SCIENCE CHINA
Information Sciences

• LETTER •

August 2020, Vol. 63 180306:1–180306:3
https://doi.org/10.1007/s11432-020-2922-2

Special Focus on mmWave and Terahertz Wireless Communications for B5G/6G

Flexible-beamwidth beam scanning for low-latency cell discovery in mmWave systems

Jiancun FAN[1], Rui XU[1], Xinmin LUO[1] & Jingon JOUNG[2*]

[1]*School of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an* 710049*, China;*
[2]*School of Electrical and Electronics Engineering, Chung-Ang University, Seoul* 06974*, South Korea*

Received 31 January 2020/Revised 15 March 2020/Accepted 19 May 2020/Published online 7 July 2020

Citation Fan J C, Xu R, Luo X M, et al. Flexible-beamwidth beam scanning for low-latency cell discovery in mmWave systems. Sci China Inf Sci, 2020, 63(8): 180306, https://doi.org/10.1007/s11432-020-2922-2

Dear editor,

To compensate for a coverage gap in mmWave communication systems [1], a directional cell search (CS) scheme based on beam scanning was proposed [2–5]. Directional beamforming using a narrow beam (NB) can improve the coverage by considering a high beam gain; however, it will introduce a significant CS delay (CSD) if the beamwidth is too narrow as the beams have to sequentially scan the entire target area in their cell searching phase to guarantee the coverage of all possible users [6]. In [7], it has been shown that an appropriate beamwidth can balance CSD and beamforming gains, which will improve average cell/system throughput (ST). Therefore, a beam with a suitable width and gain should be designed to maximize the ST. Based on this, we propose a directional beam scanning scheme with flexible beamwidth (FB) design for maximizing the ST.

System model and FB beam design. We consider a signal frame consisting of a cell discovery phase and data TX phase. In the cell discovery phase, the base station (BS) periodically broadcasts the same pilot signal K times to discover users at different directions. We assume that the duration of the broadcast signal is T_s in each broadcasting duration T_p. In the rest time $T_p - T_s$ in each broadcasting duration, the BS will wait for a response from users. The CSD τ is then expressed as a function of K (i.e., the searching times or number of searching beams) as $\tau = KT_p = KT_s/\eta$, where $\eta = \frac{T_s}{T_p}$ is the pilot signal ratio in each broadcasting duration. To scan the entire target coverage angle area Θ_t, the minimum number of scanning beams can be expressed as $K \geqslant \Theta_t/\Theta_s$, where Θ_s is the coverage angle of a single beam (i.e., the beamwidth). In general, Θ_s cannot be extremely small. For example, when uniform linear arrays (ULAs) are utilized, the Θ_s of a window-based narrow-beam design method is $0.886 \times 2\pi b/N_T$, where N_T is the number of antennas and b is a broadening factor depending on the choice of windows [8]. For simplicity, without loss of generality, we set b to such that the narrowest NB is as follows: $\Theta_s = 2\pi/N_T$. From this, it is clear that the beamwidth reduces as N_T increases for a ULA; consequently, the CSD τ increases because the required number of searching beams increases, which will decrease the ST owing to the reduced data TX time. Conversely, from beamforming theory [8], the beamforming gain, denoted by G, increases as N_T increases, which will correspondingly increase the ST. From this discussion, we observe that the CSD τ (or equivalently, the beamwidth) and beamforming gain G can be balanced by the design of K to maximize the ST. However, the change of K requires a beam design with a flexible beamwidth, which is challenging because the design of a broad beam with a large number of antennas is difficult according to beamforming theory [8]. In this study, we explore a beam broadening method based on multiple subarrays to design a desired broad FB beam [9]. We first divide the ULA into multiple subarrays and then use the su-

* Corresponding author (email: jgjoung@cau.ac.kr)

perposition of multiple subbeams generated by the multiple subarrays to form a broad FB beam.

When we divide N_T-array antennas into M subarrays, in which the mth subarray contains N_m antenna elements, the total number of array antennas satisfies $N_T = \sum_{m=0}^{M-1} N_m$. From the subarray model, the total array response $F(\theta)$ can be expressed as

$$F(\theta) = \sum_{m=0}^{M-1} \sum_{n=0}^{N_m-1} f_{m,n} \mathrm{e}^{-\mathrm{j}\omega(\theta)\left(\sum_{i=0}^{i=m} N_i - N_0 + n\right)}, \quad (1)$$

where $\omega(\theta) = 2\pi d \sin\theta/\lambda$, d is the antenna space, λ is the wavelength, and $f_{m,n}$ is the beamforming weight corresponding to the $(n+1)$th antenna element of the $(m+1)$th subarray. From (1), we can observe that the inner summation within the double summation corresponds to a subbeam formed by one subarray, and the total beam is the sum of all subbeams formed by the multiple subarrays. In this case, a broad FB beam can be obtained if the central angles of each subbeam generated by each subarray are close to each other. To ensure the flatness of the main lobe of the FB beam, the angle difference $\Theta_{d,m}$ between the central angles of the mth subbeam and the $(m+1)$th subbeam should satisfy the following condition:

$$\Theta_{d,m} = \frac{1}{2}\left(\frac{2\pi}{N_m} + \frac{2\pi}{N_{m+1}}\right), \ \forall m = 0, \ldots, M-2. \quad (2)$$

It should be noted that the weights $f_{m,n}$ corresponding to each subarray can be obtained by any classical beamforming scheme (see chapter 23 in [8]).

Combining Θ_s, N_t, and $\Theta_{d,m}$, the beamwidth of the broad FB beam becomes $\Theta_f = \sum_{m=0}^{M-2} \frac{1}{2}(\frac{2\pi}{N_m} + \frac{2\pi}{N_{m+1}}) + \frac{\pi}{N_0} + \frac{\pi}{N_{M-1}} \overset{\text{(a)}}{=} \frac{2M\pi}{N}$, where (a) is obtained if $N_m = N$, $\forall m$ for notational simplicity. From this, to complete the cell scan for the target coverage angle Θ_t with K FB beams, the beamwidth of an FB beam should satisfy the following condition: $\Theta_f \geqslant \Theta_t/K$. From this, we obtain the condition for M, i.e., $M^2 \geqslant \frac{\Theta_t N_T}{2\pi K}$, and can derive a subarray design policy as $M \geqslant \sqrt{\Theta_t N_T (2\pi K)^{-1}}$. From this, given K, we can obtain the number of required subarrays M and design the broad FB beam from (1). Meanwhile, we can adjust the direction of each subbeam to implement FB beam scanning.

Design of number of FB beams. As mentioned previously, the design of the weights $f_{m,n}$ related to the beamforming gain is significantly important in the system capacity analysis. For ease of analysis, we reformulate the array response in (1) as $F(\theta) = \sum_{t=0}^{N_T-1} f_{\varphi(t)} \mathrm{e}^{-\mathrm{j}\omega(\theta)t}$, where $\varphi(t)$ is a mapping function from t to m and n in (1) as $m = \mathrm{Mod}(t, M)$ and $n = \mathrm{floor}(t/M)$; moreover, $\mathrm{Mod}(t, M)$ and $\mathrm{floor}(t/M)$ are the modulo and floor operations, respectively.

From the Parseval identity, for any $\{f_{\varphi(t)}\}$, we have $\frac{1}{2\pi}\int_{-\pi}^{\pi} |F(\theta)|^2 \mathrm{d}\theta = \sum_{n_t=0}^{N_T-1} \left|f_{\varphi(t)}\right|^2 = 1$. In addition, we have the following inequalities:

$$\begin{aligned}\frac{1}{2\pi}\int_{-\pi}^{\pi} |F(\theta)|^2 \mathrm{d}\theta &\geqslant \frac{1}{2\pi}\int_{\Theta_c-\Theta_f/2}^{\Theta_c+\Theta_f/2} |F(\theta)|^2 \,\mathrm{d}\theta \\ &\geqslant \frac{1}{2\pi}\Theta_f G,\end{aligned}$$

where Θ_c is the direction of the broad FB beam. Here, the second inequality follows the worst-case scenario, i.e., the beamforming gain G from a broad FB beam designed in $F(\theta)$ is the minimum beam gain of the main lobe as $\min_{\theta\in[\Theta_c-\Theta_f/2, \Theta_c+\Theta_f/2]} |F(\theta)|^2 = G$.

According to beamforming theory, the maximum beamforming gain for each linear array generally cannot exceed the number of array antennas in any direction [8]. Hence, we can obtain the upper bound of the worst-case beamforming gain as $G \leqslant \min\{N_T, 2\pi K/\Theta_t\}$. By using this upper bound of the worst-case beamforming gain G, we can design the number of FB beams, i.e., K, to maximize the system capacity.

In the worst case, where the BS has to scan the entire target area to identify the user, the CSD is $\tau = KT_p$. In the data TX process, the beam gain is always greater than the FB beam gain during the pilot signal broadcasting because of the known channel state information at the BS. Consequently, the upper bound of the ST during data TX can then be expressed as a function of K, where $K < \eta T/T_s$, which is expressed as follows:

$$R(K) = \frac{1}{2} B \frac{T-\tau}{T} \log_2(1 + \alpha \mathsf{SNR}) \quad (3)$$

$$\leqslant \frac{B}{2}\left(1 - \frac{KT_s}{\eta T}\right) \log_2\left(1 + \alpha \frac{P}{\sigma^2} \min\left\{N_T, \frac{2\pi K}{\Theta_t}\right\}\right), \quad (4)$$

where the factor $1/2$ comes from a time division duplexing constraint; α is an adjustment factor considering the difference between the theoretical and practical beam gains; B is the total system bandwidth; P is the transmit power of the BS; moreover, σ^2 is the variance of the additive complex white Gaussian noise at the user. Here, the received signal-to-noise ratio (SNR) in (3) is substituted as PG/σ^2 because the BS uses the FB beam for data TX after the cell discovery is completed, and the inequality follows from the worst-case beamforming gain.

As can be seen from (4), the upper bound of the ST is a function of K, and it is evident that the ST is a decreasing function of K when $K > \frac{\Theta_t N_T}{2\pi}$. By considering the feasible region, namely, $K \leqslant \frac{\Theta_t N_T}{2\pi}$ and $K < \eta T/T_s$, and relaxing the feasible K to a continuous variable κ, Eq. (4) becomes a continuous function of κ as

$$\tilde{R}(\kappa) = \frac{B}{2}\left(1 - \frac{T_s}{\eta T}\kappa\right)\log_2\left(1 + \frac{2\pi\alpha P}{\sigma^2\Theta_t}\kappa\right) \tag{5}$$

in the feasible region of κ defined as $0 < \kappa \leqslant \min\{\Theta_t N_T/(2\pi),\ \eta T/T_s\}$.

It can also be readily shown that $\tilde{R}(\kappa)$ in (5) is a concave function with respect to κ. By relaxing the feasibility condition of κ, the first-order optimality condition, i.e., $\frac{\partial C}{\partial \kappa} = 0$, is derived as $\frac{T_s}{\eta T}\log_2\big(1 + \frac{2\pi\alpha P}{\sigma^2\Theta_t}\kappa\big) = \frac{2\pi\alpha P}{\sigma^2\Theta_t}\big(1 - \frac{T_s}{\eta T}\kappa\big)/\big(\big(1 + \frac{2\pi\alpha P}{\sigma^2\Theta_t}\kappa\big)\ln 2\big)$, and from it, we can obtain the critical point of κ as follows: $\kappa^* = \big(\frac{\eta T}{T_s} + \frac{\sigma^2\Theta_t}{2\pi\alpha P}\big)/\mathsf{W}\big\{\big(\frac{2\pi\alpha\eta P T}{\sigma^2\Theta_t T_s} + 1\big)\mathrm{e}\big\} - \frac{\sigma^2\Theta_t}{2\pi\alpha P}$, where $\mathsf{W}\{\cdot\}$ is the zeroth branch of a Lambert function. Now, considering the feasible region of κ and integer condition on K, the optimal number of FB beams is obtained as

$$K^o = \left\lceil [\min\{\kappa^*,\ \Theta_t N_T/(2\pi)\}]^+ \right\rceil, \tag{6}$$

where $[x]^+ = \max\{0, x\}$ and $\lceil x \rceil$ is the ceiling operation of x.

Simulation results and discussion. In the simulation, the system parameters are set as follows: $N_T = 128$, $N_m = 6$, $M = \{21, 21, 22, 22, 21, 21\}$, $T = 10$ ms, $T_s = 5$ μs, $\Theta_t = \sqrt{3}\pi$, $\alpha = 0.9$, $P = 45$ dBm, and $\sigma^2 = -174$ dBm/Hz. The total system bandwidth is $B = 1$ GHz. The carrier frequency is $f_c = 28$ GHz. The noise figure is 7 dB. The average path loss is 120 dB.

Figure 1 shows the ST evaluation results. The dotted lines represent the upper bound $\tilde{R}(\kappa)$ in (5), while the solid lines represent the actual ST $R(K)$ in (3). Thus, there are minor fluctuations in the ST because the change in the number of elements N in the adjacent subarrays varies with the change in the number of subarrays M when K varies. From the results, it can be observed that the relaxed upper bound $\tilde{R}(\kappa)$ is sufficiently tight to design K for the maximization of the actual ST $R(K)$. It is also observed that the ST and optimal number of FB beams generally increase as the pilot overhead η increases, because the broadcasting duration T_p and corresponding CSD τ are reduced. Furthermore, we can verify that the designed number of FB beams, K^o, marked by '○', is almost identical to the actual optimal K, marked by '×', which is obtained from (5) by using an exhaustive search, and the ST gap from the true maximum ST is marginal.

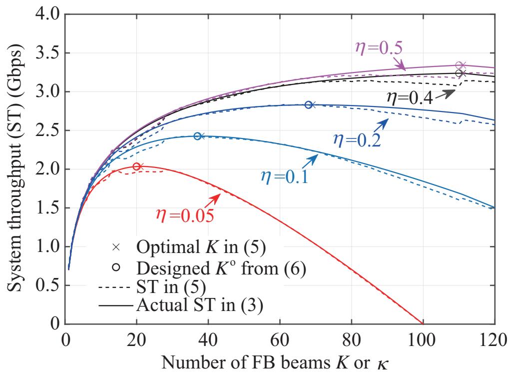

Figure 1 (Color online) The effect of different η on the optimal number of scanning beams.

Conclusion. In this study, we presented the design of an FB beam to reduce the CSD in mmWave cellular communications. The number of scanning FB beams was optimized to maximize the upper bound of the system and verified by the simulation results.

Acknowledgements This work was partially supported by National Natural Science Foundation of China (Grant No. 61671367), Key Research and Development Plan of Shaanxi Province (Grant No. 2018GY-003), and the Chung-Ang University Research Grants in 2019.

References

1 Fan J, Han L, Luo X, et al. Delay analysis and optimization of beam scanning-based user discovery in millimeter wave systems. IEEE Access, 2020, 8: 25075–25083

2 Barati C N, Hosseini S A, Rangan S, et al. Directional cell discovery in millimeter wave cellular networks. IEEE Trans Wirel Commun, 2015, 14: 6664–6678

3 Li Y, Andrews J G, Baccelli F, et al. Design and analysis of initial access in millimeter wave cellular networks. IEEE Trans Wirel Commun, 2017, 16: 6409–6425

4 Liu C, Li M, Collings I B, et al. Design and analysis of transmit beamforming for millimeter wave base station discovery. IEEE Trans Wirel Commun, 2017, 16: 797–811

5 Li Y, Luo J, Garcia M H C, et al. On the beamformed broadcasting for millimeter wave cell discovery: performance analysis and design insight. IEEE Trans Wirel Commun, 2018, 17: 7620–7634

6 Xu R, Fan J, Zhang Y, et al. Capacity analysis and optimization of millimeter wave cellular networks with beam scanning. In: Proceedings of 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), 2017. 1–5

7 Fan J, Han L, Luo X, et al. Beamwidth design for beam scanning in millimeter-wave cellular networks. IEEE Trans Veh Technol, 2020, 69: 1111–1116

8 Orfanidis S J. Electromagnetic Waves and Antennas. Rutgers University, 2016. http://www.ece.rutgers.edu/~orfanidi/ewa/

9 Rajagopal S. Beam broadening for phased antenna arrays using multi-beam subarrays. In: Proceedings of IEEE International Conference on Communications (ICC), Ottawa, 2012. 3637–3642