.

The average beam search latency and failure ratio of initial access with obtained beam pairs from different beam alignment schemes are shown in Table II. Compared with the exhaustive searching scheme, the Hash-based beam searching scheme with the proposed SSB transmissions and detection

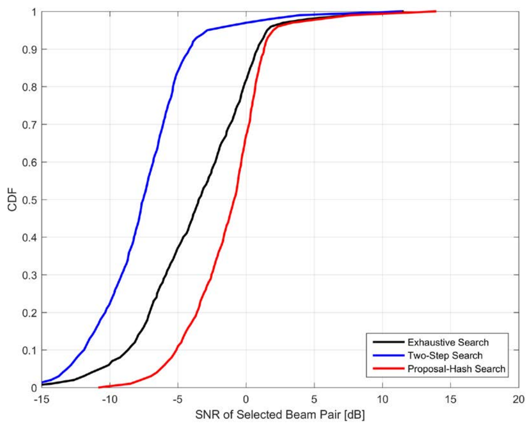

Fig. 5. Reception SNR with detected beam pair after 1 second from UE starting the SSB detection in NR UMi scenario.

algorithm reduces about half of the beam pair searching latency, i.e., 55% latency reduction. When the total search duration is given, the Hash-based method can find a better beam pair, which reduces the failure ratio of the initial access because the found beam pair is used for the transmission of initial access and following radio resource control messages until the necessary signaling for configuring UE specific beam refinement is transmitted. We show the CDF of SNR with detected beam pairs in Fig. 5. The proposed scheme has about 3 dB SNR gain compared with the exhaustive search for 50% of the UE. Only 6% UEs cannot successfully access the network with the detected beam after 1 second of beam searching. For the exhaustive search, 29% of UEs do not detect the beam pair with enough gain to access the network.

The two-step search can accelerate the beam alignment by applying wide beams. However, the wide beams cannot provide enough beamforming gain to cover the whole cell, which results in a significant failure ratio of initial access. In the NR UMi scenario, 71% of the UEs cannot access the network with the wide beam obtained from the two-step search. Without the success of the initial access, the following beam refinement procedure cannot be configured to UE and start to work. Therefore, UE has no opportunity to further search for a narrower beam with higher beamforming gain.

The evaluation results demonstrate the advantages of the proposed Hash-based algorithm. Given the same search time, the Hash-based beam search can fetch a better beam pair, which can improve the successful ratio of UE to conduct the following initial access procedures, including fetching system information and configurations, transmissions of preambles on the random access channel, and the transmissions and receptions of radio resource control signaling.

V. Conclusion

We proposed a Hash-based fast beam alignment method for 6G networks operated with sub-Terahertz MIMO, where extreme massive beams have to be used to cover a cell. The proposed scheme includes the transmission scheme of SSBs with the Hash-based beam pattern and the necessary information carried in the SSB to notify the Hash-based beam pattern. Furthermore, considering the characteristics of cell discovery and initial access procedure, a heuristic algorithm for UE beam pairing is introduced. This algorithm can work during cell search and initial access stages, where UE can only decode several discrete SSBs without detailed network configuration information. With the proposed algorithm, UE can fast eliminate the ambiguity of beam index caused by the multiple beam transmission and find a beam pair with enough gain. Simulations demonstrate that the proposed method can reduce about half of the beam alignment latency or find a better beam pair given a limited searching time. The proposed method can be implemented based on the current NR framework with SSB transmission enhancements. Future mobile systems can also apply such a beam alignment scheme during the initial access stage. Therefore, it can be a promising candidate beam alignment scheme for sub-Terahertz MIMO systems during both the 5G Evolution and 6G eras.

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