Wideband Full-Duplex Phased Array with Joint Transmit and Receive Beamforming: Optimization and Rate Gains

Tingjun Chen, Mahmood Baraani Dastjerdi, Harish Krishnaswamy, and Gil Zussman

Electrical Engineering, Columbia University

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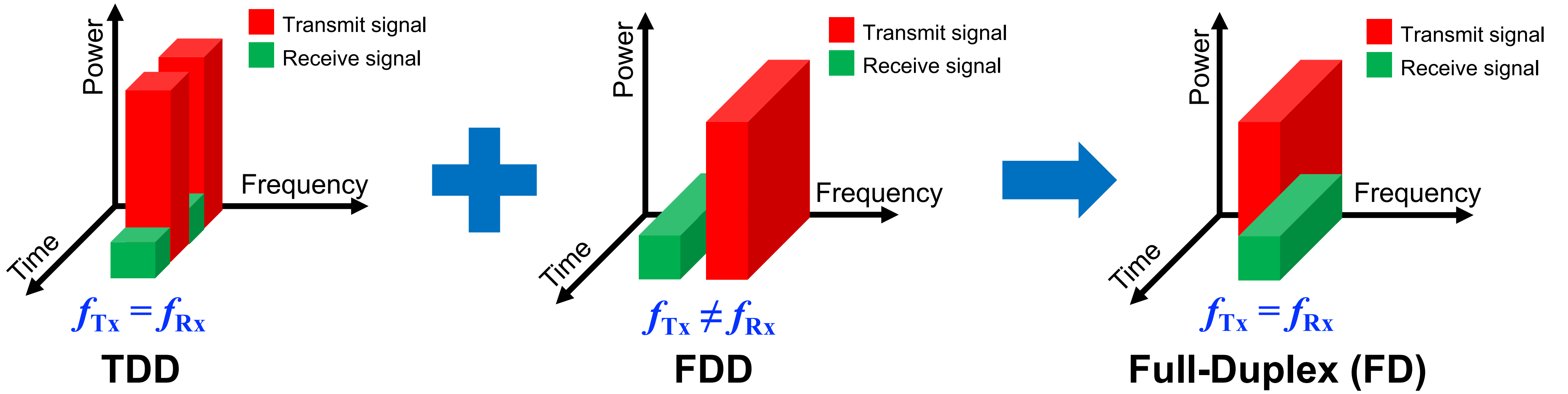
Full-Duplex Wireless

- Legacy half-duplex wireless systems separate transmission and reception in either:
  - Time: Time Division Duplex (TDD)
  - Frequency: Frequency Division Duplex (FDD)

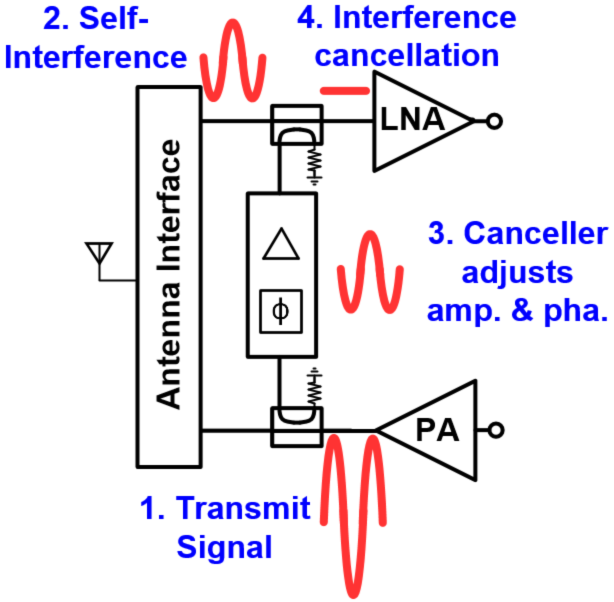
- (In-band) Full-duplex wireless: simultaneous transmission and reception on the same frequency channel

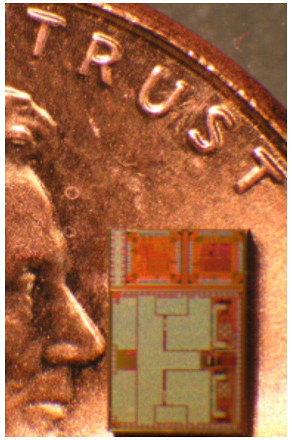


Full-Duplex Wireless

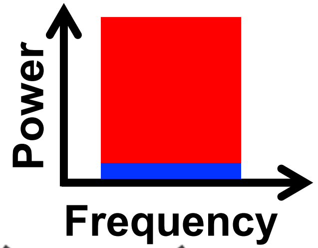
- Benefits of full-duplex wireless:
  - Increased system throughput and reduced latency
  - More flexible use of the wireless spectrum and energy efficiency

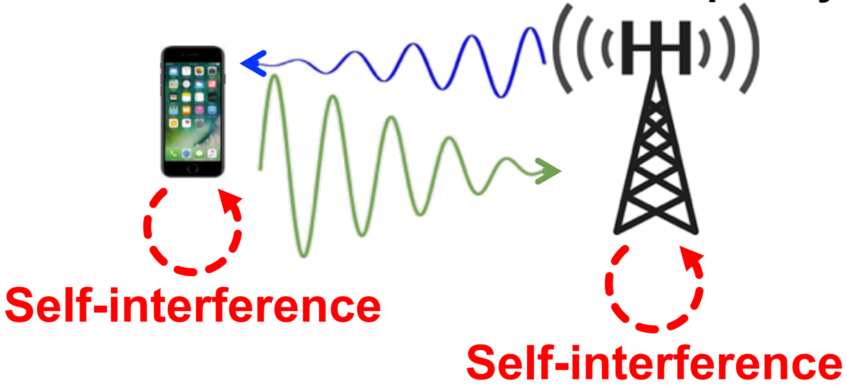
- Viability is limited by self-interference (SI)
  - Transmitted signal is **billions** of times (**10^9 or 90dB**) stronger than the desired received signal
  - Require extremely powerful self-interference cancellation (SIC)

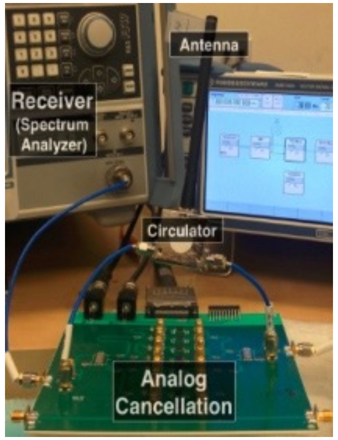




Full-duplex radios implemented in RFIC (Columbia)



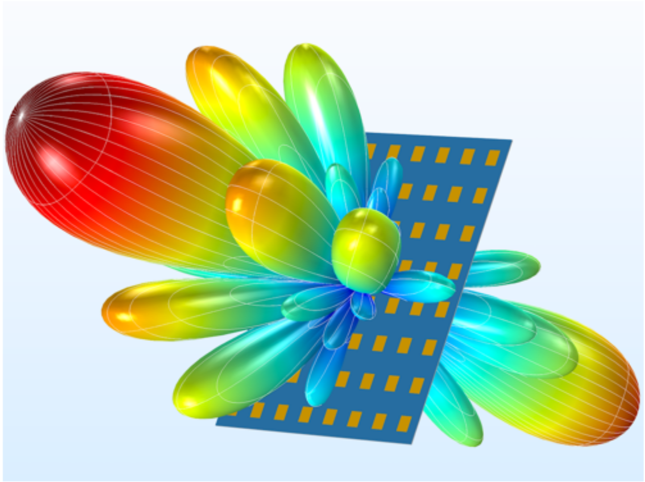




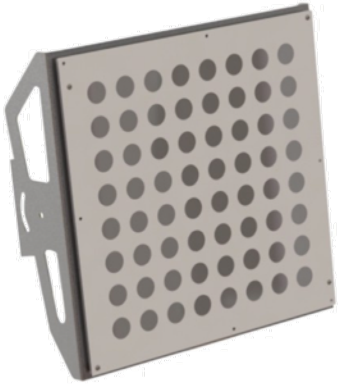
Full-duplex radios using off-the-shelf components (e.g., Stanford)

Phased Array and Beamforming (BF)

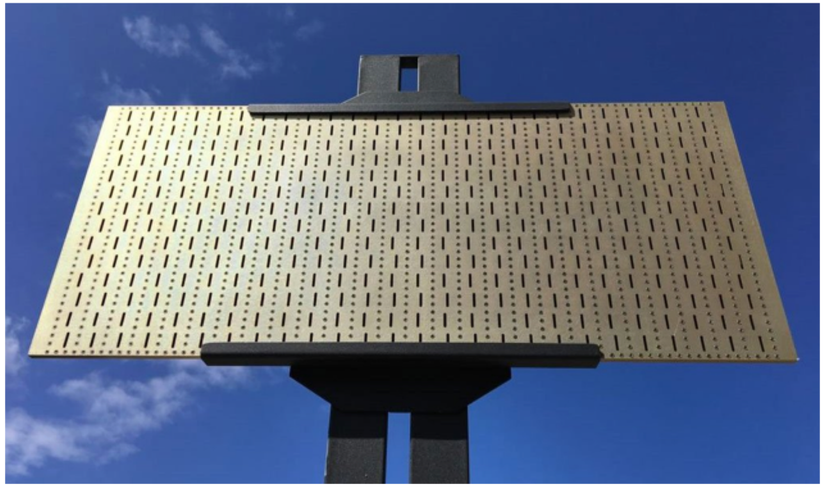
- An antenna phased array applies BF to achieve ***directional*** signal transmission (Tx) or reception (Rx)
  - Benefits: Increased Tx/Rx signal power and enhanced link distance
  - Analog BF (vs. digital BF): cost-effective, reduced system complexity and power consumption



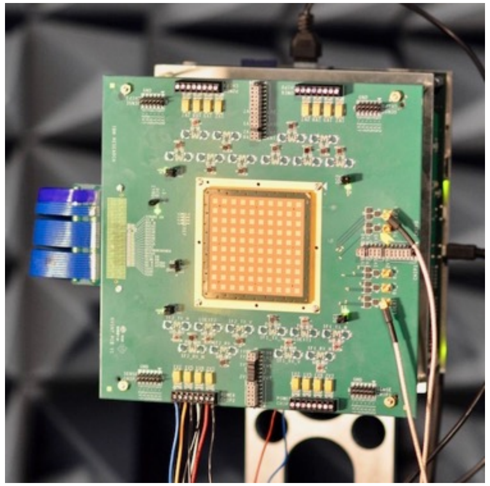
3D analog BF



5 GHz (C-band)



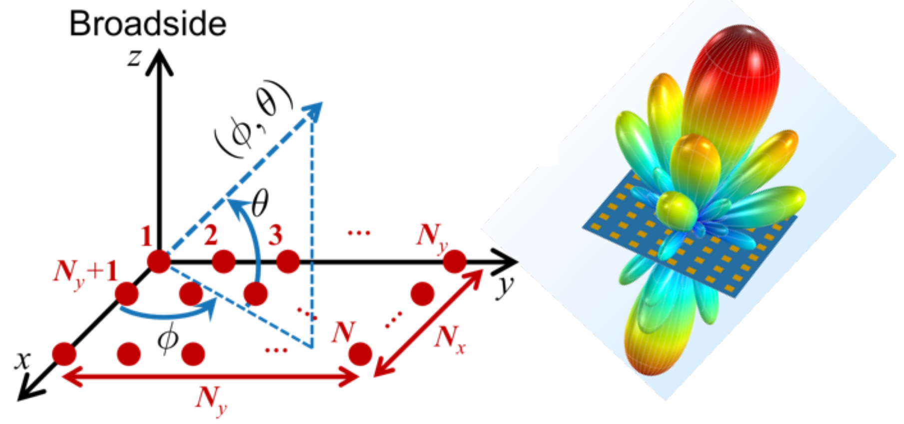
11 GHz (X-band)



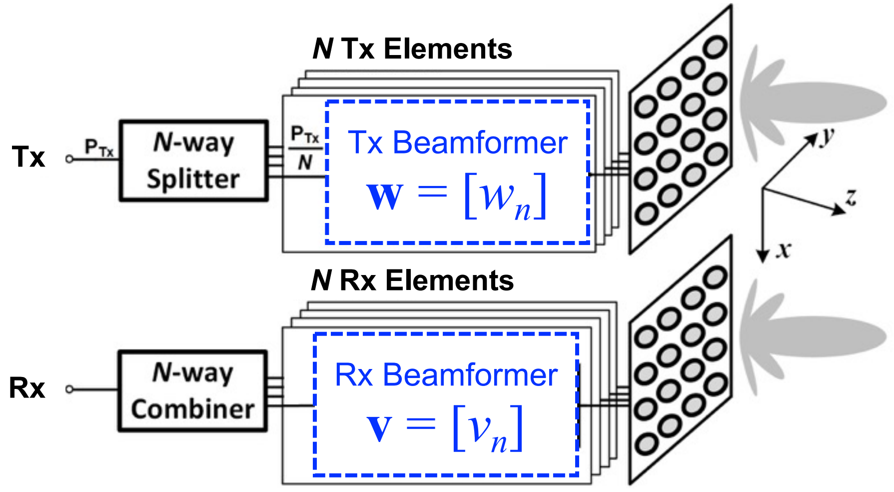
28 GHz (mmWave)

Preliminaries: An N-element (Half-Duplex) Phased Array

- Steering vector: $\mathbf{s}(\phi, \theta) = [s_n(\phi, \theta)]$
  - Set of phase delays experienced by a plane wave as it departs/reaches the array
  - Depends on array's physical property (size, geometry, etc.)



An example N-element rectangular antenna array in a spherical coordinate system



Block diagram of an N-element Tx (top) or Rx (bottom) phased array in the half-duplex (HD) setting

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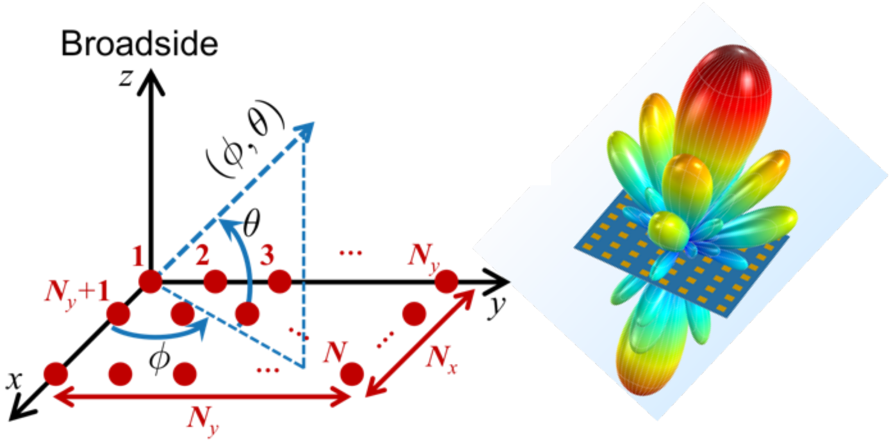
- Analog beamformer: $\mathbf{w} = [w_n]$
  - $w_n = |w_n| \cdot \exp(j\angle w_n)$ with $|w_n| \leq 1, -\pi \leq \angle w_n \leq \pi$



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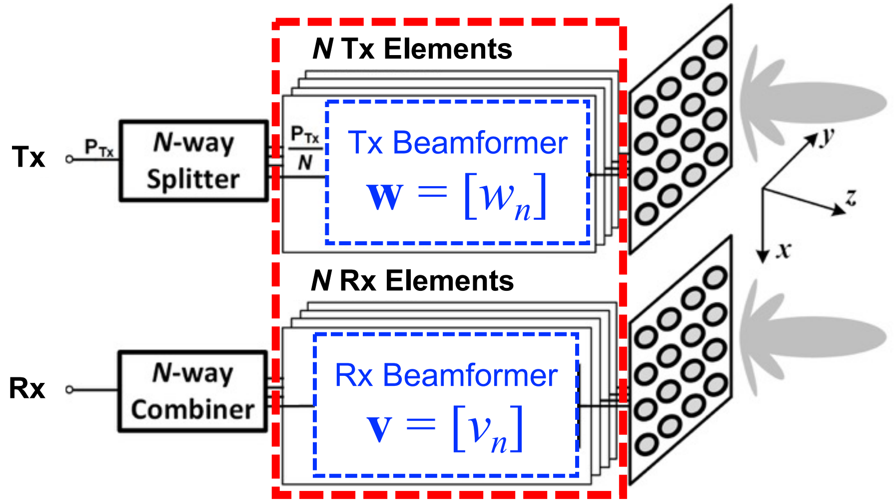

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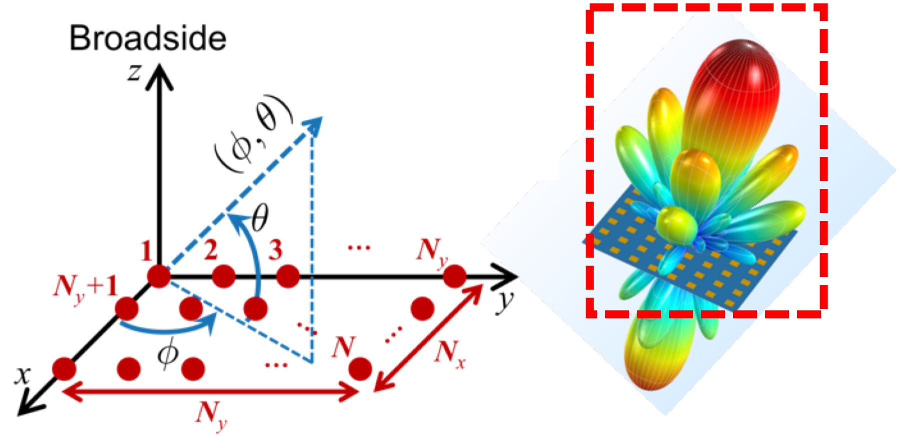
- Far-field BF gain: $G(\phi, \theta) = |\mathbf{s}^{\mathrm{T}}(\phi, \theta) \cdot \mathbf{w}|^2 / N$
  - Combined effects of all weighted antenna elements



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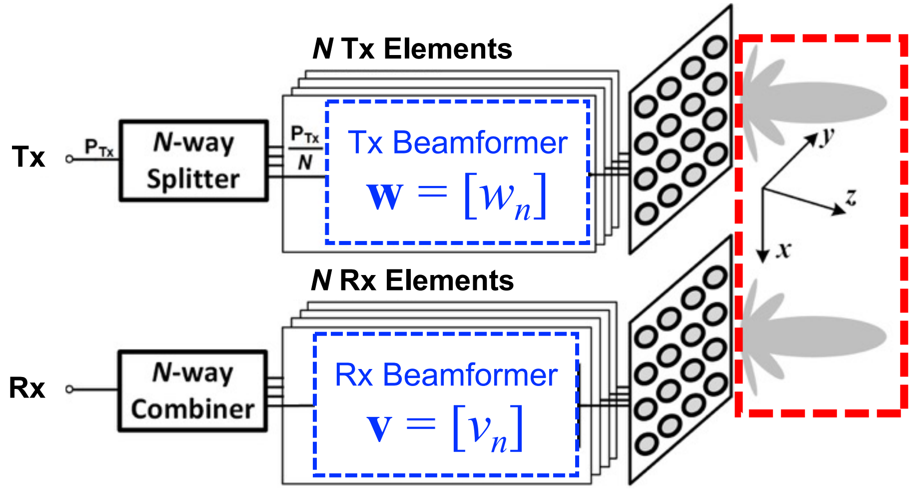

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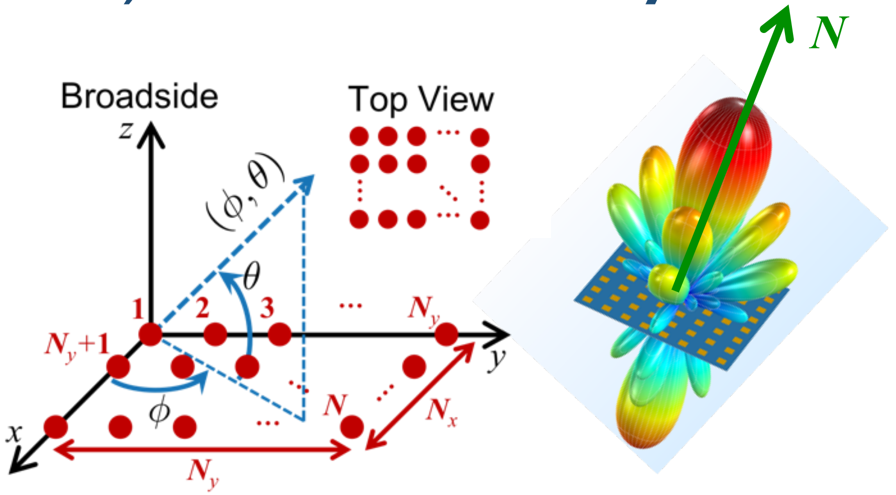
- In the desired/main beam-pointing direction $(\phi_{\text{main}}, \theta_{\text{main}})$, ***conventional*** half-duplex (HD) BF can achieve a maximum BF gain of N with $\mathbf{w}_{\text{conv}} = \mathbf{s}^*(\phi_{\text{main}}, \theta_{\text{main}})$ (i.e., conjugate BF)



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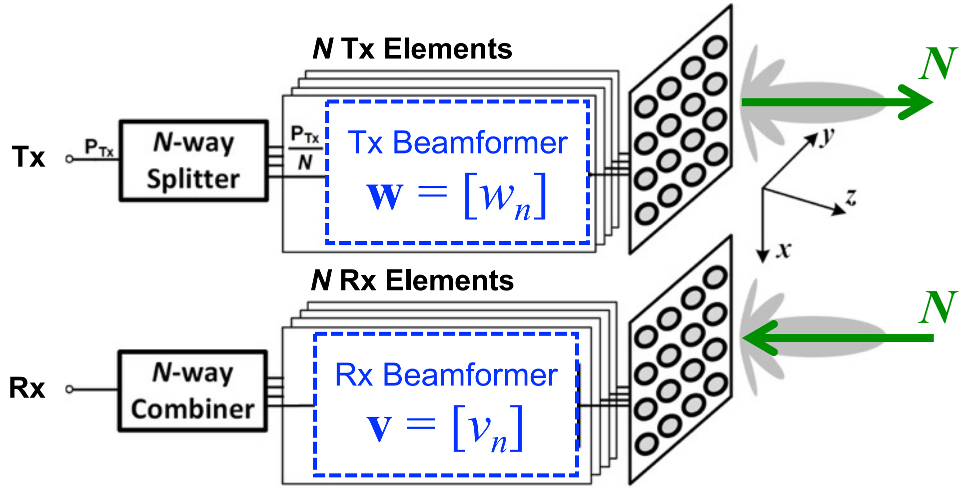

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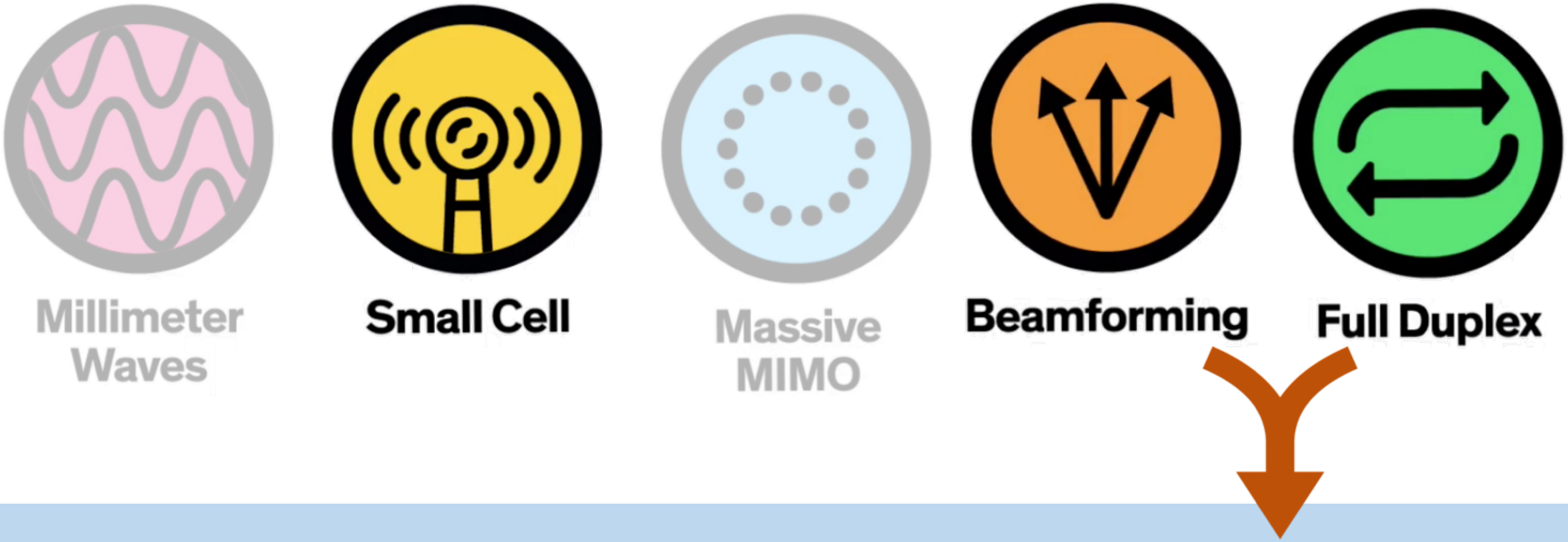
Full-Duplex Phased Array with Beamforming?

- Enabling techniques for 5G and future wireless networks

Figure source: A. Nordrum and K. Clark, "Everything you need to know about 5G," *IEEE Spectrum*, vol. 27, 2017.



<u>Question</u>: Can we simultaneously enable full-duplex communications with beamforming?

Related Work

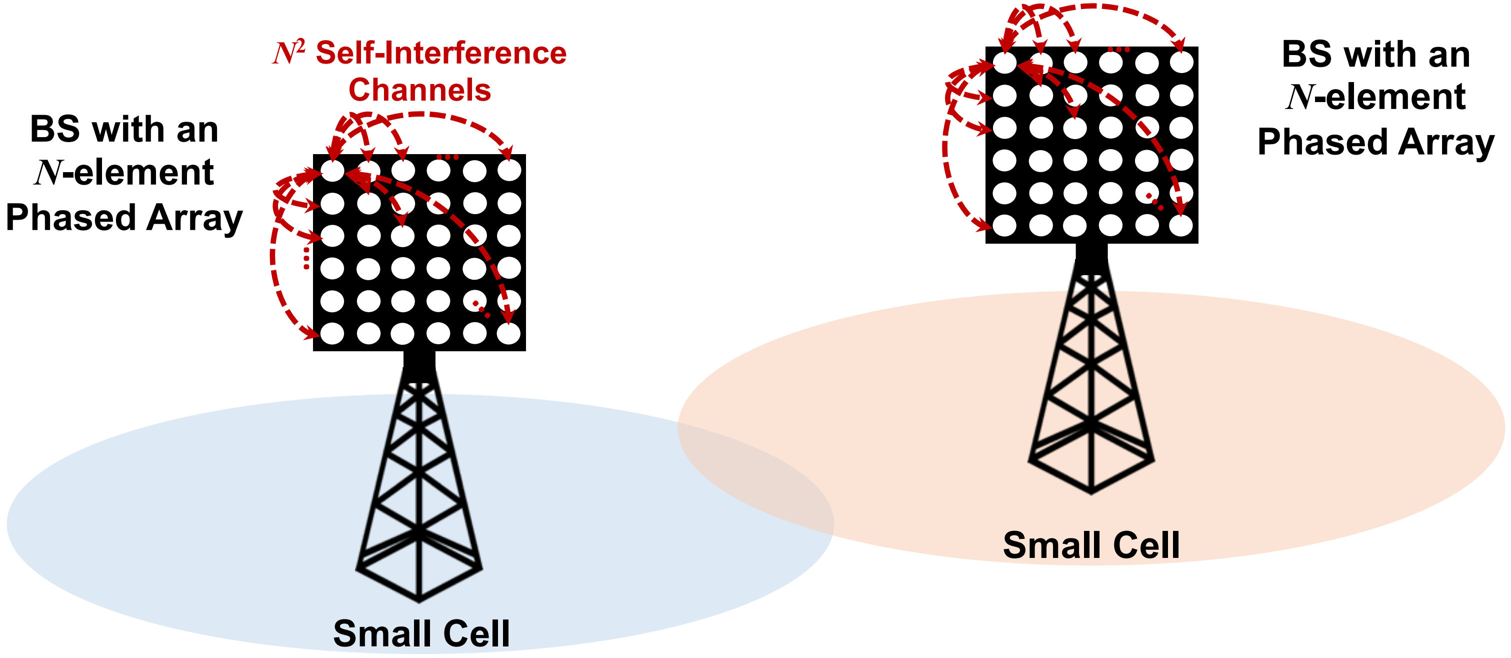
- Full-duplex SISO and MIMO radio/system design
  - Laboratory bench-top design: [Choi et al. 2010], [Duarte & Sabharwal, 2010], [Aryafar et al. 2012], [Bharadia et al. 2013/2014], [Kim et al. 2013/2015], [Korpi et al. 2016], [Sayed et al. 2017]
  - Integrated circuits (small form-factor) design: [Zhou et al. 2014/2015], [Debaillie et al. 2015], [Yang et al. 2015], [Reiskarimian et al. 2016/2017], [Zhang et al. 2017/2018], [Chen et al. 2019]
- Throughput gains and scheduling in full-duplex networks
  - [Xie & Zhang, 2014], [Nguyen et al. 2014], [Korpi et al. 2015], [Marasevic et al. 2017/2018], [Chen et al. 2018]

- (Large-scale) full-duplex multi-antenna systems
  - Full-duplex MU-MIMO downlink with digital TxBF [Everett et al. 2016]
  - Full-duplex phased array with (narrowband) analog TxBF [Aryafar & Haddad, 2018]

- ***Simultaneous TxBF and RxBF*** for full-duplex phased arrays was not considered
  - Efficient algorithm design and bandwidth consideration
- ***Rate gains*** introduced by these systems in different network scenarios were not evaluated

Network Scenarios and Objective

- A **base station (BS)** with an N-element (large-scale) phased array
- When the BS operates in FD mode:
  - N^2 self-interference (SI) channels: scalability, hardware complexity, power consumption
  - Conventional HD BF can potentially increase the self-interference power by N^2 compared to SISO case
- **Question**: How can the BS FD phased array achieve wideband RF self-interference cancellation?



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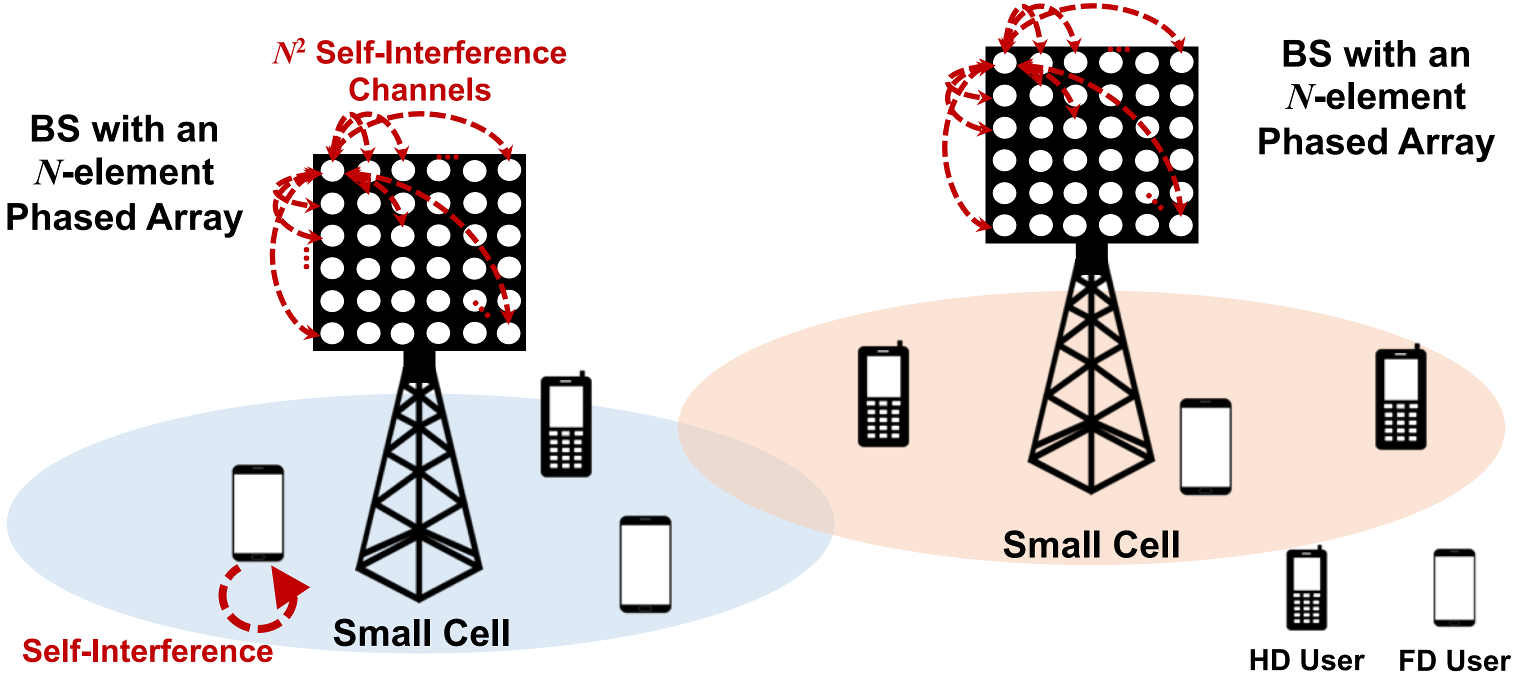
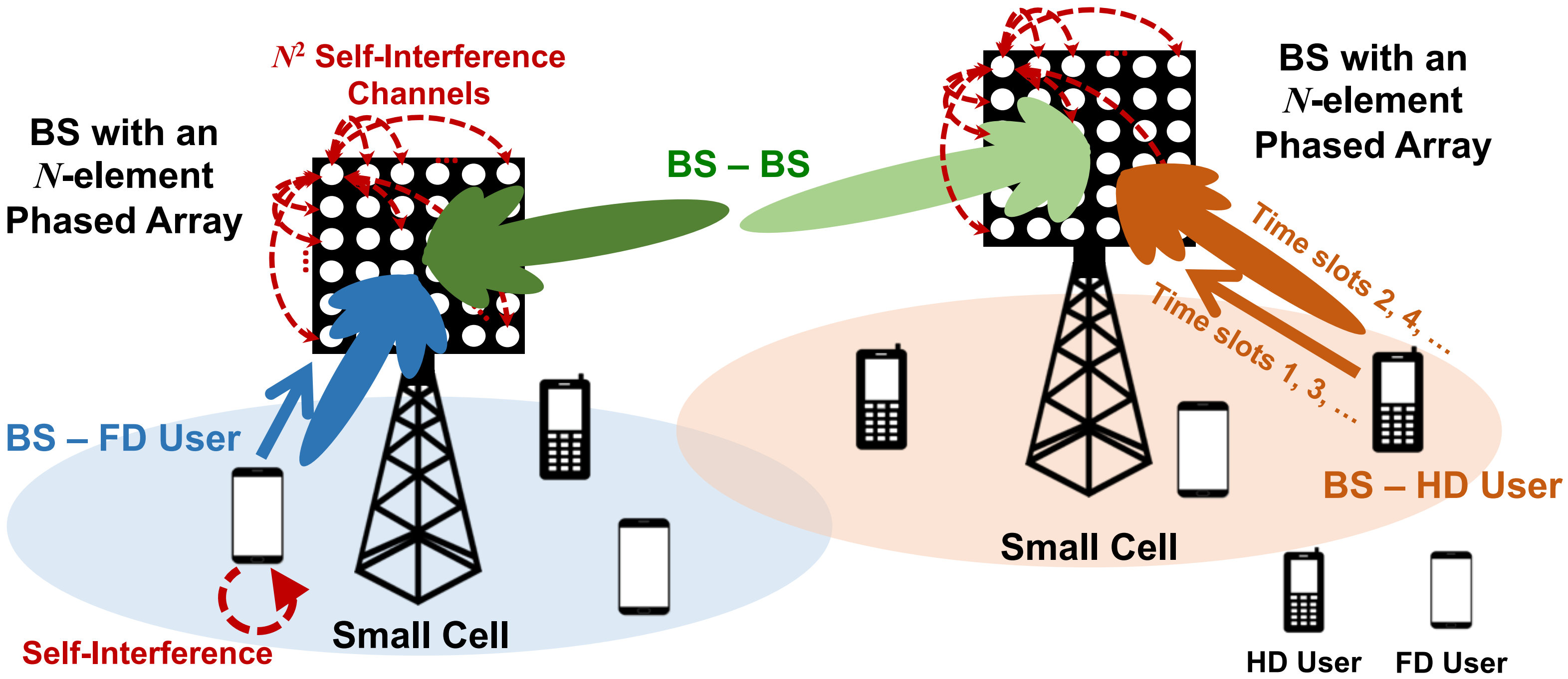
- A single-antenna **user** is HD- or FD-capable [*Zhou et al. 2017*] [*Chen et al. 2019*]



Network Scenarios and Objective

(1) Case **BS – User**: uplink-downlink transmissions in **HD** or **FD** mode

(2) Case **BS – BS**: bi-directional transmissions in **HD** or **FD** mode



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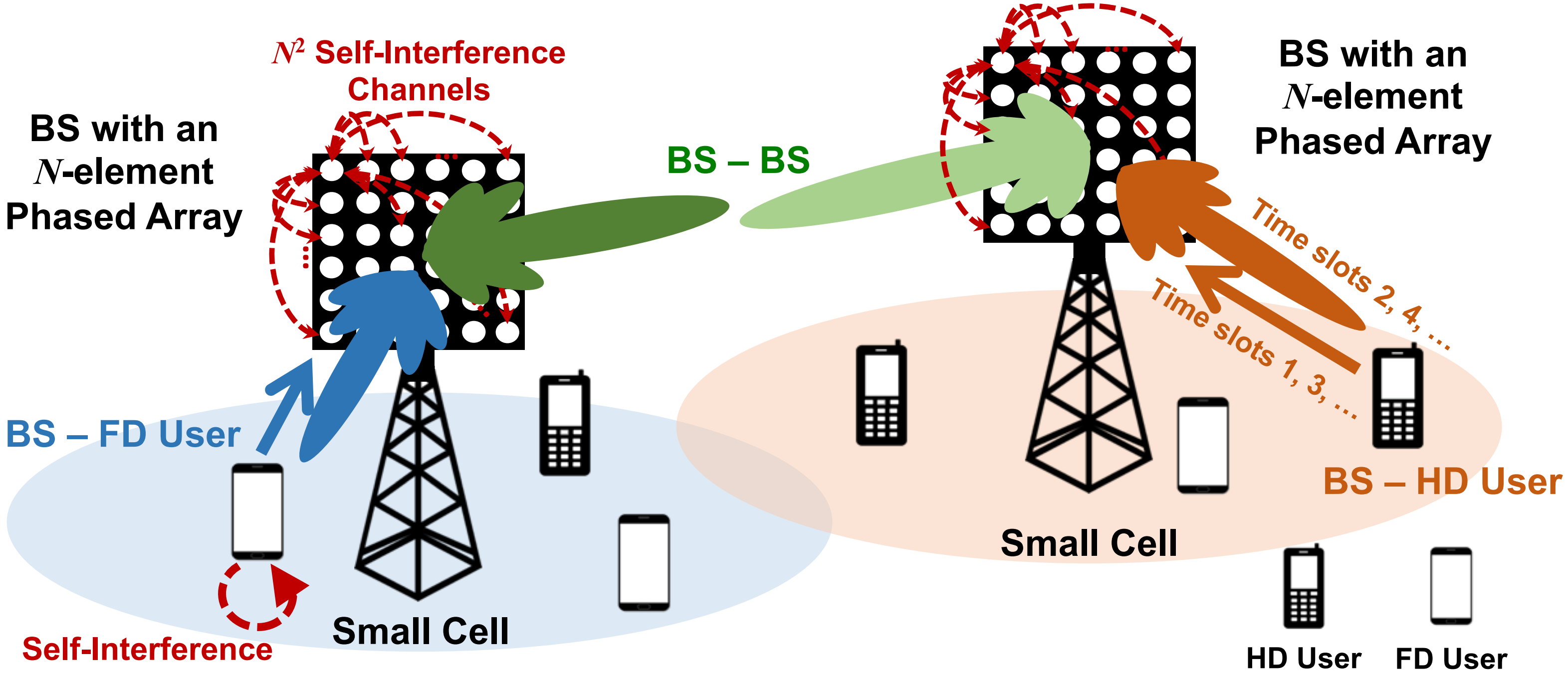
- **Goal**: Achieve (i) wideband RF self-interference cancellation at the BS, (ii) improved FD rate gains
- **Solution**: Manipulate Tx and Rx analog BF weights (a.k.a., analog beamformers), i.e., ***repurposing beamforming degrees of freedom in the spatial domain***



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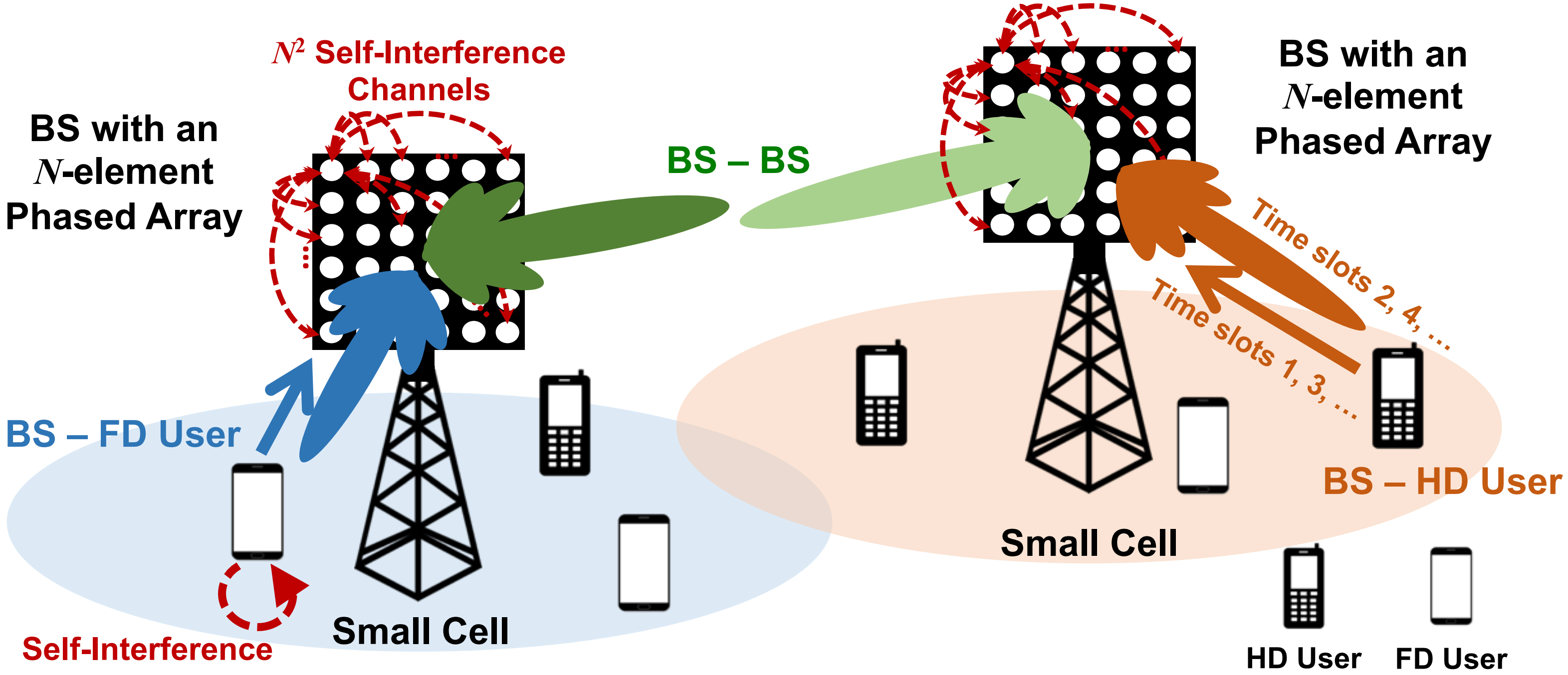
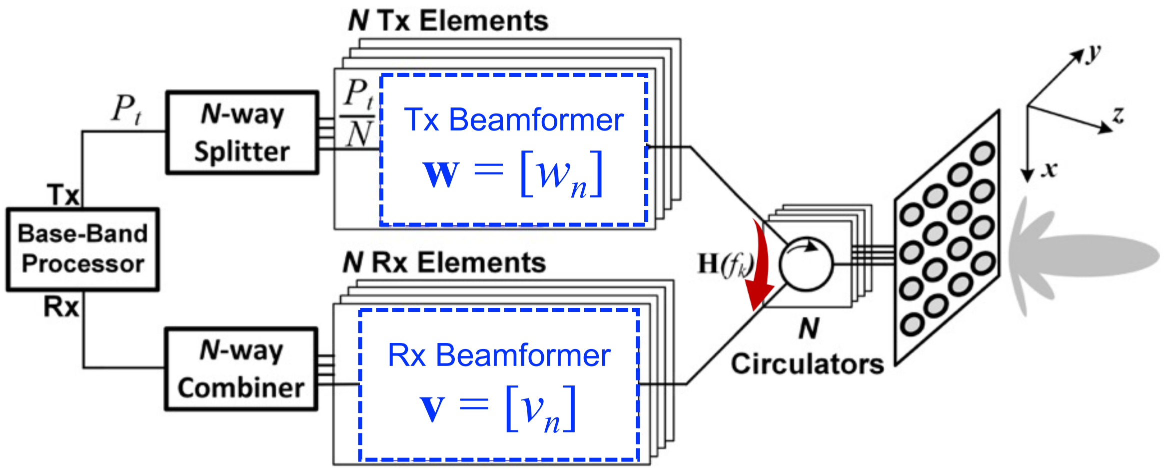
- Benefits:
  - ***No*** special canceller hardware
  - ***Reduced*** system complexity, power consumption, and ADC dynamic range at Rx
  - ***Wideband*** nature
  - ***Scalable*** to large arrays



Model: An N-element Full-Duplex Phased Array

- Each antenna is shared between a pair of Tx and Rx elements via a circulator **(including circulators)**
- **Self-interference (SI) channel matrix** in the k^{th} channel/sub-carrier: $\mathbf{H}(f_k) = [H_{mn}(f_k)]$, $k = 1, \ldots, K$
  - In realistic environments, $\mathbf{H}(f_k)$, $\forall k$, is ***frequency-selective***, and is ***neither symmetric nor Hermitian***



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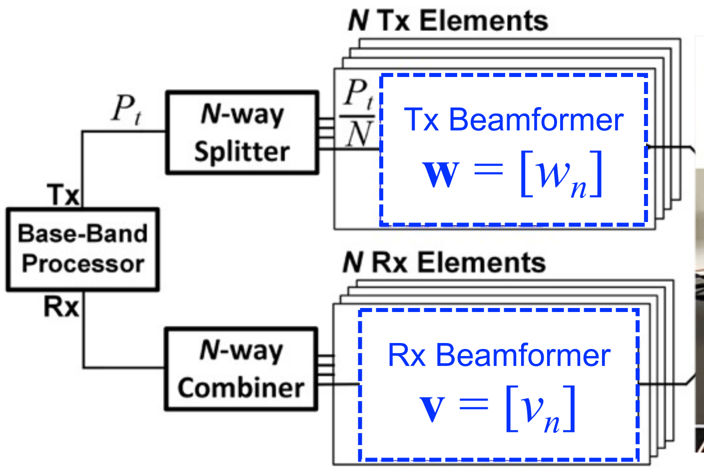
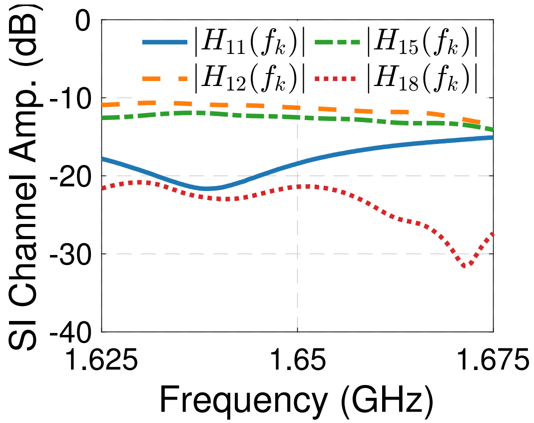
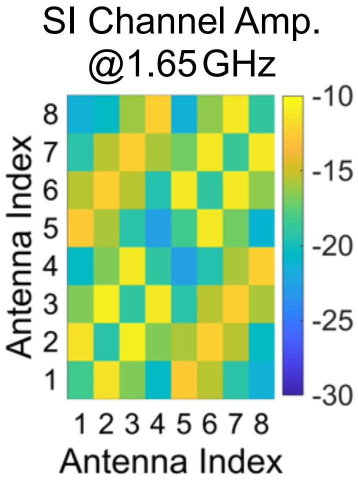
  - In realistic environments, $\mathbf{H}(f_k)$, $\forall k$, is ***frequency-selective***, and is ***neither symmetric nor Hermitian***
- **Self-interference-to-noise ratio (XINR)** at the FD BS (b):

$$\gamma_{bb}(f_k) = \underbrace{P_{\mathrm{t}}/N \cdot |\mathbf{v}^{\mathrm{T}}\mathbf{H}(f_k)\mathbf{w}|^2}_{\text{Residual SI power after TxBF \& RxBF}} \cdot \underbrace{(SIC_{\mathrm{dig}})^{-1}}_{\text{Digital SIC}} / \underbrace{P_{\mathrm{nf}}}_{\text{Array noise floor}}, \ \forall k$$

- XINR at the (single-antenna) FD user (u): $\gamma_{uu}(f_k) \leq 1$ [*Zhou et al. 2017*] [*Chen et al. 2019*]



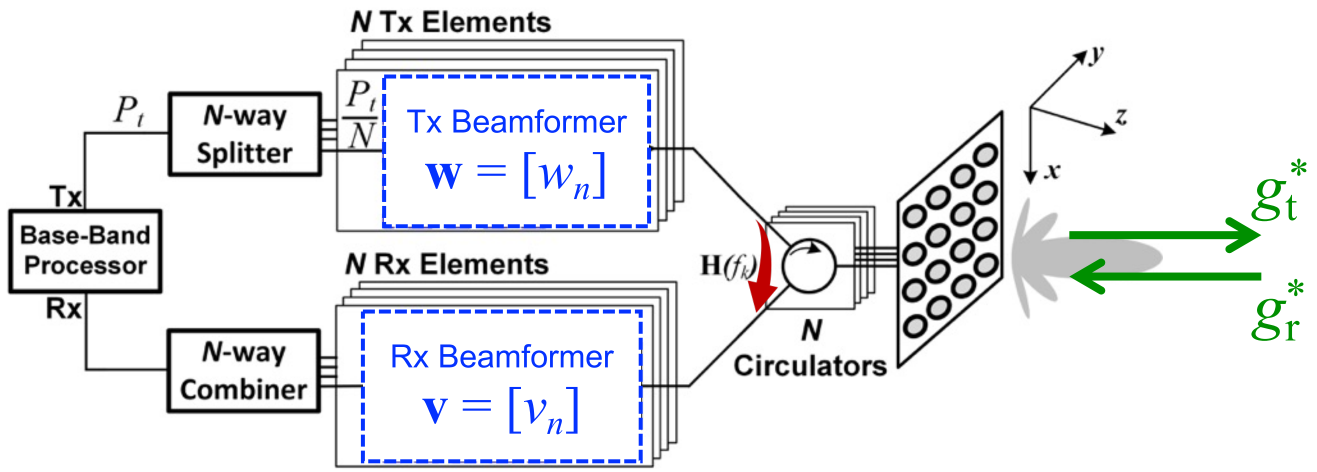




Full-Duplex Beamforming (FD BF) Gains

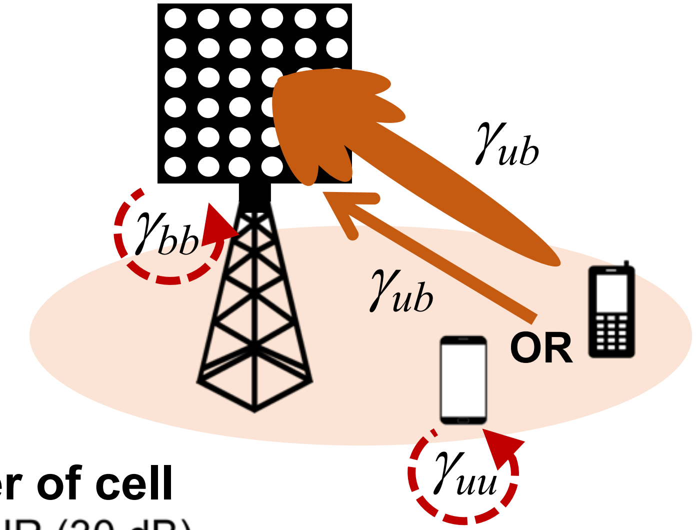
- **DEFINITION (OPTIMAL FD TXBF AND RXBF GAINS)**: For a` FD phased array with $\mathbf{H}(f_k)$ and P_{t}, the optimal FD TxBF and RxBF gains, g_{t}^* and g_{r}^*, are the maximum TxBF and RxBF gains that can be achieved with $\gamma_{bb}(f_k) \leq 1, \forall k$.

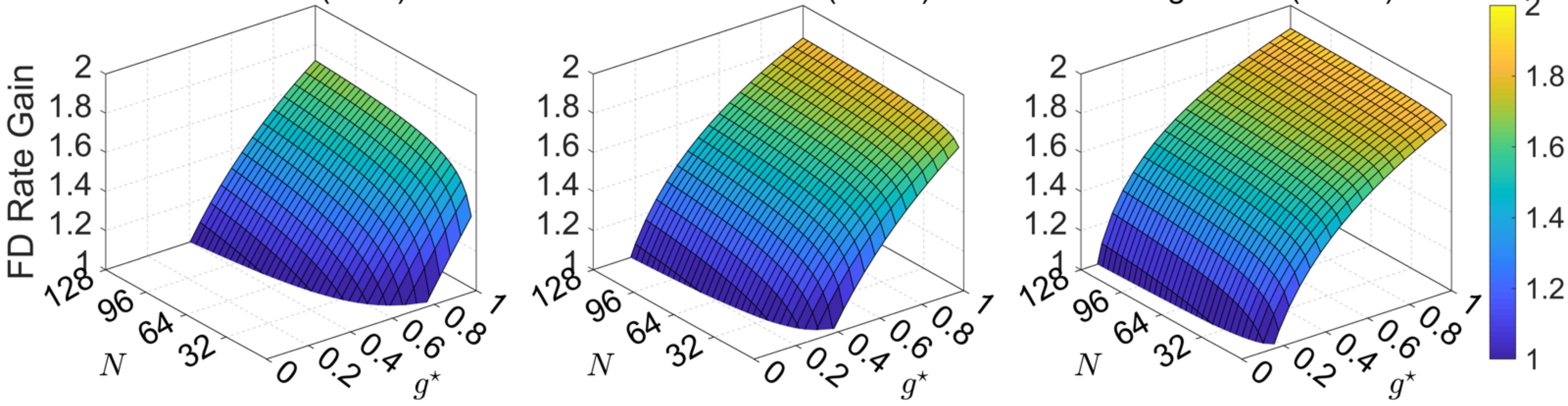
- **DEFINITION (TXBF AND RXBF GAIN LOSSES)**: The TxBF gain loss is the ratio between the maximum HD TxBF gain and the optimal FD TxBF gain, i.e., N / g_{t}^*. Similarly, the RxBF gain loss is N / g_{r}^*.
  - E.g., $3\,\mathrm{dB}$ TxBF gain loss → $g_{\mathrm{t}}^* = N/2$



Motivating Examples

- BS – User case with $g_t^* = g_r^* = g^*$
- Uplink and downlink sum rate computed using Shannon capacity formula





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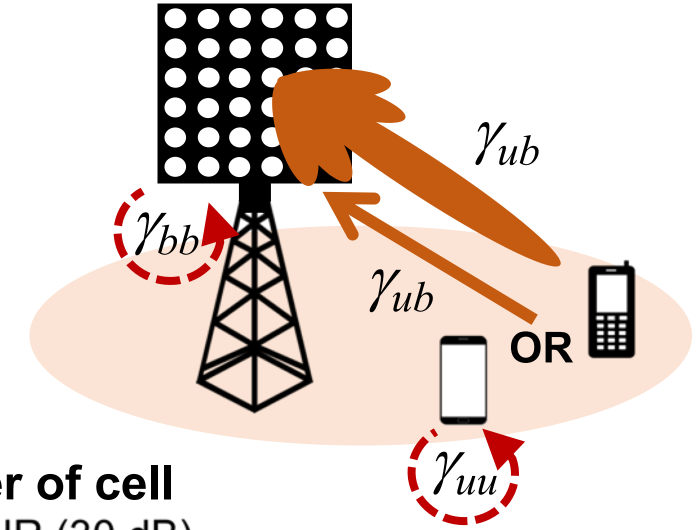
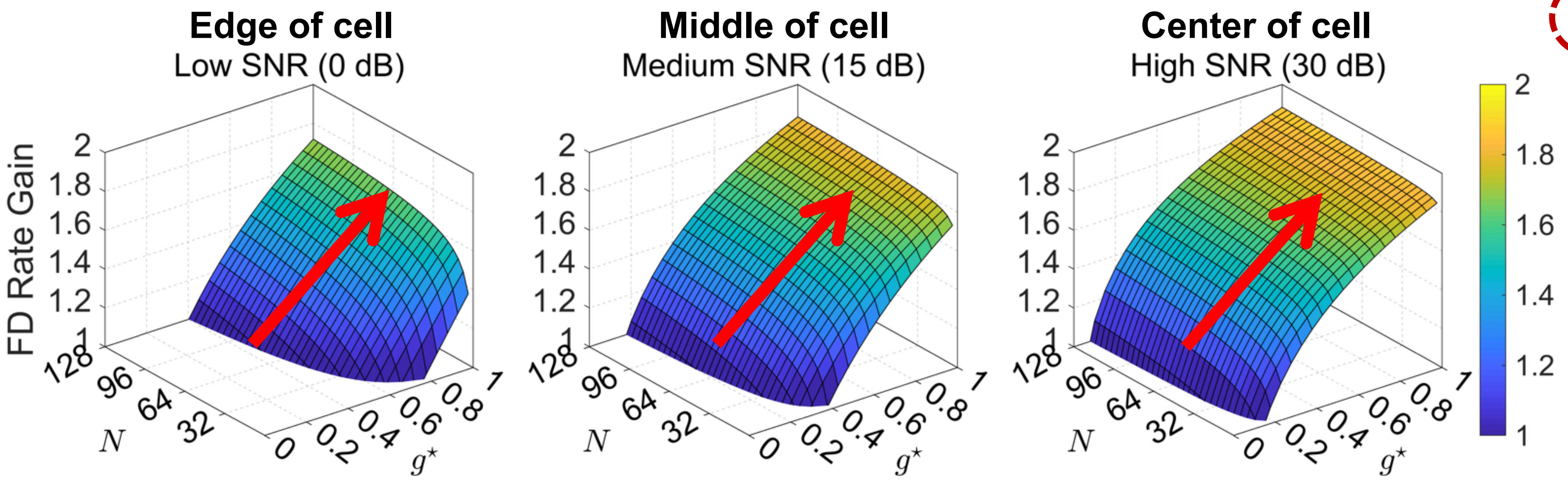


- BS – User case with $g_{\mathrm{t}}^{*} = g_{\mathrm{r}}^{*} = g^{*}$
- Uplink and downlink sum rate computed using Shannon capacity formula
- FD rate gain increases w.r.t. N and the optimal FD BF gain g^{*}



For a given phased array, maximizing the FD rate gain is equivalent to maximizing the FD TxBF and RxBF gains. Therefore, the goal is to maximize g^{*} subject to that XINR $\gamma_{bb}(f_k) \leq 1$, $\forall k$

Problem Formulation

- **<u>Objective</u>**: Maximize FD TxBF and RxBF gains
- **<u>Constraints</u>**: (i) Normalized Tx and Rx beamformers, (ii) wideband RF self-interference cancellation

(**Opt-TxRx**) $g^* = \max_{\mathbf{w},\mathbf{v}}: \{ g \}$

s.t.: $G(\phi_{\mathrm{t}}, \theta_{\mathrm{t}}) = g,\ G(\phi_{\mathrm{r}}, \theta_{\mathrm{r}}) = g,$ **(TxBF/RxBF gain in the main Tx/Rx beam-pointing direction)**

$|w_n| \leq 1,\ |v_n| \leq 1,\ \forall n,$ **(normalized TxBF and RxBF weights)**

$\gamma_{bb}(f_k) = P_{\mathrm{t}}/N \cdot |\mathbf{v}^{\mathrm{T}}\mathbf{H}(f_k)\mathbf{w}|^2 / SIC_{\mathrm{dig}} \leq P_{\mathrm{nf}},\ \forall k.$ **(XINR ≤ 1 across wideband)**

- Essentially, the Tx and Rx beamformers, $\mathbf{w}$ and $\mathbf{v}$, are ***repurposed*** such that the phased array self-interference signal is canceled to below the noise floor with minimal TxBF and RxBF gain losses

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$$\underbrace{|\mathbf{v}^\mathrm{T}\mathbf{H}(f_k)\mathbf{w}|^2}_{\textbf{\textit{Non-convex}}} \leq \beta,\ \forall k$$

- Essentially, the Tx and Rx beamformers, $\mathbf{w}$ and $\mathbf{v}$, are ***repurposed*** such that the phased array self-interference signal is canceled to below the noise floor with minimal TxBF and RxBF gain losses

An Iterative Algorithm

- **<u>Key Observation</u>**: with a fixed Rx beamformer, $\mathbf{v}$

$$\left|\mathbf{v}^{\mathsf{T}}\mathbf{H}(f_k)\mathbf{w}\right|^2 = (\mathbf{v}^{\mathsf{T}}\mathbf{H}(f_k)\mathbf{w})^{\dagger} \cdot (\mathbf{v}^{\mathsf{T}}\mathbf{H}(f_k)\mathbf{w}) = \mathbf{w}^{\dagger} \cdot \underbrace{\left(\mathbf{H}^{\dagger}(f_k)\mathbf{v}^{*}\mathbf{v}^{\mathsf{T}}\mathbf{H}(f_k)\right)}_{:= \mathbf{H}_{\mathbf{v}}(f_k)} \cdot \mathbf{w}$$

$[\cdot]^{\dagger}$: Hermitian operator

Hermitian* and *Positive Semidefinite

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Hermitian and Positive Semidefinite

- Decompose (**OPT-TXRX**) into two ***convex*** sub-problems that can be solved ***iteratively***
  - In the $(\kappa + 1)^{\mathrm{th}}$ iteration, (**ITER-TX/RX**) simultaneously maximize and balances TxBF and RxBF gains
  - Step size $\{\alpha_{\kappa}\}$: convergence speed vs. balance between TxBF and RxBF gains

(ITER-TX)

$$g_{\mathrm{t}}^{(\kappa+1)} = \max_{\mathbf{w}}\text{: } \{\, g_{\mathrm{t}} - \alpha_{\kappa+1} \cdot (g_{\mathrm{t}} - g_{\mathrm{r}}^{(\kappa)})^2 \,\}$$

$$\text{s.t.: } G(\phi_{\mathrm{t}}, \theta_{\mathrm{t}}) = g_{\mathrm{t}},\ |w_n| \leq 1,\ \forall n,$$

$$\mathbf{w}^{\dagger} \cdot \mathbf{H}_{\mathbf{v}(\kappa)}(f_k) \cdot \mathbf{w} \leq \beta,\ \forall k.$$

$\kappa = 0, 1, \ldots$

(ITER-RX)

$$g_{\mathrm{r}}^{(\kappa+1)} = \max_{\mathbf{v}}\text{: } \{\, g_{\mathrm{r}} - \alpha_{\kappa+1} \cdot (g_{\mathrm{r}} - g_{\mathrm{t}}^{(\kappa+1)})^2 \,\}$$

$$\text{s.t.: } G(\phi_{\mathrm{r}}, \theta_{\mathrm{r}}) = g_{\mathrm{r}},\ |v_n| \leq 1,\ \forall n,$$

$$\mathbf{v}^{\dagger} \cdot \mathbf{H}_{\mathbf{w}(\kappa)}(f_k) \cdot \mathbf{v} \leq \beta,\ \forall k.$$

Main Results: Performance Analysis

- **<u>Monotonicity of TxBF and RxBF Gains</u>**: With given initial Tx and Rx beamformers, $\mathbf{w}^{(0)}$ and $\mathbf{v}^{(0)}$, and step size, $\{\alpha_\kappa\}$, under the iterative algorithm, it holds that:

$$g_{\mathrm{t}}^{(\kappa+1)} \geq g_{\mathrm{t}}^{(\kappa)},\ g_{\mathrm{r}}^{(\kappa+1)} \geq g_{\mathrm{r}}^{(\kappa)},\ \forall \kappa.$$

(Iter-Tx)

$$g_{\mathrm{t}}^{(\kappa+1)} = \max_{\mathbf{w}}:\ \{\ g_{\mathrm{t}} - \alpha_{\kappa+1} \cdot (g_{\mathrm{t}} - g_{\mathrm{r}}^{(\kappa)})^2\ \}$$

$$\text{s.t.:}\ \ G(\phi_{\mathrm{t}},\ \theta_{\mathrm{t}}) = g_{\mathrm{t}},\ |w_n| \leq 1,\ \forall n,$$

$$\mathbf{w}^\dagger \cdot \mathbf{H}_{\mathbf{v}(\kappa)}(f_k) \cdot \mathbf{w} \leq \beta,\ \forall k.$$

$\kappa = 0,\ 1,\ \ldots$

(Iter-Rx)

$$g_{\mathrm{r}}^{(\kappa+1)} = \max_{\mathbf{v}}:\ \{\ g_{\mathrm{r}} - \alpha_{\kappa+1} \cdot (g_{\mathrm{r}} - g_{\mathrm{t}}^{(\kappa+1)})^2\ \}$$

$$\text{s.t.:}\ \ G(\phi_{\mathrm{r}},\ \theta_{\mathrm{r}}) = g_{\mathrm{r}},\ |v_n| \leq 1,\ \forall n,$$

$$\mathbf{v}^\dagger \cdot \mathbf{H}_{\mathbf{w}(\kappa)}(f_k) \cdot \mathbf{v} \leq \beta,\ \forall k.$$

Main Results: Performance Analysis

- **MONOTONICITY OF TXBF AND RXBF GAINS**: With given initial Tx and Rx beamformers, $\mathbf{w}^{(0)}$ and $\mathbf{v}^{(0)}$, and step size, $\{\alpha_\kappa\}$, under the iterative algorithm, it holds that:

$$g_{\mathrm{t}}^{(\kappa+1)} \geq g_{\mathrm{t}}^{(\kappa)},\ g_{\mathrm{r}}^{(\kappa+1)} \geq g_{\mathrm{r}}^{(\kappa)},\ \forall \kappa.$$

- **TERMINATION CONDITION**: $\max\{g_{\mathrm{t}}^{(\kappa+1)} - g_{\mathrm{t}}^{(\kappa)},\ g_{\mathrm{r}}^{(\kappa+1)} - g_{\mathrm{r}}^{(\kappa)}\} \leq \delta$

- **CONVERGENCE SPEED**: The iterative algorithm will terminate in at most N/δ iterations since $g_{\mathrm{t}}, g_{\mathrm{r}} \leq N$

(ITER-TX)

$$g_{\mathrm{t}}^{(\kappa+1)} = \max_{\mathbf{w}}:\ \{\ g_{\mathrm{t}} - \alpha_{\kappa+1}\cdot(g_{\mathrm{t}} - g_{\mathrm{r}}^{(\kappa)})^2\ \}$$

$$\text{s.t.:}\ \ G(\phi_{\mathrm{t}},\ \theta_{\mathrm{t}}) = g_{\mathrm{t}},\ |w_n| \leq 1,\ \forall n,$$

$$\mathbf{w}^\dagger \cdot \mathbf{H}_{\mathbf{v}(\kappa)}(f_k)\cdot \mathbf{w} \leq \beta,\ \forall k.$$

$\kappa = 0,\ 1,\ \ldots$

(ITER-RX)

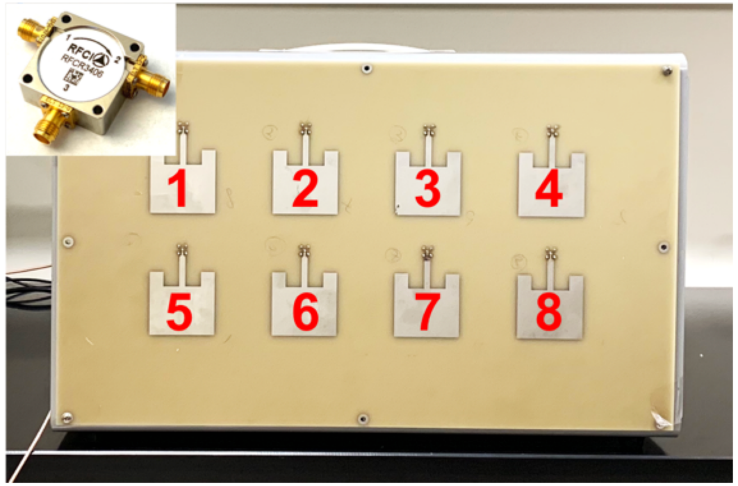
$$g_{\mathrm{r}}^{(\kappa+1)} = \max_{\mathbf{v}}:\ \{\ g_{\mathrm{r}} - \alpha_{\kappa+1}\cdot(g_{\mathrm{r}} - g_{\mathrm{t}}^{(\kappa+1)})^2\ \}$$

$$\text{s.t.:}\ \ G(\phi_{\mathrm{r}},\ \theta_{\mathrm{r}}) = g_{\mathrm{r}},\ |v_n| \leq 1,\ \forall n,$$

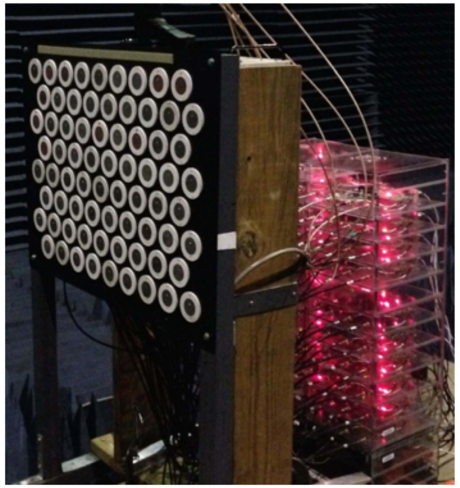
$$\mathbf{v}^\dagger \cdot \mathbf{H}_{\mathbf{w}(\kappa)}(f_k)\cdot \mathbf{v} \leq \beta,\ \forall k.$$

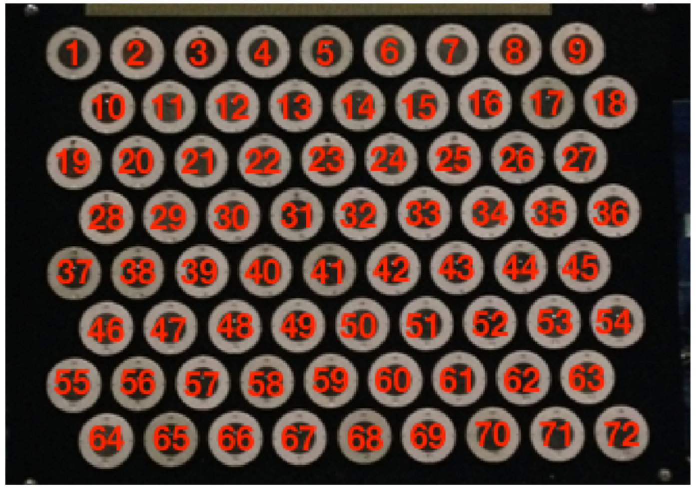
Evaluation – Measurements and Traces

- A custom-designed 1.65 GHz 8-element rectangular array with circulators
  - $N = 8$, $B = \{10, 20, \ldots, 50\}$ MHz
  - Varying signal bandwidth, B



- The Rice Argos 2.4 GHz 72-element hexagonal array
  - Integrate circulators into the FD SI channel measurement dataset [*Everett et al. 2016*]
  - $B = 20$ MHz, $N = \{9, 18, \ldots, 72\}$
  - Varying N and antenna array geometries





The self-interference channel matrix, $\mathbf{H}(f_k)$, $\forall k$, is ***neither symmetric nor Hermitian***

Evaluation – Setup and Benchmarks

- Tx power: up to $+30\,\mathrm{dBm}$, digital SIC: $40\,\mathrm{dB}$, Rx element noise floor: $-90\,\mathrm{dBm}$, step size: $\alpha_\kappa = 1/\kappa^2$
- Considered schemes:
  1) Conventional HD BF (**Conv**): conjugate BF
  2) Optimal joint FD BF (**Opt**): solving (**Opt-TxRx**) using a non-linear solver
  3) Iterative FD BF (**Iter**): iteratively solving (**Iter-Tx**) and (**Iter-Rx**) using CVX ($\delta = 0.01$)

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- (**Iter**) vs. (**Opt**): Runtime improvements and achieved FD rate gains
  - (**OPT-TXRX**): non-convex
  - (**ITER-TX**) and (**ITER-RX**): convex, converges in <10 iterations

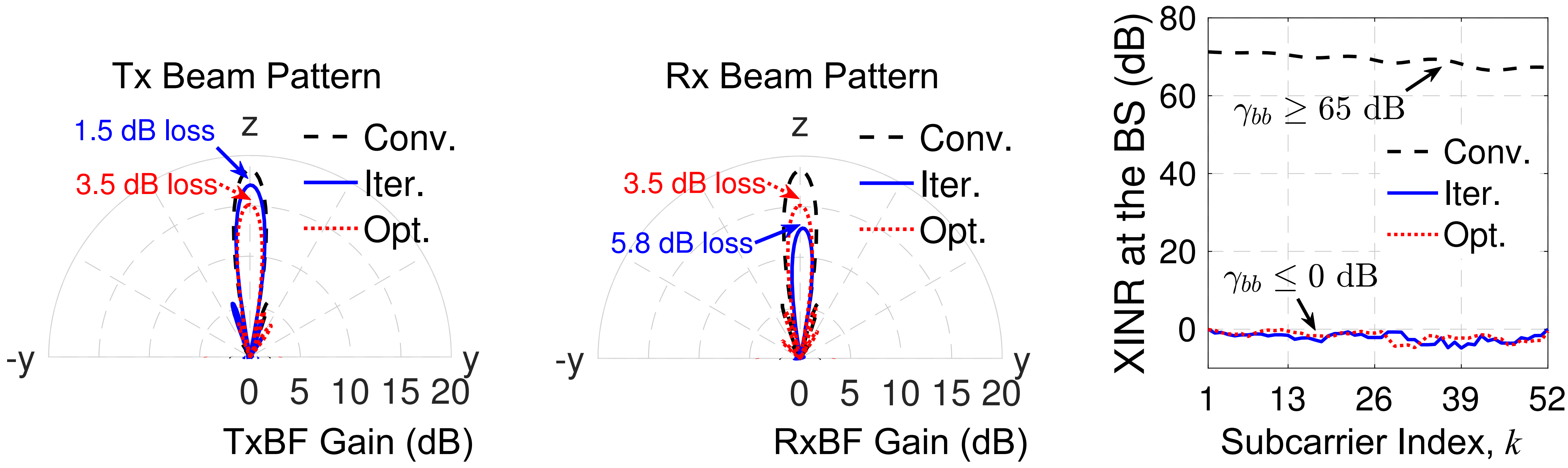
N	9	18	27	36	45	54	63	72
Runtime Improvements	0.99x	1.72x	2.41x	2.12x	2.70x	3.18x	5.51x	6.00x

N	9	18	27	36	45	54	63	72
Ratio b/w achieved FD Rate Gains	0.93	0.97	0.98	0.99	>0.99	>0.99	>0.99	>0.99

Evaluation – RF Self-Interference Cancellation

Conjugate HD BF Gain: $10\log_{10}(72) = 18.6\,\mathrm{dB}$

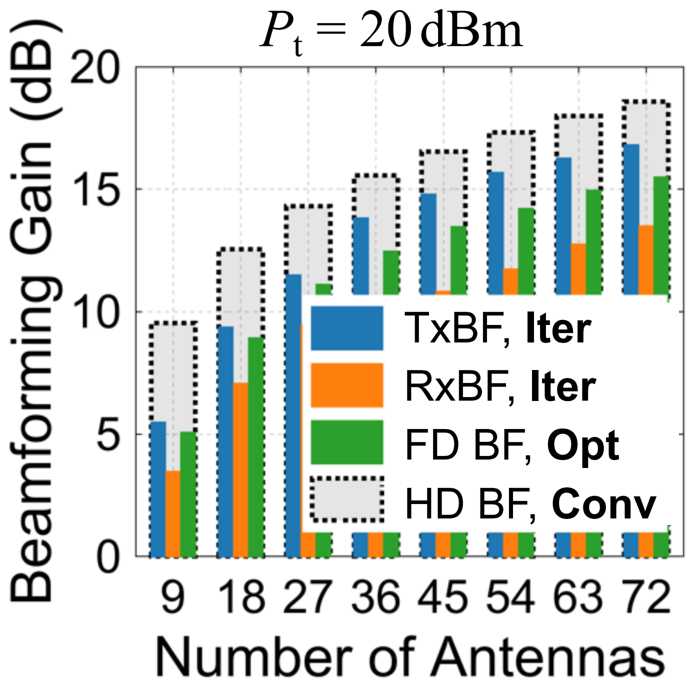
- Tx and Rx beam patterns and beamforming gains with $N = 72$, $P_\mathrm{t} = 30\,\mathrm{dBm}$, $B = 20\,\mathrm{MHz}$

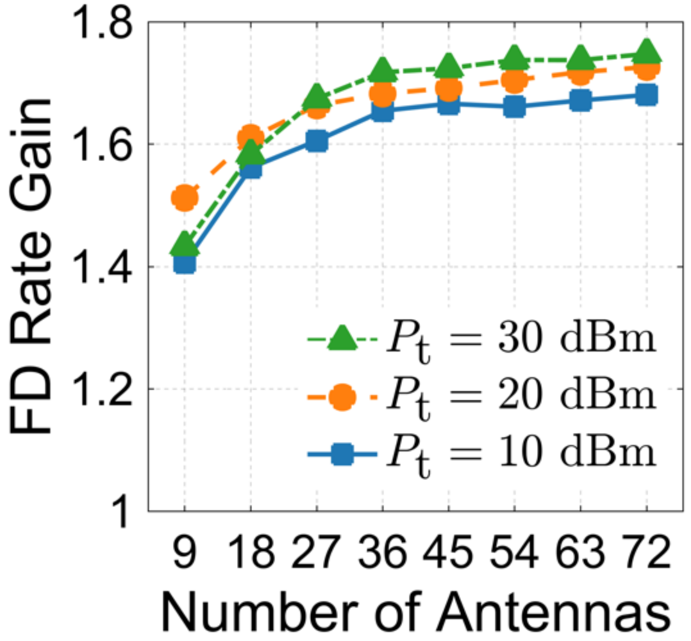


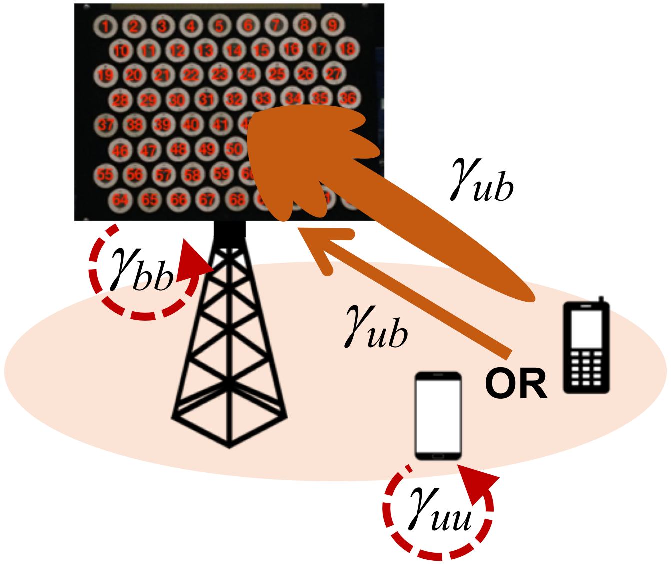
- TxBF/RxBF gain loss of **1.5/5.8 dB** → **over 65 dB** RF self-interference cancellation across **20 MHz** bandwidth
- This translates to an FD rate gain of **1.69/1.75/1.79 x** at **0/15/30 dB** link SNR

Evaluation – Effects of N and P_t

- $N = \{9, 18, \ldots, 72\}$ with $B = 20\,\mathrm{MHz}$



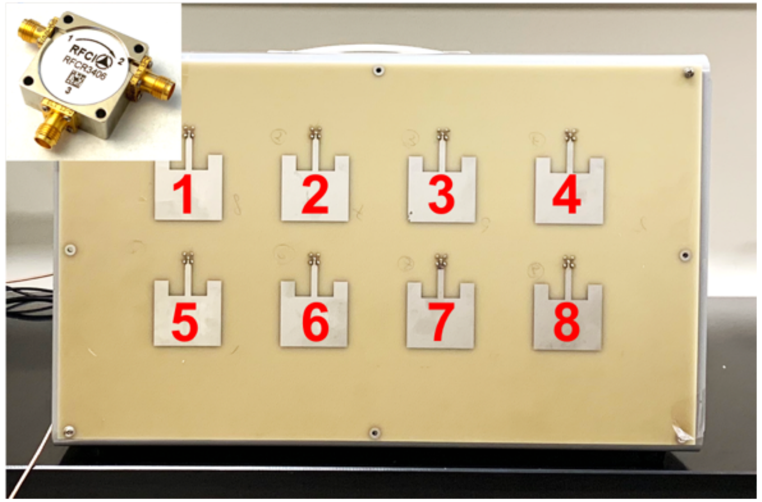


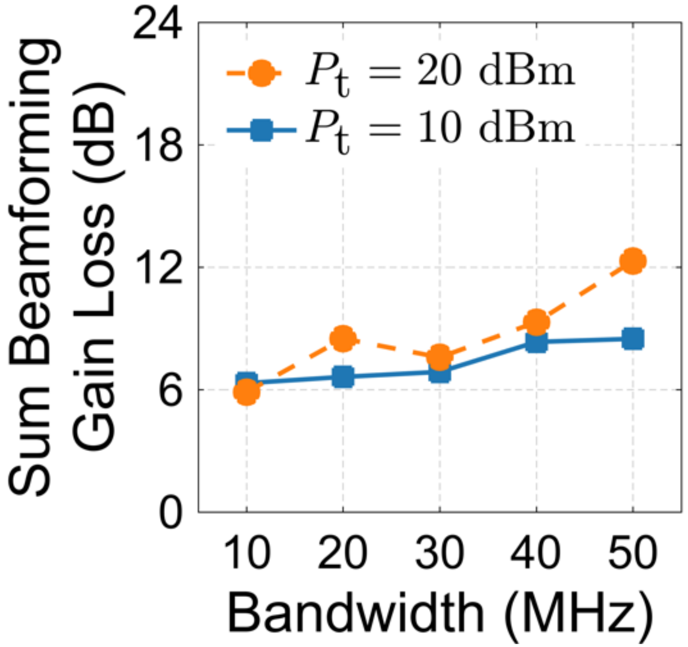


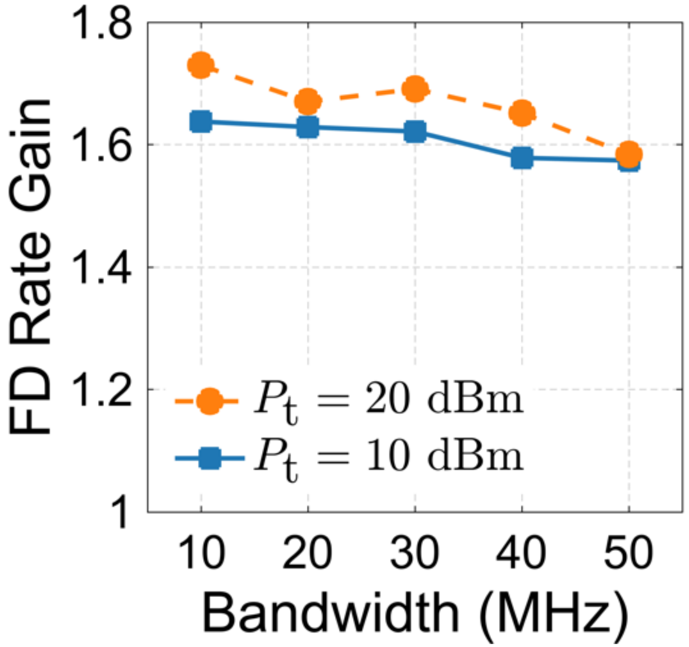
- Larger values of N → smaller FD TxBF and RxBF losses (***more BF degrees of freedom can be repurposed***)
- Larger values of N and higher Tx power P_t → higher FD rate gains

Evaluation – Effects of Bandwidth, B

- $N = 8$, $B = \{10, 20, \ldots, 50\}$ MHz



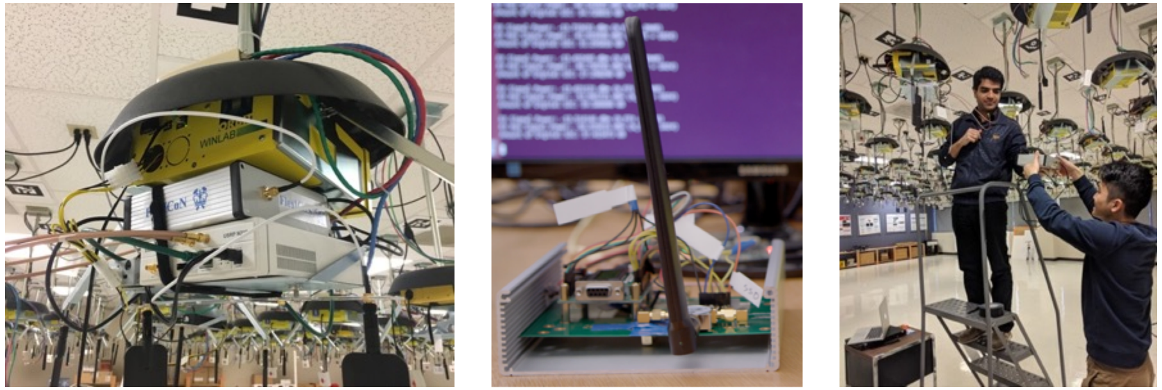




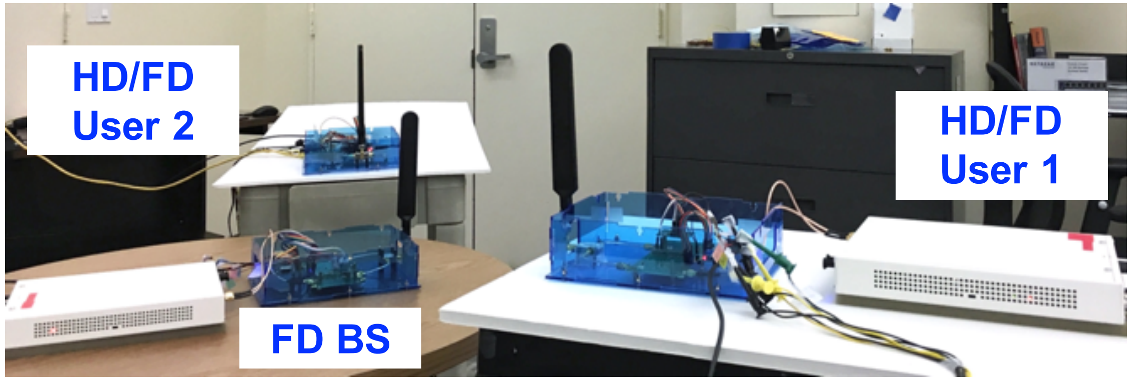
- Sum TxBF and RxBF gain loss of **12.3 dB** at $P_t = 20\,\mathrm{dBm}$ and with $B = 50\,\mathrm{MHz}$
- Correspond to FD rate gains of at least **1.57 x**

The Columbia FlexICoN Project

- **F**ull-Dup**lex** Wireless: From **I**ntegrated **C**ircuits t**o** **N**etworks (FlexICoN)
  - Focus on IC-based implementations of single- and multi-antenna full-duplex radios
  - Full-duplex radio/system development, algorithm design, and experimental evaluation
  - Integration of full-duplex capability in the open-access ORBIT and city-scale PAWR COSMOS testbeds



A programmable Gen-1 full-duplex node installed in ORBIT

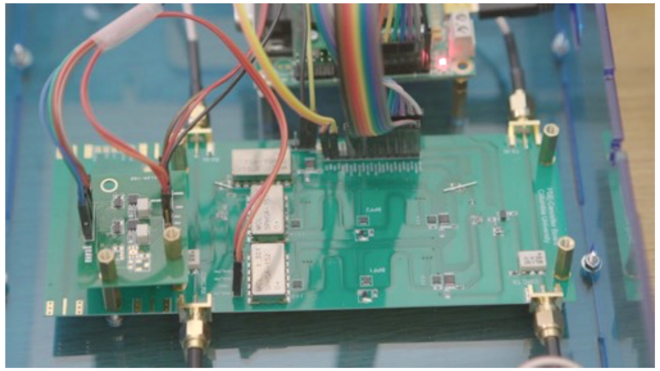


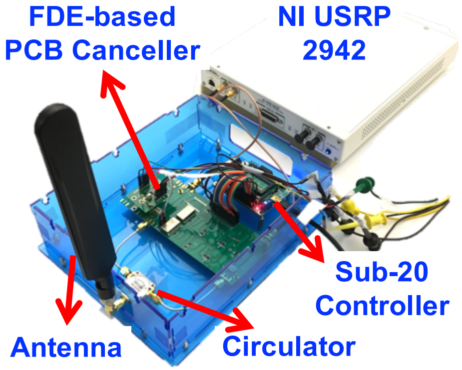
Gen-2 wideband full-duplex radios and testbed

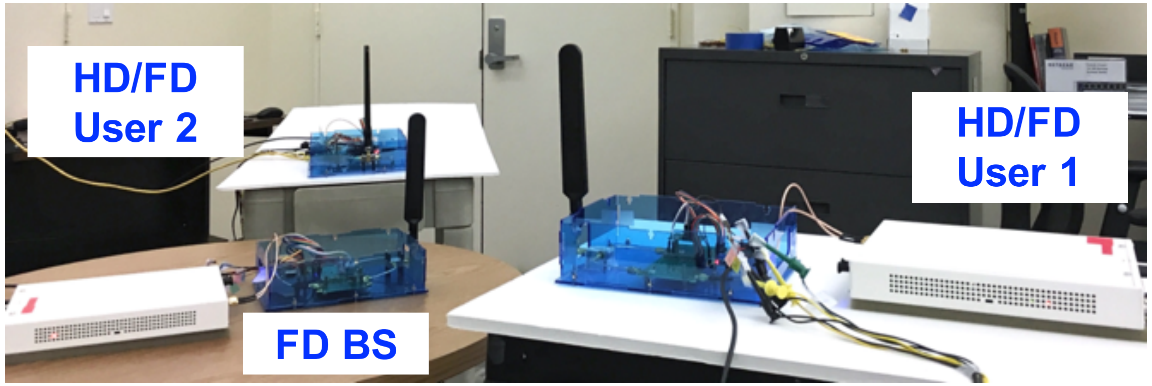
- **T. Chen**, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex wireless via frequency-domain equalization: Design and experimentation," in *Proc. ACM MobiCom'19 (to appear)*, 2019.
- **T. Chen**, J. Diakonikolas, J. Ghaderi, and G. Zussman, "Hybrid scheduling in heterogeneous half- and full-duplex wireless networks," in *Proc. IEEE INFOCOM'18*, 2018.
- **T. Chen**, M. Baraani Dastjerdi, G. Farkash, J. Zhou, H. Krishnaswamy, and G. Zussman,"Open-access full-duplex wireless in the ORBIT testbed," *arXiv preprint arXiv:1801.03069v2*, 2018.
- "Tutorial: Full-duplex wireless in the ORBIT testbed," available at http://www.orbit-lab.org/wiki/Tutorials/k0SDR/Tutorial25
- "Open-access full-duplex wireless in the ORBIT testbed: Instructions and code," available at https://github.com/Wimnet/flexicon_orbit

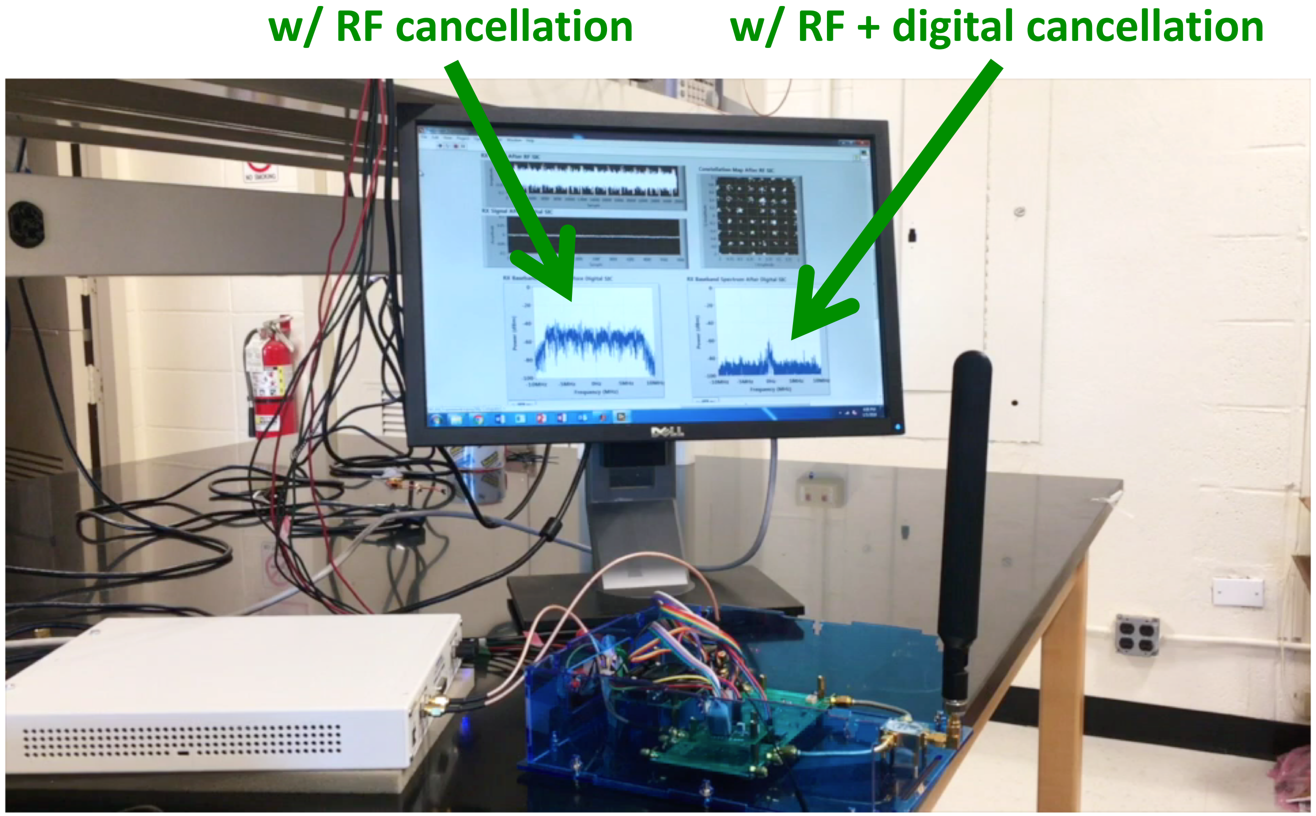
Gen-2 Wideband Full-Duplex Radios and Testbed

- Total self-interference cancellation: **95 dB** (RF + digital) with **20 MHz** bandwidth, up to **108 Mbps** data rate
- Full-duplex: average link rate gain of **1.87x**, average network rate gain is **93%** of the analytical value









- <u>**T. Chen**</u>, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, “Wideband compact full-duplex wireless via frequency-domain equalization: Design and experimentation,” in *Proc. ACM MobiCom’19 (to appear)*, 2019.

Summary

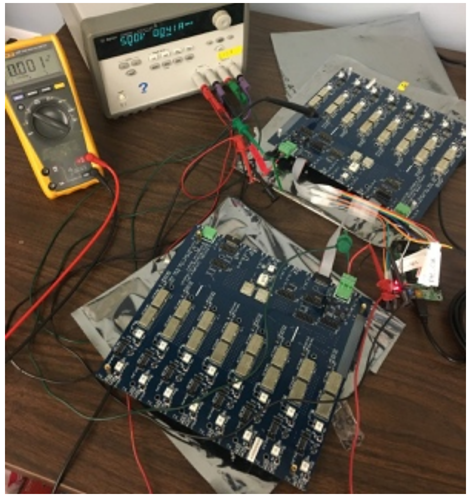
- FD phased arrays achieving wideband RF self-interference cancellation and improved FD rate gains via repurposing Tx and Rx analog beamformers (i.e., spatial degrees of freedom)

- An efficient iterative algorithm for obtaining the optimal Tx and Rx beamformers in the FD setting with provable performance guarantees

- Performance evaluation using measurements and traces

- Future directions:
  - Extension to large-scale FD MIMO/hybrid MIMO-phased array systems
  - Experimental evaluation using existing/customized full-duplex testbeds
  - Integration in the open-access city-scale PAWR COSMOS testbed

16-element phased array using discrete components



Thank you!

tingjun@ee.columbia.edu

http://www.ee.columbia.edu/~tc2668

Tingjun Chen, Mahmood Baraani Dastjerdi, Harish Krishnaswamy, and Gil Zussman, "Wideband Full-Duplex Phased Array with Joint Transmit and Receive Beamforming: Optimization and Rate Gains".

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

wim.net
Wireless & Mobile Networking Lab