An Efficient Joint Tx-Rx Beam Search Scheme in mmWave Massive MIMO Systems (Invited Paper)

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Abstract. This paper addresses the beam search complexity for massive multiple-input multiple-output (MIMO) in millimeter Wave (mmWave) band. In the mmWave massive MIMO systems, high-directional beams are used to against the severe path loss. However, it is faced with many challenges. One of them is that the beam search complexity and management overhead problems hinder the practical implement with a large number of antennas. To cope with the problem, an efficient joint transmit and receive (Tx-Rx) beam search scheme is proposed in this paper. In the initialization phase, the initial Tx-Rx beam pair is calculated by the coarse beam sweeping. Then, Rosenbrock algorithm is used to search the optimal beam pair in a two dimensional discrete space formed by the indexes of transmit beam and receive beam. In addition, double beam link is used to solve the link failure caused by channel block. Numerical simulation results are given to verify the effectiveness of the proposed scheme. Compared with the traditional beam search schemes, the proposed scheme can greatly reduce the search complexity and management overhead.

Keywords: Beam search · Rosenbrock algorithm · mmWave Massive MIMO · Beamforming · 5G

1 Introduction

To meet the high user data rate and high spectrum efficiency in the future wireless mobile communication, mmWave (millimeter-wave) band attracts attention

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of the academia. However it suffers a serious attenuation caused by atmosphere. In order to against the path loss and improve the quality of link transmission, beamforming technology is used to provide high antenna gain and reduce inter-user interference by conducting directional transmission in the massive MIMO (multiple-input multiple-output) systems [1,2]. MIMO systems equipped with a large number of antennas and working at the mmWave band are called mmWave massive MIMO systems.

In the mmWave massive MIMO systems, beamforming enhances transmission signal to noise ratio (SNR) by making BS and UE aligned. However, when the number of antennas at the BS is large and beam width is very narrow, it faces many new challenges [2]. The first one is the coverage of the broadcast channel, which needs to make trade-offs of beam width, transmitting power and coverage range [3]. Secondly, beam management consisting beam searching, beam reporting, beam switching is necessarily to be studied. For beam searching, it requires a fast and accurate search scheme to find out the transmit and receive (Tx-Rx) beam pair which meets the transmission requirements in numerous beams with affordable signaling overhead [2]. Then the beam reporting stage is start, the optimal beam or beam group indexes and other related information are feedback from UE to BS [2]. Besides that, since the width of high directional beam is very narrow, a slight movement of UE will make the transmission beam pair mismatches, especially in a high mobility environment, the beam switching should be considered [4].

In the codebook based MIMO systems, codebooks are pre-defined. Beam search aims to select the optimal transmit and receive codebooks, corresponding to the optimal beam pair. A simple idea is the exhaustive search mechanism, but the significant protocol overhead and the computational complexity make it unfeasible. To deal with the problem, a classic scheme named two-stage search was proposed in IEEE 802 series standard draft [5]. The basic idea is firstly conducting the sector-level search, consisting of sweeping low-resolution codebooks (corresponding to coarse beams) and choosing the optimal one. The second stage is beam refinement determining the optimal high resolution codebook (corresponding to the fine beam) in the selected sector. It reduces the search overhead to a certain extent. But in case of a large codebook, the overhead is costly and its impracticable for massive MIMO systems.

Meanwhile, some researchers had proposed some beam search schemes to reduce the management overhead [6–8]. In [6], an unconstrained direct search method namely Rosenbrock algorithm was used to select the optimal beam pair at 60 GHz band, but it needs a pre-search process to iteratively discover the initial value. In [7], two factors making link failure, UE mobility and human block, were simply modeled. The former needs to search beams around the current beam pair to find another suitable one. The latter needs to switch an alternative link. However, the model is linear and independent of the moving speed, which may result in inaccurate application. A multi-device multi-path beamforming training method was proposed in [8]. It reduces the overall overhead of the system, but status of multi-device is the same and the optimization goal is not global.

To address the excessive searching overhead and computational complexity, an efficient joint Tx-Rx beam search scheme is proposed in this paper. In the initial phase, the initial search value is simply calculated by the optimal coarse beam pair obtained by the sweeping process to against the multipath effect and to avoid search failure due to the local optimum. Rosenbrock algorithm is used to search the optimal beam pair in a two dimensional discrete space formed by the indexes of Tx-Rx beams. The search process can be conducted at one side, so the search process can be performed at BS side. This can reduce the information exchanged between UE and BS, thus reducing management overhead and the implementation complexity at UE side. At the same time, double beam link can be performed to select several suitable beam pairs to against channel blockage and user interference. The simulation results show that, compared with the exhaustive search and two-stage search scheme, the proposed scheme can significantly reduce the beam search times.

The rest of this paper is organized as follows. The system model is presented in Sect. 2. The Joint Tx-Rx beam search scheme is proposed and described in Sect. 3. Simulation evaluations are shown in Sect. 4. Conclusions are drawn in Sect. 5.

2 System Model

In the mmWave massive MIMO systems, to reduce transmitting power and hardware complexity, the hybrid transceiver structure is adopted, as shown in Fig. 1. In the case of DL (downlink), the data stream is firstly digitally precoded, then processed by IFFT (Inverse Fast Fourier Transform), PSC (Parallel Serial Converter), ADC (Analog-to-Digital Conversion), etc. And then the PS (Phase Shifter) adjusts weights to generate a Tx beam at BS side. UE receives the signal with an Rx beam and processes it reversely.

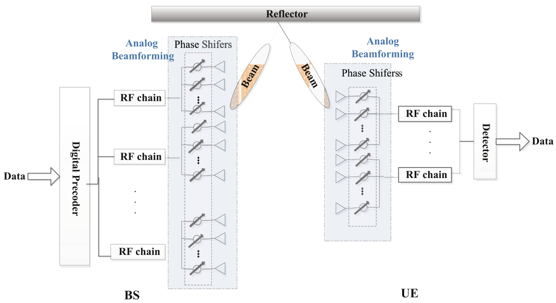


Fig. 1. System model

2.1 Antenna Model

Assume the antenna model is isotropic radiate and it has spherical radiation pattern and equal antenna gain for all spatial directions [9]. In order to simplify the channel model and consider the basic characteristics of the real antennas, assume that all beams are arranged in order and cover the entire communication space. And the optimal beam pair in this paper maximizes the received SNR.

With a large number of antennas, the beam can be equivalent to the basic directional beam. Assuming a 2D antenna model (which can be scalable to 3D), the main lobe gain can be expressed by the Gaussian attenuation function, and side lobe gain is a constant, which can be expressed,

$$G(\theta) = \begin{cases} G_0 \exp(-\alpha\theta^2), \theta < \frac{\theta_{ML}}{2} \\ G_C, else \end{cases} \tag{1}$$

where θ is the azimuth angle in the range $[-\pi, \pi]$, G_0 is the maximum antenna gain, G_C is the side lobe gain, θ_{ML} is the width of main lobe $\theta_{ML} \approx 2.6\theta_{-3\mathrm{dB}}$ which is only depended to the half power beam width $\theta_{-3\mathrm{dB}}$. The parameter α is a constant and can be calculated by $\theta_{-3\mathrm{dB}}$, because $\frac{G}{G_0} = \exp(-\alpha(\frac{\theta_{-3\mathrm{dB}}}{2})^2) = \frac{1}{2}$. Hence $\alpha = \frac{4\ln(2)}{\theta^2_{-3\mathrm{dB}}}$. In decibel scale, the beam gain can be rewritten as follows,

$$G_{dB}(\theta) = \begin{cases} G_{0,dB} - 12\left(\frac{\theta}{\theta_{-3\mathrm{dB}}}\right)^2, \theta < \frac{\theta_{ML}}{2} \\ G_{C,dB}, else \end{cases}. \tag{2}$$

2.2 Path Loss

Unlike the widely used cellular low frequency band, mmWave band is greatly influenced by the atmosphere. There are little scatters in the environment, the penetration loss is high and the reflection effect is obvious. These features directly influence the channel characteristics. The path loss is the ratio of the receive signal power to the transmit signal power. It not only depends on the distance from UE to BS but also on the frequency. Thus the path loss is especially serious in the millimeter band. The mean of path loss can be expressed as follows [9],

$$PL(d) = PL_0 + n \cdot 10log(\frac{d}{d_0}) \tag{3}$$

where d is the distance from UE to BS, d_0 is the reference distance, PL_0 is the path loss at the reference distance, n is the path loss exponent.

2.3 Received SNR

Codebooks, corresponding to the beams, are pre-defined in the codebook based MIMO systems. In the two dimensional discrete space formed by the indexes of Tx and Rx beam, the received SNR, represented by γ, can be simplified so that it is dependent on the transmit and receive codebooks (p, q),

$$\gamma(p, q) = P_t + G_t(p) + G_r(q) - PL - N \tag{4}$$

where P_t, G_t, G_r are the transmitting power, the Tx beam gain and Rx beam gain. N is the mean noise power.

3 Scheme Design

In order to reduce the computational complexity and management overhead caused by beam search, we propose an efficient joint Tx-Rx beam search scheme. The beam search scheme aims to find out the optimal beam pair resulting in the largest received SNR. The maximum optimal objective function is written as follows,

$$\begin{aligned} &\max_{(p,q)} \gamma(p,q) \\ &s.t. (p,q) \in R^2 \end{aligned} \tag{5}$$

where R^2 is the two dimensional discrete integer space formed by the Tx and Rx beam indexes.

Owing to the antenna array placement, complex wireless transmission environment, beam sidelobes and other reasons, the analytic formula of the objective function does not exist. Even if it is an unconstrained numeric optimization problem [6], the gradient of the analytical formula cannot be calculated. This means the efficient gradient descent algorithm cannot be used. Therefore, we propose an efficient direct search method - Rosenbrock algorithm. It can control the search direction by calculating the value of the objective function, find the peak direction and find out the optimal beam pair efficiently. As shown in Fig. 2, the global optimum value is at the peak.

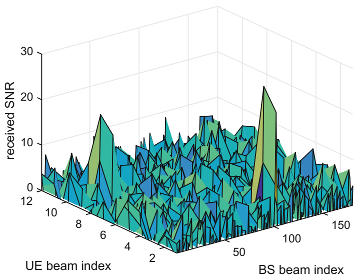


Fig. 2. Optimization objective function

Since Rosenbrock algorithm is essentially greedy, it is easy to fall into the local optimum, may resulting in an inaccuracy search. Therefore, it is necessary to set a suitable initial value. Once UE firstly discovers a cell or the communication link fails completely, it is necessary to conduct the synchronization and random access procedures. For the control signal transmission such as the synchronization signal and the broadcast channel, the coarse beams are swept to obtain the optimal beam pair. Thus, it is feasible to calculate the initial search value by the optimal coarse beam.

In fact, there are many reasons for beam failure, such as UE movement, UE rotation and obstacle block [10]. The best way to deal with the above cases is different. Due to the beam pair is misaligned, the first two cases need to search the re-aligned beam pair. In the last case, beams are aligned still but the link is blocked. The solution is switching the alternate communication link. Therefore, it is essential to find the optimal and suboptimal transmission beam pair in the initial access stage. As a result, it is necessary to search for an alternate beam pair and double beam link method can reduce the probability of transmission link failure. In this paper, the optimal beam pair is used to transmission and the sub-optimal beam pair is considered as an alternative one.

3.1 Scheme Procedure

Beam search process is shown in Fig. 3. Firstly, coarse beams are scanned. BS broadcasts the reference signal to UE using different transmit beams and UE receives the pilot separately using different receiving beams. Then the best two beam pairs are detected among the candidate ones and reported to BS. Then the center fine beams are positioned from the selected coarse beams and set as the initial values to the Rosenbrock algorithm respectively. Define all fine beams converging coarse beam are candidate beams and start search process. Finally select and switch the beam pair with the largest received SNR, store the suboptimal one as alternative link.

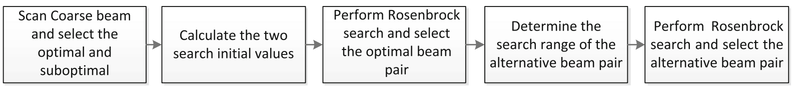


Fig. 3. Procedure of the joint Tx-Rx beam search scheme

The details of the Rosenbrock algorithm, the initial value setting and the double beam link are described below.

3.2 Rosenbrock Algorithm

The Rosenbrock algorithm consists of two procedures: pattern probing and pattern moving. The former aims to find the direction in which objective function increases. The latter construct new orthogonal directions.

At the pattern probing stage, set the center high resolution beam pair corresponding to the low resolution optimal one to the initial point $x(0) = (p^{(1)}, q^{(1)})$, the magnification factor $\mu > 1$, the shrink factor $0 < \nu < 1$, the initial search direction $d^{(1)} = (1, 0)^T$, $d^{(2)} = (0, 1)^T$, the initial steps (ξ_1, ξ_2). Assuming the first probing direction is $d^{(1)}$, make $y^{(1)} = x(0)$, and calculate $f(y^{(1)} + \xi_1 d^{(1)})$. If it is more than $f(y^{(1)})$, make $y^{(2)} = y^{(1)} + \xi_1 d^{(1)}$, $\xi_1 = \mu \cdot \xi_1$. If it is less than $f(y^{(1)})$, make $y^{(2)} = y^{(1)}$, $\xi_1 = \nu \cdot \xi_1$. Next, let $y^{(2)}$ an origin point and probing along $d^{(2)}$. Process it the same as above, then we get $y^{(3)}$. Two orthogonal directions are completed and let $y^{(n)} = y^{(3)}$. A probing round is finished and the next round starts from the initial point $y^{(1)} = y^{(n)}$. After several rounds of probing, pattern probing finished until both directions fail. Then the last point is $x(k) = y^{(n+1)}$.

Then start pattern moving stage and construct new search directions. The increase direction of objective function can be expressed,

$$x(k) - x(k-1) = \sum_{i=1}^{n} \lambda_i d_i \tag{6}$$

where d_i is the ith orthogonal direction, λ_i is the distance moving along ith direction. Note $P = x(k) - x(k-1)$ and the next pattern probing should refer to the increase direction. Define $P^{(1)}, P^{(2)}, \cdots, P^{(n)}$ which satisfy,

$$P^{(j)} = \begin{cases} d_j, if \lambda_j \\ \sum\limits_{i=j}^{n} \lambda_j d_j, if \lambda_j \neq 0 \end{cases} \tag{7}$$

Since the search directions are orthogonal, Schmidt orthogonalization is introduced. Thus we can get,

$$Q^{(j)} = \begin{cases} P^{(j)}, if\, j = 1 \\ P^{(j)} - \sum\limits_{i=1}^{j-1} \frac{Q^{(i)T} P^{(j)}}{Q^{(i)T} Q^{(i)}}, if\, j > 1 \end{cases} \tag{8}$$

Normalize it.

$$\overline{d}^{(j)} = \frac{Q^{(j)}}{\left\| Q^{(j)} \right\|}. \tag{9}$$

Therefore the new probing directions are constructed.

Two stages above process alternately till finding out the maximum point of optimization function.

3.3 Initial Value Setting

Assume the arrangement and numbering order of the two-level beams are the same, all the fine beams covering each coarse beam can be determined. The total numbers of coarse beams and fine beams are respectively M, $N(M < N)$. If the target coarse beam index is p_c, the indexes of in its coverage ranges $\left[(p_w - 1) \cdot \frac{N}{M} + 1, p_w \cdot \frac{N}{M}\right]$, and the index of the center fine beam is as follows,

$$p_f = floor[(p_w - \frac{1}{2}) \cdot \frac{N}{M} + \frac{1}{2}] \tag{10}$$

where, $floor(\bullet)$ is the ceiling function. The index of the center fine beam corresponding to optimal coarse beam is set to the initial value of the Rosenbrock algorithm. Then it is easy to find the peak of the objective function.

3.4 Double Beam Link

Actually, it is unreliable to identify the reasons for the decline of link quality only by the reduction of SNR. When the link quality is degraded, the performance of the alternative beam pair is estimated. If the communication requirement can be met, directly switch the alternative beam pair and beam search process is not required immediately. If the link quality is still poor, start to search beams.

The alternative beam pair search is described below. Firstly, sweep the coarse beam and select the optimal as well as suboptimal coarse beam pair. Then find indexes of the corresponding center fine beams. The indexes of the optimal ones are set as the initial value of Rosenbrock algorithm and find out the optimal fine beam. Next conduct the alternate beam pair search. Set the fine beam indexes corresponding to the sub-optimal coarse beam pair as the initial value and remove the beams covered by the optimal coarse beam pair from search range. Then find out the suboptimal beam pair and store it as an alternative one.

One round of Rosenbrock search process can find out the best two beam pairs in fact, but in this paper we conduct two search processes to find the transmission and the alternative beam link. Because it is extremely possible that the suboptimal beam pair is the nearby beam of the optimal beam pair, not the reflection beam pair. Therefore delimiting the search again at the second search phase is necessary.

4 Performance Evaluation

Numerical simulations and analysis are conducted to verify the effectiveness of the joint Tx-Rx beam search scheme (abbreviated by JS). The comparison schemes are the exhaustive search mechanism (abbreviated by ES) and the two-stage search mechanism (abbreviated by TS). Simulation parameters are shown as Tables 1 and 2.

Table 1. System simulation parameters

Parameters	Value	Parameters	Value
Simulation area	80 m * 60 m	d_0	10 m
BS location	(40 m, 30 m)	PL_0	82.02 dB
Carrier frequency	28 GHz	n	2.36
Low beam resolution at UE	90°	P_t	30 dBm
Low beam resolution at BS	30°	N	−35 dBm

Firstly, the accuracy of the joint Tx-Rx beam search scheme is evaluated. In the simulation, assume the high beam resolution of UE is a constant 30° and the high beam resolution of BS is set as the variable. Only finding out one pair of

Table 2. Rosenbrock algorithm simulation parameters

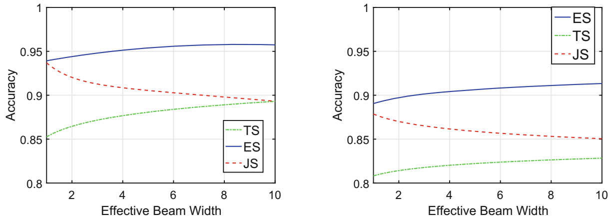
Parameters	Value
Magnification factor μ	2
Shrink factor ν	-0.5
Initial search direction	$d^{(1)}$, $d^{(2)}$
Initial search step	$\xi_1 = \xi_2 = 1$

beams i.e., the optimal beam pair, consider it successful when the search result is the same as the optimal beam pair. Searching for two pairs of beams i.e., the optimal and suboptimal beam pair, regard it as a success once the selected indexes of the two beam pairs are matched. Simulation drop of independent beam search is 10000. Calculate the success frequency to approximately estimate the accuracy, i.e., $accuracy = \frac{drops_{successful}}{drops_{total}}$, where $drops_{total}$ is the total simulation drop, $drops_{successful}$ is the successful simulation drop.

Simulation result of the proposed scheme and the comparison schemes is shown as Fig. 4 where the scale of the x-axis is the effective beam width. (a) is the accuracy result of searching one beam pair and (b) is that of two beam pairs. It can be seen that among the three schemes from figure (a), the accuracy of ES is the highest and more than 0.9, JS is the second and TS is the worst. The ES scheme traverses all beam pairs thus can easily find out the optimal beam pair. The JS scheme is a two dimensional joint search method, while the TS scheme separately considers BS and UE side. Obviously the former is more efficient and accurate. In addition, when the beam resolution is higher (the effective beam width is smaller), the performance of JS scheme improves more than that of the TS method. When the resolution gets lower, its advantage reduces. This proves that in the high beam resolution and quantities beam cases, the JS scheme is more efficient and accurate. Seen from figure (b), in case of searching the optimal and alternate beam pairs, the accuracy difference between the JS scheme and the ES scheme is much smaller than that in the case of searching for one beam pair, and difference between the TS scheme is slightly increased. That proves the JS scheme has advantages when double beam link mechanism is used.

Next the complexity of the three search schemes is evaluated. The variables are the numbers of Tx and Rx beams. In the successful case, the mean number of the searched beams is simulated. Evaluation of the JS scheme complexity is still compared with the ES and the TS scheme.

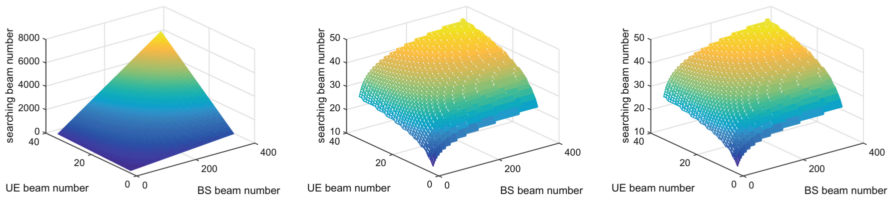
Figure 5(a)–(c) are the searched beam numbers of the ES, the TS and proposed scheme respectively. It can be seen that the search number of the ES scheme is the largest, the TS scheme is the second and the proposed scheme is the least. Since the ES scheme needs to traverse all beam pairs to select the best beam pair, it maximizes the search number. The TS scheme is the deformation of the first one. Compared with ES scheme, the search time will reduce an order of magnitude. But when the beam number is massive, search overhead will still be considerable. In comparison with the TS scheme, the search number



(a) Accuracy of searching one beam pair.

(b) Accuracy of searching two beam pairs.

Fig. 4. Accuracy of the joint Tx-Rx search scheme in comparison of the exhaustive search and two-stage search.



(a) ES scheme.

(b) TS scheme.

(c) JTRBS scheme.

Fig. 5. Search times of the joint Tx-Rx search scheme in comparison of the exhaustive search and two-stage search

of the proposed scheme can be reduced an order of magnitude. In addition, the search number of the first two schemes increases rapidly when the number of beams becomes very large. While that of the proposed scheme increase still, the growth rate is significantly slower. The results prove that the proposed scheme has a great advantage of reducing the computational complexity and management overhead of beam search in the mmWave massive MIMO systems.

5 Conclusion

An efficient joint Tx-Rx beam search scheme was proposed in the mmWave massive MIMO systems. An unconstrained optimization method, Rosenbrock algorithm is used to conduct joint Tx-Rx beam search in a two dimensional space. The optimal coarse beam pair obtained in the initial access is calculated as the initial value to approach the peak of objective function. So it can reduce the search time while ensuring the accuracy which is advantageous in reducing the management overhead. The conduct of the beam search process at the BS side can reduce the computational complexity of the UE. To against channel blockage the double beam link search process was used in the proposed scheme, enhancing the robustness of the system.

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