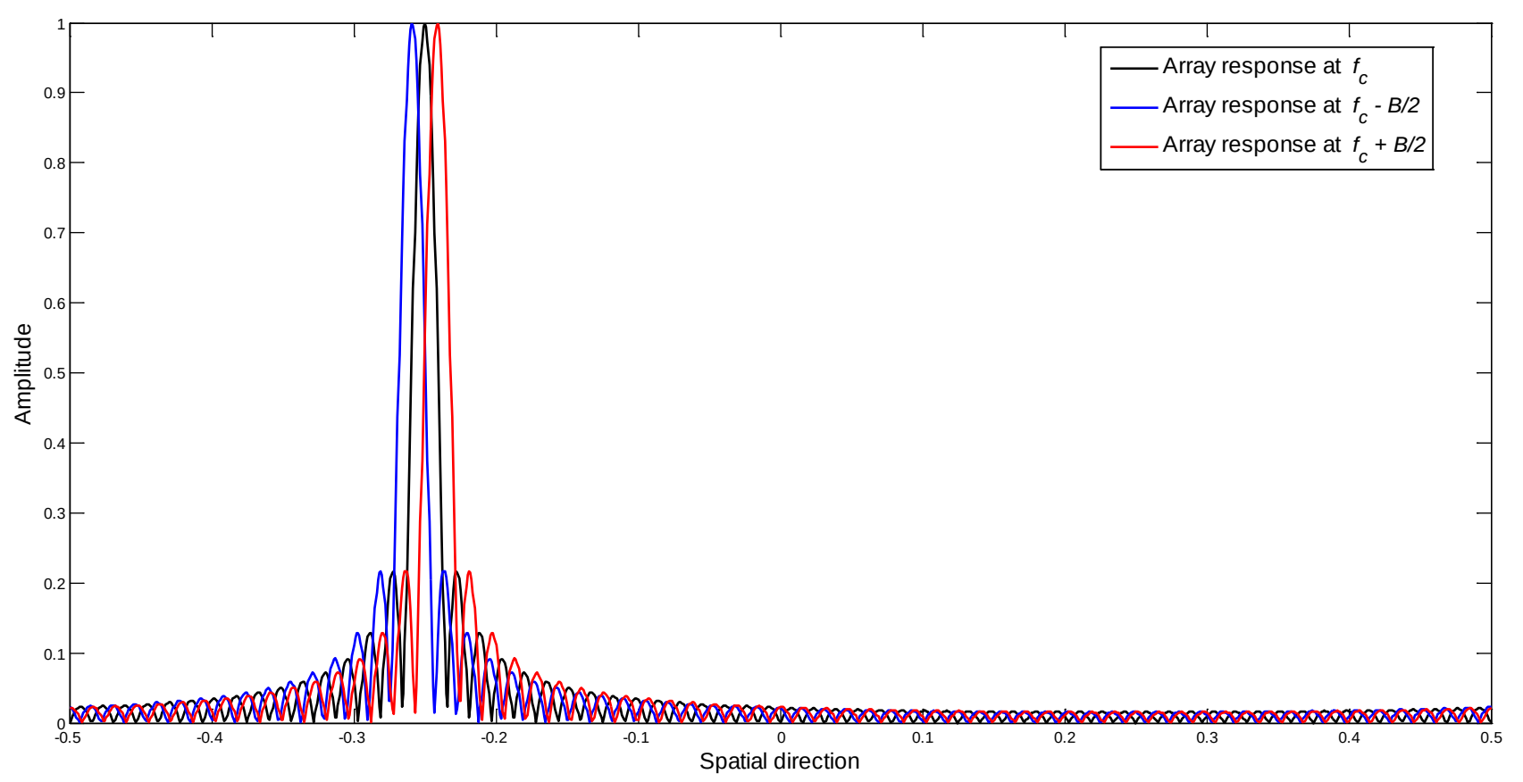
Wideband Millimeter-Wave MIMO Systems with Lens Array: Architecture and Precoding Design

Xinyu Gao[1], Linglong Dai[1], and Akbar M. Sayeed[2]
[1]Department of Electronic Engineering, Tsinghua University, Beijing, China
[2]Department of Electrical and Computer Engineering, University of Wisconsin, Madison, USA

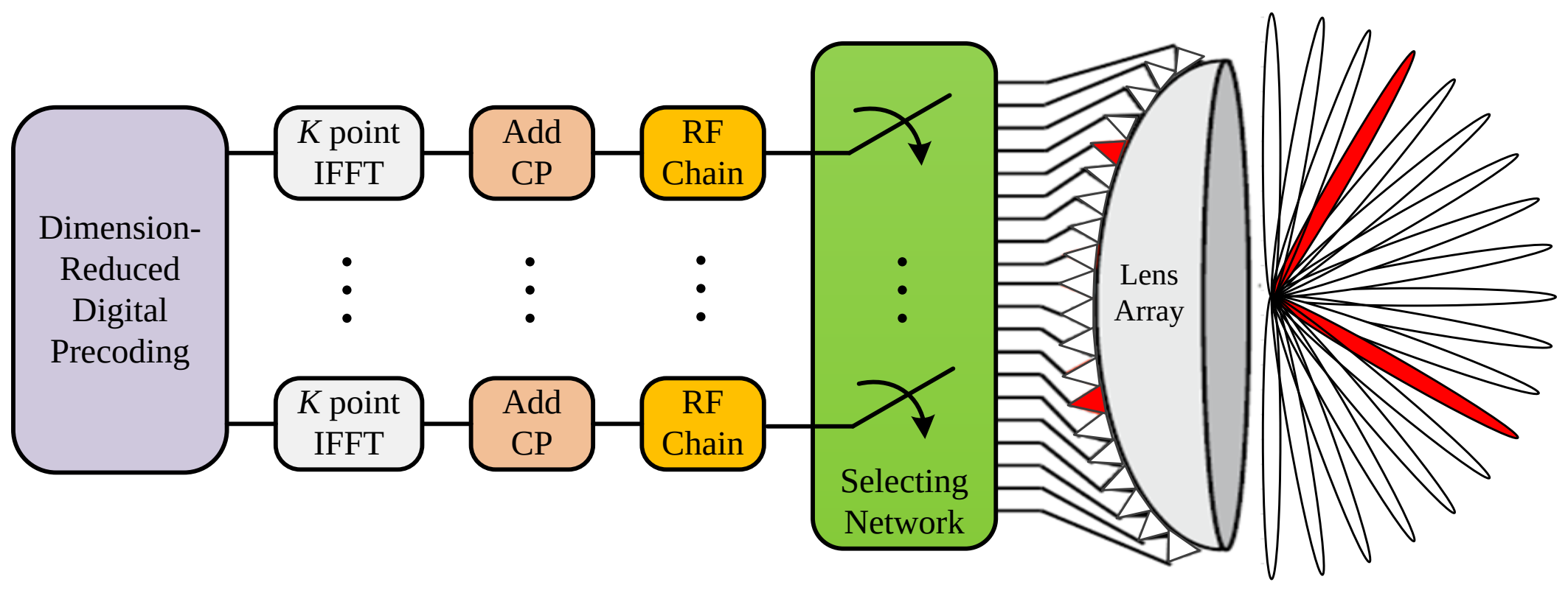
Technical backgroud

Wideband mmWave MIMO with beam squint [1]

- The spatial direction at frequency f is defined as $\varphi(f)=(f/c)d\sin\theta$, where θ is physical direction, c is light speed, and d is antenna spacing designed according to carrier frequency f_c as $d=c/2f_c$, which is fixed among bandwidth B.
- For narrowband mmWave MIMO, $f\approx f_c$ and $\varphi(f)\approx(1/2)\sin\theta$, which is frequency-independent
- For wideband mmWave MIMO, $f\neq f_c$ and $\varphi(f)$ is frequency-dependent. This effect is called as beam squint.



Traditional lens-based mmWave MIMO architecture [2]



- Lens array concentrates mmWave signals from different directions (beams) on different antennas, and transforms the spatial channel into the sparse beamspace channel due to the limited scattering of mmWave communications [1, 2].
- Selecting network is employed to select dominant beams to reduce the MIMO dimension and the number of RF chains without obvious performance loss [1, 2].

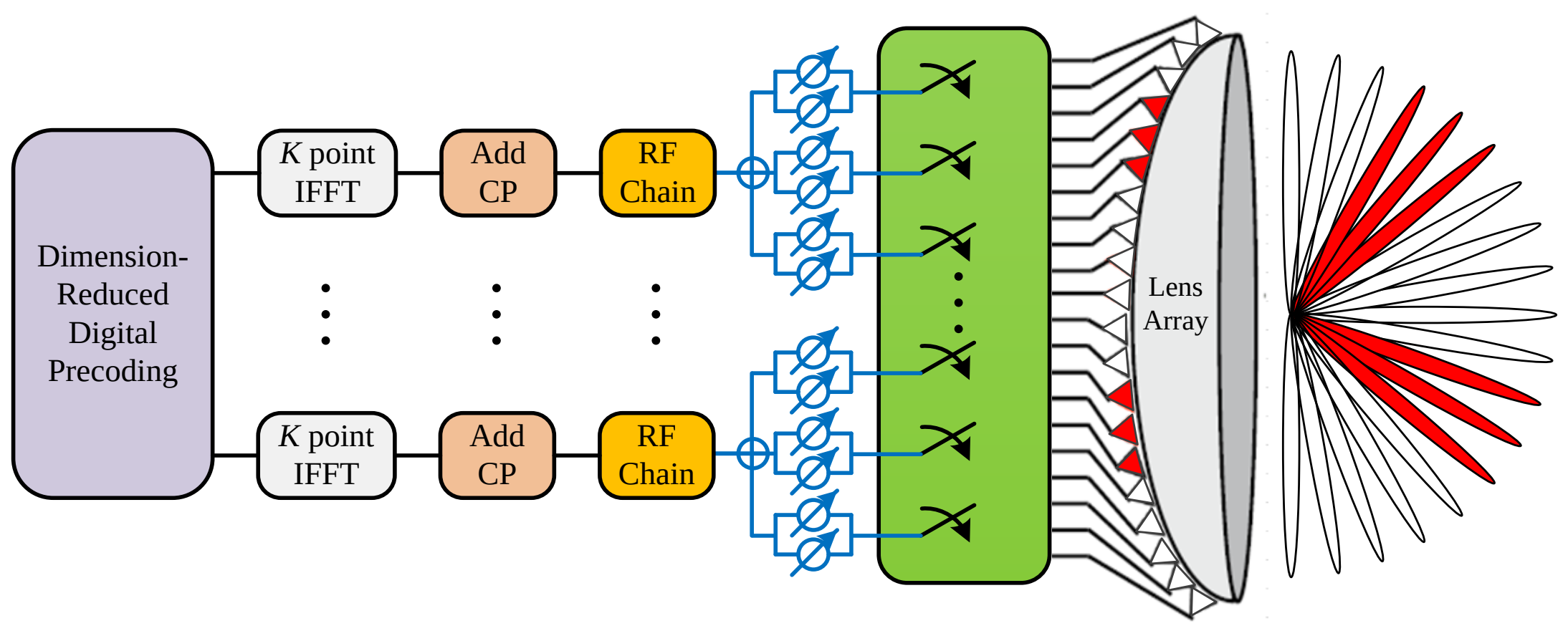
Challenge and motivation

- For wideband mmWave MIMO with beam squint, the signals on the same path will be concentrated on different antennas at different frequencies. This means that we need to select more beams for one data stream compared with the narrowband mmWave MIMO to guarantee the performance.
- In traditional architecture, each RF chain is connected to only one beam via switch. This means that more RF chains are required for wideband mmWave MIMO systems, leading to higher power consumption and hardware cost.

Proposed architecture

Principle

- 1) Each data stream is supported by only one RF chain; 2) Each RF chain is connected to a set of beams via sub-connected phase shifter network; 3) The signal on each beam is adjusted by two phase shifters.



Advantages

- By employing lens array, the array gain can be preserved even with the sub-connected phase shifter network.
- Several beams can be selected for each data stream and combined by the sub-connected phase shifter network. Each data stream can be supported by only one RF chain without obvious performance.
- The required number of phase shifters is quite small since: 1) we use the sub-connected phase shifter network; 2) the MIMO dimension has been significantly reduced by the selecting network.

System model

- The point-to-point system model at subcarrier k:

$$\mathbf{y}[k]=\mathbf{W}_{\mathrm{BB}}^{H}[k]\mathbf{W}_{\mathrm{RF}}^{H}\mathbf{S}_{\mathrm{R}}^{H}\tilde{\mathbf{H}}[k]\mathbf{S}_{\mathrm{T}}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[k]\mathbf{s}[k]+\mathbf{W}_{\mathrm{BB}}^{H}[k]\mathbf{W}_{\mathrm{RF}}^{H}\mathbf{S}_{\mathrm{R}}^{H}\mathbf{n}[k],$$

- $\tilde{\mathbf{H}}[k]=\mathbf{U}_{\mathrm{R}}^{H}\mathbf{H}[k]\mathbf{U}_{\mathrm{T}}$ is the sparse beamspace channel, $\mathbf{U}_{\mathrm{T}}$ and $\mathbf{U}_{\mathrm{R}}$ are the spatial DFT matrices realized by lens arrays.
- Transmit beam selector $\mathbf{S}_{\mathrm{T}}$, receive beam selector $\mathbf{S}_{\mathrm{R}}$, analog precoder $\mathbf{F}_{\mathrm{RF}}$, and analog combiner $\mathbf{W}_{\mathrm{RF}}$ are realized by analog circuit, which cannot be adjusted on different subcarriers.
- Digital precoder $\mathbf{F}_{\mathrm{BB}}[k]$ and combiner $\mathbf{W}_{\mathrm{BB}}[k]$ are realized in baseband, which can be adjusted on different subcarrier.

Beam selection

Design $\mathbf{S}_{\mathrm{T}}$ and $\mathbf{S}_{\mathrm{R}}$ to preserve the channel power

- Decouple the designs of $\mathbf{S}_{\mathrm{T}}$ and $\mathbf{S}_{\mathrm{R}}$ into two parts.
- Part 1, assume $\mathbf{S}_{\mathrm{R}}=\mathbf{I}$ and focus on the design of $\mathbf{S}_{\mathrm{T}}$. The optimization problem can be presented as

$$\left(\mathbf{S}_{\mathrm{T}}^{\square}\right)=\underset{\mathbf{S}_{\mathrm{T}}}{\arg\max}\,\mathrm{tr}\left(\mathbf{S}_{\mathrm{T}}^{H}\left(\frac{1}{K}\sum_{k=1}^{K}\tilde{\mathbf{H}}^{H}[k]\tilde{\mathbf{H}}[k]\right)\mathbf{S}_{\mathrm{T}}\right).$$

It means that $\mathbf{S}_{\mathrm{T}}$ should be designed to select $N_{\mathrm{T}}^{\mathrm{B}}$ largest diagonal elements of $\sum_{k=1}^{K}\tilde{\mathbf{H}}^{H}[k]\tilde{\mathbf{H}}[k]$.

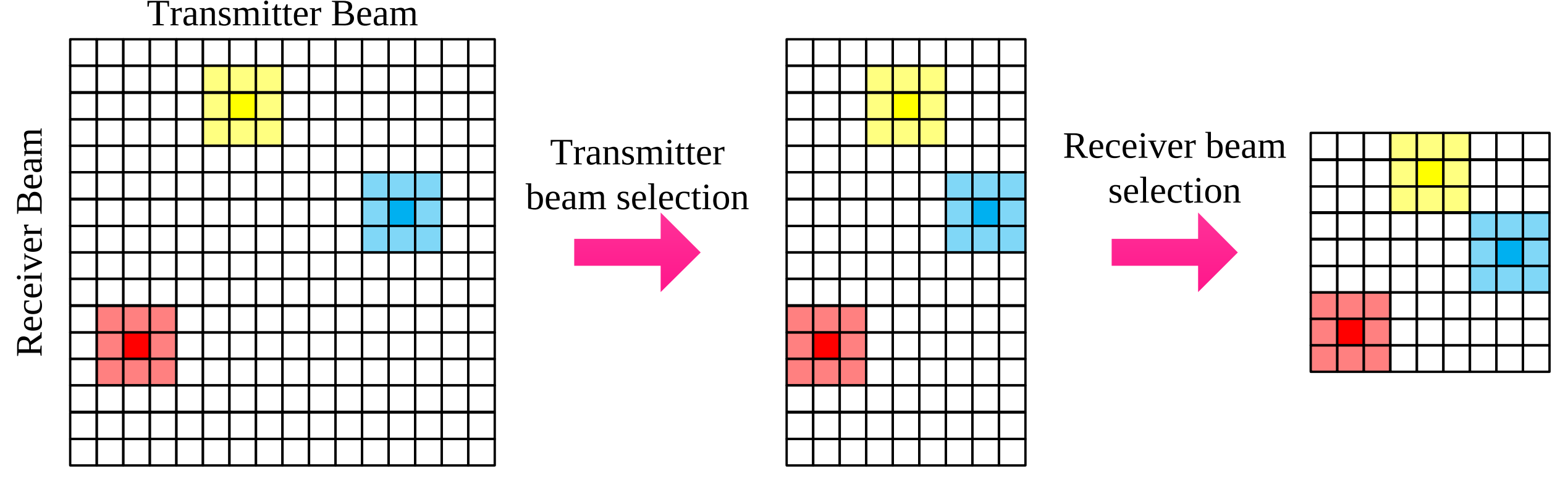
- Part 2, design $\mathbf{S}_{\mathrm{R}}$ based on $\mathbf{S}_{\mathrm{T}}$. The optimization problem can be presented as

$$\left(\mathbf{S}_{\mathrm{R}}^{\square}\right)=\underset{\mathbf{S}_{\mathrm{R}}}{\arg\max}\,\mathrm{tr}\left(\mathbf{S}_{\mathrm{R}}^{H}\left(\frac{1}{K}\sum_{k=1}^{K}\tilde{\mathbf{H}}[k]\mathbf{S}_{\mathrm{T}}\mathbf{S}_{\mathrm{T}}^{H}\tilde{\mathbf{H}}^{H}[k]\right)\mathbf{S}_{\mathrm{R}}\right),$$

which means that $\mathbf{S}_{\mathrm{R}}$ is designed to select $N_{\mathrm{R}}^{\mathrm{B}}$ largest diagonal elements of $\sum_{k=1}^{K}\tilde{\mathbf{H}}[k]\mathbf{S}_{\mathrm{T}}\mathbf{S}_{\mathrm{T}}^{H}\tilde{\mathbf{H}}^{H}[k]$.

- According to the analysis in [1], the numbers of selected transmit beams and receive beams should be

$$N_{\mathrm{T}}^{\mathrm{B}}=\left\lceil\frac{N_{\mathrm{T}}B}{2f_c}\right\rceil,\quad N_{\mathrm{R}}^{\mathrm{B}}=\left\lceil\frac{N_{\mathrm{R}}B}{2f_c}\right\rceil.$$



Beamspace precoding

Design $\mathbf{F}_{\mathrm{RF}}$ and $\mathbf{F}_{\mathrm{BB}}[k]$ to maximize the achievable sum-rate

- Assume the combining is ideal. Based on $\tilde{\mathbf{H}}_{\mathrm{r}}[k]=\mathbf{S}_{\mathrm{R}}^{H}\tilde{\mathbf{H}}[k]\mathbf{S}_{\mathrm{T}}$, the optimization problem can be presented as [3]

$$\max_{\mathbf{F}_{\mathrm{RF}},\mathbf{F}_{\mathrm{BB}}[k]}\frac{1}{K}\sum_{k=1}^{K}\tilde{R}[k]=\max_{\mathbf{F}_{\mathrm{RF}},\mathbf{F}_{\mathrm{BB}}[k]}\frac{1}{K}\sum_{k=1}^{K}\log_2\left|\mathbf{I}_{N_{\mathrm{s}}}+\frac{\rho}{\sigma^2N_{\mathrm{s}}}\tilde{\mathbf{H}}_{\mathrm{r}}[k]\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[k]\mathbf{F}_{\mathrm{BB}}^{H}[k]\mathbf{F}_{\mathrm{RF}}^{H}[k]\tilde{\mathbf{H}}_{\mathrm{r}}^{H}[k]\right|,$$

where $\left\|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[k]\right\|_F^2=N_{\mathrm{s}}$ and $\mathbf{F}_{\mathrm{RF}}$ is a block diagonal matrix with constant-amplitude nonzero elements.

- Optimal digital precoder is $\mathbf{F}_{\mathrm{BB}}[k]=\mathbf{V}_{\mathrm{eff}}[k]\mathbf{P}_{\mathrm{eff}}^{1/2}[k]$, $\mathbf{V}_{\mathrm{eff}}[k]$ is the right singular matrix of $\tilde{\mathbf{H}}_{\mathrm{r}}[k]\mathbf{F}_{\mathrm{RF}}$, and $\mathbf{P}_{\mathrm{eff}}^{1/2}[k]$ is the water filling solution [3]. By employing Jensen's inequality and high SNR approximation, the target becomes [4]

$$\frac{1}{K}\sum_{k=1}^{K}\tilde{R}[k]\approx\frac{1}{K}\sum_{k=1}^{K}\log_2\left|\mathbf{I}_{N_{\mathrm{s}}}+\frac{\rho}{\sigma^2N_{\mathrm{s}}}\mathbf{F}_{\mathrm{RF}}^{H}\tilde{\mathbf{H}}_{\mathrm{r}}^{H}[k]\tilde{\mathbf{H}}_{\mathrm{r}}[k]\mathbf{F}_{\mathrm{RF}}\right|\approx\log_2\left|\mathbf{I}_{N_{\mathrm{s}}}+\frac{\rho}{\sigma^2N_{\mathrm{s}}}\mathbf{F}_{\mathrm{RF}}^{H}\left(\frac{1}{K}\sum_{k=1}^{K}\tilde{\mathbf{H}}_{\mathrm{r}}^{H}[k]\tilde{\mathbf{H}}_{\mathrm{r}}[k]\right)\mathbf{F}_{\mathrm{RF}}\right|.$$

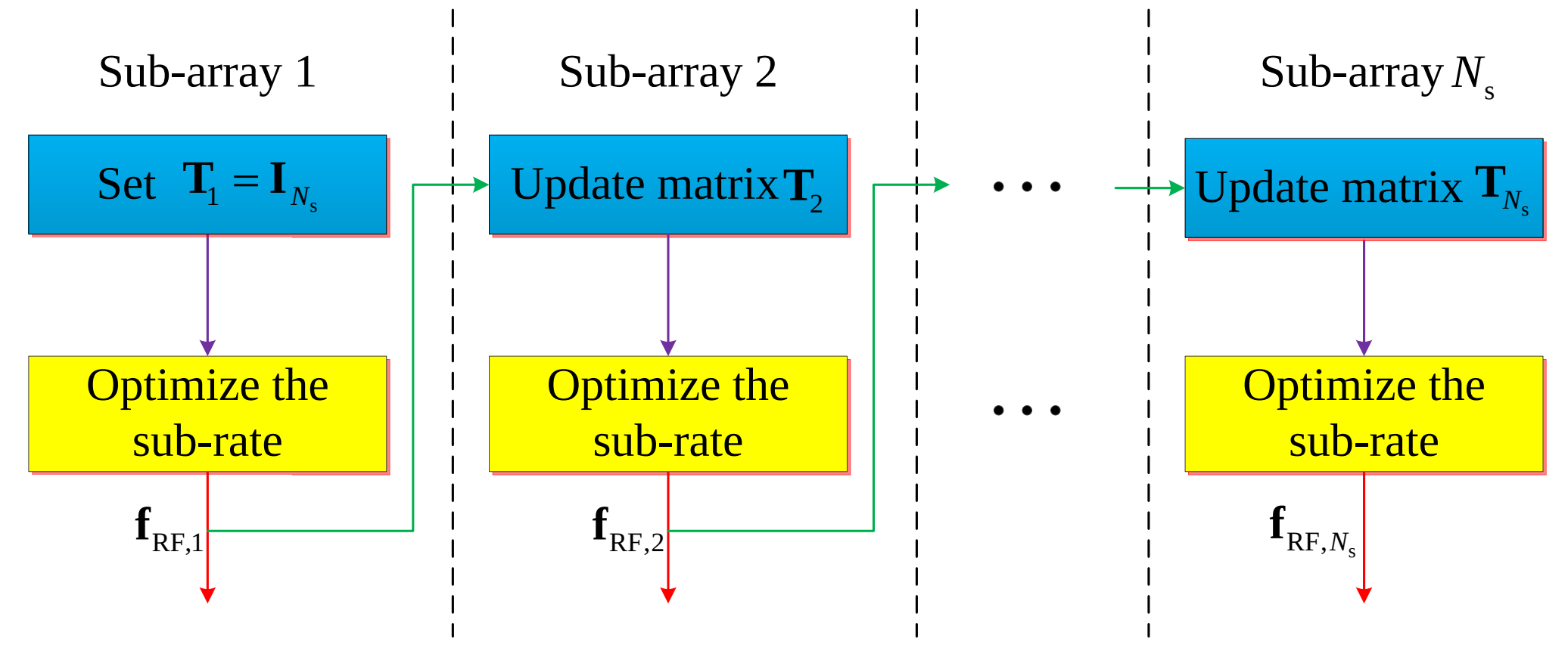
Problem decomposition

- Defining $\mathbf{R}=(1/K)\sum_{k=1}^{K}\tilde{\mathbf{H}}_{\mathrm{r}}^{H}[k]\tilde{\mathbf{H}}_{\mathrm{r}}[k]=\mathbf{Q}^{H}\mathbf{Q}$ and following the same mathematical derivation in [5], we have

$$\frac{1}{K}\sum_{k=1}^{K}\tilde{R}[k]\approx\sum_{n=1}^{N_{\mathrm{s}}}\log_2\left(1+\frac{\rho}{\sigma^2N_{\mathrm{s}}}\mathbf{f}_{\mathrm{RF},n}^{H}\mathbf{Q}^{H}\mathbf{T}_n^{-1}\mathbf{Q}\mathbf{f}_{\mathrm{RF},n}\right),$$

where $\mathbf{f}_{\mathrm{RF},n}$ is the n-th column of $\mathbf{F}_{\mathrm{RF}}$, $\mathbf{T}_1=\mathbf{I}_{N_{\mathrm{s}}}$, and $\mathbf{T}_n=\mathbf{I}_{N_{\mathrm{s}}}+\left(\rho/\sigma^2N_{\mathrm{s}}\right)\mathbf{Q}\mathbf{F}_{\mathrm{RF},n-1}\mathbf{F}_{\mathrm{RF},n-1}^{H}\mathbf{Q}$, $\mathbf{F}_{\mathrm{RF},n-1}=\left[\mathbf{f}_{\mathrm{RF},1},\mathbf{f}_{\mathrm{RF},2},\cdots,\mathbf{f}_{\mathrm{RF},n-1}\right]$.

- The optimization problem is decomposed into several sub-problems, and each one only considers one sub-array. We can optimize one sub-array, eliminate its contribution, and then optimize the next one.



Optimization on each sub-array

- The optimization target on each sub-array is

$$\log_2\left(1+\frac{\rho}{\sigma^2N_{\mathrm{s}}}\mathbf{f}_{\mathrm{RF},n}^{H}\mathbf{G}_n\mathbf{f}_{\mathrm{RF},n}\right)=\log_2\left(1+\frac{\rho}{\sigma^2N_{\mathrm{s}}}\bar{\mathbf{f}}_{\mathrm{RF},n}^{H}\bar{\mathbf{G}}_n\bar{\mathbf{f}}_{\mathrm{RF},n}\right),$$

where $\mathbf{G}_n=\mathbf{Q}^{H}\mathbf{T}_n^{-1}\mathbf{Q}$, $\bar{\mathbf{f}}_{\mathrm{RF},n}$ contains the nonzero elements of $\mathbf{f}_{\mathrm{RF},n}$, $\bar{\mathbf{G}}_n$ is the corresponding sub-matrix of $\mathbf{G}_n$.

- The solution is $\bar{\mathbf{f}}_{\mathrm{RF},n}=\mathbf{V}_{\bar{G}}(:,1)$, where $\mathbf{V}_{\bar{G}}$ is the right singular matrix of $\bar{\mathbf{G}}_n$.
- Note that each element of $\bar{\mathbf{f}}_{\mathrm{RF},n}$ has the amplitude smaller than 1. It can be always realized by two phase shifters in the proposed architecture.
- After the beamspace precoder has been designed, the beamspace combiner can be obtained in a similar way based on the effective channel matrix $\tilde{\mathbf{H}}_{\mathrm{r}}[k]\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[k]$.

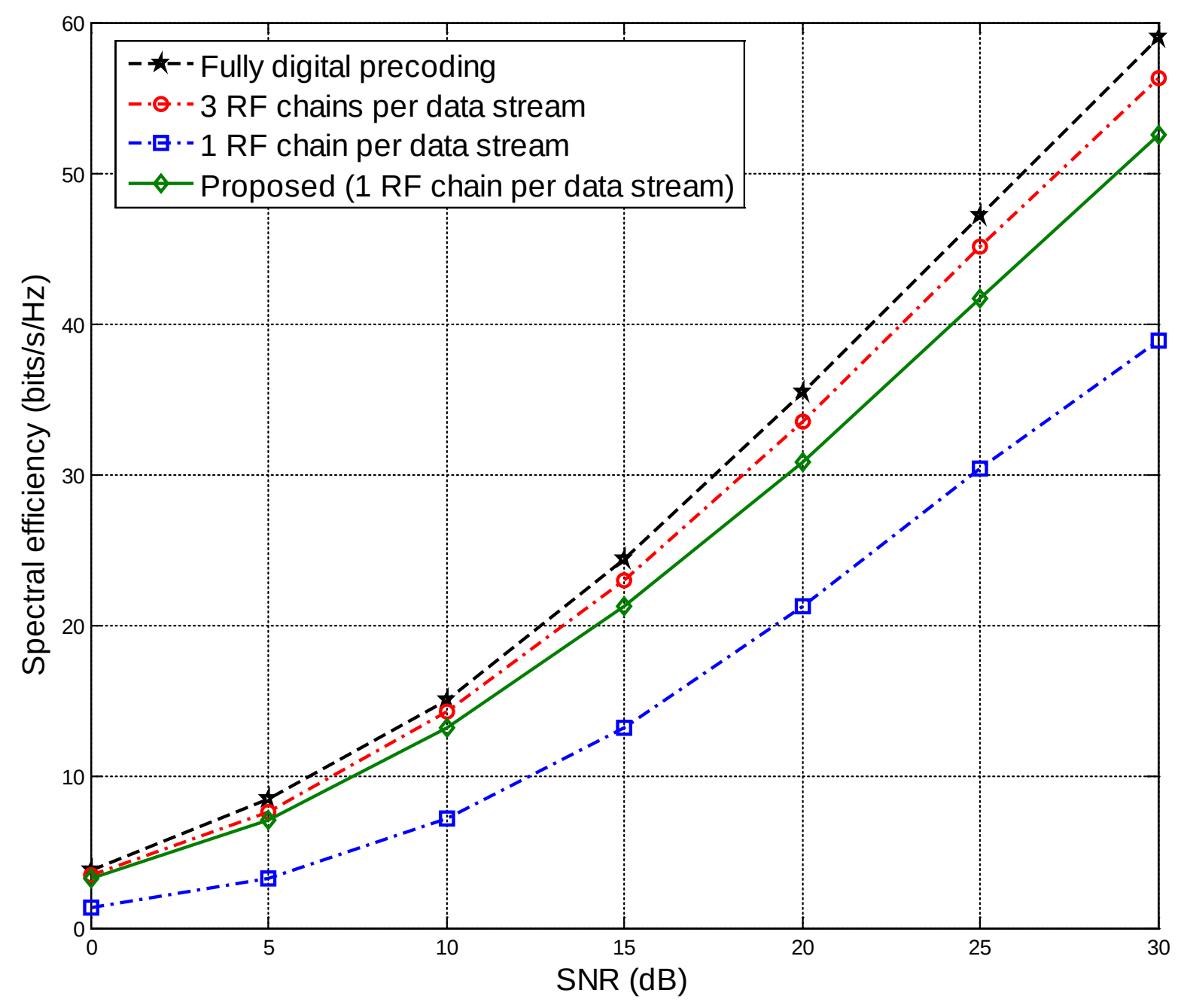
Simulation results

Simulation parameters

- Transmitter: $N_{\mathrm{T}}=64$ - element lens array, $N_{\mathrm{T}}^{\mathrm{RF}}=8$ RF chains, and $N_{\mathrm{s}}=8$ data streams.
- Receiver: $N_{\mathrm{R}}=64$ - element lens array and $N_{\mathrm{R}}^{\mathrm{RF}}=8$ RF chains.
- Channel: 10 paths. Each path has the gain following $\mathcal{CN}(0,1)$ and physical AoA and AoD following $\mathcal{U}(-\pi/2,\pi/2)$.
- OFDM setup: maximum delay of all paths is 20ns, the delay of each path follows $\mathcal{U}(0,20)$, the carrier frequency is 28 GHz, the number of subcarriers is 128, and the bandwidth is 2GHz.

Observations

- In the proposed architecture, we select $N_{\mathrm{T}}^{\mathrm{B}}=\lceil N_{\mathrm{T}}B/2f_c\rceil=3$ transmit beams and $N_{\mathrm{R}}^{\mathrm{B}}=\lceil N_{\mathrm{R}}B/2f_c\rceil=3$ receive beams for each data stream but with only 1 RF chain at the transmitter and 1 RF chain at the receiver.
- Much better performance than the traditional scheme with 1 RF chain per data stream [2].
- Close to the traditional scheme with 3 RF chains per data stream [1].



Conclusions

- We propose a new architecture for wideband mmWave MIMO systems with lens array, which is realized by combining the sub-connected phase shifter network and lens array together.
- We propose a low-complexity beam selection scheme to preserve the channel power as much as possible.
- We decompose the optimization problem of beamspace precoding into several sub-problems, each of which only considers one sub-array. We optimize these sub-problems in an one-by-one fashion.
- It shows that our scheme achieves the near-optimal performance with much less RF chains than traditional schemes. That means we can overcome beam squint with lower energy consumption and hardware cost.

References

[1] J. Brady and A. Sayeed, "Wideband communication with high-dimensional arrays: New results and transceiver architectures," in *Proc. IEEE ICC Workshops*, June 2015, pp. 1042-1047.
[2]J. Brady *et al.*, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," *IEEE Trans. Ant. and Propag.*, vol. 61, no. 7, pp. 3814-3827, July 2013.
[3] A. Alkhateeb and R. W. Heath, "Frequency selective hybrid precoding for limited feedback millimeter wave systems," *IEEE Trans. Commun.*, vol. 64, no. 5, pp. 1801-1818, May 2016.
[4] F. Sohrabi and W. Yu, "Hybrid analog and digital beamforming for mmWave OFDM large-scale antenna arrays," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 7, pp. 1432-1443, July 2017.
[5] X. Gao *et al.*, "Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 998-1009, Apr. 2016.