SAMSUNG

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

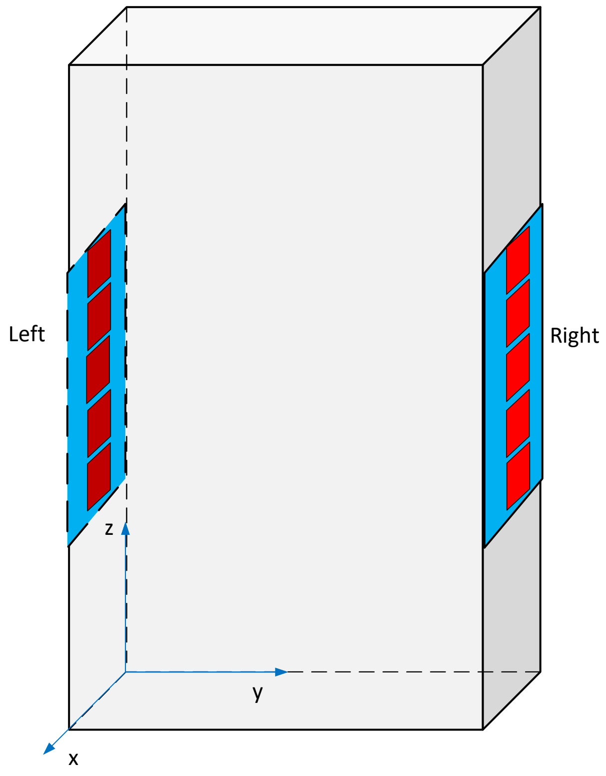
Jianhua Mo*, Daehee Park+, Boon Loong Ng*, Vutha Va*, Anum Ali*, Chonghwa Seo+, and Jianzhong Charlie Zhang*

*Standards and Mobility Innovation Lab, Samsung Research America, Plano, TX, USA

+Samsung Electronics, Suwon, Korea

Motivation (1/2)

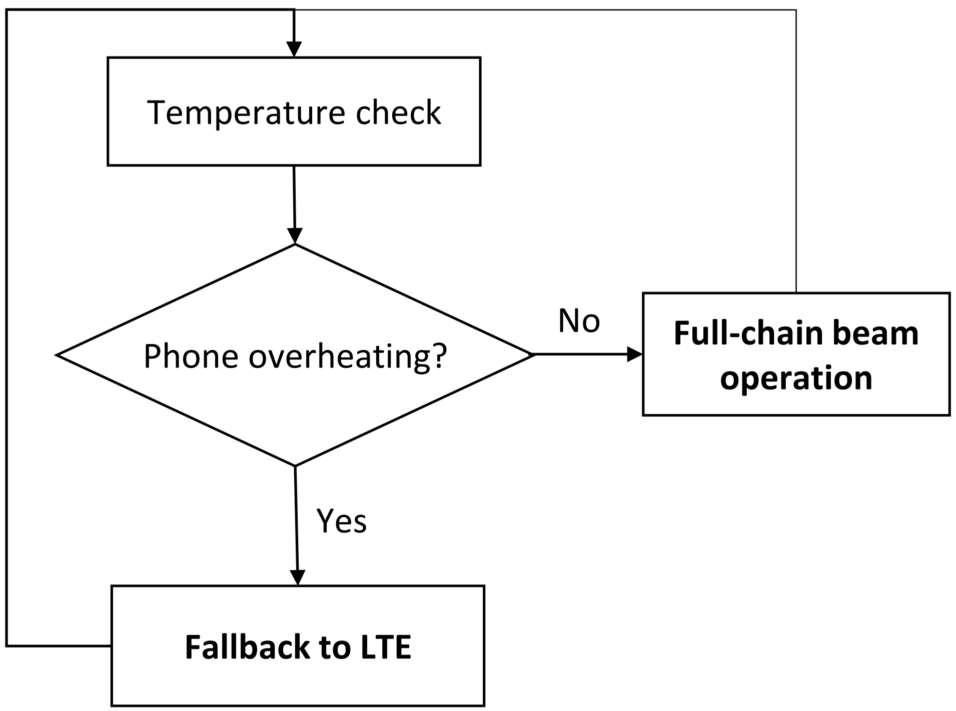
- Antenna arrays are adopted by mmWave UE to increase the beamforming gain, and thus SNR and throughput.
  - In the figure, there are two 1x5 antenna arrays on the left and right edge of the phone.
- The power consumption (and temperature) also increases with number of active antenna elements.
  - Power consumption is one of the reasons that limit the mmWave 5G utilization.

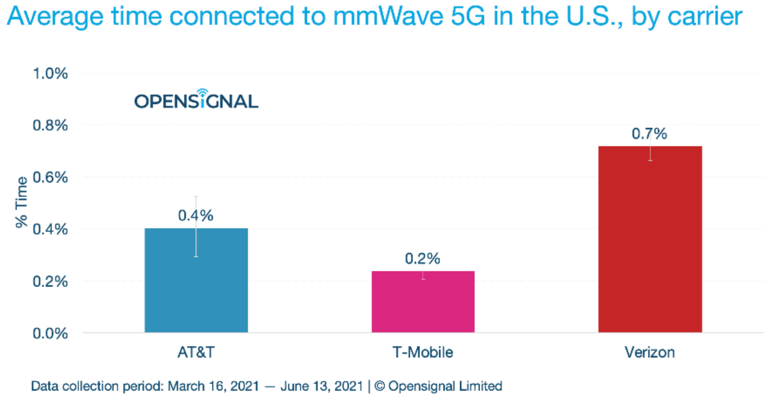


Motivation (2/2)

- 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 mmWave antenna module incur additional latency and power consumption.
- Opensignal* reports (March-June 2021) that the average time connected to mmWave 5G in the US is less than 1%.
- The **sub-chain beam** operation can help reduce the chance of LTE fallback.

Current mmWave 5G phone operation





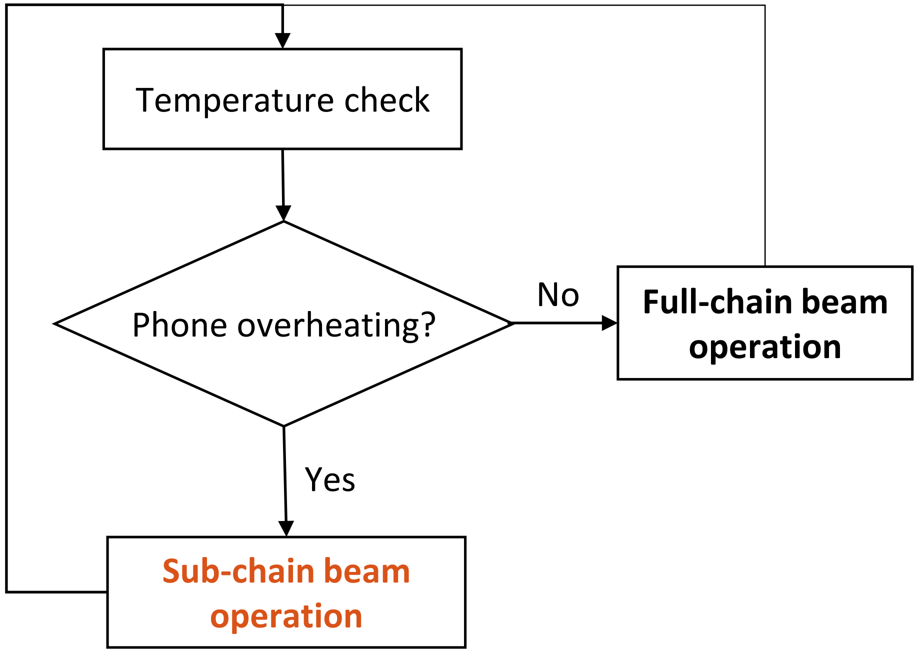
Sub-chain beam

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	$[1\ -1\ 1\ -1\ 1]^T$	$[1\ j\ j\ 0\ -1]^T$	$[0\ -1\ -1\ 1\ 0]^T$	$[0\ -1\ 1\ 0\ 0]^T$	$[0\ 1\ 0\ 0\ 0]^T$

- To reduce the power consumption and control UE temperature, UE can choose to reduce # activated antenna elements.
- Such kind of beam which is based on a part of the array is called ‘**sub-chain beam**’.

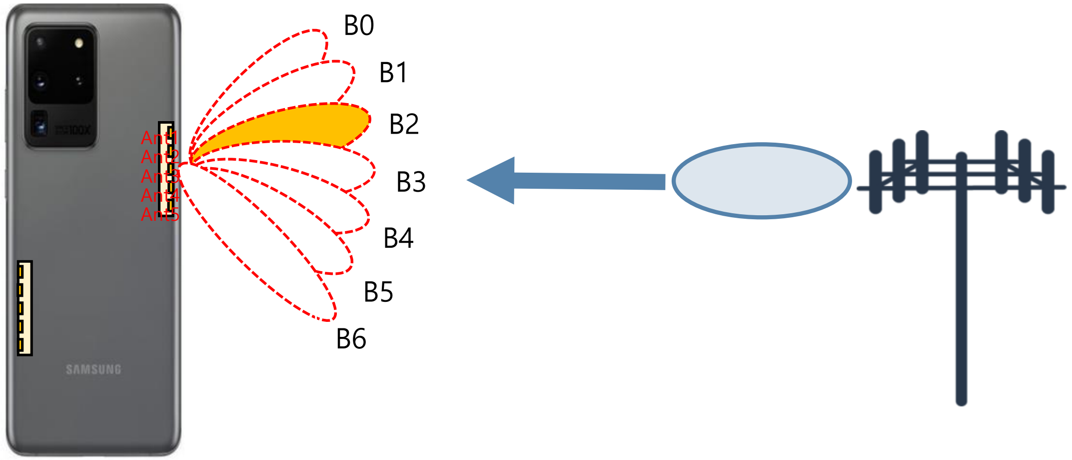
- An example of sub-chain beam codebooks
  - *K*-beam codebook
  - 5 antennas per chain
  - 2-bit phase shifters: Possible phases: 1, j, -1, -j
  - “0” means that the antenna element is deactivated

<u>Proposed mmWave 5G phone operation</u>

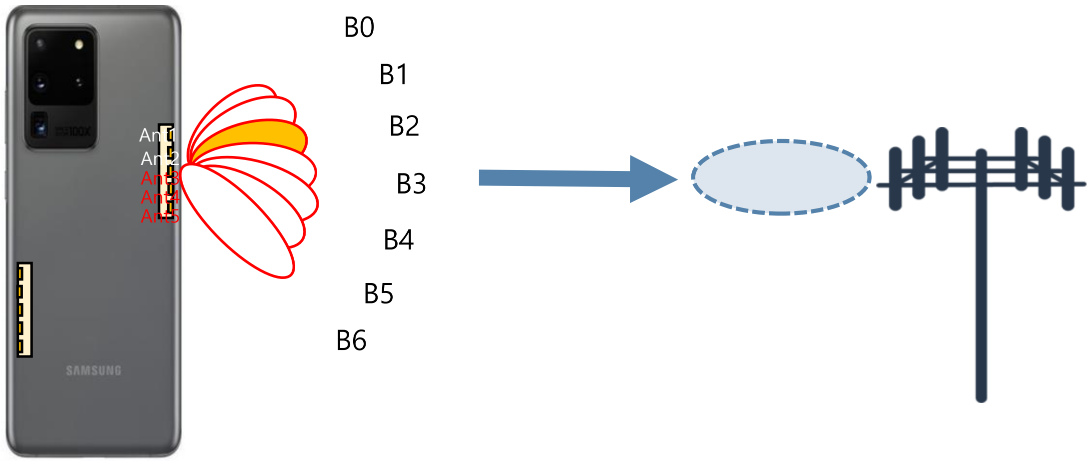


Downlink-Uplink beam correspondence

Downlink(DL): All antenna elements activated

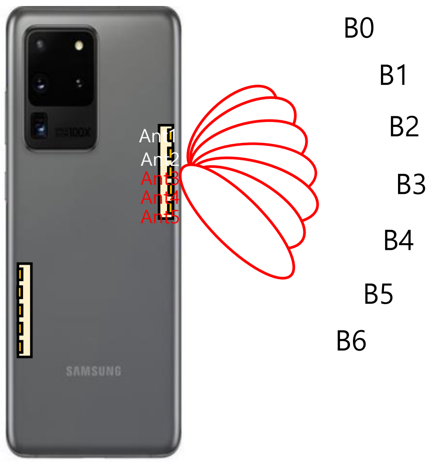


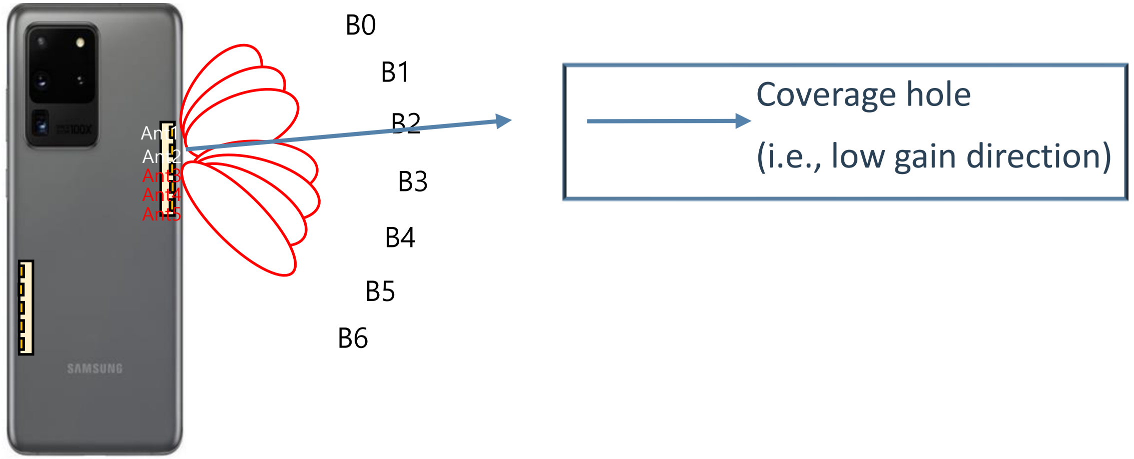
Uplink(UL): 3 antenna elements activated



- 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





- Spherical coverage means the gain distribution over the whole sphere, i.e., no clear coverage holes at any direction.
  - The codebook in the right figure is worse than that in the left figure.
- The sub-chain beam codebook should cover the angular domain without holes.

Summary of design considerations

Inter-chain beam correspondence

Spherical coverage

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	$[1\ {-1}\ 1\ {-1}\ 1]^T$	$[1\ j\ j\ 0\ {-1}]^T$	$[0\ {-1}\ {-1}\ 1\ 0]^T$	$[0\ {-1}\ 1\ 0\ 0]^T$	$[0\ 1\ 0\ 0\ 0]^T$

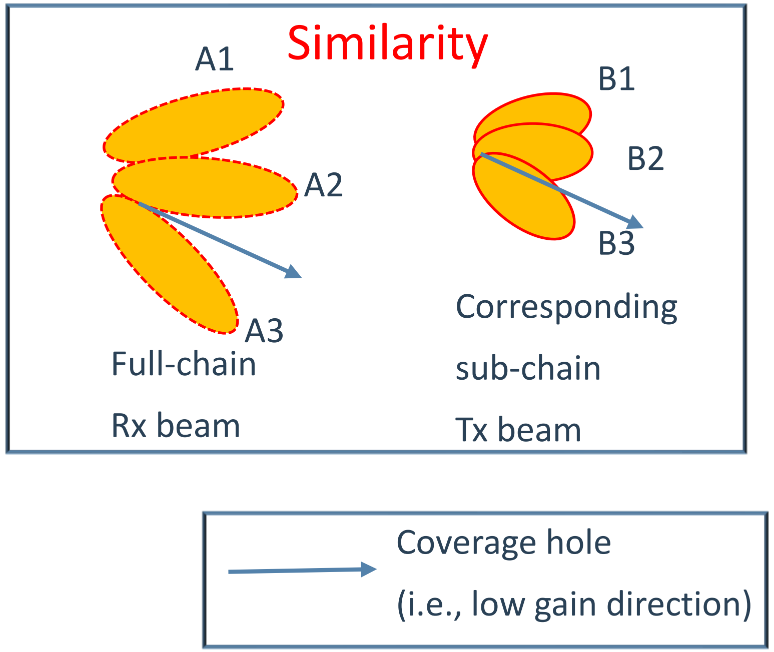
- Inter-chain beam correspondence: the beams in each **row** should be similar.
- Spherical coverage: the beams in each **column** should cover the sphere well.

Sub-chain beam design metrics

- 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.

Similarity metric: example

- 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.



Sub-chain codebook design for similarity score

- Design sub-chain beams individually to resemble the full-chain beams
  - Assume a uniform sampling of $N_p \left(\mathrm{e.g.}, N_p > 10{,}000\right)$ points on the sphere, $(\theta_1, \phi_1), \cdots, \left(\theta_{N_p}, \phi_{N_p}\right)$.
  - 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 similarity score is always larger than 0.
  - The candidate sub-chain beam with the largest similarity score is chosen.

Sub-chain codebook design for similarity score

- We adopt the data-driven method for codebook design [1].
  - $M(\theta, \phi) \in \mathbb{C}^{L\times L}$: E-field response data of the L-element antenna array in a direction
  - E-field data can be obtained from the simulation or measurement.
  - Beam pattern: $B(\theta_n, \phi_n) = \boldsymbol{w}^H \boldsymbol{M}(\theta_n, \phi_n)\boldsymbol{w}$

- The beam design problem is: $\left(c_i = \sum_{n=1}^{N_p} G_i^2(\theta_n, \phi_n)\right)$

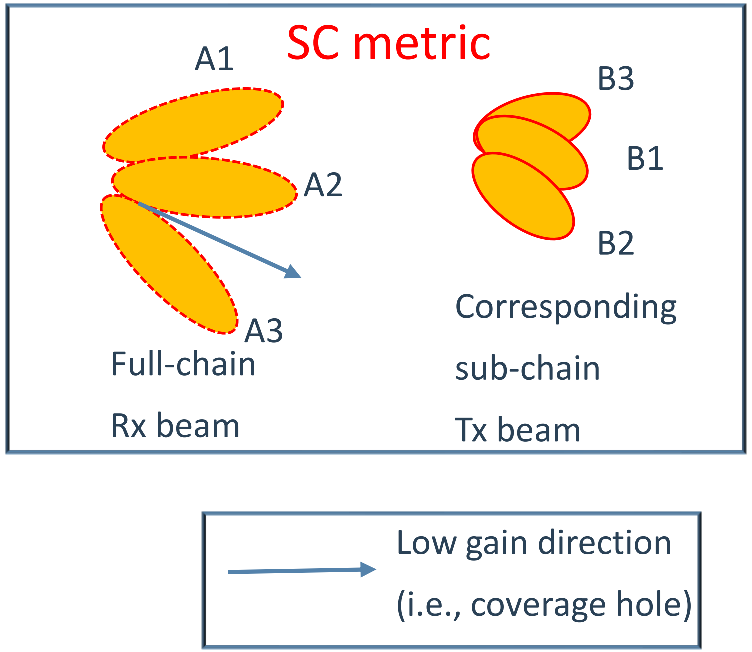
$$\frac{1}{c_i}\sum_{n=1}^{N_p} G_i(\theta_n, \phi_n) B(\theta_n, \phi_n) = \frac{1}{c_i}\sum_{n=1}^{N_p} G_i(\theta_n, \phi_n)\boldsymbol{w}^H \boldsymbol{M}(\theta_n, \phi_n)\boldsymbol{w} = \frac{1}{c_i}\boldsymbol{w}^H\left(\sum_{n=1}^{N_p} G_i(\theta_n, \phi_n)\boldsymbol{M}(\theta_n, \phi_n)\right)\boldsymbol{w}$$

- The problem can be solved by an iterative algorithm (e.g., Algorithm 2 in [1])

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

SC metric: example

- 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.



Sub-chain codebook design for spherical coverage

- Has to jointly design the sub-chain beams.
- The iterative K-Means algorithm [1] is adopted.
  - The Assignment is initialized by the full-chain codebook.
  - In the update step, it is difficult to solve the optimization problem with L0 norm constraint.
  - We thus solve $\binom{L}{m} \times K$ optimization problems by exhausting all the possible combinations.
  - Since L and K is not large, it is efficient to solve it.

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.

$$\boldsymbol{w}_k = ar\underset{\boldsymbol{w}}{g\max}\, \boldsymbol{w}^H \left(\textstyle\sum_{(\theta,\varphi)\in D_k} \boldsymbol{M}(\theta, \varphi)\right)\boldsymbol{w}$$

$$s.t. \ \|w_\ell\| = 1$$

$$\|\boldsymbol{w}\|_0 = m$$

$$\angle w_\ell \in \{0, 1, \ldots 2^b - 1\} \times \frac{2\pi}{2^b}$$

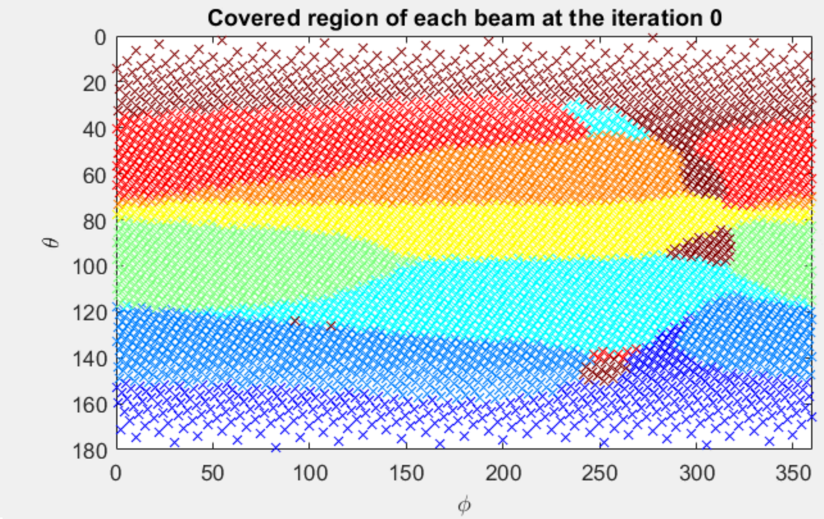
m-chain codebook

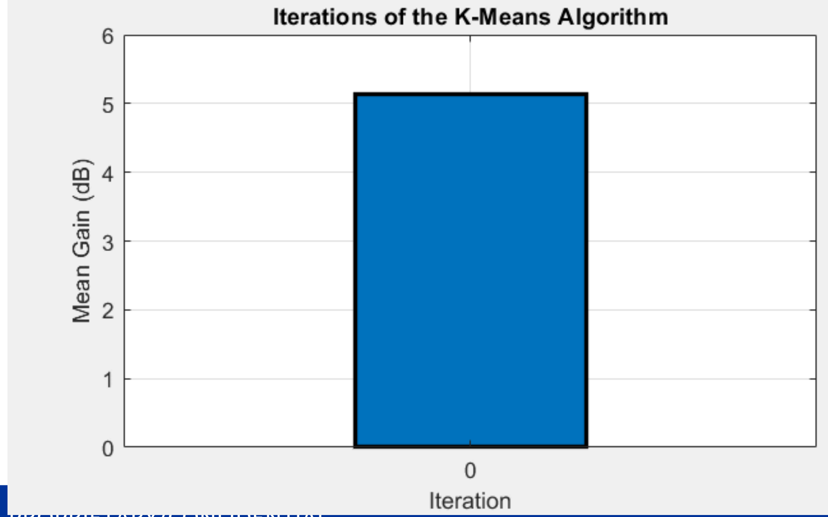
[1] J. Mo *et al.*, "Beam Codebook Design for 5G mmWave Terminals," in *IEEE Access*, vol. 7, pp. 98387-98404, 2019

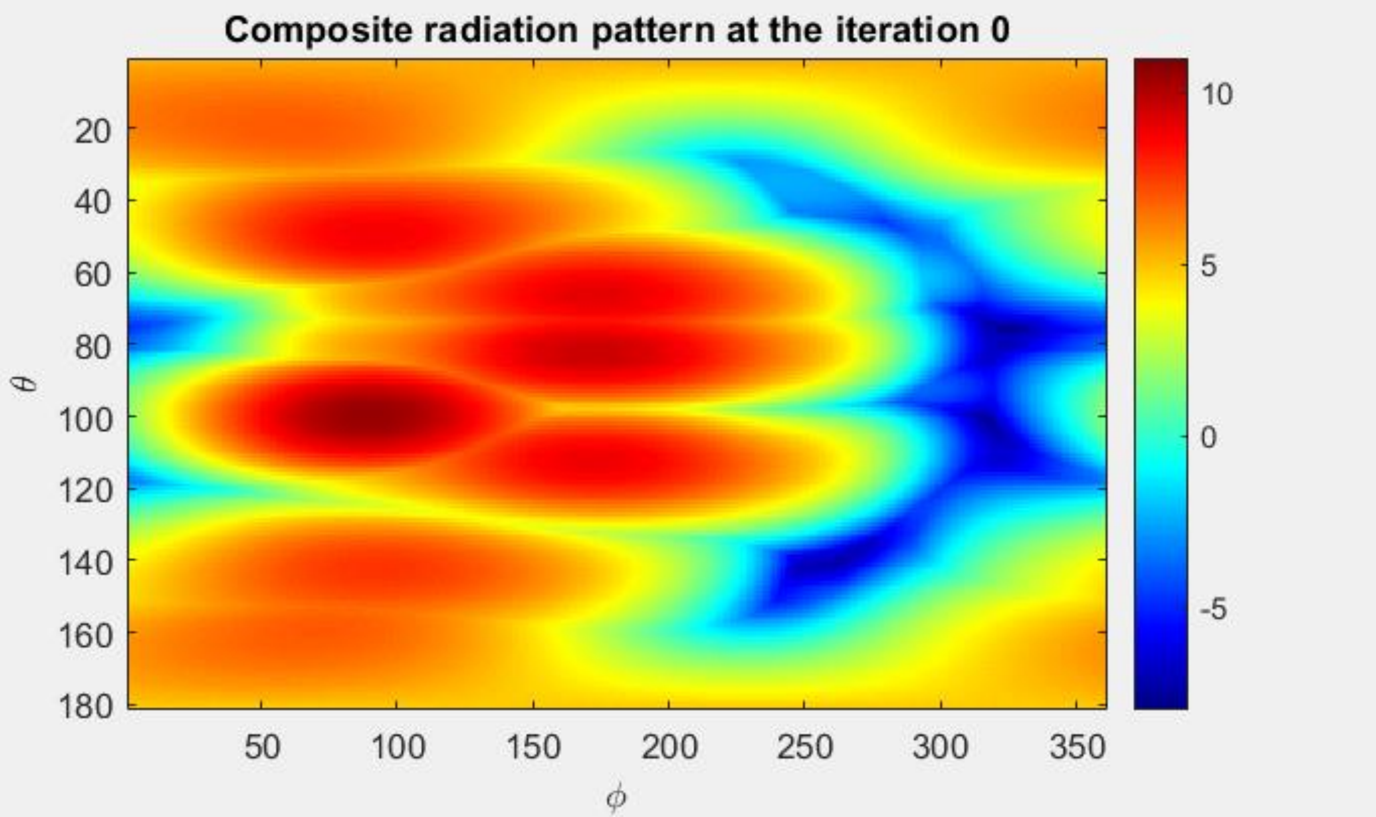
K-Means algorithm: example

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

- 1 X 4 linear array, 5 bits phase shifter, codebook size 8



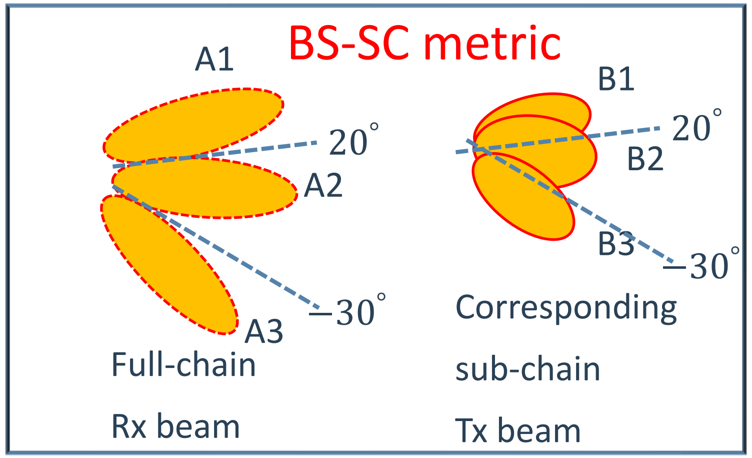




K-Means algorithm usually converges within a few iterations.

BC-SC metric: example

- 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.



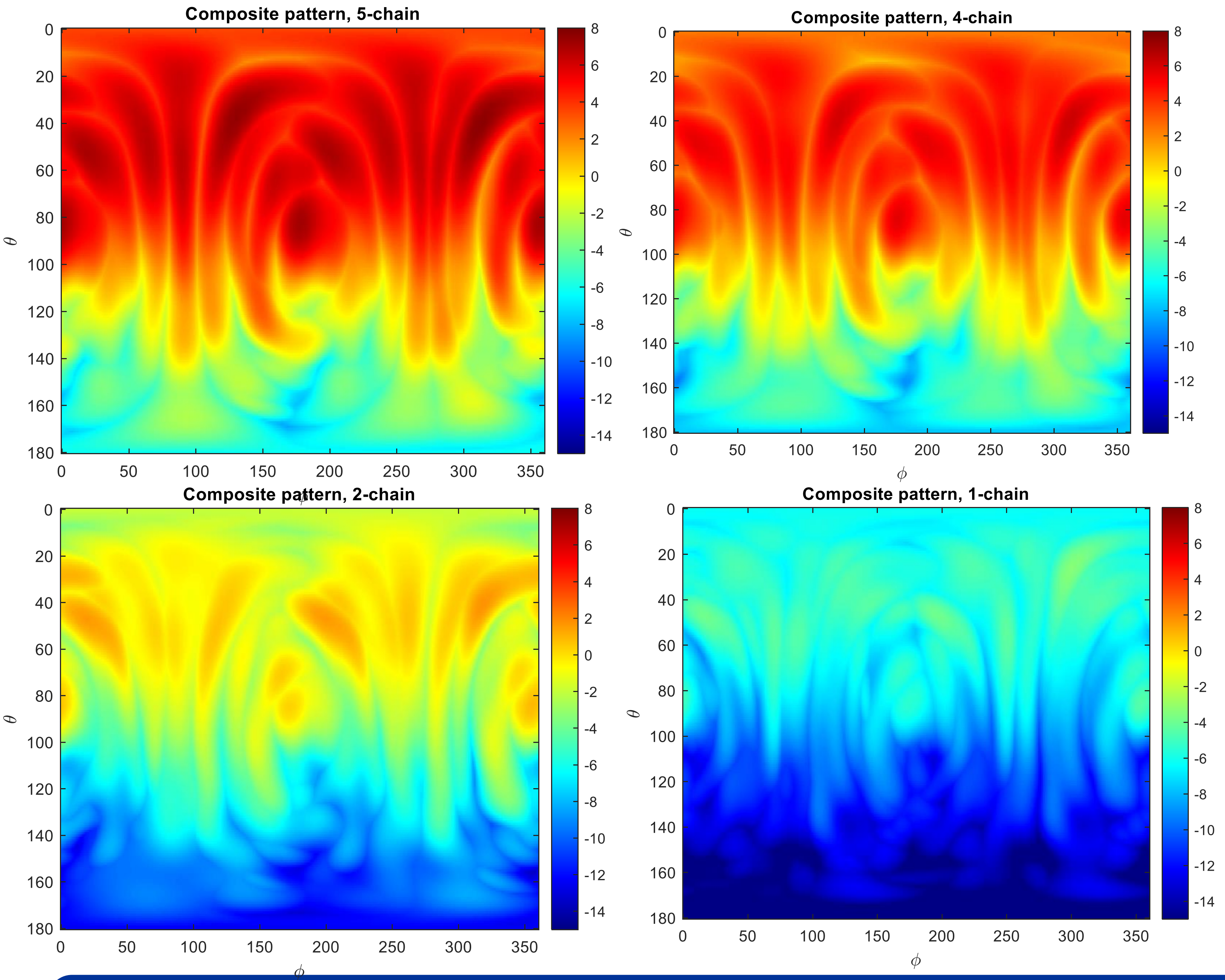
Sub-chain codebook design for beam correspondence spherical coverage

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

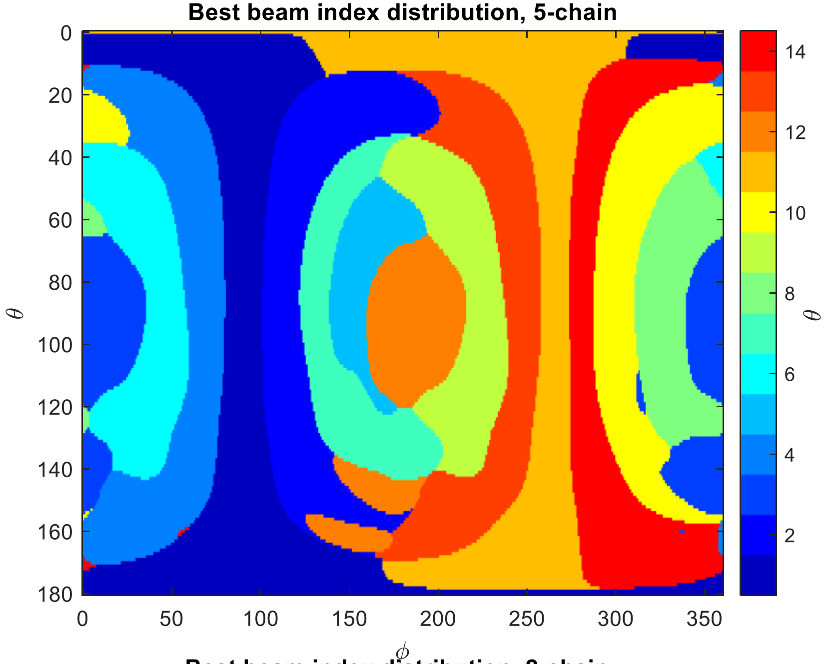
$$\sum_{(\theta_n,\phi_n)\in D_k} B(\theta_n,\phi_n) = \sum_{(\theta_n,\phi_n)\in D_k} \boldsymbol{w}^H \boldsymbol{M}(\theta_n,\phi_n)\boldsymbol{w} = \boldsymbol{w}^H \left(\sum_{(\theta_n,\phi_n)\in D_k} \boldsymbol{M}(\theta_n,\phi_n)\right)\boldsymbol{w} \triangleq \boldsymbol{w}^H \boldsymbol{M}'\boldsymbol{w}$$

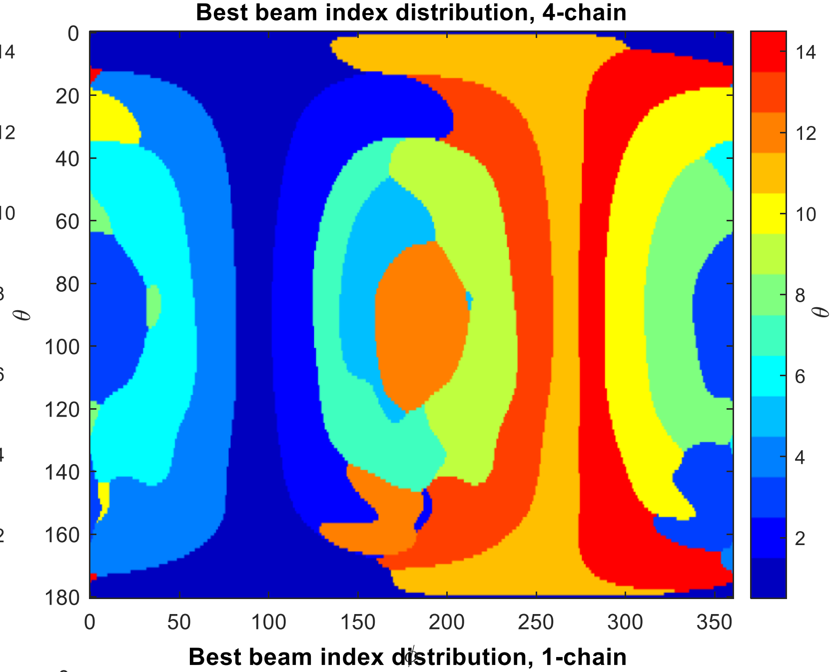
  - In contrast, for the Similarity metric, the summation is over the sphere and weighted by the full-chain beam pattern $\left(c_i = \sum_{n=1}^{N_p} G_i^2(\theta_n,\phi_n)\right)$

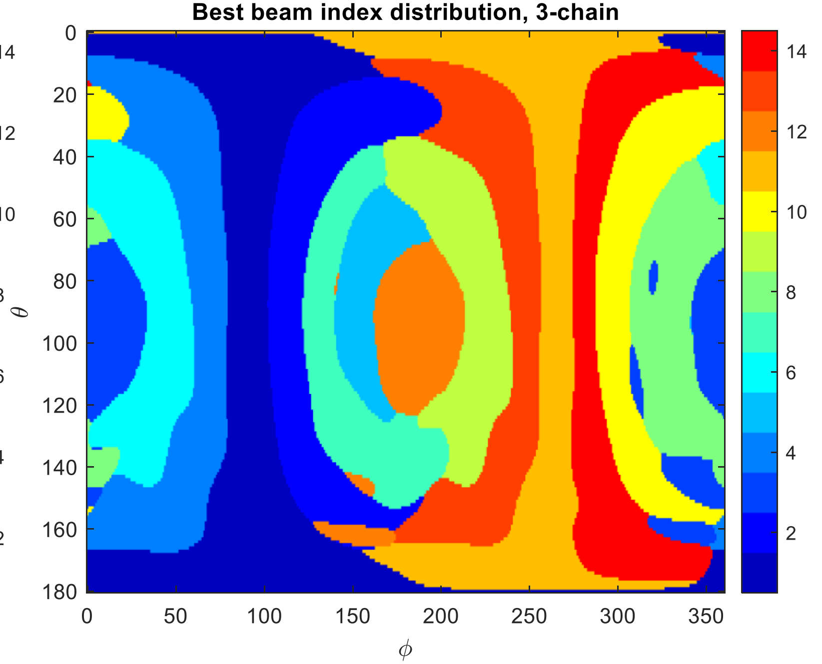
$$\frac{1}{c_i}\sum_{n=1}^{N_p} G_i(\theta_n,\phi_n)B(\theta_n,\phi_n) = \frac{1}{c_i}\sum_{n=1}^{N_p} G_i(\theta_n,\phi_n)\boldsymbol{w}^H\boldsymbol{M}(\theta_n,\phi_n)\boldsymbol{w} = \frac{1}{c_i}\boldsymbol{w}^H\left(\sum_{n=1}^{N_p} G_i(\theta_n,\phi_n)\boldsymbol{M}(\theta_n,\phi_n)\right)\boldsymbol{w}$$

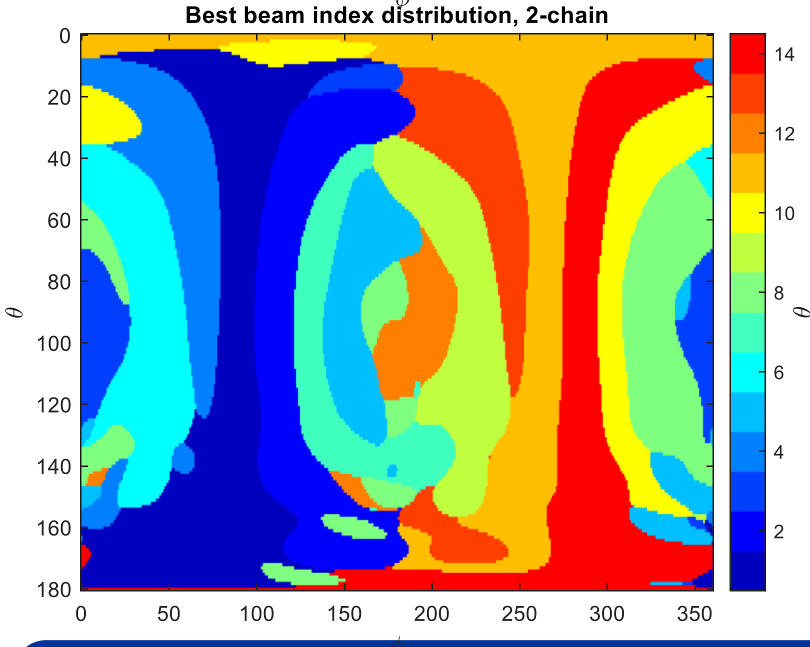


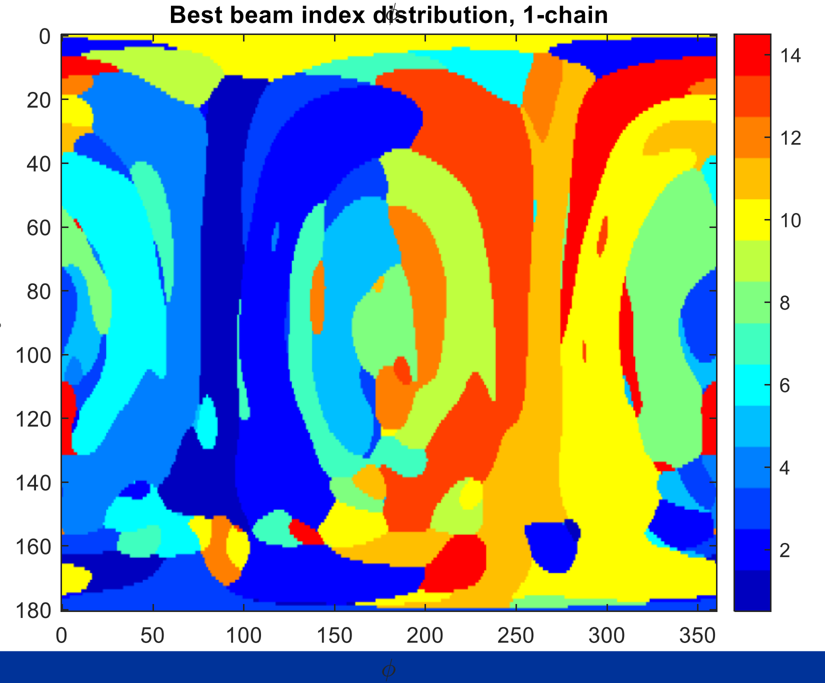
- Simulation setup
  - 14-beam codebook
  - 2 linear arrays of 5 antenna
  - 5-bit phase shifters
- BC-SC maximization





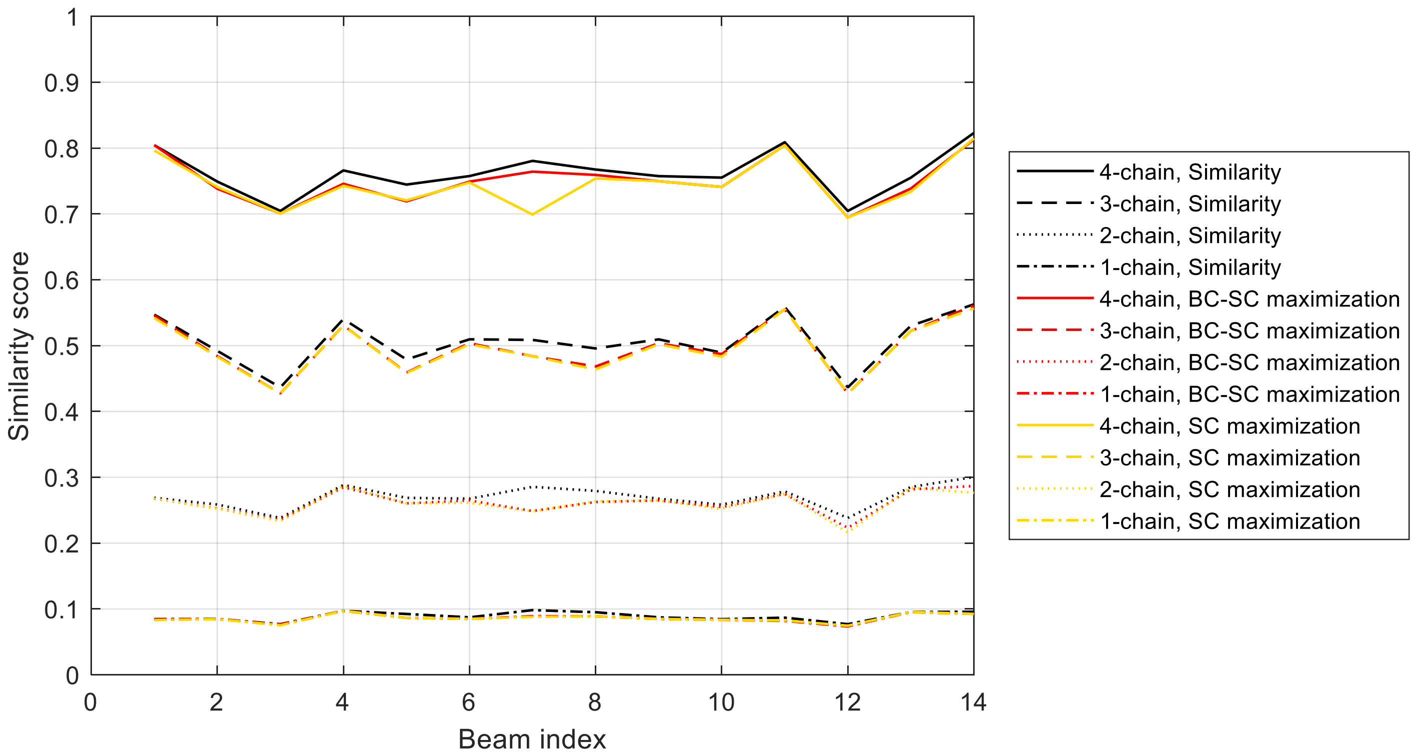






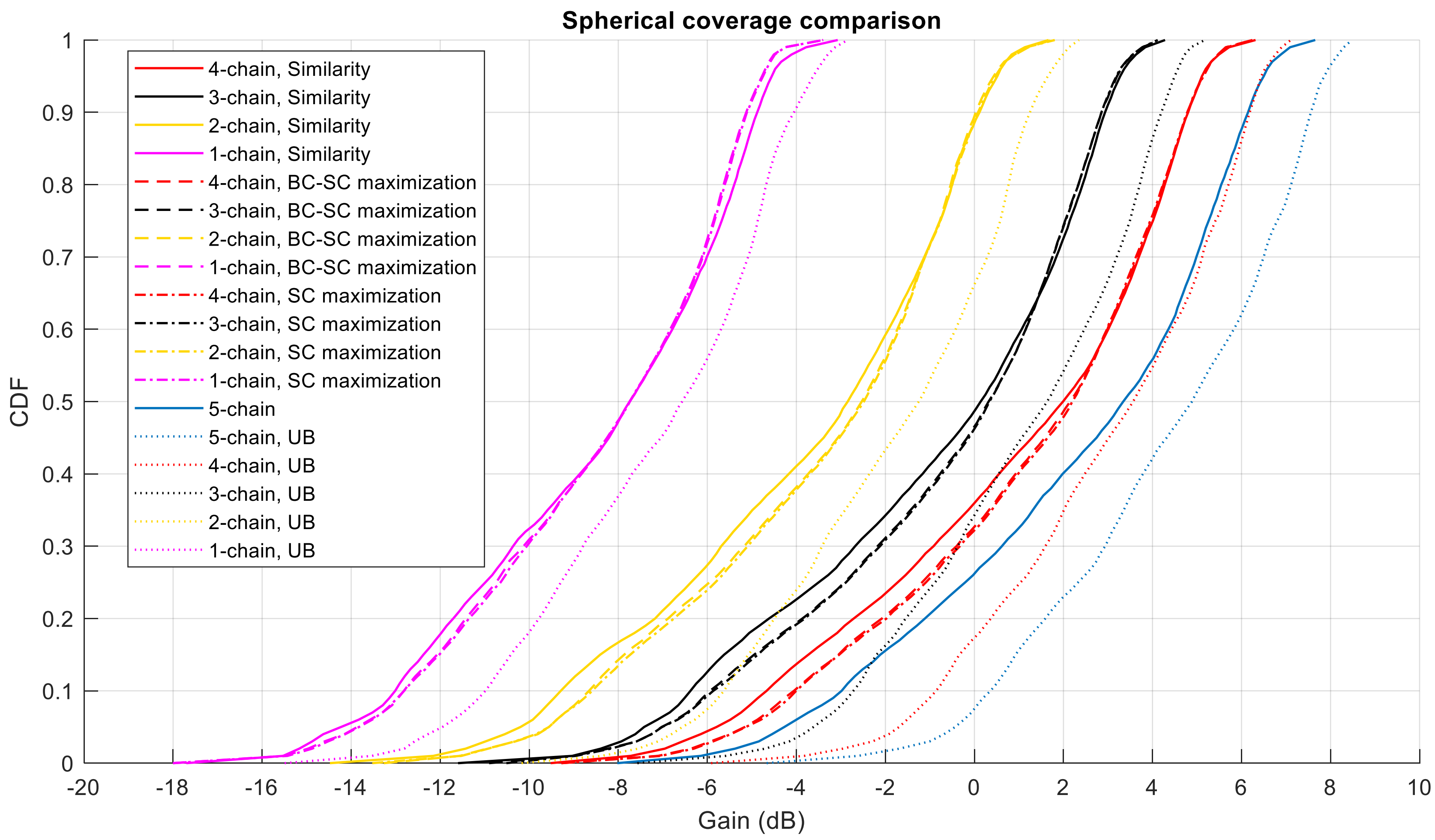
- BC-SC maximization
- The pattern shapes and the best beam index distribution of full-chain and sub-chain codebooks are similar.

Similarity score



- The codebook by Similarity metric results in the largest similarity score.
- The codebook of “BC-SC maximization” leads to a slightly higher similarity score than that of “SC maximization”.
- Due to the initialization of “SC maximization” design, the resulting sub-chain beams map well to the full-chain beams, although the mapping is not required. For other initializations, the resulting sub-chain beams may not map to the full-chain beams (example in Appendix)

Spherical coverage comparison



- The codebook of “SC maximization” is slightly better than that of “BC-SC maximization”, and much better than the that of “Similarity”.
- Compared to the 5-chain case, the gain CDF of 4, 3, 2, 1-chain codebook is around 1, 3, 6, 10 dB worse.

Conclusion

- Power saving and temperature control is a big challenge for 5G mmWave.
- Sub-chain beam codebooks are proposed to avoid LTE fallback as well as overheating.
- We presented methods to design the sub-chain beam codebooks.
  - Three design metrics have been proposed.
  - The proposed design of "BC-SC maximization" optimizes both the inter-chain beam correspondence and the spherical coverage.

Thank you!

Sub-chain beam operation

Basic UE procedure for determining DL/UL beam operation scheme

Notation	Definition
$N_{ch}(i)$	Number of chains for i-th antenna module
$N_{UL}(i)$	Number of chains for uplink transmission of i-th antenna module
$N_{DL}(i)$	Number of chains for downlink reception of i-th antenna module

- UE can choose to either use the same number of chains during the reception and transmission or not.
  - The scheme of $N_{UL} = N_{DL}$ limits the choice of UE operation, but maintains the beam correspondence and thus channel reciprocity.
  - The scheme of $N_{UL} \neq N_{DL}$ is more flexible for UE to adjust the chains according to the power usage, temperature, battery level, channel strength/quality, etc
- In one typical scenario, the UE uses sub chains for transmission but full chains for the reception, i.e., $N_{UL} \leq N_{DL} = N_{ch}$.
  - Transmission consumes much more power than the reception
  - The DL data rate requirement is usually higher than the UL.

Temperature control

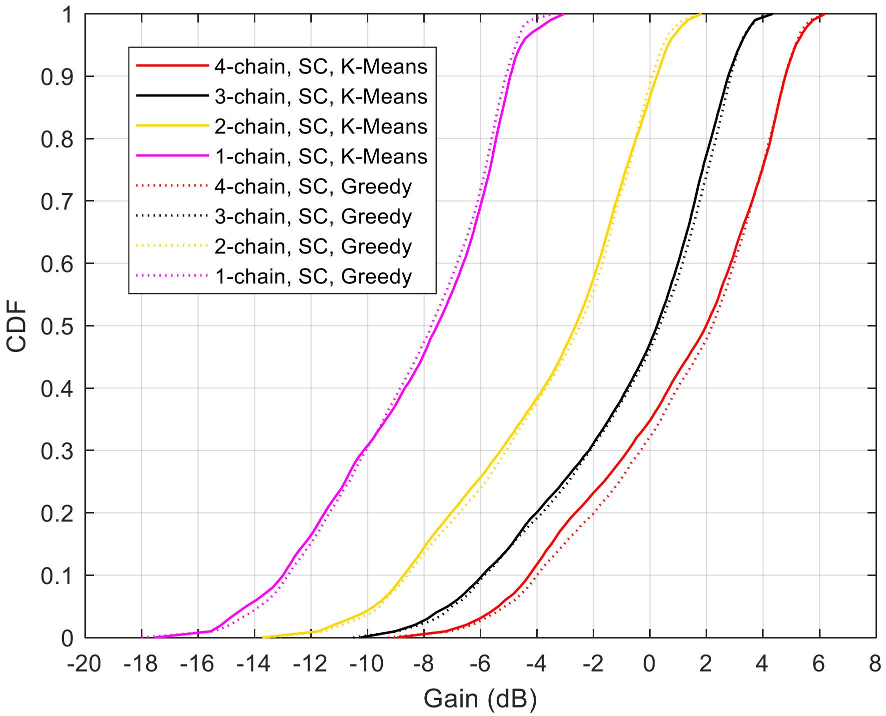
- The UE may gradually reduce the number of chains as the temperature increases.
  - In first option, UE first reduces N_{UL} to the minimum, and then reduces N_{DL} since transmission usually consumes more power than reception.
    - UE can set $[N_{DL}, N_{UL}] = [5\ 5] \rightarrow [5\ 4] \rightarrow [5\ 3] \rightarrow [5\ 2] \rightarrow [5\ 1] \rightarrow [4\ 1] \rightarrow [3\ 1] \rightarrow [2\ 1] \rightarrow [1\ 1]$ as the temperature increase.
  - In the second option, UE iteratively reduces N_{UL} and N_{DL}. For example, $[N_{DL}, N_{UL}] = [5\ 5] \rightarrow [5\ 4] \rightarrow [4\ 4] \rightarrow [4\ 3] \rightarrow [3\ 3] \rightarrow [3\ 2] \rightarrow [2\ 2] \rightarrow [2\ 1] \rightarrow [1\ 1]$.

Other considerations of sub-chain beam operation

- Signal strength/quality
- Battery level
- Maximum permissible exposure (MPE)
- Beam sweeping during the change of chains
- Beam management parameter adjustment for sub-chain beam codebook
- Per-module sub-chain control
- Beam measurement table update when changing the number of chains

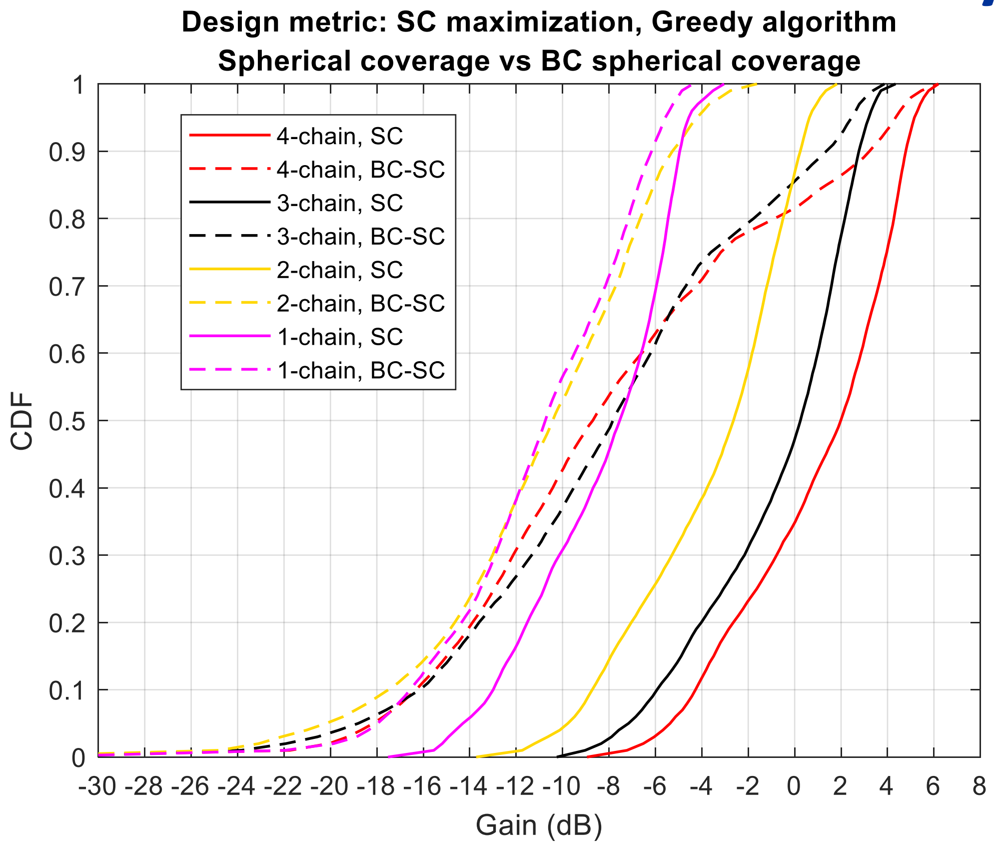
Spherical coverage maximization codebook by Greedy algorithm

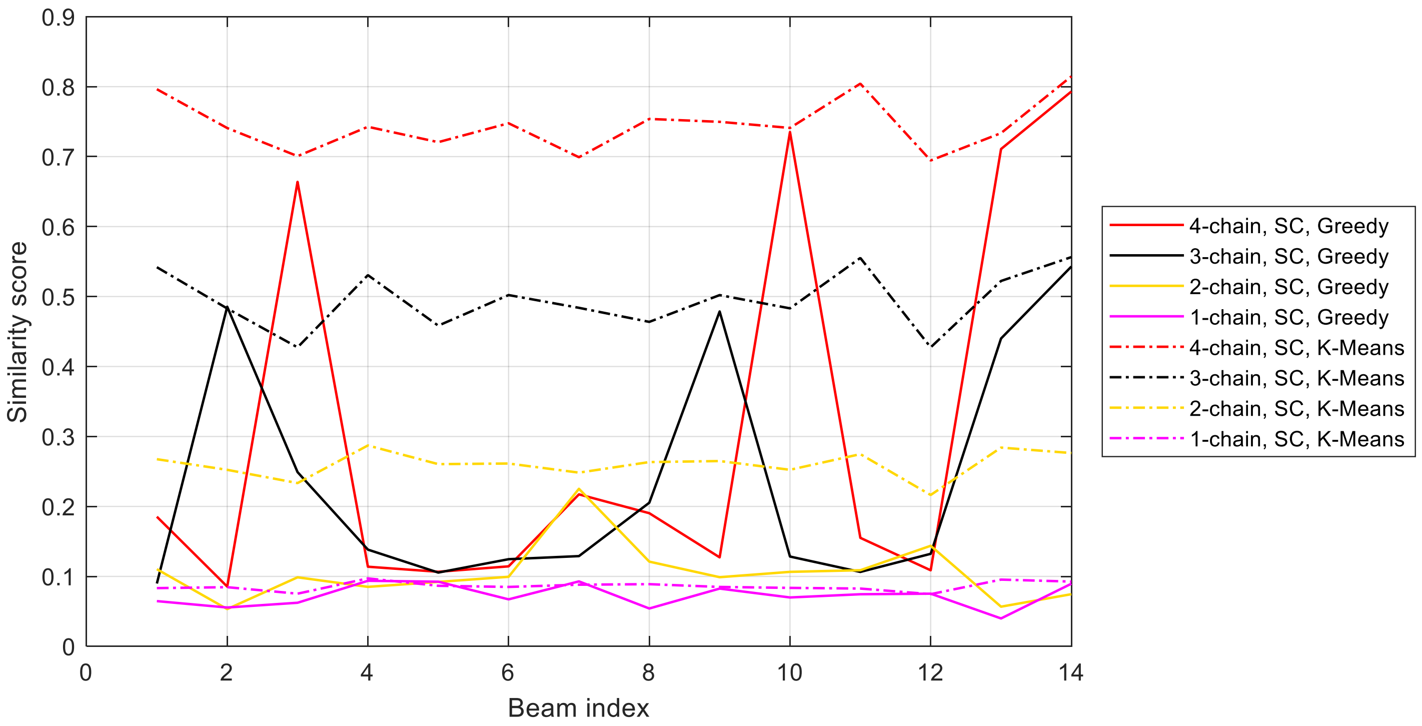
SC-maximization codebook by Greedy algorithm



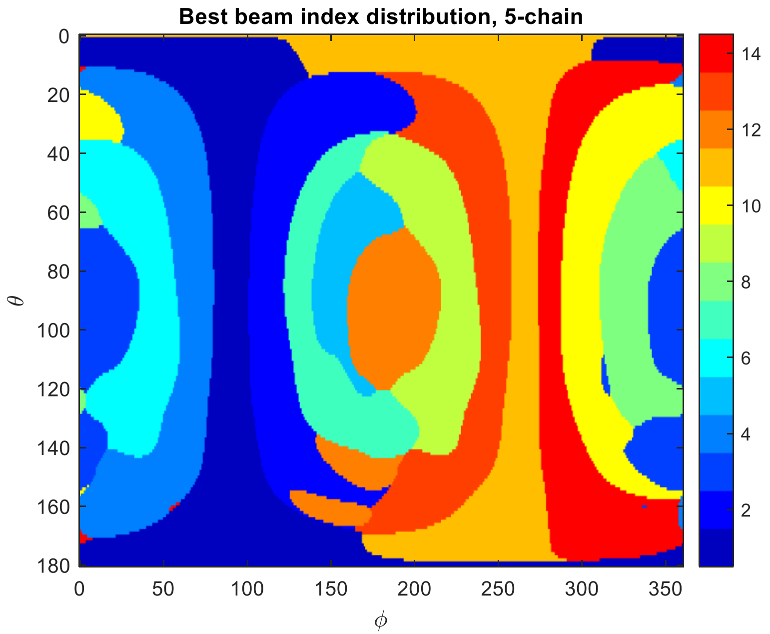
- We provide an example sub-chain codebook without good mapping to full-chain codebook.
- Design the sub-chain codebook maximizing the spherical coverage by **Greedy algorithm**.
  - There is no similarity/mapping considered in the design.
  - Simply map the full-chain and sub-chain based on the beam index.
- The spherical coverage of the Greedy algorithm is comparable with that of K-Means algorithm.

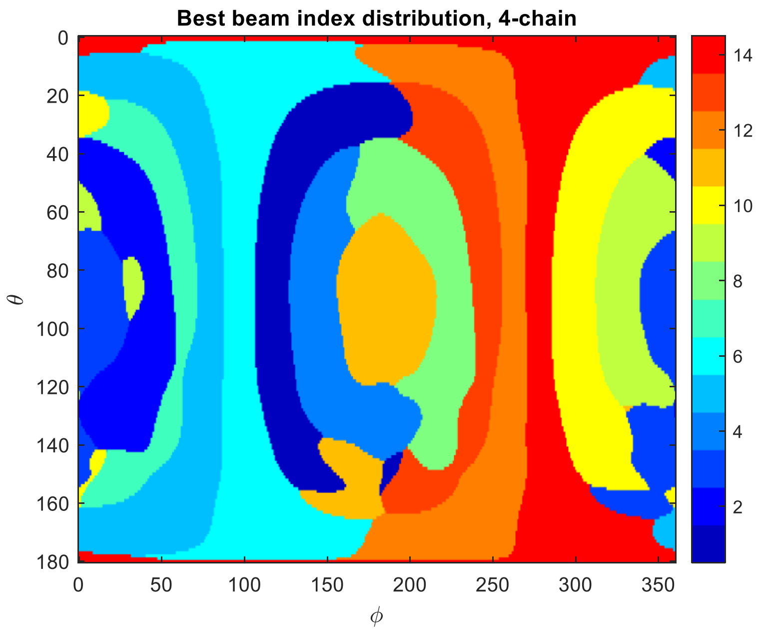
SC-maximization codebook by Greedy algorithm

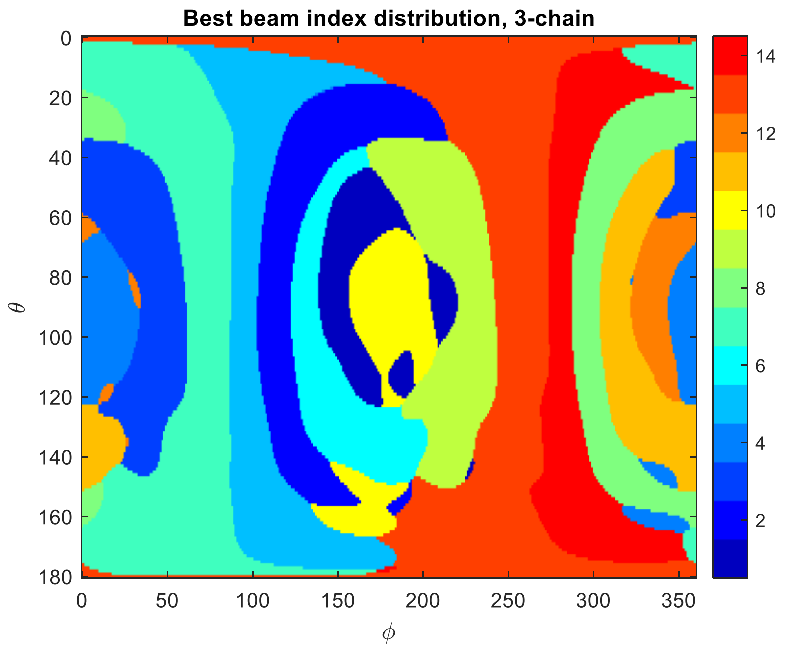


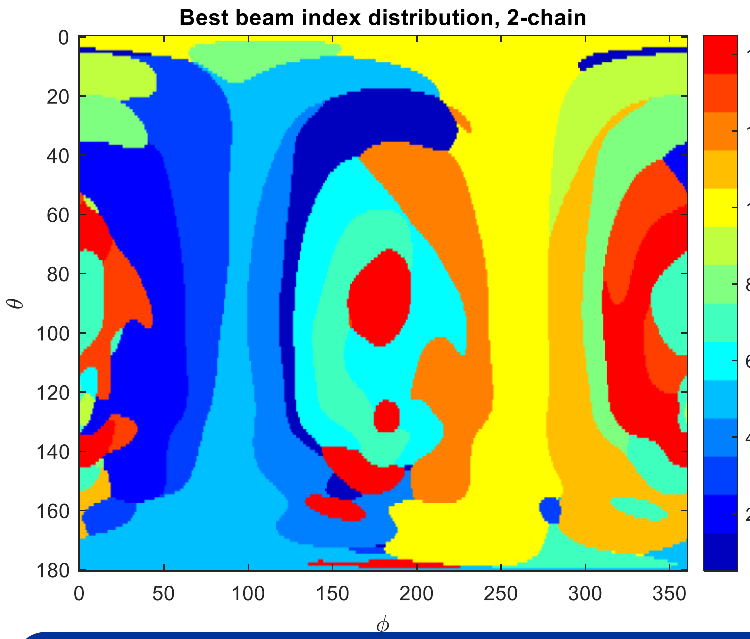


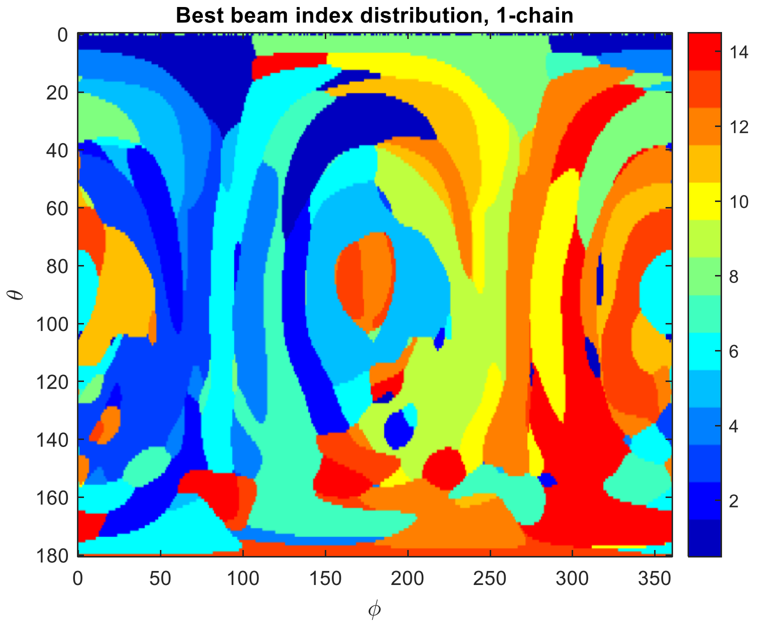
- The BC spherical coverage of the codebook by Greedy algorithm is really bad since the mapping is bad.
- The similarity score is also smaller than the K-Means algorithm.





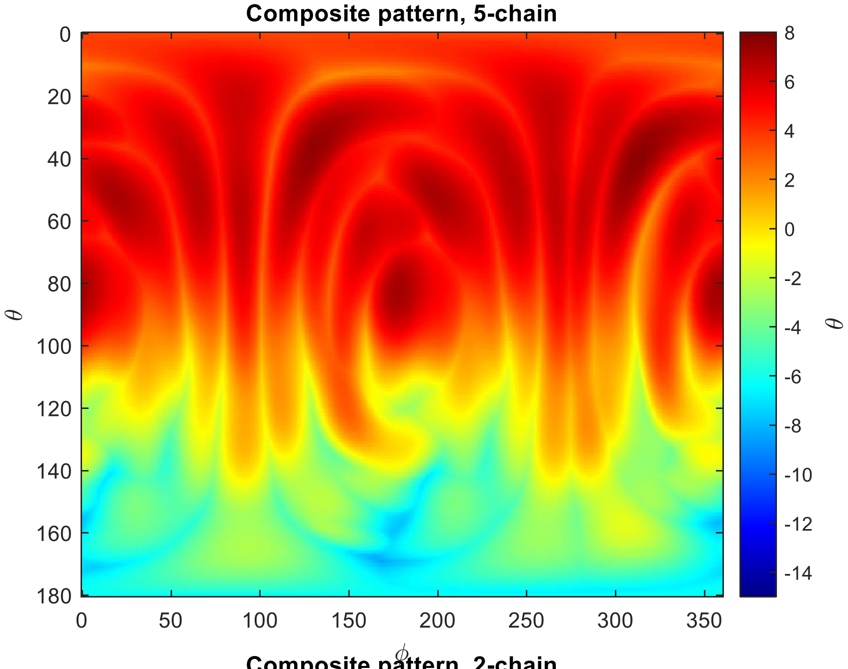


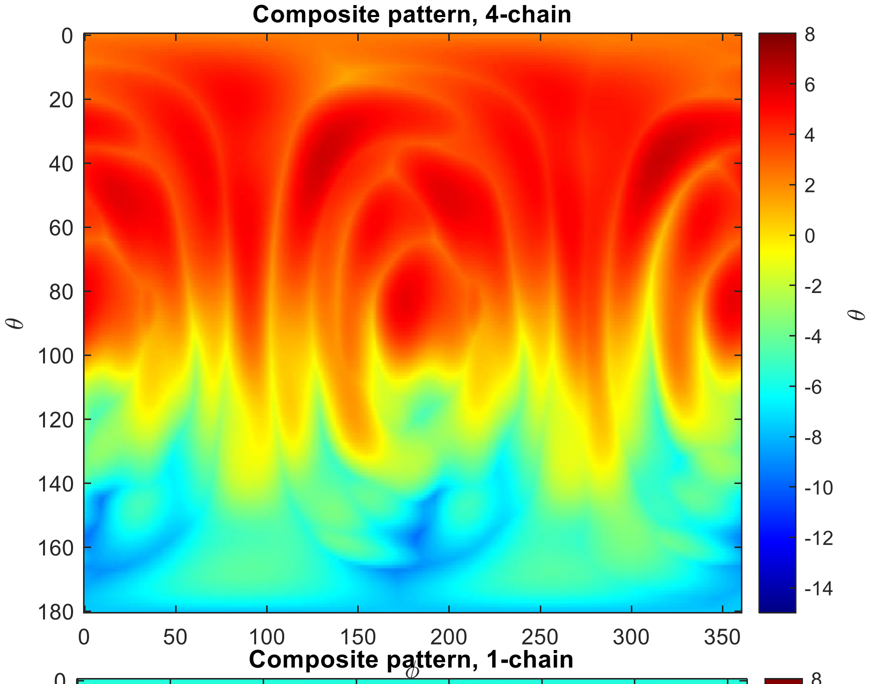


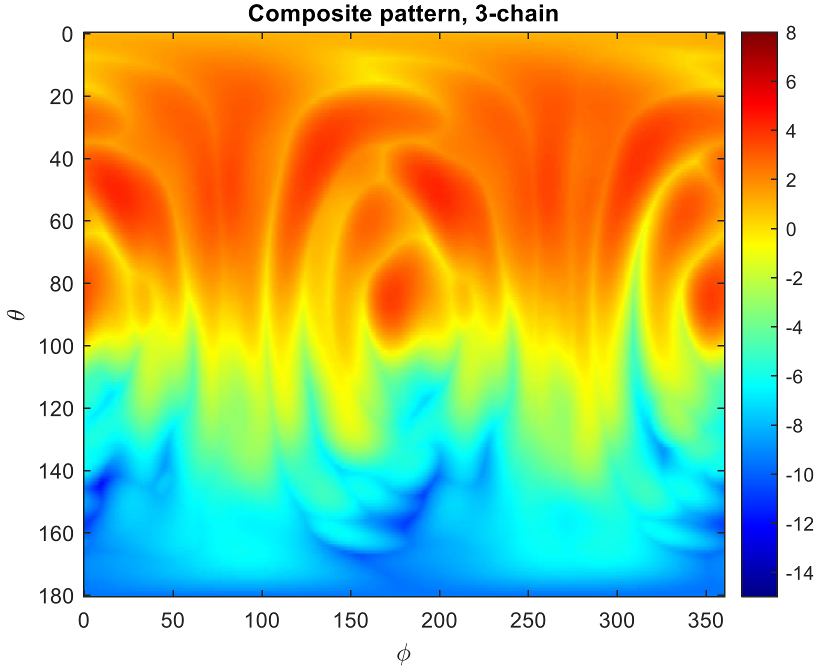


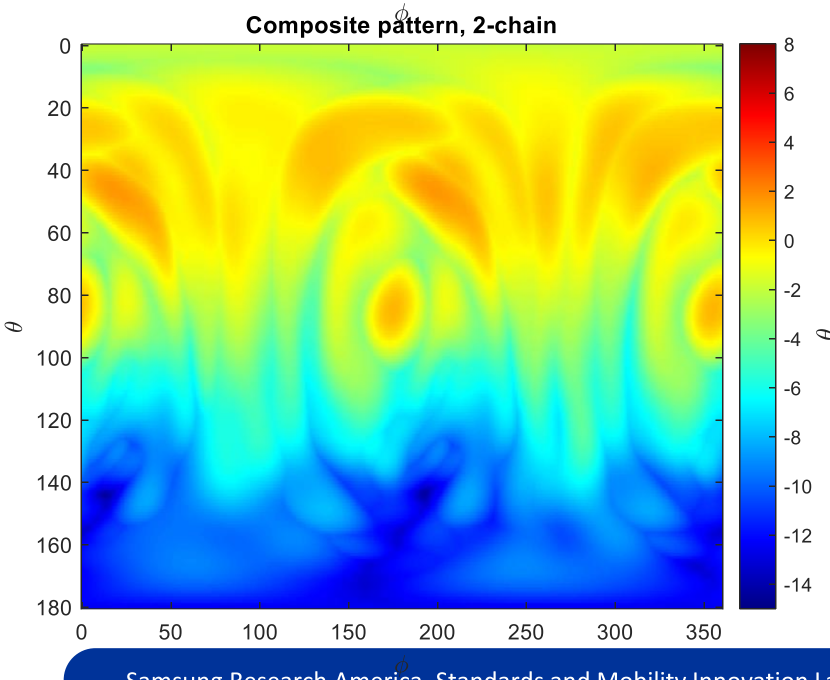
- SC maximization, Greedy algorithm
- Note that the beam distribution of sub-chain codebook is quite different from the full-chain one.

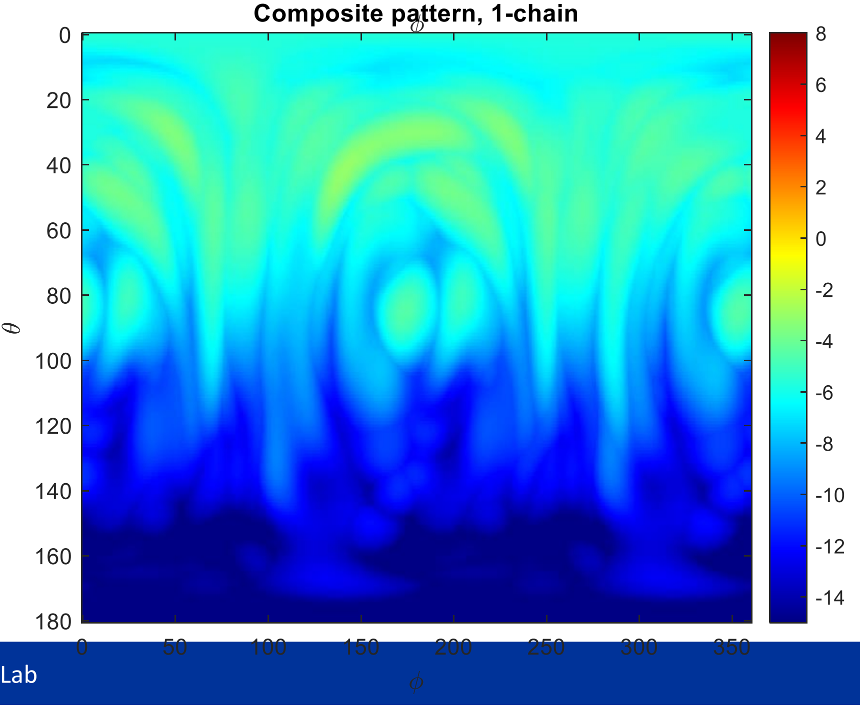
Appendix: Radiation pattern plots of the three codebooks


Composite pattern, 5-chain
θ
ϕ

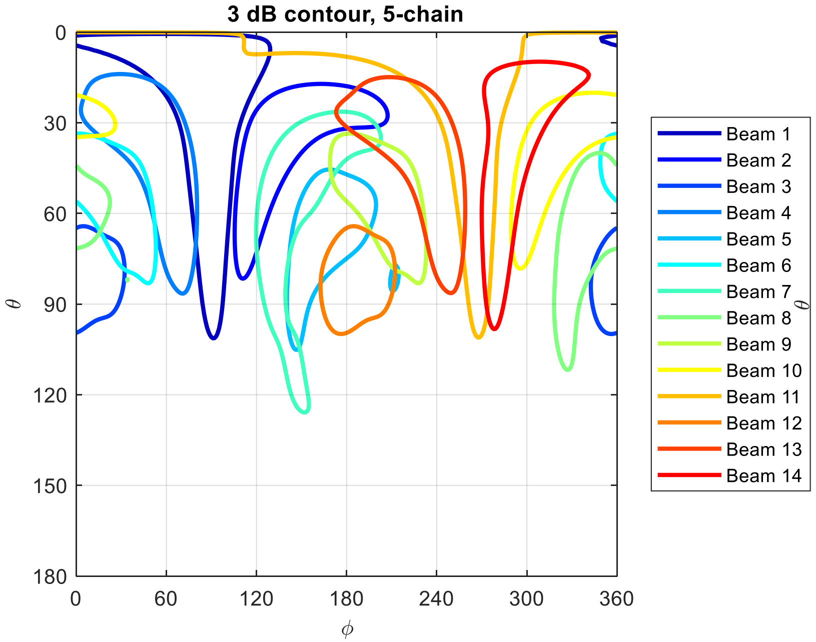

Composite pattern, 4-chain
θ
ϕ

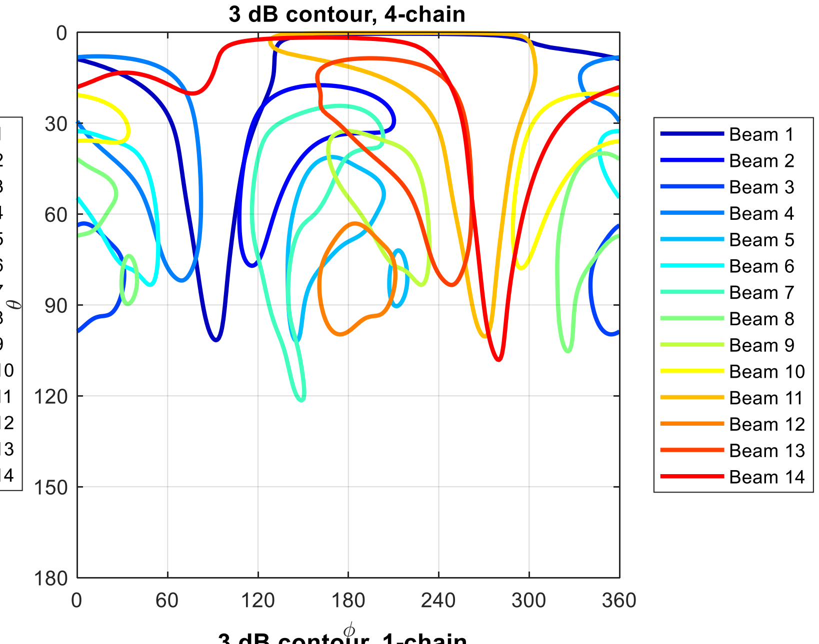

Composite pattern, 3-chain
θ
ϕ

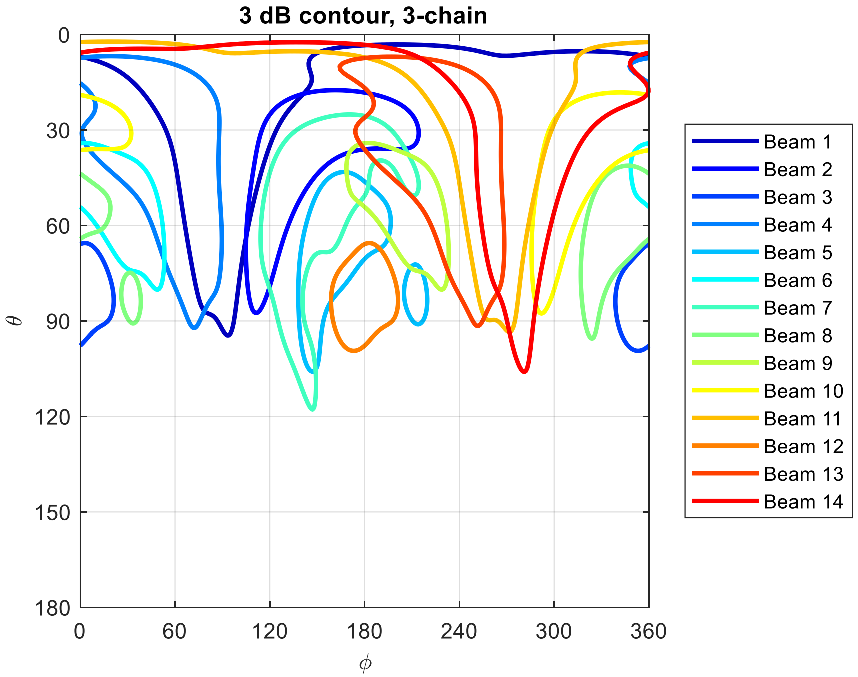

Composite pattern, 2-chain
θ
ϕ

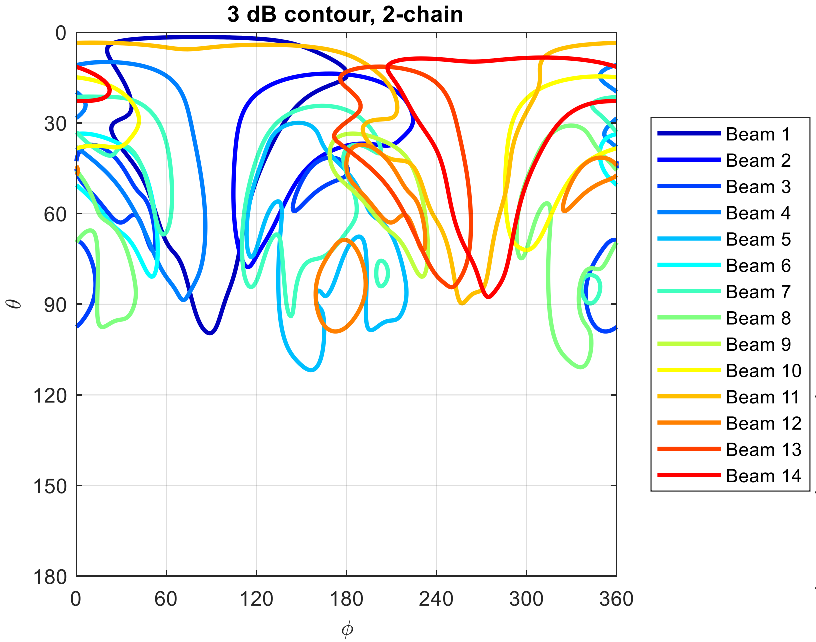

Composite pattern, 1-chain
θ
ϕ

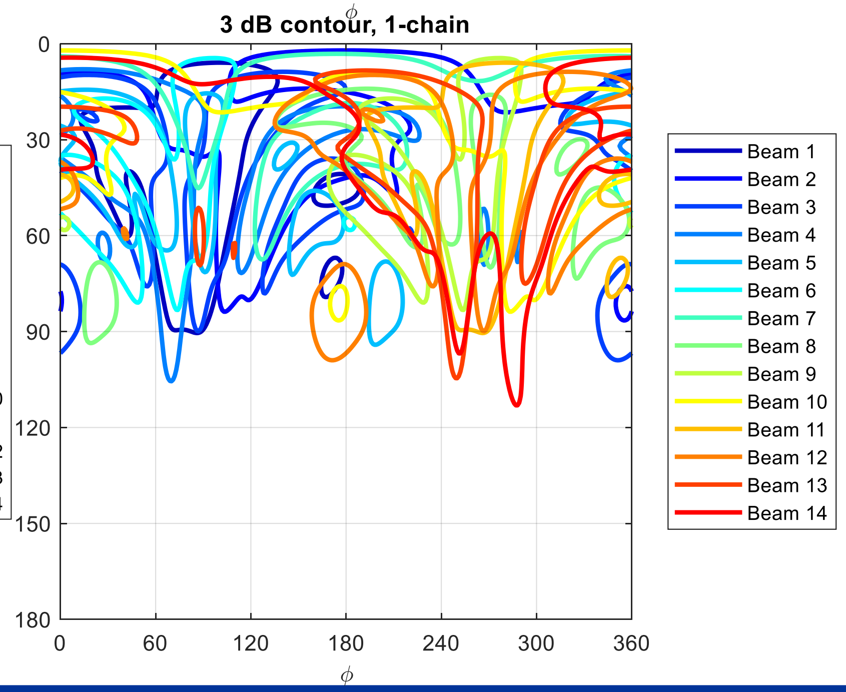
- Similarity


3 dB contour, 5-chain
0
30
60
90
120
150
180
θ
0
60
120
180
240
300
360
ϕ
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
Beam 8
Beam 9
Beam 10
Beam 11
Beam 12
Beam 13
Beam 14

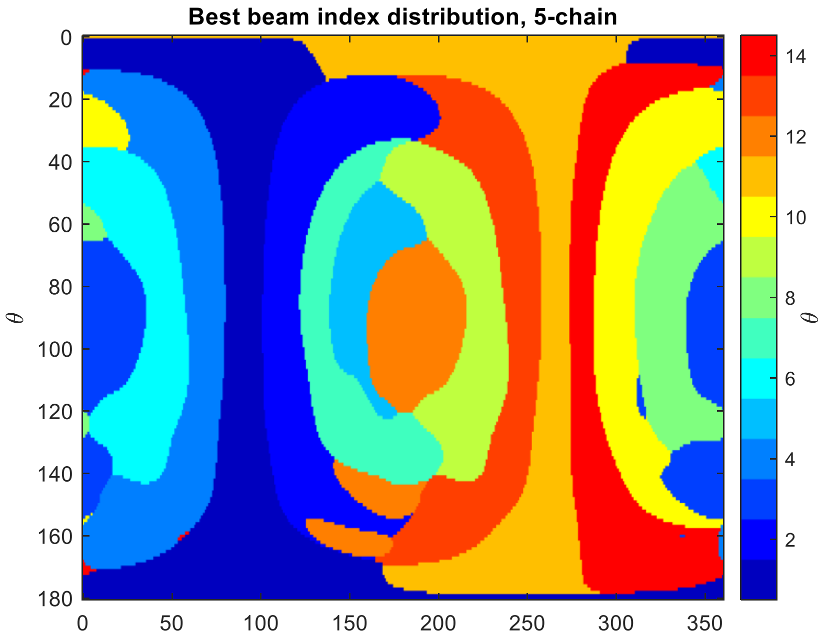

3 dB contour, 4-chain
0
30
60
90
120
150
180
θ
0
60
120
180
240
300
360
ϕ
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
Beam 8
Beam 9
Beam 10
Beam 11
Beam 12
Beam 13
Beam 14

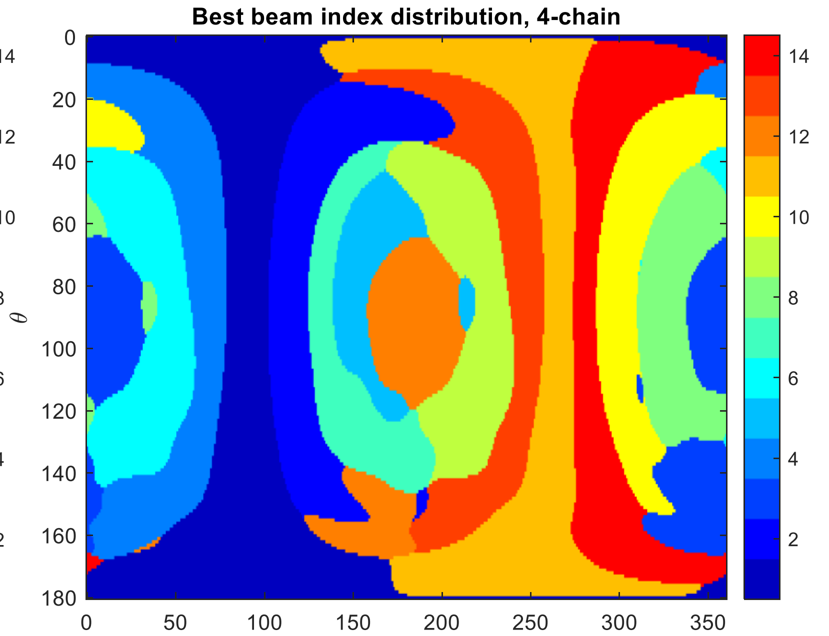

3 dB contour, 3-chain
0
30
60
90
120
150
180
θ
0
60
120
180
240
300
360
ϕ
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
Beam 8
Beam 9
Beam 10
Beam 11
Beam 12
Beam 13
Beam 14

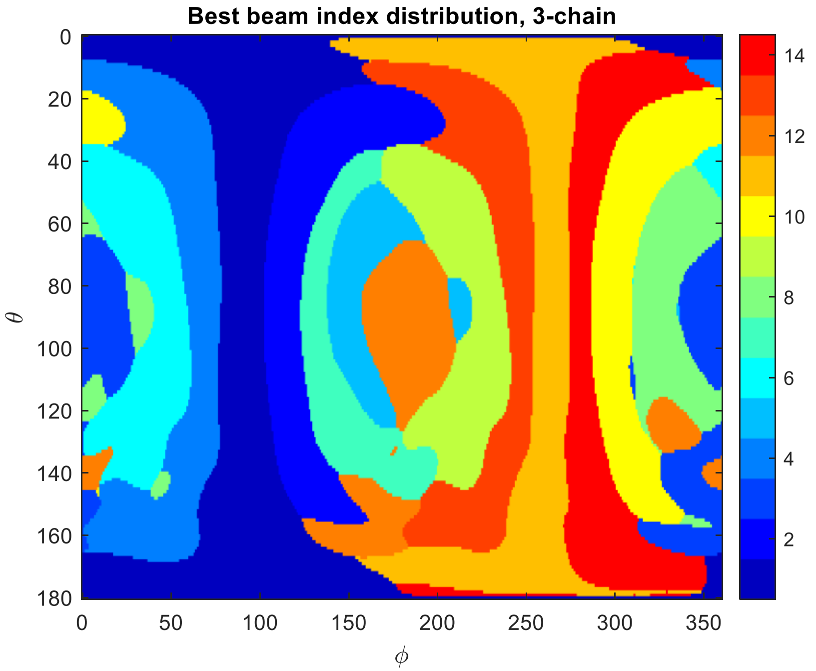

3 dB contour, 2-chain
0
30
60
90
120
150
180
θ
0
60
120
180
240
300
360
ϕ
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
Beam 8
Beam 9
Beam 10
Beam 11
Beam 12
Beam 13
Beam 14

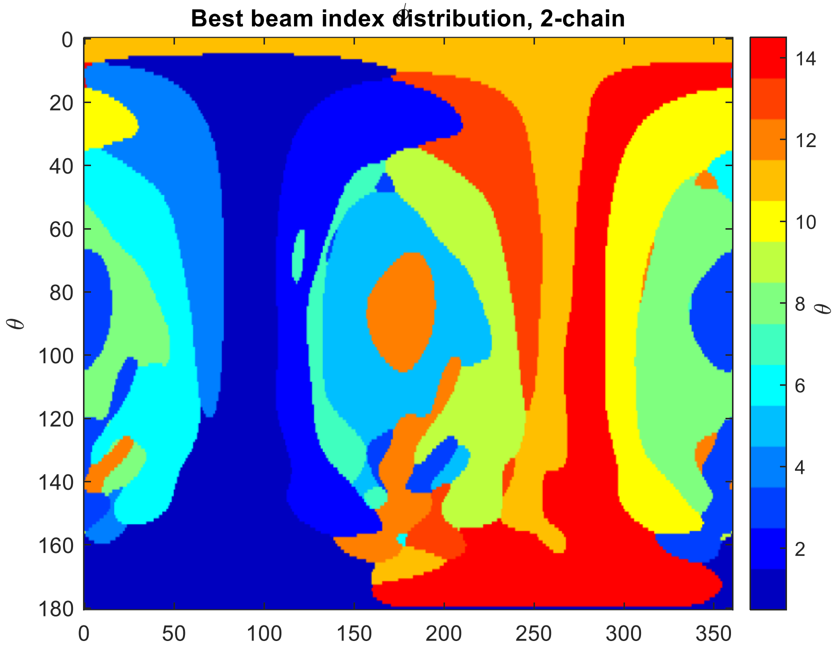

3 dB contour, 1-chain
0
30
60
90
120
150
180
0
60
120
180
240
300
360
ϕ
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
Beam 8
Beam 9
Beam 10
Beam 11
Beam 12
Beam 13
Beam 14

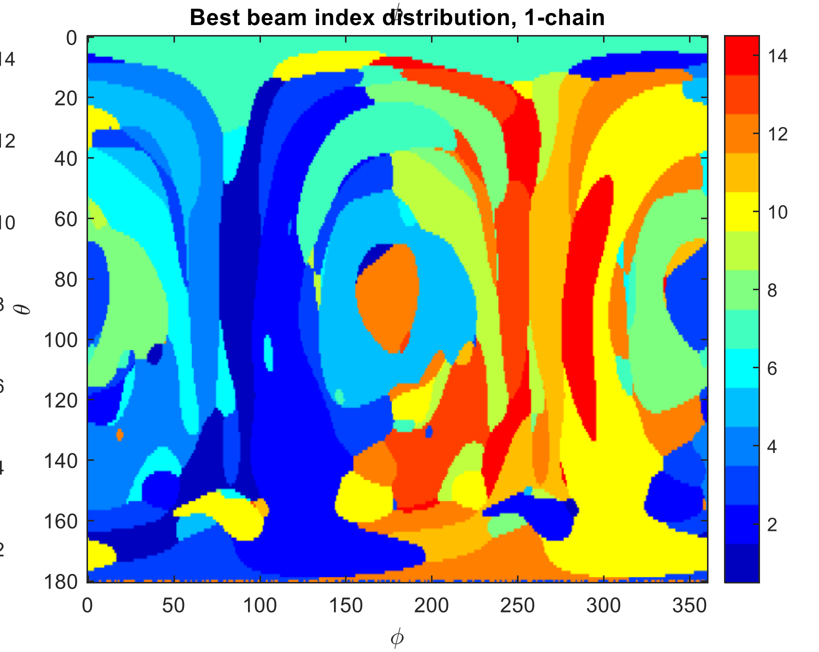
- Similarity


Best beam index distribution, 5-chain
θ
φ

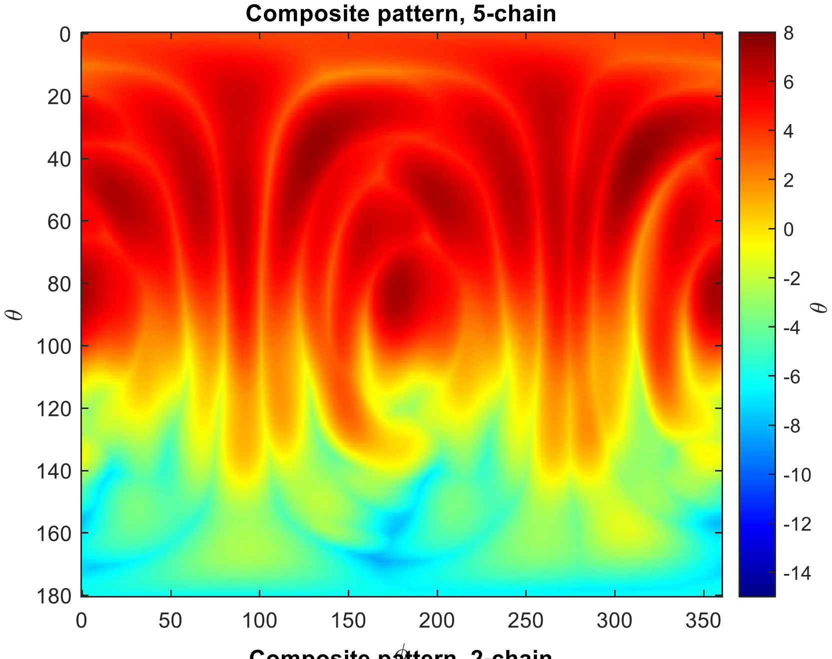

Best beam index distribution, 4-chain
θ
φ

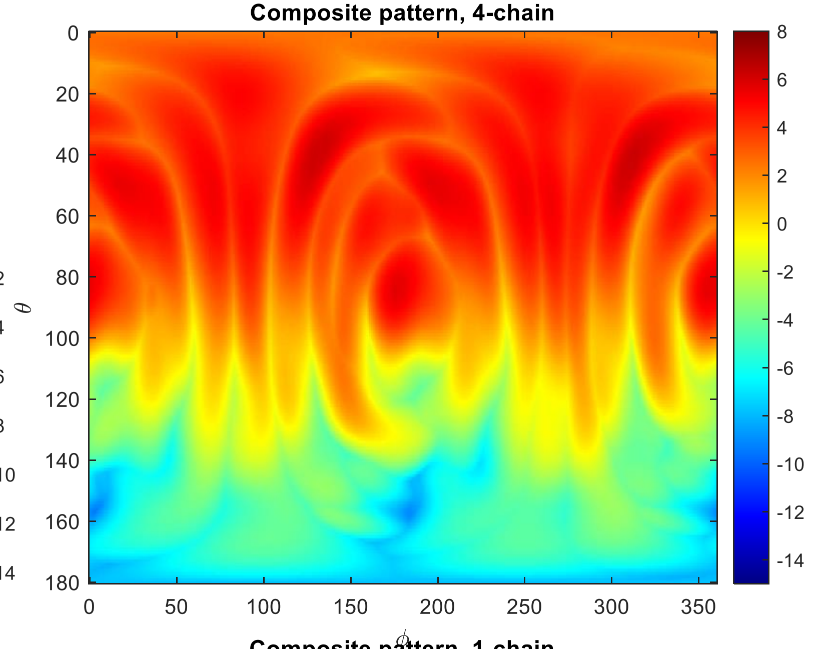

Best beam index distribution, 3-chain
θ
φ

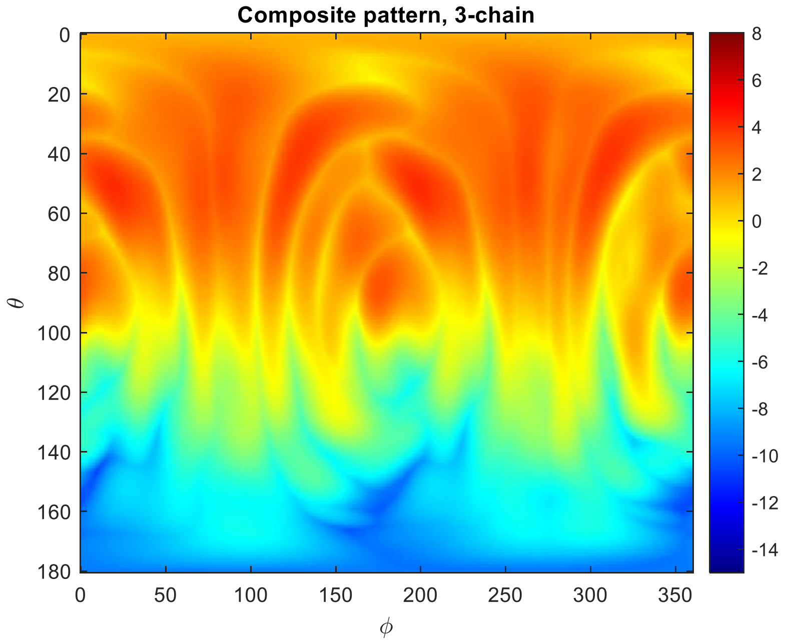

Best beam index distribution, 2-chain
θ
φ

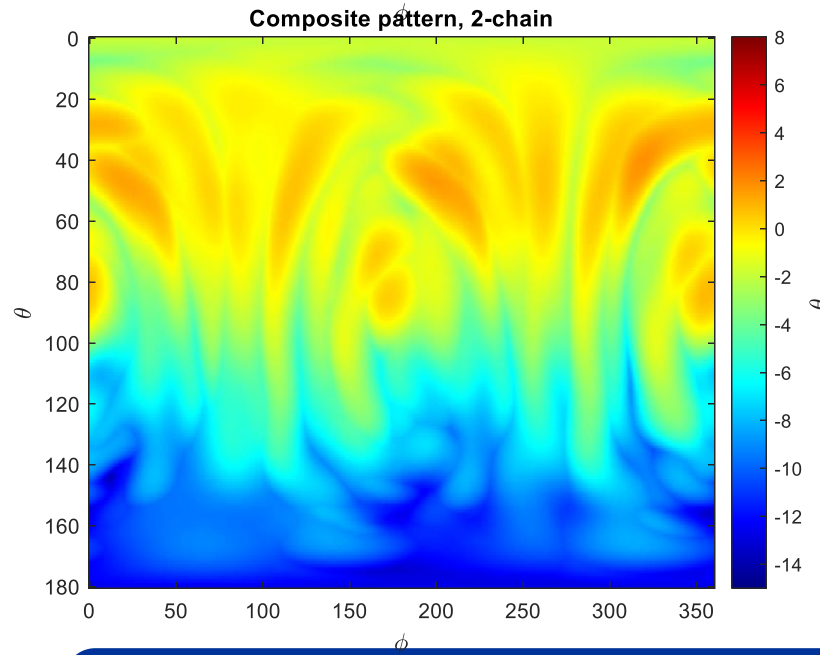

Best beam index distribution, 1-chain
θ
φ

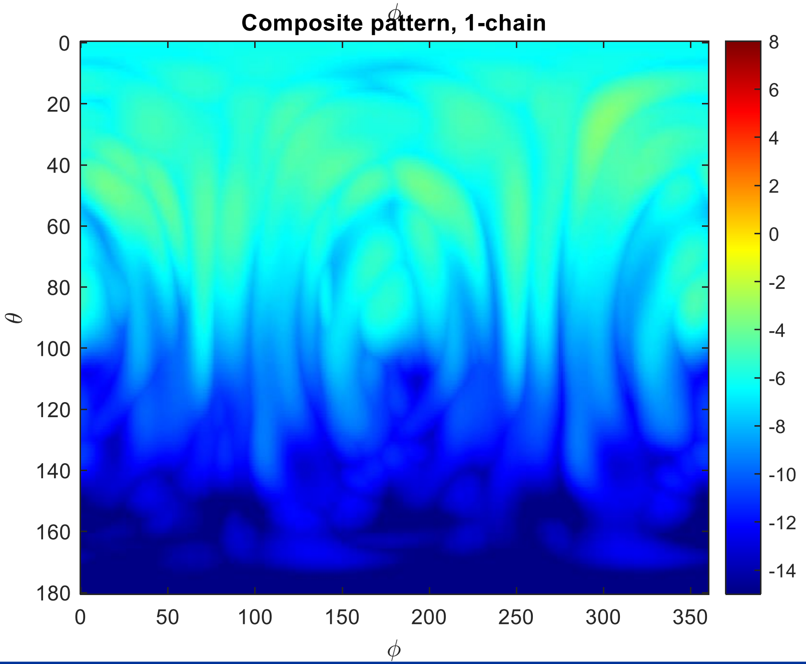
- Similarity



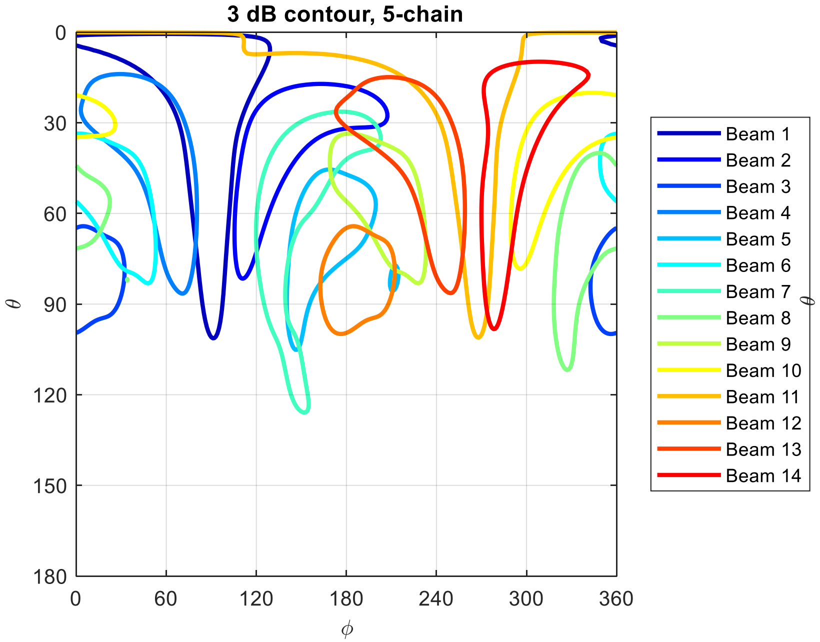


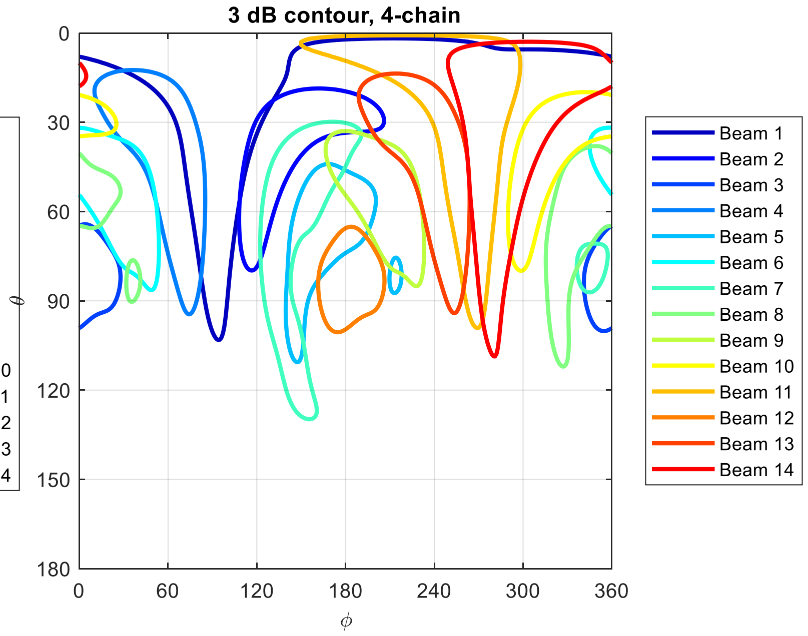


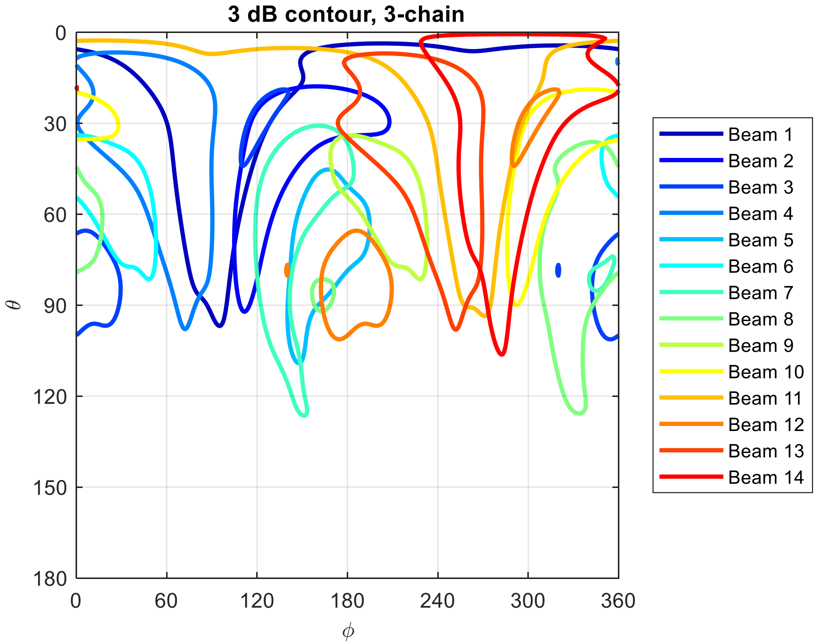


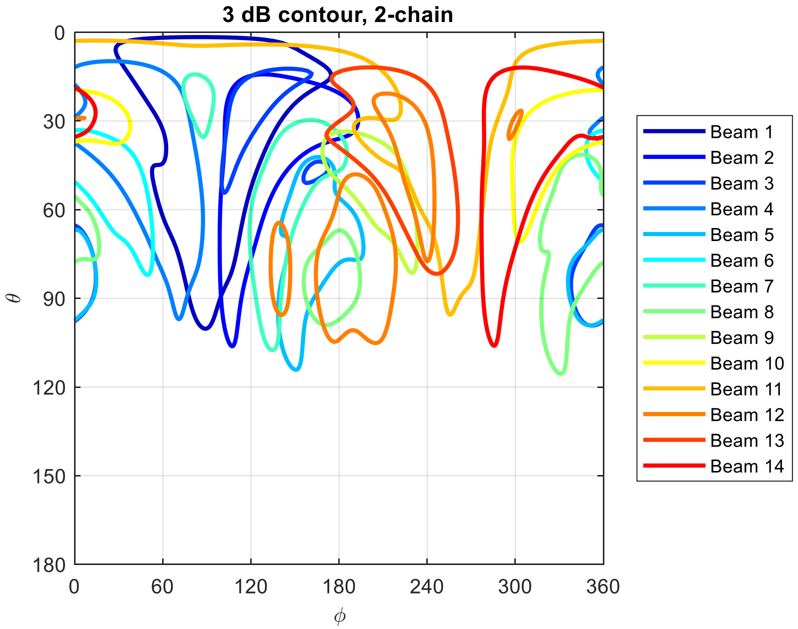


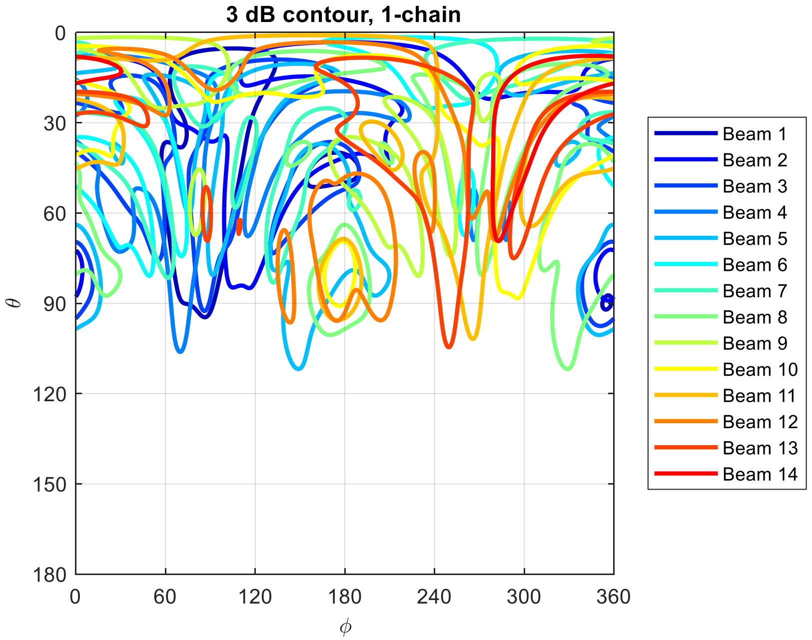
- SC maximization, K-Means algorithm



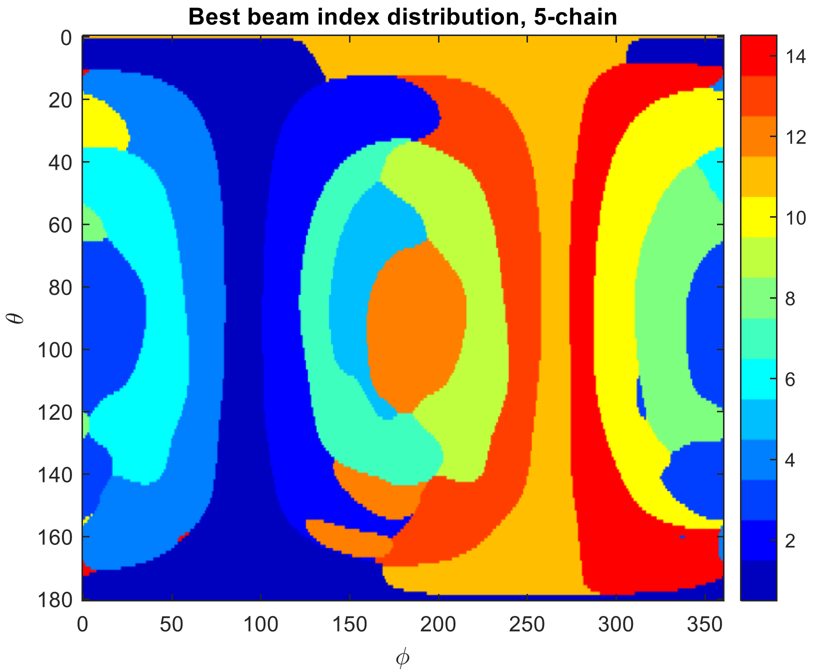


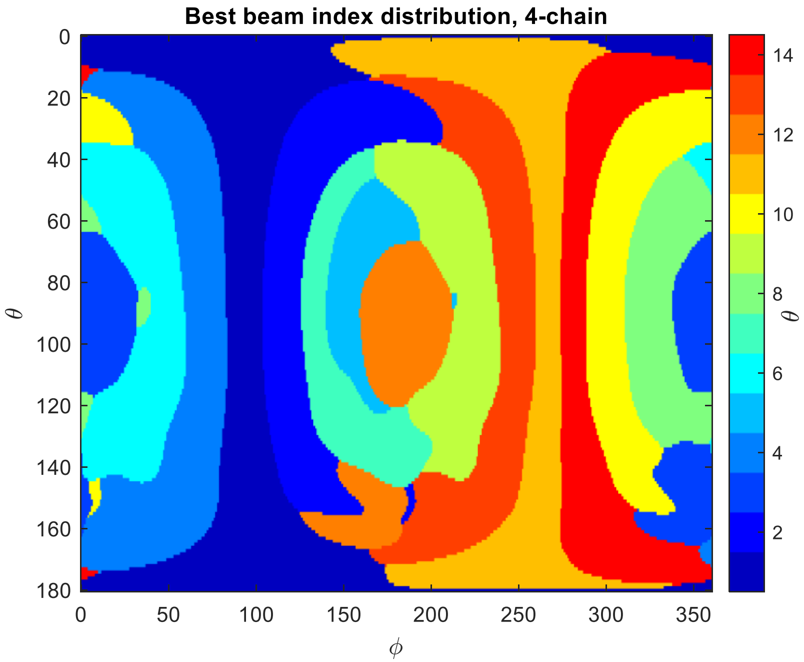


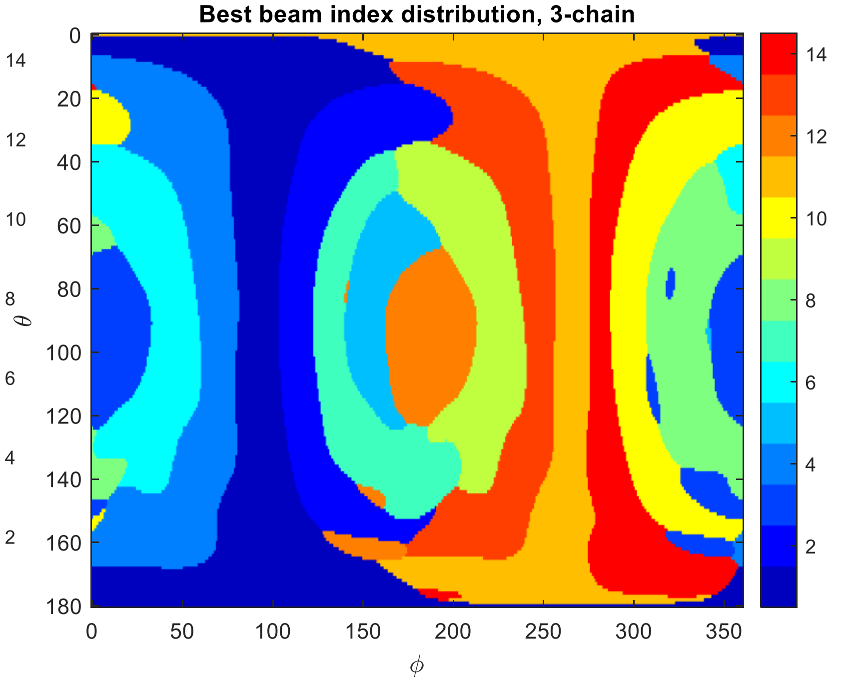


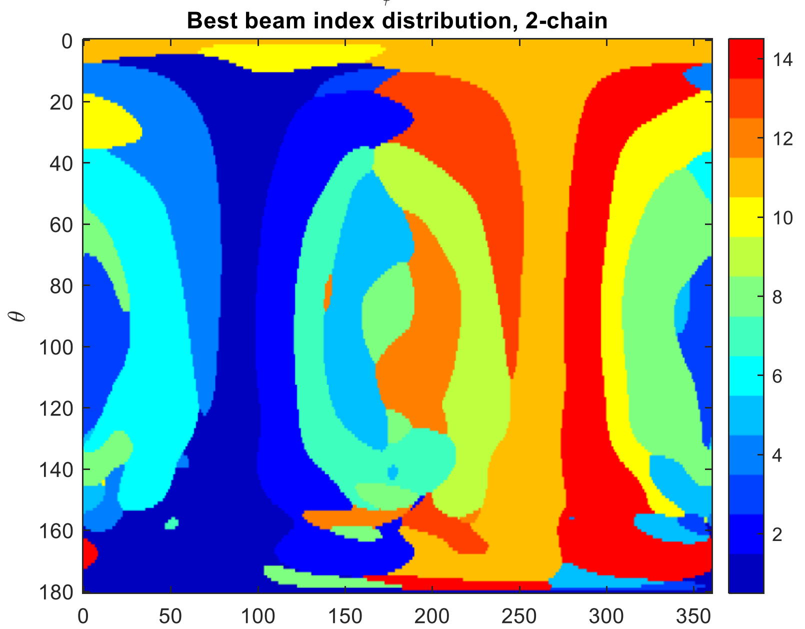


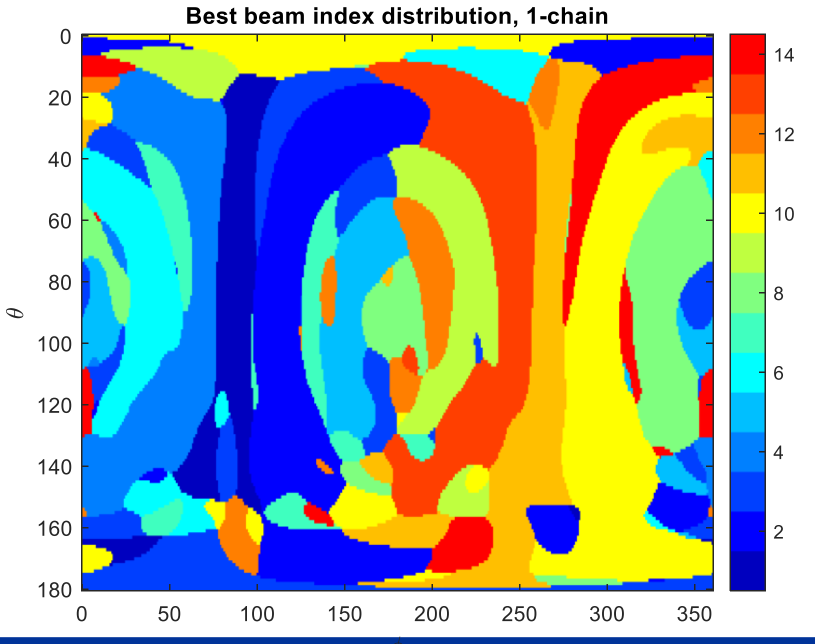
- SC maximization, K-Means algorithm



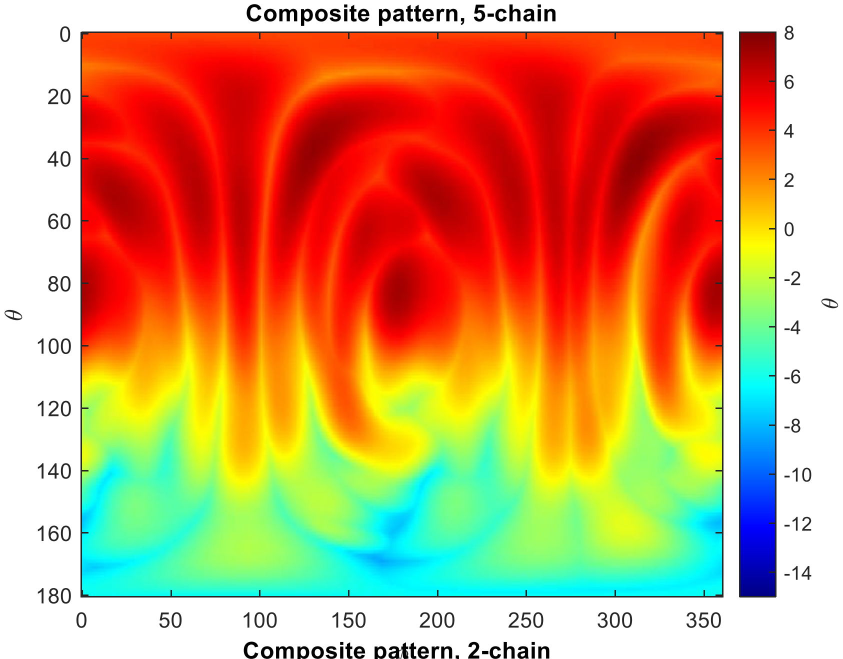


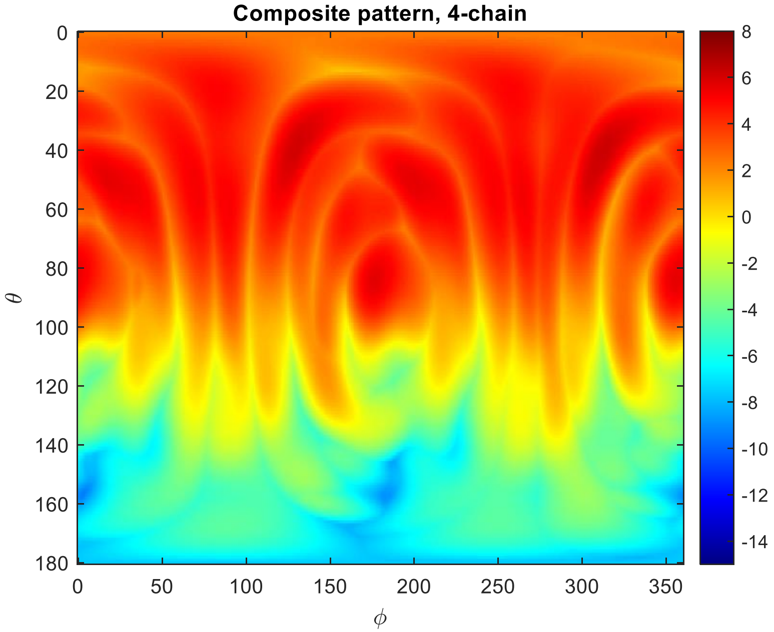


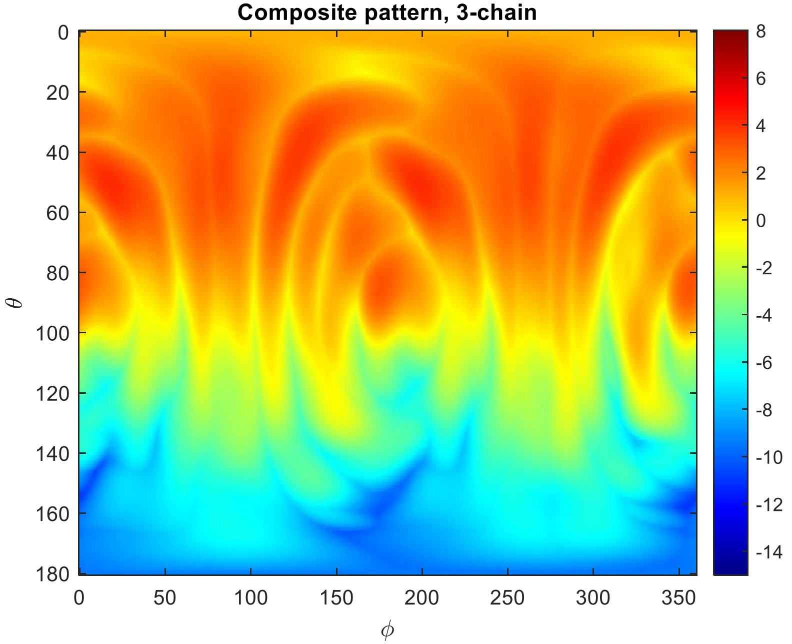


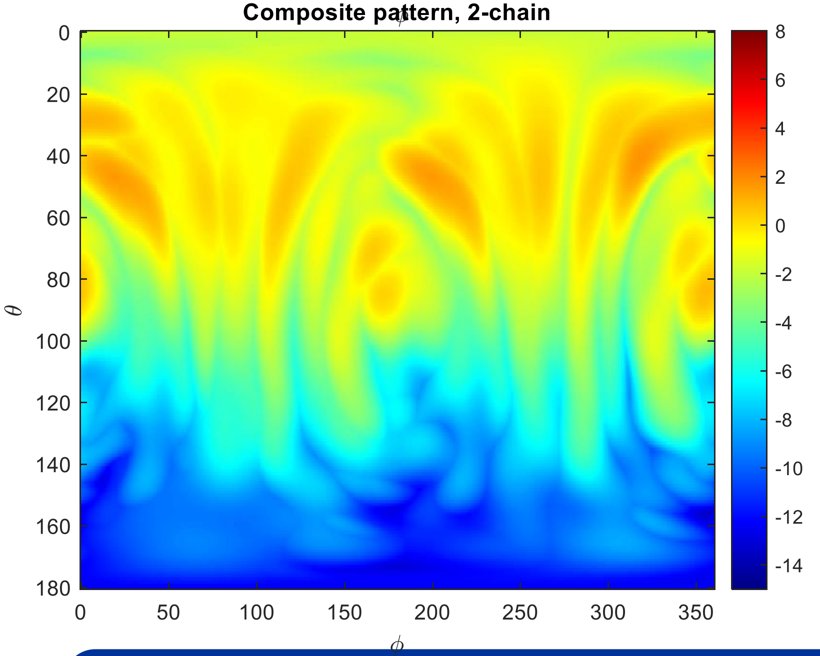


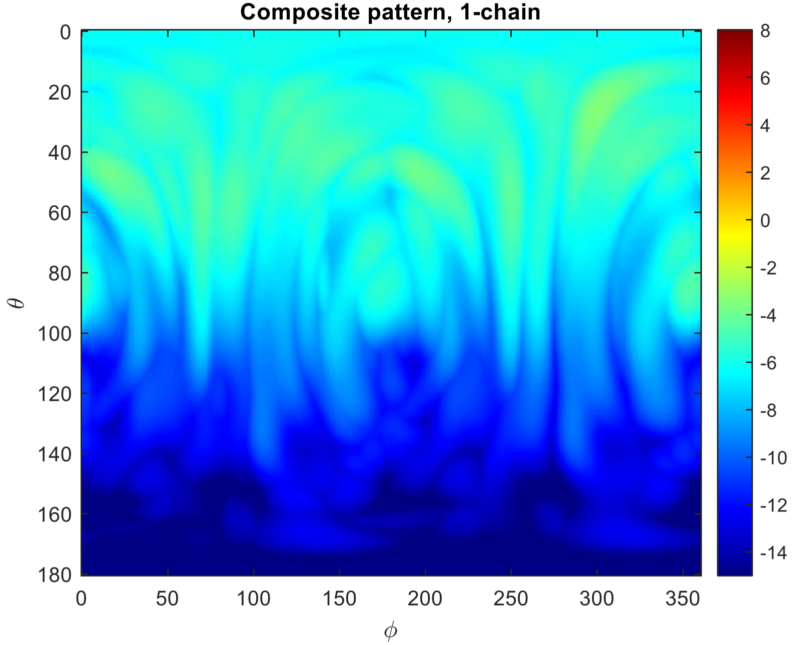
- SC maximization, K-Means algorithm



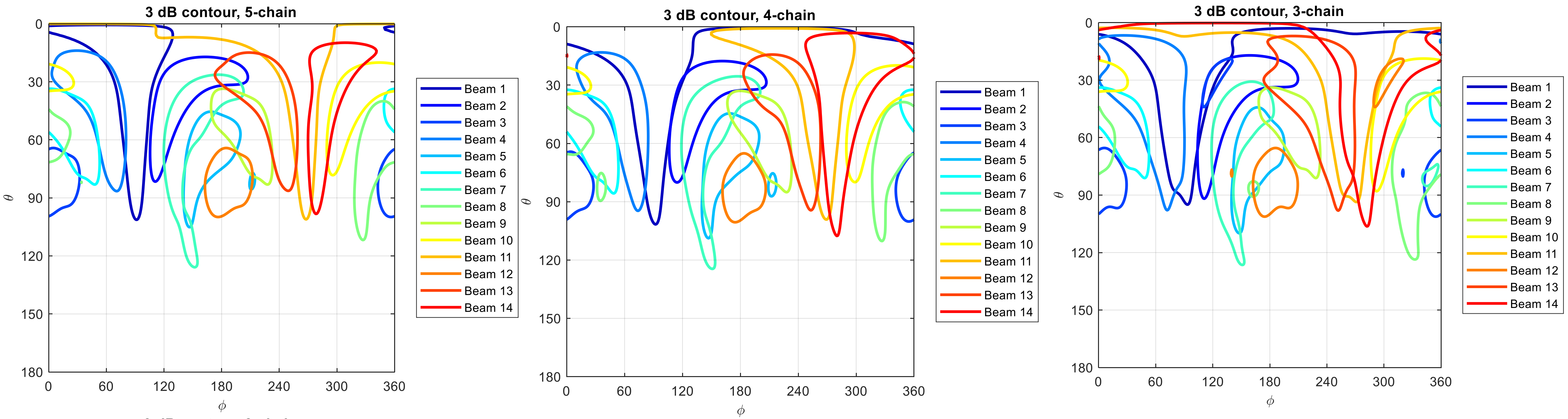


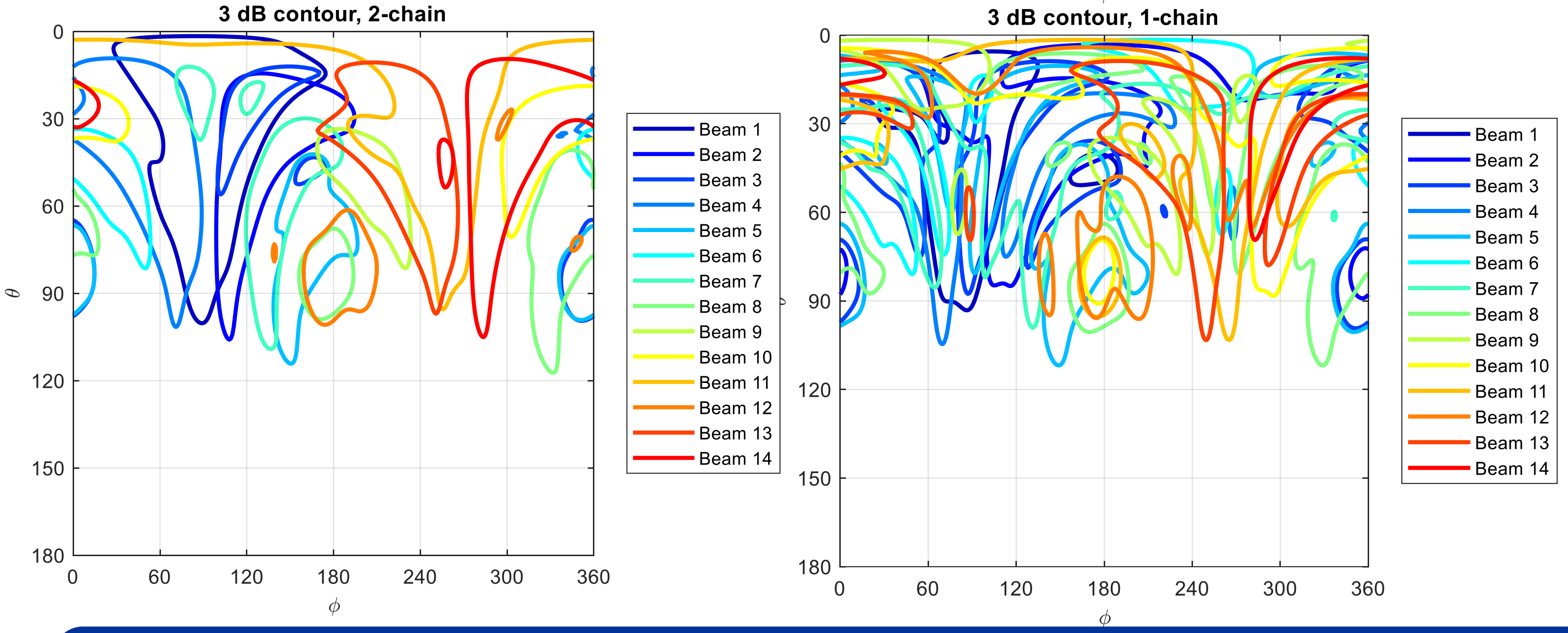




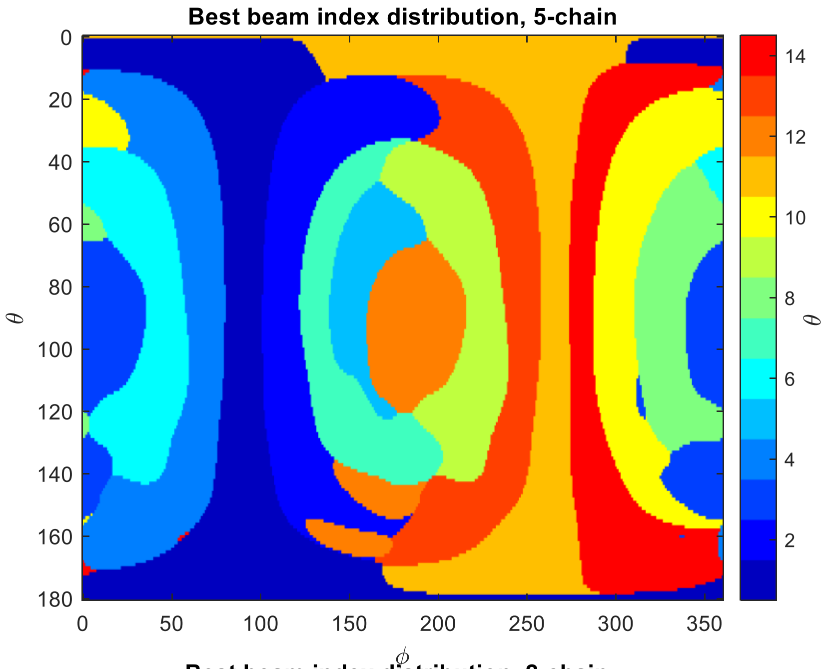


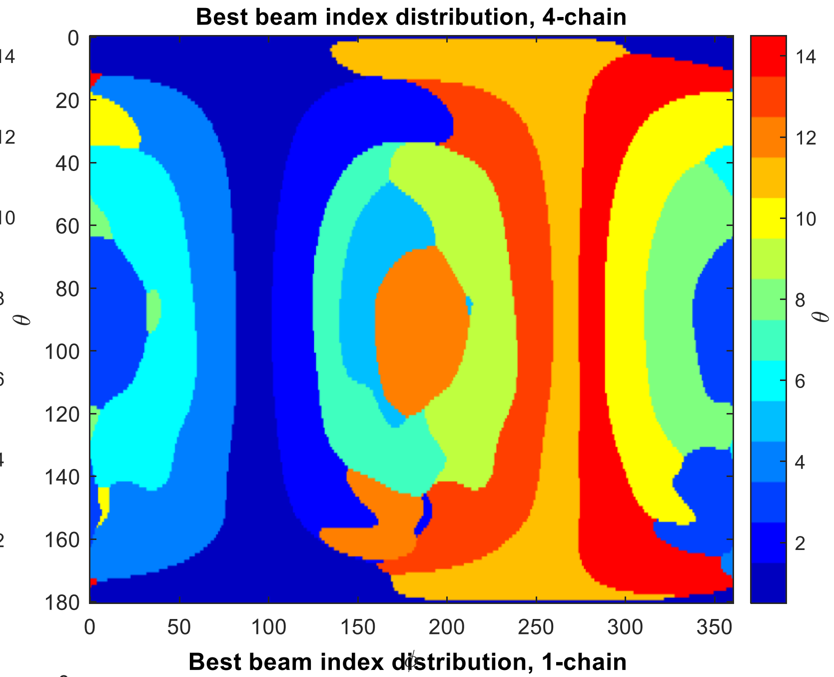
- BC-SC maximization

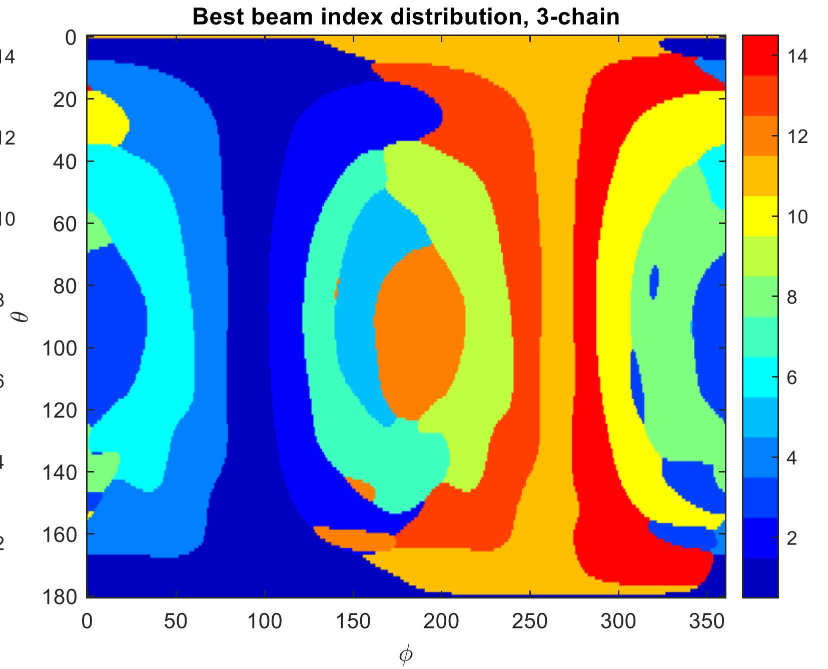


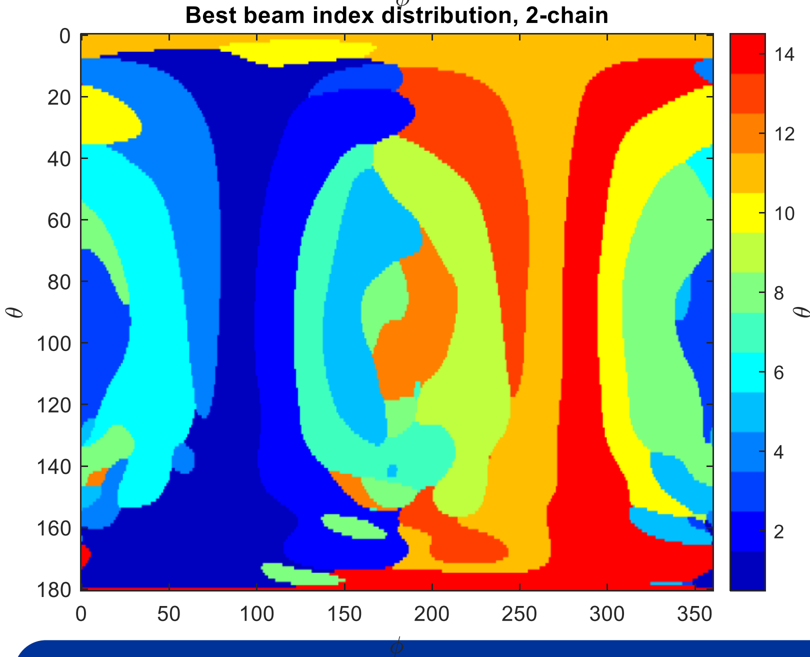


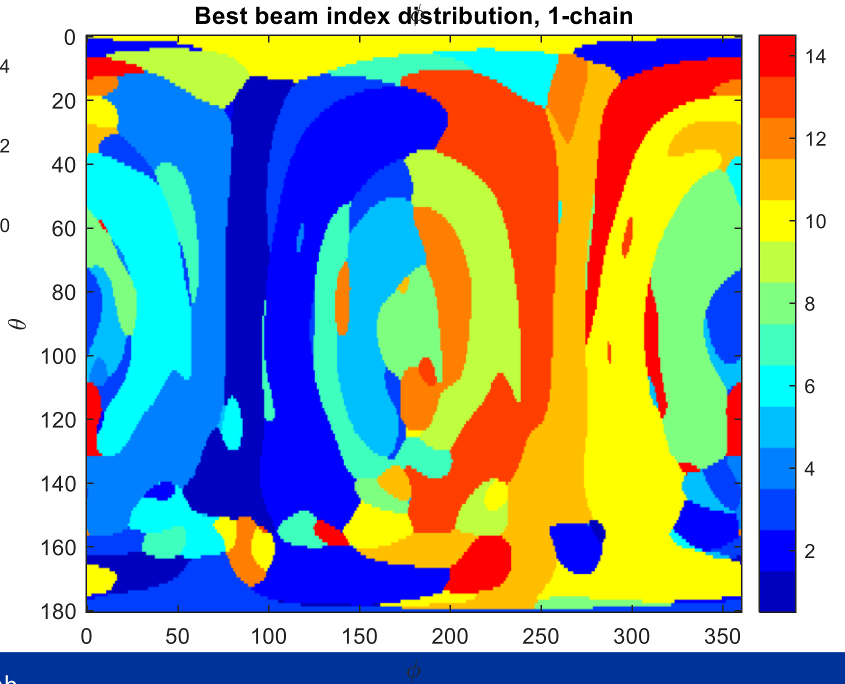
- BC-SC maximization











- BC-SC maximization