# Full-Duplex Communications

Presenter: Elyes Balti (ebalti@utexas.edu)

*Advisor*: Prof. Brian L. Evans (bevans@ece.utexas.edu)

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The University of Texas at Austin

Wireless Networking & Communications Group (WNCG)

Embedded Signal Processing Laboratory (ESPL)

The University of Texas at Austin
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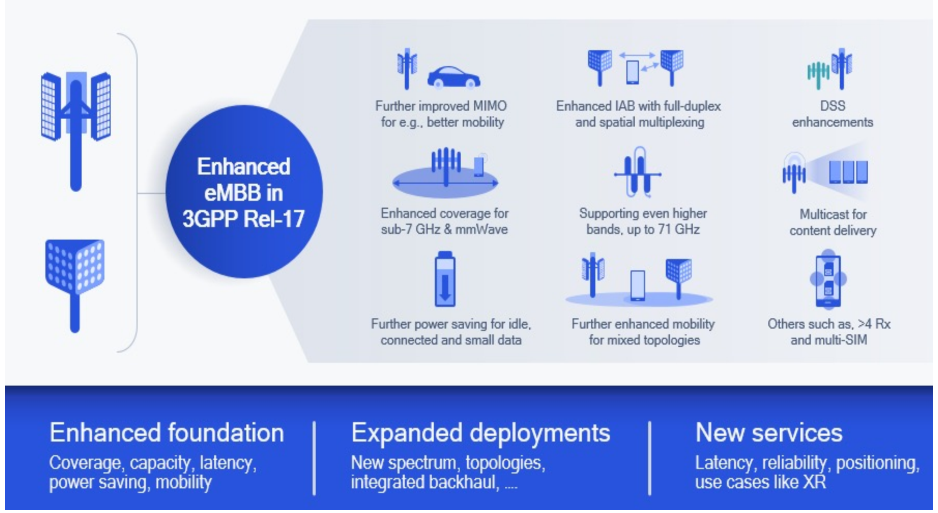
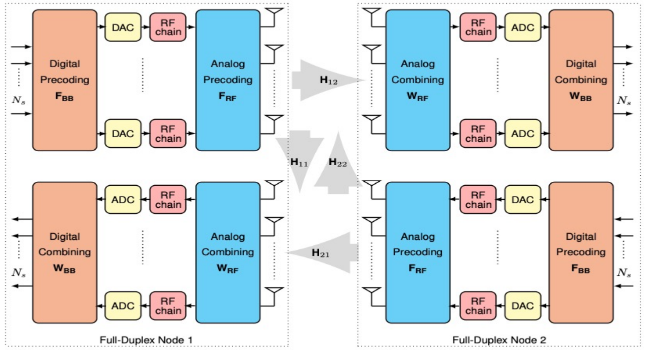
# Motivation

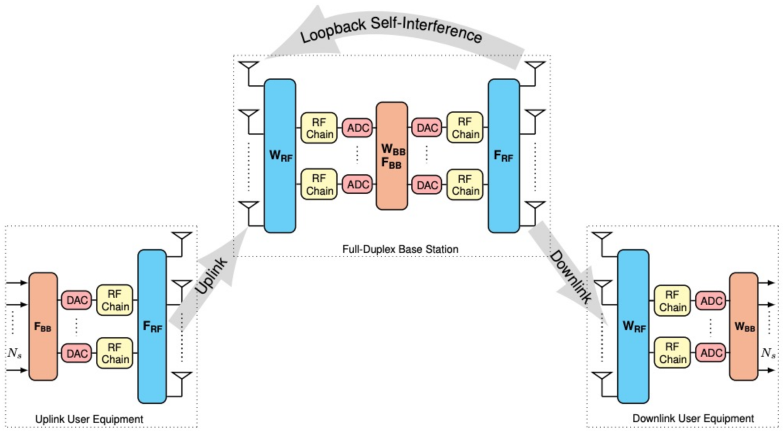
- Benefits: double the spectral efficiency, reduce the latency, enhance the reliability/coverage due to the transmission and reception at the same resource block (time/frequency), and reduction of the number of antennas by a factor of 2 (e.g., shared TX and RX arrays of full-duplex transceivers).
- Applications: machine-to-machine, cellular systems, integrated access and backhaul.
- Currently proposed in 3GPP Release 17.




Integrated Access and Backhaul




Machine-to-Machine




Cellular

https://www.qualcomm.com/news/onq/2019/12/13/3gpp-charts-next-chapter-5g-standards


E. Balti and N. Mensi, "Zero-Forcing Max-Power Beamforming for Hybrid mmWave Full-Duplex MIMO Systems," *2020 4th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, 2020, pp. 344-349

E. Balti and B. L. Evans, "Hybrid Beamforming Design for Wideband MmWave Full-Duplex Systems," *arxiv*, 2021

# Problems/Challenges

- Vulnerable to the loop-back self-interference (SI).
- SI signal power can be up to x1000-10000 times the received signal power.
- In cellular systems, the SI is large with the cell-edge users.
- ADCs saturation by the SI resulting in low spectral efficiency.
- Without SI cancellation, full-duplex systems are dysfunctional.
- Requires robust beamformers to cancel the SI.
- Beamforming design is complex and subject to different constraints.
- Design suboptimal beamformers to reduce the complexity at the expense of the performance.

# System Model

- Analog-only architecture, i.e., supports a single stream.
- The received signal at the nodes 1 and 2 are:

$$y_1 = \mathbf{w}_{r1}^H\left(\sqrt{\epsilon_{21}}\,\mathbf{H}_{21}\mathbf{w}_{t2}\,s_2 + \sqrt{\epsilon_{11}}\,\mathbf{H}_{11}\mathbf{w}_{t1}\,s_1 + \mathbf{n}_1\right)$$
$$y_2 = \mathbf{w}_{r2}^H\left(\sqrt{\epsilon_{12}}\,\mathbf{H}_{12}\mathbf{w}_{t1}\,s_1 + \sqrt{\epsilon_{22}}\,\mathbf{H}_{22}\mathbf{w}_{t2}\,s_2 + \mathbf{n}_2\right)$$

- The sum rate (cost function) is expressed by

$$R = \log_2\left(1 + \frac{\epsilon_{21}\left|\mathbf{w}_{r1}^H\mathbf{H}_{21}\mathbf{w}_{t2}\right|^2}{1 + \epsilon_{11}\left|\mathbf{w}_{r1}^H\mathbf{H}_{11}\mathbf{w}_{t1}\right|^2}\right) + \log_2\left(1 + \frac{\epsilon_{12}\left|\mathbf{w}_{r2}^H\mathbf{H}_{12}\mathbf{w}_{t1}\right|^2}{1 + \epsilon_{22}\left|\mathbf{w}_{r2}^H\mathbf{H}_{22}\mathbf{w}_{t2}\right|^2}\right)$$

- Channel from node *u* to node *v* is given

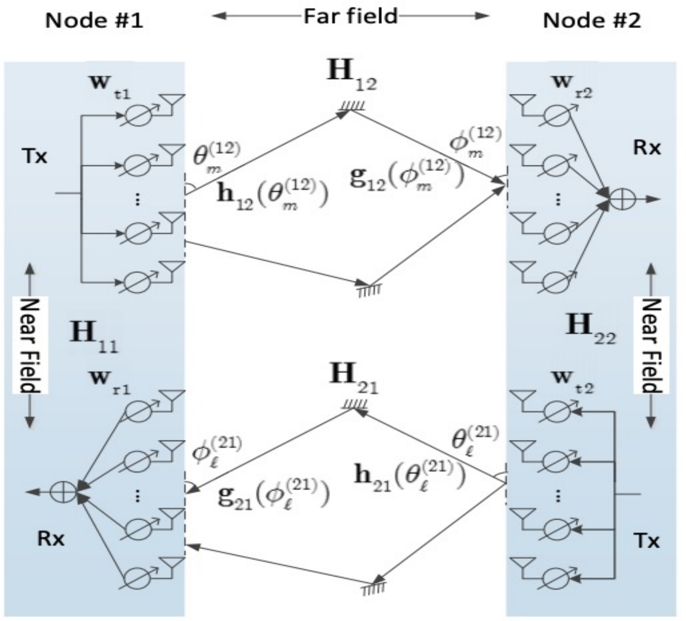
$$\mathbf{H}_{uv} = \sqrt{\frac{N_{TX}N_{RX}}{N_{cl}N_{ray}}}\sum_{k=1}^{N_{cl}}\sum_{\ell=1}^{N_{ray}}\alpha_{k,\ell}\,\mathbf{a}_{\mathrm{RX}}(\phi_{k,\ell})\mathbf{a}_{\mathrm{TX}}^H(\theta_{k,\ell})$$

- The *p*-th and *q*-th entry of the LOS self-interference channel is given by

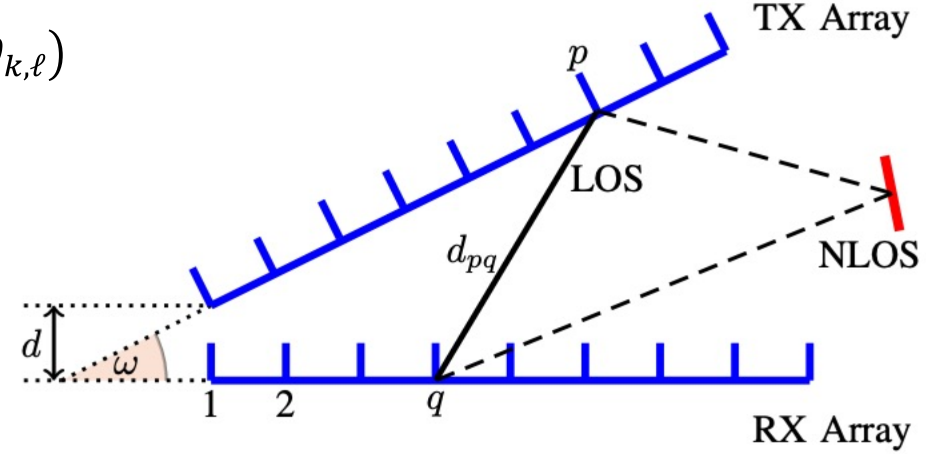
$$[\mathbf{H}_{\mathrm{los}}]_{pq} = \frac{1}{d_{pq}}e^{-j2\pi\frac{d_{pq}}{\lambda}}$$

- The aggregate self-interference channel at the node *u* is expressed by

$$\mathbf{H}_{uu} = \sqrt{\frac{\kappa}{\kappa+1}}\,\mathbf{H}_{\mathrm{los}} + \sqrt{\frac{1}{\kappa+1}}\,\mathbf{H}_{\mathrm{nlos}}$$




Two-node Full-Duplex System




Full-Duplex Transceiver Arrays

X. Liu, Z. Xiao, L. Bai, J. Choi, P. Xia, and X.-G. Xia, "Beamforming based full-duplex for millimeter-wave communication," Sensors, vol. 16, no. 7, 2016.

# Zero-Forcing Max-Power

- The optimization problem can be formulated as

$$\max_{\mathbf{w}_{t1},\mathbf{w}_{t2},\mathbf{w}_{r1},\mathbf{w}_{r2}} \left|\mathbf{w}_{r1}^{H}\mathbf{H}_{21}\mathbf{w}_{t2}\right|^2, \left|\mathbf{w}_{r2}^{H}\mathbf{H}_{12}\mathbf{w}_{t1}\right|^2 \text{ (received power)}$$

$$\text{Subject to } \|\mathbf{w}_{t1}\|^2 = \|\mathbf{w}_{r1}\|^2 = 1$$

$$\|\mathbf{w}_{t2}\|^2 = \|\mathbf{w}_{r2}\|^2 = 1$$

$$\mathbf{w}_{r1}^{H}\mathbf{H}_{11}\mathbf{w}_{t1} = \mathbf{w}_{r2}^{H}\mathbf{H}_{22}\mathbf{w}_{t2} = 0 \text{ (zero-forcing constraint)}$$

- The unconstrained solution (without accounting for the Constant Amplitude (CA) Constraint) consists of two projections:

1. Projection 1: $\mathbf{w}_{r1} = \mathbf{H}_{21}\mathbf{w}_{t2}, \mathbf{w}_{r2} = \mathbf{H}_{12}\mathbf{w}_{t1}, \mathbf{w}_{t1} = \mathbf{H}_{12}{}^{H}\mathbf{w}_{r2}, \mathbf{w}_{t2} = \mathbf{H}_{21}{}^{H}\mathbf{w}_{r1}$ (maximize the received power).
2. Projection 2: Project the beamformers on the Zero-Forcing null-space.

- The solutions are given by

$$\mathbf{w}_{r1} = \mathbf{H}_{21}\mathbf{w}_{t2} - \left\langle \mathbf{H}_{21}\mathbf{w}_{t2}, \frac{\mathbf{H}_{11}\mathbf{w}_{t1}}{\|\mathbf{H}_{11}\mathbf{w}_{t1}\|} \right\rangle \frac{\mathbf{H}_{11}\mathbf{w}_{t1}}{\|\mathbf{H}_{11}\mathbf{w}_{t1}\|}$$

$$\mathbf{w}_{r2} = \mathbf{H}_{12}\mathbf{w}_{t1} - \left\langle \mathbf{H}_{12}\mathbf{w}_{t1}, \frac{\mathbf{H}_{22}\mathbf{w}_{t2}}{\|\mathbf{H}_{22}\mathbf{w}_{t2}\|} \right\rangle \frac{\mathbf{H}_{22}\mathbf{w}_{t2}}{\|\mathbf{H}_{22}\mathbf{w}_{t2}\|}$$

$$\mathbf{w}_{t1} = \mathbf{H}_{12}{}^{H}\mathbf{w}_{r2} - \left\langle \mathbf{H}_{12}{}^{H}\mathbf{w}_{r2}, \frac{\mathbf{H}_{11}{}^{H}\mathbf{w}_{r1}}{\|\mathbf{H}_{11}{}^{H}\mathbf{w}_{r1}\|} \right\rangle \frac{\mathbf{H}_{11}{}^{H}\mathbf{w}_{r1}}{\|\mathbf{H}_{11}{}^{H}\mathbf{w}_{r1}\|}$$

$$\mathbf{w}_{t2} = \mathbf{H}_{21}{}^{H}\mathbf{w}_{r1} - \left\langle \mathbf{H}_{21}{}^{H}\mathbf{w}_{r1}, \frac{\mathbf{H}_{22}{}^{H}\mathbf{w}_{r2}}{\|\mathbf{H}_{22}{}^{H}\mathbf{w}_{r2}\|} \right\rangle \frac{\mathbf{H}_{22}{}^{H}\mathbf{w}_{r2}}{\|\mathbf{H}_{22}{}^{H}\mathbf{w}_{r2}\|}$$

- Third projection into the subspace of the CA constraint, i.e., each entry of the solution must satisfy

$$[\mathbf{w}]_n = \frac{e^{j\phi_n}}{\sqrt{N}}, \ \phi_n\text{: drawn from the feasible set of the phase shifter.}$$

# Beam Steering

- The beamformers are expressed in terms of the array response as

$$\mathbf{w}_{t1} = \mathbf{a}_{\mathrm{TX}}(\theta_\ell)$$

$$\mathbf{w}_{r2} = \mathbf{a}_{\mathrm{RX}}(\phi_\ell)$$

$$\mathbf{w}_{t2} = \mathbf{a}_{\mathrm{TX}}(\theta_m)$$

$$\mathbf{w}_{r1} = \mathbf{a}_{\mathrm{RX}}(\phi_m)$$

# Angle Search

- Consider a set of feasible angles for each beamformers
- Perform exhaustive search over all the set of feasible phase shifters to maximize the sum rate.
- The feasible set are subject to quantization.
- Increasing the angles resolution will improve the sum rate but with higher complexity.

# Lower Bound MMSE

- The sum rate can be lower bounded as

$$R \geq \log_2\left(\frac{\epsilon_{21}\mathbf{w}_{r1}^H\mathbf{H}_{21}\mathbf{w}_{t2}\mathbf{w}_{t2}{}^H\mathbf{H}_{21}^H\mathbf{w}_{r1}}{\mathbf{w}_{r1}^H\left(\mathbf{I}+\ \epsilon_{11}\mathbf{H}_{11}\mathbf{w}_{t1}\mathbf{w}_{t1}^H\mathbf{H}_{11}^H\right)\mathbf{w}_{r1}}\frac{\epsilon_{12}\mathbf{w}_{r2}^H\mathbf{H}_{12}\mathbf{w}_{t1}\mathbf{w}_{t1}{}^H\mathbf{H}_{12}^H\mathbf{w}_{r2}}{\mathbf{w}_{r2}^H\left(\mathbf{I}+\ \epsilon_{22}\mathbf{H}_{22}\mathbf{w}_{t2}\mathbf{w}_{t2}^H\mathbf{H}_{22}^H\right)\mathbf{w}_{r2}}\right) = R_1$$

- The optimal $\mathbf{w}_{r1}$ and $\mathbf{w}_{r2}$ (before normalization) are given by

$$\mathbf{w}_{r1} = \left(\mathbf{I}+\epsilon_{11}\mathbf{H}_{11}\mathbf{w}_{t1}\mathbf{w}_{t1}^H\mathbf{H}_{11}^H\right)^{-1}\mathbf{H}_{21}\mathbf{w}_{t2} \text{ (*)}$$

$$\mathbf{w}_{r2} = \left(\mathbf{I}+\epsilon_{22}\mathbf{H}_{22}\mathbf{w}_{t2}\mathbf{w}_{t2}^H\mathbf{H}_{22}^H\right)^{-1}\mathbf{H}_{12}\mathbf{w}_{t1} \text{ (**)}$$

- A new lower bound can be derived using (*) and (**)

$$R_1 \geq \log_2\left(\epsilon_{12}\epsilon_{21}\frac{\mathbf{w}_{t2}{}^H\mathbf{H}_{21}^H\mathbf{H}_{21}\mathbf{w}_{t2}}{\mathbf{w}_{t2}^H\left(\mathbf{I}+\ \epsilon_{22}\mathbf{H}_{22}^H\mathbf{H}_{22}\right)\mathbf{w}_{t2}}\frac{\mathbf{w}_{t1}{}^H\mathbf{H}_{12}^H\mathbf{H}_{12}\mathbf{w}_{t1}}{\mathbf{w}_{t1}^H\left(\mathbf{I}+\ \epsilon_{11}\mathbf{H}_{11}^H\mathbf{H}_{11}\right)\mathbf{w}_{t1}}\right) = R_2$$

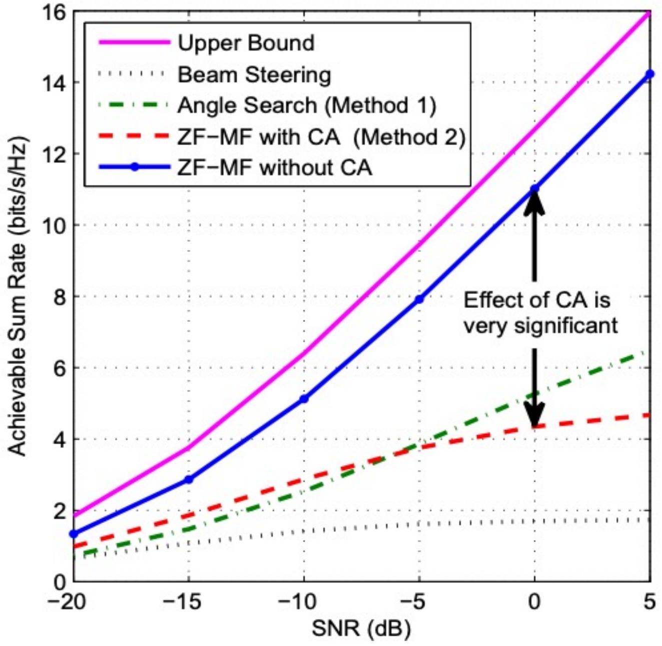
- Generalized Rayleigh quotient problem with respect to $\mathbf{w}_{t1}, \mathbf{w}_{t2}$. The solutions are given by

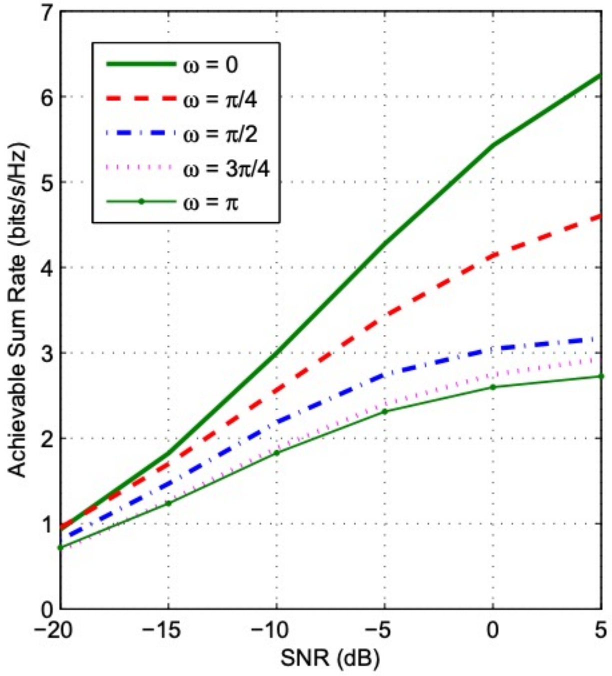
$$\mathbf{w}_{t1} = \text{pEigVect}\left(\left(\mathbf{I}+\epsilon_{11}\mathbf{H}_{11}\mathbf{H}_{11}^H\right)^{-1}\mathbf{H}_{12}^H\mathbf{H}_{12}\right)$$

$$\mathbf{w}_{t2} = \text{pEigVect}\left(\left(\mathbf{I}+\epsilon_{22}\mathbf{H}_{22}\mathbf{H}_{22}^H\right)^{-1}\mathbf{H}_{21}^H\mathbf{H}_{21}\right)$$

- pEigVect(A) is the principal eigenvector of A.

# Performance Results




- Unconstrained ZF outperforms the other approaches.
- The CA constraint completely degrades the performances since it violates the ZF constraint.
- The angle between the TX and RX arrays at the full-duplex nodes may mitigate the self-interference.
- With a careful choice of angle, the TX and RX arrays can be isolated to suppress the self-interference

Z. Xiao, P. Xia and X. Xia, "Full-Duplex Millimeter-Wave Communication," in *IEEE Wireless Communications*, vol. 24, no. 6, pp. 136-143, Dec. 2017

# Extension to Hybrid Architecture

- Consists of digital and analog parts.
- Supports multiple spatial streams.
- To avoid the violation of the ZF constraint, we properly handle the CA constraint to minimize the rate losses.
- We propose to enhance the ZF max-power approach.
- We refer to ***alternating projection*** method to design the beamformers: The first handles the ZF constraint and the second deals with the CA constraint.
- We construct two nested iterative processes: Outer cycle for ZF and inner cycle for CA.
- In the $n$-th ZF cyclic maximization, the generic analog solution is expressed as

$$\mathbf{w}^{(n)} = \left(\mathbf{I} - \frac{\alpha\alpha^H}{\|\alpha\|^2}\right)\mathbf{w}^{(n-1)}$$

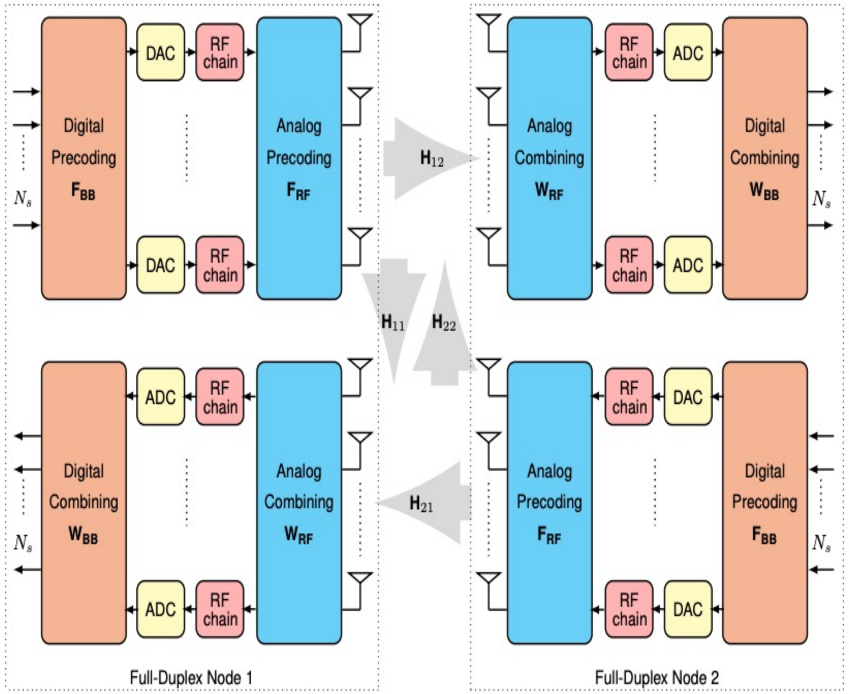
- The digital beamformers (without normalization) are given by (iteratively)

$$\mathbf{W}_{BB,1} = \mathbf{W}_{RF,1}^H \mathbf{H}_{21} \mathbf{F}_{RF,2} \mathbf{F}_{BB,2} \text{ (Fix } \mathbf{F}_{BB,2}\text{)}$$

$$\mathbf{W}_{BB,2} = \mathbf{W}_{RF,2}^H \mathbf{H}_{21} \mathbf{F}_{RF,1} \mathbf{F}_{BB,1} \text{(Fix } \mathbf{F}_{BB,1}\text{)}$$

$$\boldsymbol{F}_{BB,1} = \boldsymbol{F}_{RF,1}^H {\mathbf{H}_{12}}^H \boldsymbol{W}_{RF,2} \boldsymbol{W}_{BB,2} \text{ (Fix } \boldsymbol{W}_{BB,2}\text{)}$$

$$\boldsymbol{F}_{BB,2} = \boldsymbol{F}_{RF,2}^H {\mathbf{H}_{21}}^H \boldsymbol{W}_{RF,1} \boldsymbol{W}_{BB,1} \text{(Fix Fix } \boldsymbol{W}_{BB,1}\text{)}$$




Machine-to-Machine

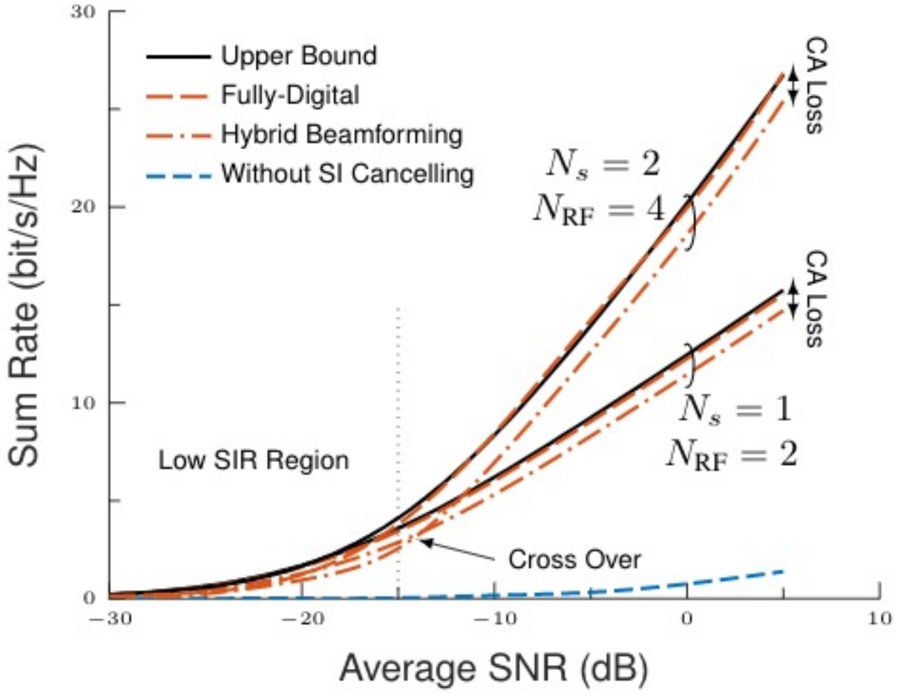

E. Balti and N. Mensi, "Zero-Forcing Max-Power Beamforming for Hybrid mmWave Full-Duplex MIMO Systems," *2020 4th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, 2020, pp. 344-349

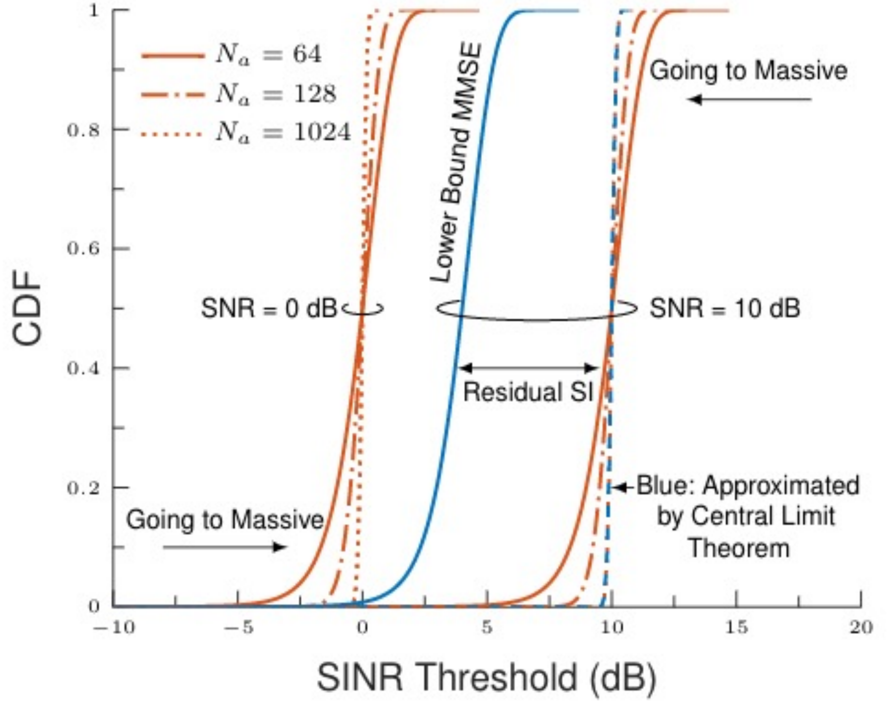
# Extension to Hybrid Architecture

- The self-interference becomes more critical in hybrid architecture.
- The proposed method completely suppress the self-interference, while the residual loss is incurred by the CA (minimized).
- The proposed approach beats the lower bound MMSE method.

## Simulation parameters

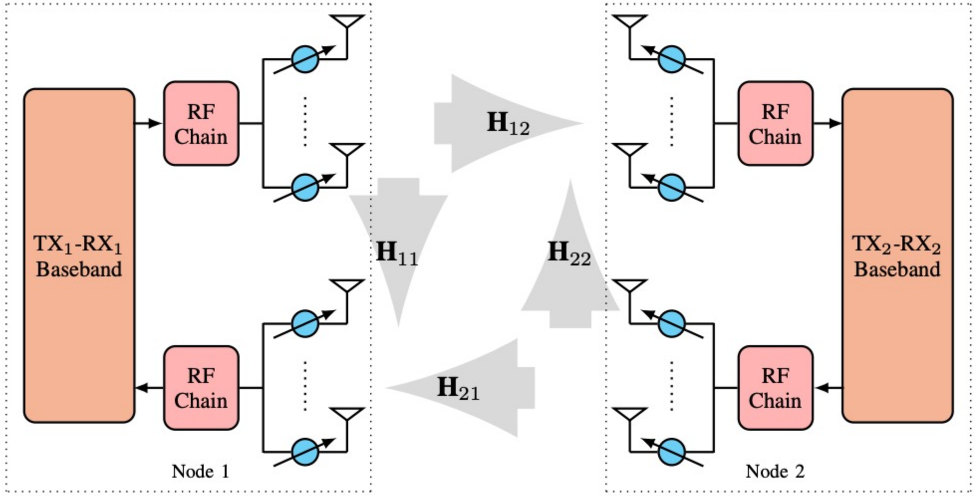
| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Carrier frequency | 28 GHz | Bandwidth | 850 MHz |
| TX antennas | 16 | RX antennas | 16 |
| Number of clusters | 6 | Rays per cluster | 8 |
| Angular spread | 20° | Transceivers gap ($d$) | $2\lambda$ |
| Tranceivers incline ($\omega$) | $\frac{\pi}{6}$ | Rician factor | 5 dB |
| SI power ($\tau$) | 30 dB | Antenna separation | $\frac{\lambda}{2}$ |
| Spatial streams ($N_s$) | 2 | RF chains ($N_{RF}$) | 4 |



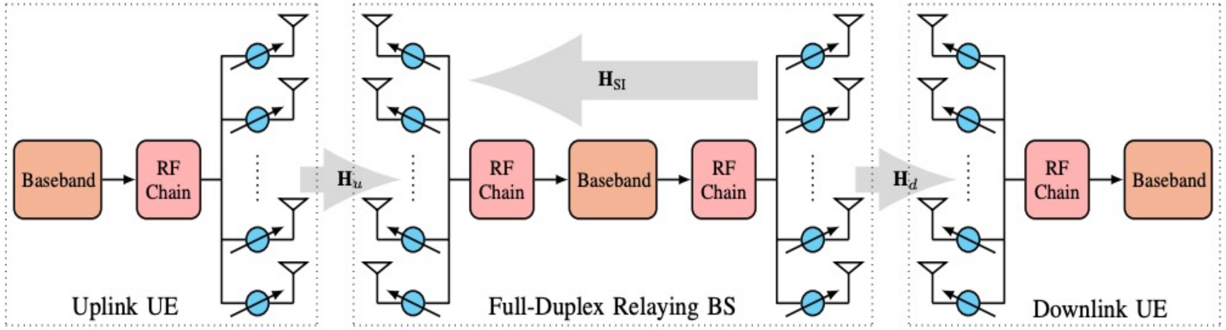




E. Balti and N. Mensi, "Zero-Forcing Max-Power Beamforming for Hybrid mmWave Full-Duplex MIMO Systems," *2020 4th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, 2020, pp. 344-349

# Gradient Search Approach




Analog-only two-node system




Analog-only cellular system

Gradient Search

**Algorithm 1** Adaptive Gradient Ascent

**Input:** $\delta,\ \epsilon,\ \mathbf{H}_{uv},\ \mathbf{H}_{vu},\ \mathbf{H}_{vv},\ \mathbf{H}_{uu}\ (u,\ v \in \{0,\ 1\},\ u \neq v)$

**Output:** $\mathbf{w}_v^\star,\ \mathbf{f}_u^\star$

**Initialize** $\mathbf{w}_v = \mathbf{w}_v^{(0)},\ \mathbf{f}_u = \mathbf{f}_u^{(0)}$

**while** $|\mathcal{I}^{(n+1)} - \mathcal{I}^{(n)}| > \epsilon$ **do**

$\quad \mathbf{w}_v^{(n+1)} \leftarrow \mathbf{w}_v^{(n)} + \delta \nabla_{\mathbf{w}_v} \mathcal{I}^{(n)}$

$\quad \mathbf{w}_v^{(n+1)} \leftarrow \frac{\mathbf{w}_v^{(n+1)}}{\|\mathbf{w}_v^{(n+1)}\|_2}$ ▷ Unit-norm constraint

$\quad \mathbf{w}_v^{(n+1)} \leftarrow \frac{\mathbf{w}_v^{(n+1)}}{\sqrt{N_{r,v}}\,|\mathbf{w}_v^{(n+1)}|}$ ▷ CA constraint

$\quad \mathbf{f}_u^{(n+1)} \leftarrow \mathbf{f}_u^{(n)} + \delta \nabla_{\mathbf{f}_u} \mathcal{I}^{(n)}$

$\quad \mathbf{f}_u^{(n+1)} \leftarrow \frac{\mathbf{f}_u^{(n+1)}}{\|\mathbf{f}_u^{(n+1)}\|_2}$

$\quad \mathbf{f}_u^{(n+1)} \leftarrow \frac{\mathbf{f}_u^{(n+1)}}{\sqrt{N_{t,u}}\,|\mathbf{f}_u^{(n+1)}|}$

$\quad$ **if** $\mathcal{I}^{(n+1)} < \mathcal{I}^{(n)}$ **then**

$\quad\quad$ Adapt $\delta$

$\quad$ **end if**

**end while**

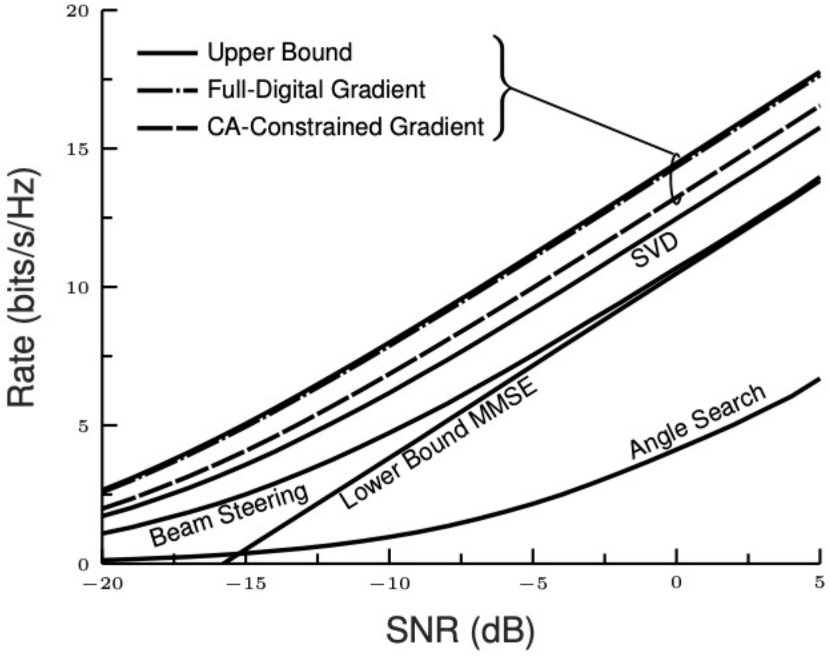
**return** $\mathbf{w}_v^\star,\ \mathbf{f}_u^\star$

- Evaluate the gradients of the sum rate with respect to the beamformers.
- Adapt the step-size to adjust the fluctuation of the cost function during the optimization cycle.

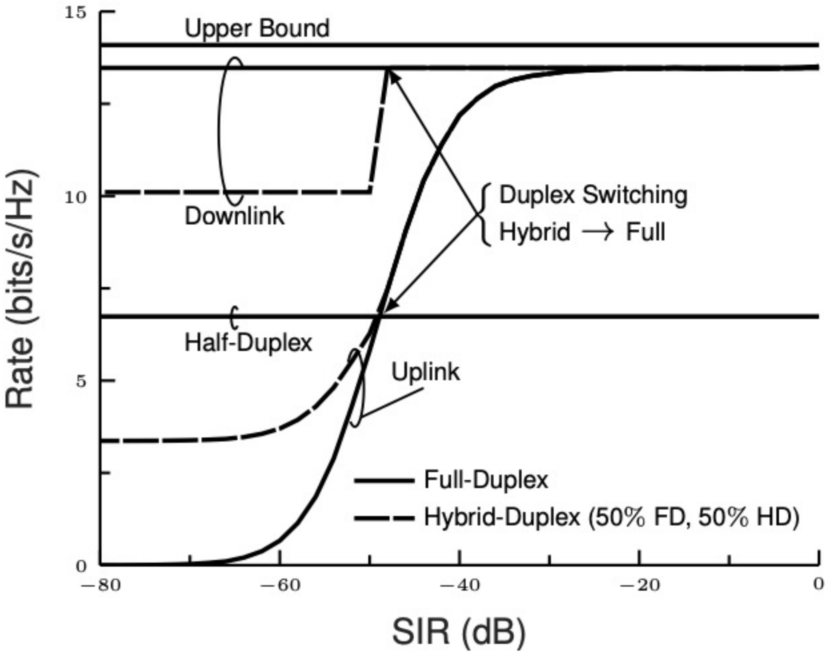
E. Balti, "Adaptive Gradient Search Beamforming for Full-Duplex mmWave MIMO Systems," *arxiv*, 2020

# Gradient Search Approach

- The gradient achieves better sum rate than the conventional approach.
- For low SIR, half-duplex provides the uplink user with better rate but at the expense of the downlink UE.
- Hybrid duplex can be adapted with the SIR.




Analog-only two-node system




Analog-only cellular system

Simulation parameters

| | |
|---|---|
| Carrier frequency | 28 GHz |
| Bandwidth | 850 MHz |
| Number of transmit antennas | 16 |
| Number of receive antennas | 16 |
| Antenna separation | $\frac{\lambda}{2}$ |
| Antenna correlation | None |
| Number of clusters | 6 |
| Number of rays per cluster | 8 |
| Angular spread | 20° |
| Distance between FD node arrays | $2\lambda$ |
| Angle between FD node arrays | $\frac{\pi}{6}$ |
| Self-interference power | 0 dB |
| Rician factor | 5 dB |
| Step size ($\delta$) | 1 |
| Convergence criterion ($\epsilon$) | 1e-5 |

E. Balti, "Adaptive Gradient Search Beamforming for Full-Duplex mmWave MIMO Systems," *arxiv*, 2020

# Appendix

**1. Extension to wideband full-duplex cellular systems:**

- E. Balti and B. L. Evans, "Hybrid Beamforming Design for Wideband MmWave Full-Duplex Systems," *arxiv*, 2021

**2. Application of adaptive LMS for self-interference cancellation:**

- E. Balti and B. L. Evans, ”Adaptive Self-Interference Cancellation for Full-Duplex Wireless Communication Systems," *arxiv*, 2021
- Reproducible research: : https://github.com/ebalti/Full-Duplex-Steepest-Descent

# Extensions

**1. Multiuser single-cell systems**

- Additional constraints to account for the multiuser interference or intra-cell interference.

**2. Multiuser multicell systems**

- More constraints relative to the inter-cell interference.

**3. Conducting link level simulation based on 3 GPP Release 17 for Integrated Access and Backhaul.**

**4. Low resolution ADCs**

**5. Comparison with the intelligent reflecting surfaces**

- Establishing trade-off between spectral and energy efficiency.