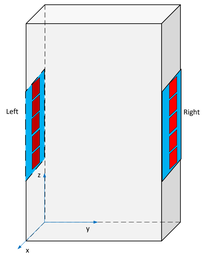
Sub-Chain Beam for mmWave Devices: A Trade-off between Power Saving and Beam Correspondence

Paper# 1336

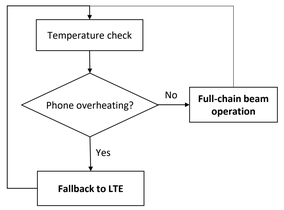
Jianhua Mo*, Daehee Park+, Boon Loong Ng*, Vutha Va*, Anum Ali*, Chonghwa Seo+, and Jianzhong Charlie Zhang*

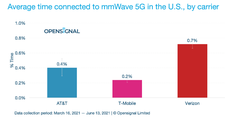
***Standards and Mobility Innovation Lab, Samsung Research America, Plano, TX, USA +Samsung Electronics, Suwon, Korea**

Motivation



Current mmWave 5G phone operation





- Antenna arrays are adopted by mmWave UE to increase the beamforming gain.
- The power consumption (and temperature) also increases with number of active antenna elements.
- The current mmWave 5G phone would just do LTE fallback whenever there is an overheating issue.
- The LTE fallback is not desired in general.
  - The maximum data rate decreases from Gbps to a few hundred Mbps or less.
  - The frequent off/on of the antenna array incur additional latency and power consumption.
- Opensignal® reports (2021) that the average time connected to mmWave 5G in US is less than 1%.
- The sub-chain beam operation can help reduce the chance of LTE fallback.

Sub-chain beam operation

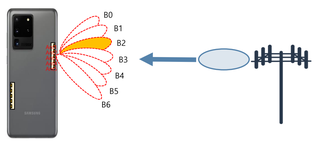
Proposed mmWave 5G phone operation

Beam index	Full-chain beam	4-Ant beam	3-Ant beam	2-Ant beam	1-Ant beam
1	$[1\ 1\ 1\ 1\ 1]^T$	$[1\ 1\ 1\ 1\ 0]^T$	$[0\ 0\ 1\ 1\ 1]^T$	$[0\ 1\ 0\ 1\ 0]^T$	$[0\ 0\ 0\ 0\ 1]^T$
2	$[1\ j\ -1\ -j\ 1]^T$	$[1\ j\ 1\ j\ 0]^T$	$[j\ -1\ -j\ 0\ 0]^T$	$[1\ j\ 0\ 0\ 0]^T$	$[0\ 0\ 1\ 0\ 0]^T$
…	…	…	…	…	…
K	$[1\ -1\ 1\ -1\ 1]^T$	$[1\ j\ j\ 0\ -1]^T$	$[0\ -1\ -1\ 1\ 0]^T$	$[0\ -1\ 1\ 0\ 0]^T$	$[0\ 1\ 0\ 0\ 0]^T$

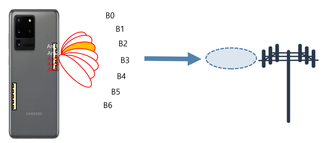
- An example of sub-chain beam codebooks
  - A *K*-beam codebook
  - 5 antennas per chain
  - 2-bit phase shifters:
  - Possible phases: 1, j, -1, -j
  - "0" means that the antenna element is deactivated

Challenges of sub-chain beam codebook design

Downlink(DL): All antenna elements activated



Uplink(UL): 3 antenna elements activated

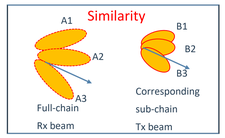


- DL-UL beam correspondence is an important design criterion in 5G standards.
  - Definition: The best Rx beam in the DL direction is also the best Tx beam in the UL direction.
  - If there is no DL-UL beam correspondence, additional separate UL beam management procedure will be required.
- Example above: **If 5-chain B2 is the best Rx beam, the corresponding 3-chain B2 should be the best Tx beam.**

- Spherical coverage means the gain distribution over the whole sphere, i.e., no clear coverage holes at any direction.
- The sub-chain beam codebook should have good spherical coverage.

Sub-chain beam codebook Design

- Design metric 1: Similarity score
  - Ensure **inter-chain beam correspondence** (one-to-one mapping between sub-chain and full-chain beam)
  - Benefit: Beam sweeping is not needed when switching from full-chain beams to sub-chain beams.
- Design metric 2: Spherical coverage ('SC')
  - The sub-chain codebook is to maximize the spherical coverage.
  - There is NO inter-chain beam correspondence.
  - A fresh beam sweeping may be needed to determine the best beam if # chains changes.
- Design metric 3: Maximize the beam correspondence spherical coverage in ('BC-SC')
  - **This is a metric in between Similarity (Metric 1) and Spherical coverage (Metric 2).**
  - Sub-chain beams are designed to maximize the radiation pattern over the full-chain beam's coverage region.
  - A fresh beam sweeping is not necessary in this option.
- We have developed algorithms according to the different metrics.



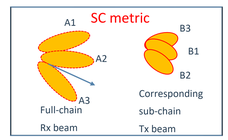
- Consider a simple example with just 3 beams within a beambook.
- Design
  - The 3 sub-chain beams are designed to mimic the beam shape of 3 full-chain beams.
    - B1 is designed to mimic A1.
    - B2 is designed to mimic A2.
    - B3 is designed to mimic A3.
- Operation
  - When the UE switches from full-chain to sub-chain (e.g., to save the Tx power), it directly changes from Ai to Bi, since it knows that Bi is similar to Ai.
    - We call it "one-to-one mapping" or "inter-chain beam correspondence" in the paper.
- Application
  - It could be used for URLLC where less latency is preferred.
- Pros: Do not need to sweep {B1, B2, B3} to determine the best sub-chain beam.
- Cons: The spherical coverage could be bad.

- Design method:
  - Design sub-chain beams individually to resemble the full-chain beams
    - Assume a uniform sampling of N_p(e.g., $N_p > 10{,}000$) points on the sphere, $(\theta_1, \phi_1), \cdots, (\theta_{N_p}, \phi_{N_p})$.
    - Calculate the similarity score defined as,

$$s_{i,j} = \frac{1}{\sum_{n=1}^{N_p} G_i^2(\theta_n, \phi_n)} \sum_{n=1}^{N_p} G_i(\theta_n, \phi_n) B_j(\theta_n, \phi_n)$$

where $G_i(\theta, \phi)$ is the i-th full-chain beam pattern (unit: linear), and $B_j(\theta, \phi)$ is the j-th candidate sub-chain beam pattern (unit: linear).

    - The term $\sum_{n=1}^{N_p} G_i^2(\theta_n, \phi_n)$ is to normalize the score such that the score of two same beams is 1.
    - The candidate sub-chain beam with the largest similarity score is chosen.



- Design
  - The 3 sub-chain beams are designed to optimize the spherical coverage.
    - E.g., there is no clear coverage hole for the beambook {B1, B2, B3}.
- Operation
  - When the UE switches from full-chain to sub-chain, it has to sequentially sweep {B1, B2, B3} to determine the best one.
- Application
  - The UE cares a lot about the beam gain.
  - It could be a UE with a low-gain antenna or small antenna array, but a high requirement on the data rate.
- Pros: the spherical coverage of sub-chain beambook is good.
- Cons: need to sweep {B1, B2, B3} to determine the best sub-chain beam.

- Design method: K-Means algorithm in [1]

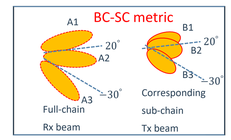
Assignment step: Assign each direction to the beam which has the largest gain.
This means partitioning the set of directions into K subsets.
$D_k = \{(\theta, \phi) | k = argmax_{1 \le j \le K} \boldsymbol{w}_j^H \boldsymbol{M}(\theta, \phi) \boldsymbol{w}_j\}$

Update step: Optimize a new beam to serve all directions in every subset.

$$\boldsymbol{w}_k = \underset{\boldsymbol{w}}{argmax}\, \boldsymbol{w}^H \left(\sum_{(\theta,\varphi) \in D_k} \boldsymbol{M}(\theta, \varphi)\right) \boldsymbol{w}$$
$$s.t.\ \|w_\ell\| = 1$$
$$\|\boldsymbol{w}\|_0 = m$$
$$\angle w_\ell \in \{0, 1, \ldots 2^b - 1\} \times \frac{2\pi}{2^b}$$

m-chain codebook

[1] J. Mo *et al.*, "Beam Codebook Design for 5G mmWave Terminals," in *IEEE Access*, vol. 7, pp. 98387–98404, 2019



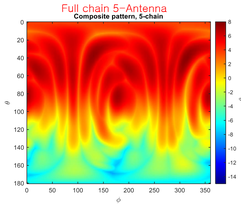
- Design
  - The 3 sub-chain beams are designed to **mimic the coverage region, instead of shape**, of the corresponding the full-chain beams.
    - E.g., A2 covers the region [- 30-deg, 20-deg], which means that A2 has higher gain than A1 and A3 in this region. B2 is then designed to cover the region [- 30-deg, 20-deg]. B2 could have very different shapes than A2.
- Operation
  - When the UE switches from full-chain to sub-chain, it picks the corresponding sub-chain beam. Same to the "Similarity metric" operation.
    - Since the corresponding sub-chain beam covers the same region, it is safe to omit the beam sweeping.
- Application
  - Can apply to most of the scenarios, since it has low latency and high data rate.
- Pros:
  - Do not need to sweep {B1, B2, B3}.
  - The spherical coverage is better than the "Similarity metric" beambook since it does not have coverage holes.
- Cons: The overall spherical coverage could be slightly worse than the "SC metric" beambook.

- Design method:
  - First, determine the coverage region of each full-chain beam
    - Determine the coverage region of the K full-chain beams as $D_1, D_2, \ldots D_K$
  - Second, design the sub-chain beams separately to maximize the average gain over the full-chain beam coverage region.
    - Solve the below optimization problem ($\boldsymbol{w} \in \mathbb{C}^{L \times 1}, \boldsymbol{M} \in \mathbb{C}^{L \times L}$)

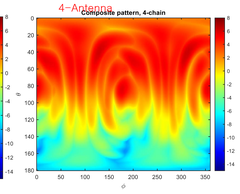
$$\sum_{(\theta_n, \phi_n) \in D_k} B(\theta_n, \phi_n) = \sum_{(\theta_n, \phi_n) \in D_k} \boldsymbol{w}^H \boldsymbol{M}(\theta_n, \phi_n) \boldsymbol{w} = \boldsymbol{w}^H \left(\sum_{(\theta_n, \phi_n) \in D_k} \boldsymbol{M}(\theta_n, \phi_n)\right) \boldsymbol{w}$$
$$\triangleq \boldsymbol{w}^H \boldsymbol{M}' \boldsymbol{w}$$

Results

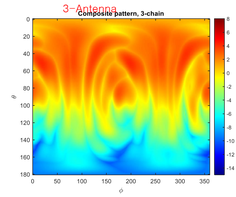
Full chain 5-Antenna



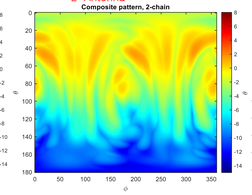
4-Antenna



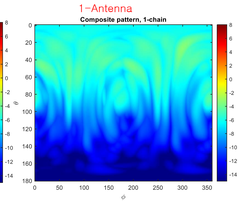
3-Antenna



2-Antenna



1-Antenna



- Simulation setup
  - 14-beam codebook
  - 2 linear arrays of 5 antenna
  - 5-bit phase shifters
  - BC-SC metric is adopted
- The sub-chain beams are weaker than the full-chain beams, as expected.
- However, the pattern shapes and the best beam index distribution of full-chain and sub-chain codebooks are similar.
- **Our proposed design preserves the beam correspondence between the full-chain and sub-chain codebooks.**