Full-duplex wireless communications: concept and applications

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Outline

- Background
- Full-duplex wireless
- FD amplify and forward relaying
- Conclusion

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Background (1983-2010)

- **Tehran (12m), Iran (70m)**
- **Language: Farsi (persian)**

Background (1983-2010)

- **Tehran, Iran**
- **Bachelors in Electronics (Tehran, 2001)**
- **Worked in industry 2007-2010**

Background (2010-Present)

- **2010: Tehran (12m) to Ilmenau (20k)**
- ***„über alles gipfeln ist ruh“***
- **MSCSP experience:**
  - **Signal processing, MOCO, AASP**
- **Institute for Theoretical Information Technology (RWTH Aachen)**
  - **Information theory and networking**

IEEE International Symposium on Information Theory (ISIT) will take place in the historic city of Aachen, Germany, from June 25 to 30, 2017 …

  - **Resource optimization and planning in wireless networks**
  - **Compressive sensing**
    - **Coordinating Priority Programm COSIP**

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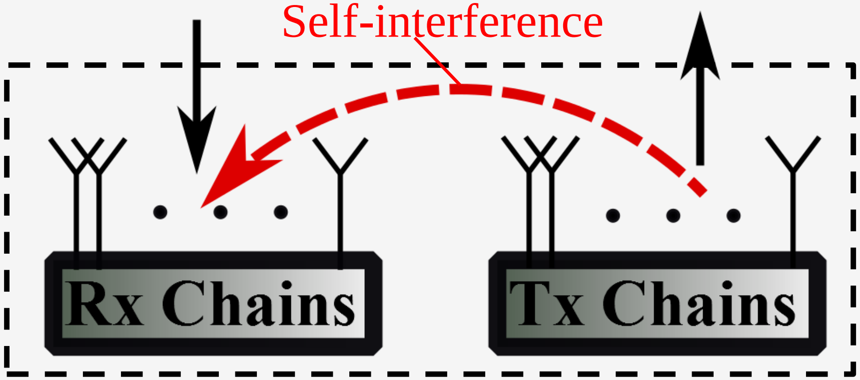
Full-Duplex Operation

- Full-duplex: simultaneous transmission and reception using the same channel

Full-duplex transceiver:



- **Motivation:** enhanced spectral efficiency, latency, security, …
- **Challenge:** Strong loopback self-interference must be suppressed
  - Limited dynamic range in Tx and Rx chains (analog domain errors)
  - Inaccurate channel knowledge

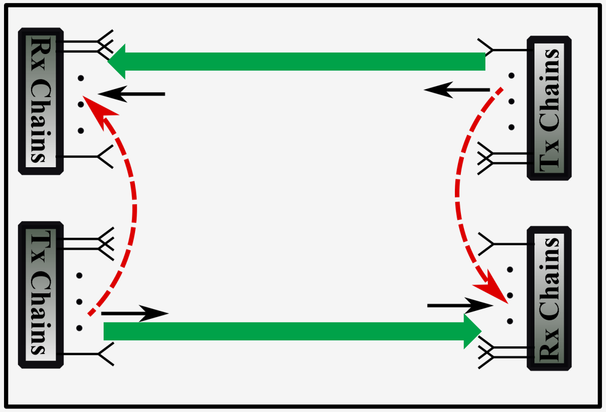
➡ Advanced cancellation methods were recently developed, e.g., [BMK], [BK:14]

[BMK:13] D. Bharadia, E. McMilin, S. Katti. Full Duplex Radios. *ACM 2013.*

[BK:14] Bharadia, D., and S. Katti. "Full Duplex MIMO Radios."*11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14). USENIX Association.*

Full-duplex wireless: applications

- FD bi-directional setup:

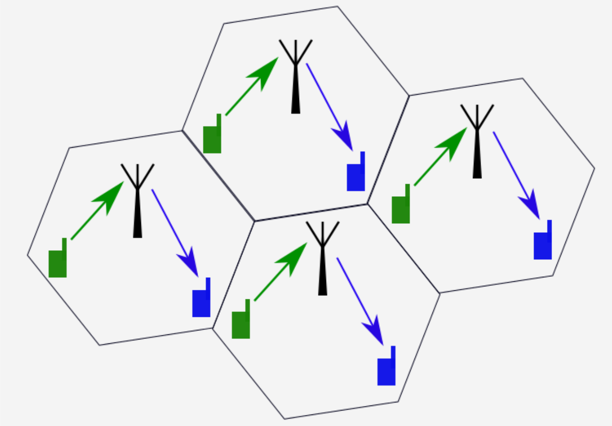


- FD-enabled relaying:

S 1 **HD-Relay (one-way)** 2 **D**

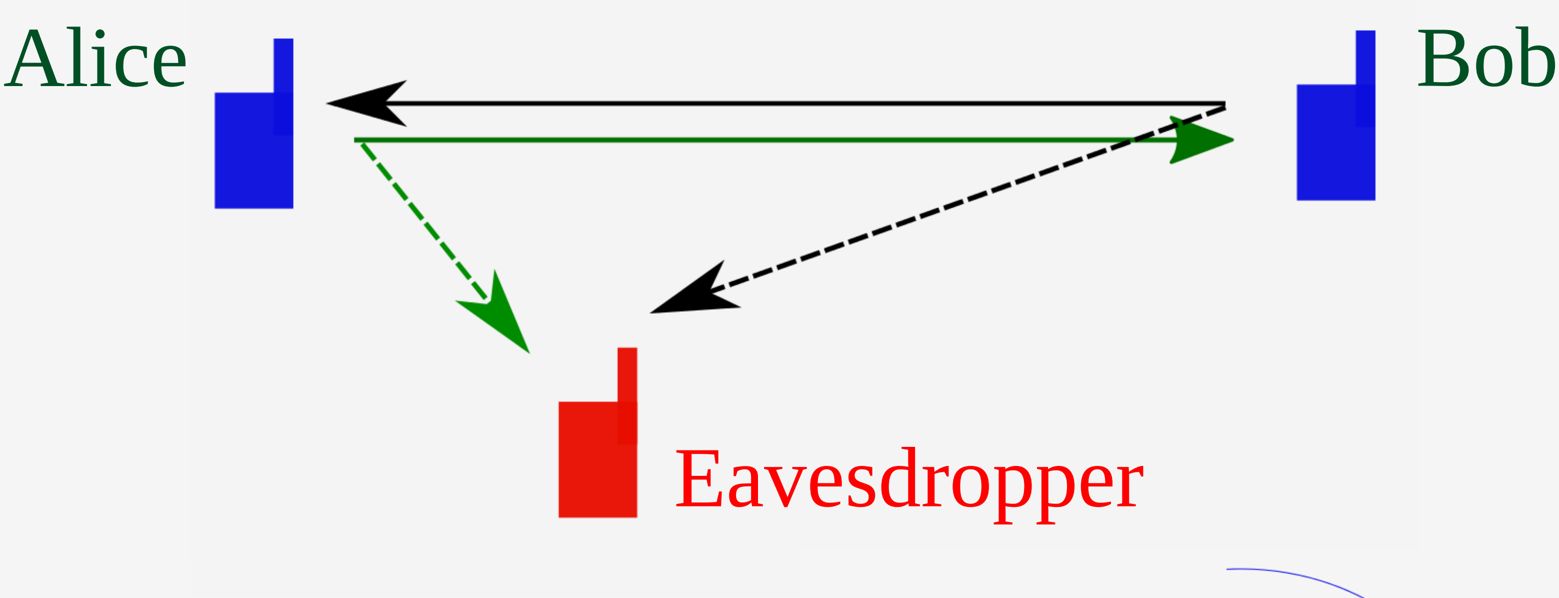
S 1 **FD-Relay (one-way)** 1 **D**

- FD Cellular networking:

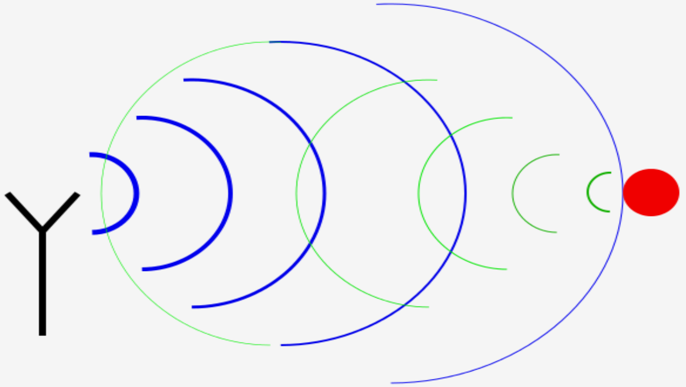


Ex. Use-Case: Wiretap Channel

- Example FD use-case: FD wiretap channel



- FD radar



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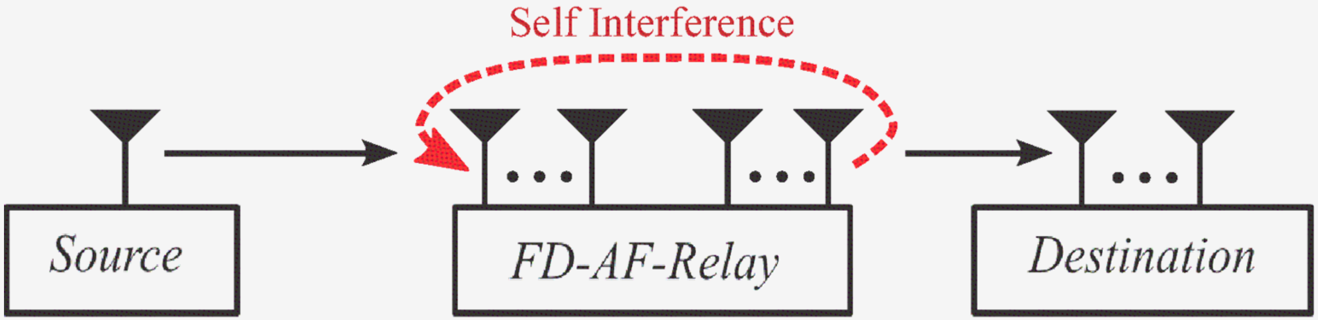
System Model: AF-FD Relaying

- Single antenna source, multiple antenna destination, and relay nodes
- Relay: FD and amplify-and-forward

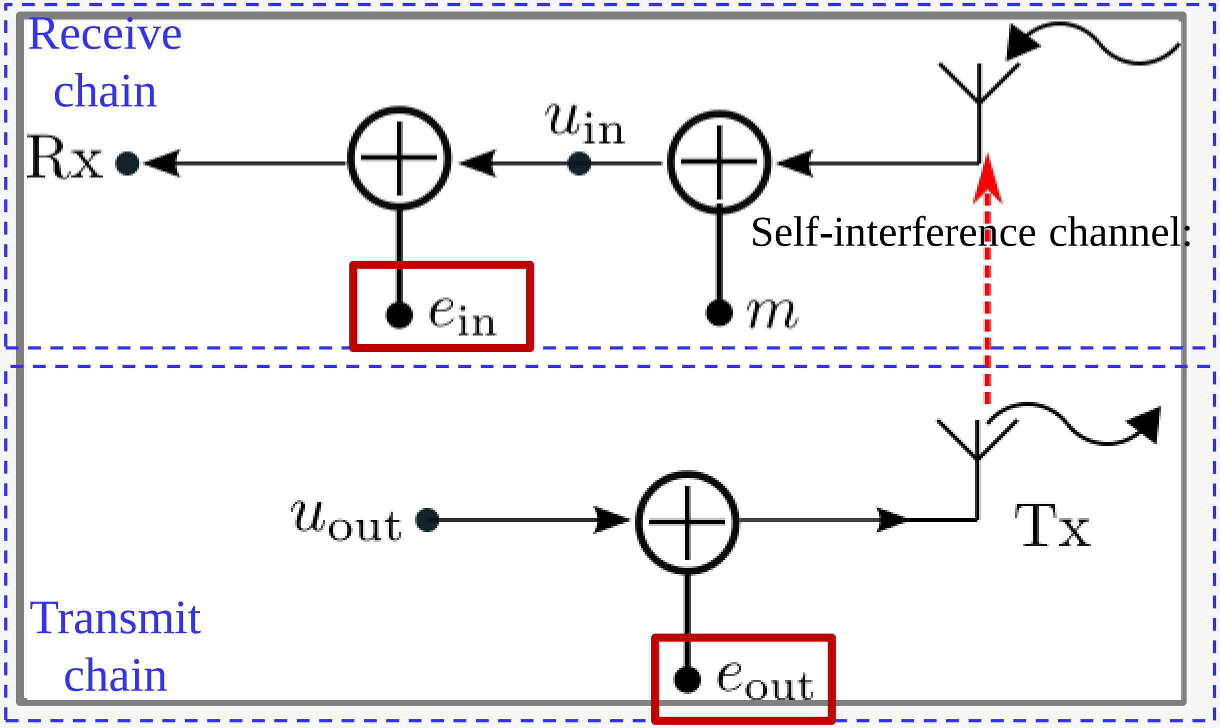


- Flat-fading channels
- Stationary setup ⇨ Perfect CSI is available
- Prior work:

[TZH:16] Taghizadeh, Omid, Jianshu Zhang, and Martin Haardt. "Transmit beamforming aided amplify-and-forward MIMO full-duplex relaying with limited dynamic range.“ *Signal Processing* 127 (2016): 266-281.

- Simplified model
  - Computational efficiency

Full-Duplex Transceiver Model



m : AWGN at the receiver

$u_{\text{in}}, u_{\text{out}}$: Intended received and transmitted signals

Proportional to the signal intensity [DMBS:12], [DMBSR:12]

$$\boldsymbol{e}_{\text{out}} \sim \mathcal{CN}\left\{\mathbf{0}, \kappa \operatorname{diag}\left(\mathbb{E}\left\{\boldsymbol{u}_{\text{out}}\boldsymbol{u}_{\text{out}}^{H}\right\}\right)\right\}$$

$$\boldsymbol{e}_{\text{in}} \sim \mathcal{CN}\left\{\mathbf{0}, \beta \operatorname{diag}\left(\mathbb{E}\left\{\boldsymbol{u}_{\text{in}}\boldsymbol{u}_{\text{in}}^{H}\right\}\right)\right\}$$

FD Transceiver inaccuracy roots in

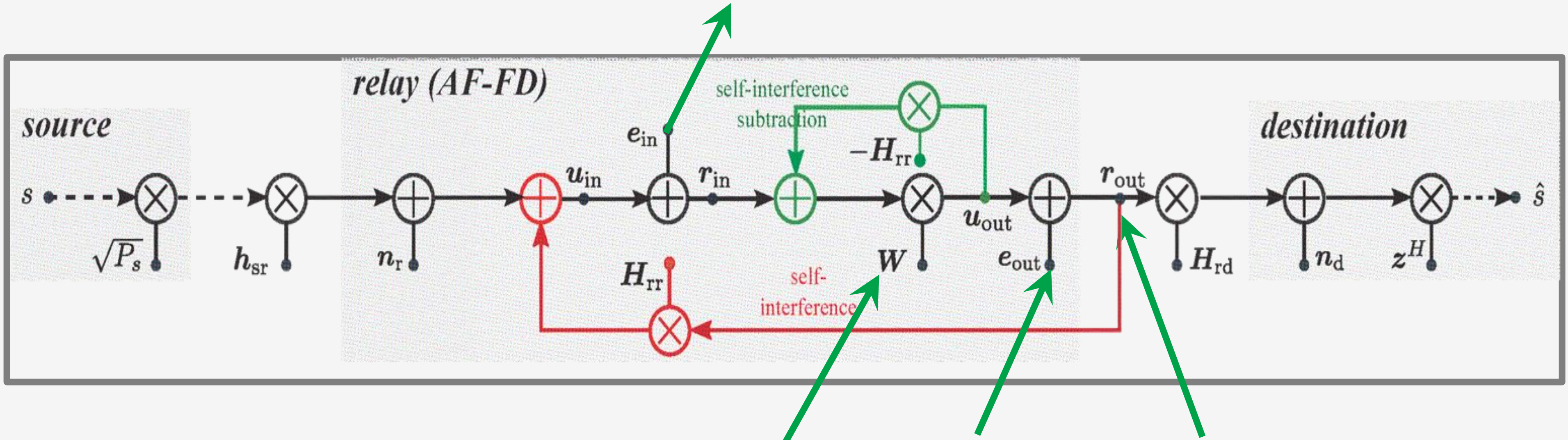
- Thermal noise
- Tx/Rx chain distortions
- Channel estimation error

[DMBS:12] B. Day, A. Margetts, D. Bliss, and P. Schniter. Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range. *IEEE Tran. Sig. Proc.*, 2012.

[DMBSR:12] B. Day, A. Margetts, D. Bliss, and P. Schniter. Full-duplex MIMO relaying: Achievable rates under limited dynamic range. Selected Areas in Communications, IEEE Journal on, 30:1541–1553, Sept. 2012.

System Model: End-to-End Relay Link

Rx Distortion signal



Relay Amplification Tx Distortion signal Relay Tx signal

- Increase in relay Tx power results in increased distortion power
- Increase in distortion power results in increased relay Tx power

⇒ Distortion loop !

⇒ This effect dominates the performance for a low dynamic range system

Previous Approaches: Multiple-Antenna FD AF Relaying

- Neglecting the transceiver inaccuracies → perfect cancellation
  - Perfect SIC by estimating the received interference signal [LKPL:12], …
  - Perfect SIC with self-interference power threshold [KKC:14], [TZH:16], …
  - Perfect SIC with interference transmit zero-forcing [SKZYS:14], [CP:12], [CPa:12], [URW:15], …

[URW:15] U. Ugurlu, T. Riihonen, and R. Wichman, “Optimized in-band fullduplex MIMO relay under single-stream transmission,” Vehicular Technology, IEEE Transactions on, vol. PP, no. 99, pp. 1–1, Jan. 2015.

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[SKZYS:14] H. Suraweera, I. Krikidis, G. Zheng, C. Yuen, and P. Smith, “Lowcomplexity end-to-end performance optimization in MIMO full-duplex relay systems,” IEEE Transactions on Wireless Communications, vol. 13, no. 2, pp. 913–927, Feb. 2014.

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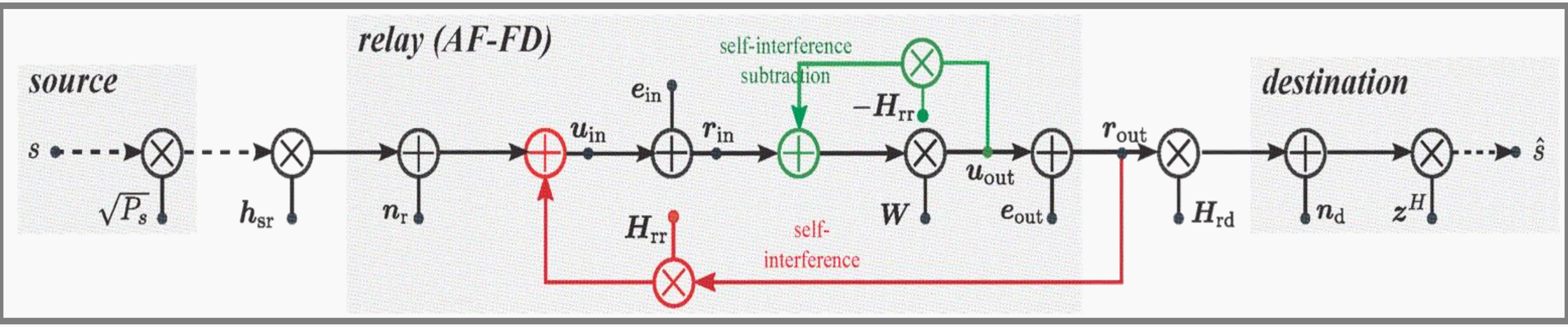
[KKC:14] Y. Y. Kang, B.-J. Kwak, and J. H. Cho, “An optimal full-duplex af relay for joint analog and digital domain self-interference cancellation,” Communications, IEEE Transactions on, vol. 62, no. 8, pp. 2758–2772, Aug 2014.

[LKPL:12] K. Lee, H. Kwon, M. Jo, H. Park, and Y. Lee, “MMSE-based optimal design of full-duplex relay system,” in IEEE Vehicular Technology Conference (VTC Fall), Sept 2012.

System Model: End-to-End Relay Link



- Received signal at the Relay:

Known SI

Tx distortion

Rx distortion

$$\boldsymbol{r}_{\text{in}} = \underbrace{\boldsymbol{h}_{\text{sr}}\sqrt{P_s}s + \boldsymbol{H}_{\text{rr}}(\boldsymbol{u}_{\text{out}} + \boldsymbol{e}_{\text{out}}) + \boldsymbol{n}_{\text{r}}}_{=:\boldsymbol{u}_{\text{in}}} + \boldsymbol{e}_{\text{in}}$$

- Relay process:

$$\boldsymbol{r}_{\text{supp}} = \boldsymbol{r}_{\text{in}} - \boldsymbol{H}_{\text{rr}}\boldsymbol{u}_{\text{out}}, \qquad \boldsymbol{u}_{\text{out}} := \boldsymbol{W}\boldsymbol{r}_{\text{supp}}$$

Relay amplification

- Received signal :

$$\boldsymbol{y} = \boldsymbol{H}_{\text{rd}}\left(\boldsymbol{W}\boldsymbol{r}_{\text{supp}} + \boldsymbol{e}_{\text{out}}\right) + \boldsymbol{n}_{\text{d}}, \qquad \hat{s} = \boldsymbol{z}^H\boldsymbol{y}$$

Relay Operation: Single Antenna Setup

- Relay Tx Signal power where no inaccuracy exists:

$$\boxed{\mathbb{E}\{r_{\text{out}}r_{\text{out}}^*\} = |w|^2\left(P_s\,|h_{\text{sr}}|^2 + M\right)}$$

➡ Similar to the known HD formulation

- Relay Tx signal power in FD mode:

$$\mathbb{E}\{r_{\text{out}}r_{\text{out}}^*\} = \frac{(\eta+1)\,|w|^2\left(P_s\,|h_{\text{sr}}|^2 + M\right)}{1 - |w|^2\left(|h_{\text{rr}}|^2\,\eta + (\gamma+1)\,|\delta|^2\right)}$$

Distortion-free Relay Tx power

Distortion-loop effect

  - No longer a quadratic function over w

- SENR maximization:

$$\boxed{max\quad\left(\text{SENR} = \frac{P_s|w|^2\,|h_{\text{sr}}|^2}{\frac{(1+\eta)|w|^2\left(P_s|h_{\text{sr}}|^2+M\right)}{1-|w|^2 b} - P_s\,|h_{\text{sr}}|^2\cdot|w|^2 + \ell}\right),\quad s.t.\quad \mathbb{E}\{r_{\text{out},k}\cdot r_{\text{out},k}^*\} \le P_{\max}}$$

➡ Unique optimum solution is obtained in closed form **[TRCM:15]**

Relay Operation: Multiple Antenna Setup

- Relay Tx covariance where no inaccuracy exists ($\kappa = \beta = 0$)

$$\boxed{\boldsymbol{Q} := \mathbb{E}\{\boldsymbol{r}_{\text{out}}\boldsymbol{r}_{\text{out}}^{H}\} = \boldsymbol{W}\left(P_s \boldsymbol{h}_{\text{sr}}\boldsymbol{h}_{\text{sr}}^{H} + \sigma_{\text{n}}^{2}\boldsymbol{I}\right)\boldsymbol{W}^{H}}$$

➡ Similar to the known HD formulation

- Relay Tx signal power in FD mode:

$$\boxed{\begin{array}{c} \text{vec}\left(\boldsymbol{Q}\right) = \left(\boldsymbol{I}_{M_{\text{t}}^2} - \left(\boldsymbol{W}^{*} \otimes \boldsymbol{W}\right)\boldsymbol{A}\right)^{-1}\left(\boldsymbol{W}^{*} \otimes \boldsymbol{W}\right)\boldsymbol{a} \\ \boxed{\begin{array}{l} \boldsymbol{A} := \beta \boldsymbol{S}_{\text{D}}\left(\boldsymbol{H}_{\text{rr}}^{*} \otimes \boldsymbol{H}_{\text{rr}}\right)\left(\boldsymbol{I}_{M_{\text{t}}^2} + \kappa \boldsymbol{S}_{\text{D}}\right) + \kappa\left(\boldsymbol{H}_{\text{rr}}^{*} \otimes \boldsymbol{H}_{\text{rr}}\right)\boldsymbol{S}_{\text{D}}, \\ \boldsymbol{a} := \left(\boldsymbol{I}_{M_{\text{r}}^2} + \beta \boldsymbol{S}_{\text{D}}\right)\text{vec}\left(P_{\text{s}}\boldsymbol{h}_{\text{sr}}\boldsymbol{h}_{\text{sr}}^{H} + \sigma_{\text{nr}}^{2}\boldsymbol{I}_{M_{\text{r}}}\right) \end{array}} \end{array}}$$

- Desired and error signal power at the destination:

$$P_{\text{desired}} = \mathbb{E}\{|\boldsymbol{z}^{H}\boldsymbol{H}_{\text{rd}}\boldsymbol{W}\boldsymbol{h}_{\text{sr}}\sqrt{P_s}s|^2\}, \; P_{\text{error}} = P_{\text{tot}} - P_{\text{desired}},$$
$$P_{\text{tot}} = \mathbb{E}\{|\boldsymbol{z}^{H}\boldsymbol{H}_{\text{rd}}\boldsymbol{r}_{\text{out}} + \boldsymbol{z}^{H}\boldsymbol{n}_{\text{d}}|^2\}$$

➡ Our goal: SENR maximization

Performance Optimization: FD AF Relay

- **Optimization problem:**

$$\max_{P_{\mathrm{s}},\boldsymbol{z},\boldsymbol{W}} \frac{P_{\mathrm{desired}}}{P_{\mathrm{error}}}$$

$$\text{s.t.} \quad \boldsymbol{Q} \in \mathcal{H}, \quad \mathrm{tr}\left(\boldsymbol{Q}\right) \leq P_{\mathrm{r,max}}, \quad P_{\mathrm{s}} \leq P_{\mathrm{s,max}}$$

Source Tx power

Rx linear equalizer

Relay amplification

Relay Tx Covariance

Relay power const.

Source power const.

- **Gradient projection**
  - Moving in SD direction
  - Projection into feasible region

$$\tilde{\boldsymbol{W}}^{(\ell)} = \mathcal{P}\left(\boldsymbol{W}^{(\ell)} + \tau \cdot \nabla_{\boldsymbol{W}^*}\left(\frac{P_{\mathrm{desired}}}{P_{\mathrm{error}}}\right)\right),$$

  - Line search for stepsize (Armijo rule):

$$\boldsymbol{W}^{(\ell+1)} = \delta^{(\ell)}\boldsymbol{W}^{(\ell)} + (1-\delta^{(\ell)})\tilde{\boldsymbol{W}}^{(\ell)}$$

  - A local optimum solution is obtained

➡ Multiple initial points

➡ Optimal performance indicator BUT computationally complex

Performance Optimization: FD AF Relay

- **Optimization problem:**

$$\boxed{\max_{P_{\mathrm{s}},\boldsymbol{z},\boldsymbol{W}} \frac{P_{\mathrm{desired}}}{P_{\mathrm{error}}} \quad \text{s.t.} \quad \boldsymbol{Q} \in \mathcal{H}, \quad \mathrm{tr}\left(\boldsymbol{Q}\right) \leq P_{\mathrm{r,max}}, \quad P_{\mathrm{s}} \leq P_{\mathrm{s,max}}}$$

Source Tx power

Rx linear equalizer

Relay amplification

Relay Tx Covariance

Relay power const.

Source power const.

- **Iterative quadratic approximation**
  - Relay Tx covariance:

$$\boxed{\boldsymbol{Q}^{(\ell)} \approx \boldsymbol{W}^{(\ell)} \mathcal{R}\left(\boldsymbol{Q}^{\star(\ell-1)}\right) \boldsymbol{W}^{(\ell)^{H}}}$$

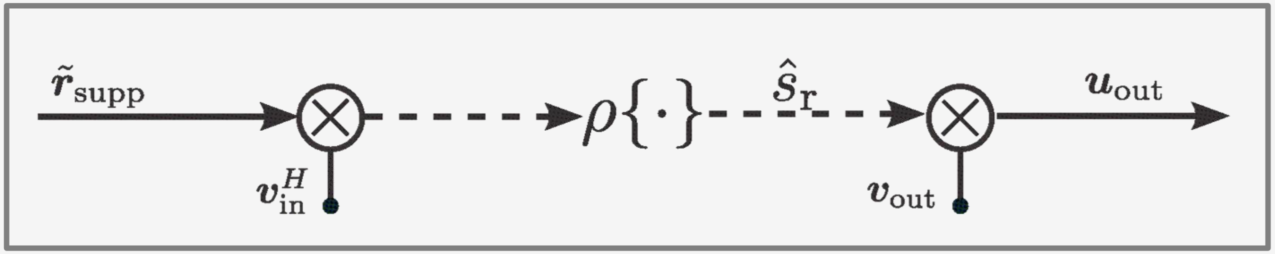
$$\begin{aligned}\mathcal{R}\left(\boldsymbol{Q}\right) := {} & P_{\mathrm{s}} \boldsymbol{h}_{\mathrm{sr}} \boldsymbol{h}_{\mathrm{sr}}^{H} + \sigma_{\mathrm{nr}}^{2} \boldsymbol{I}_{M_{\mathrm{r}}} + \beta \mathrm{diag}\left(P_{\mathrm{s}} \boldsymbol{h}_{\mathrm{sr}} \boldsymbol{h}_{\mathrm{sr}}^{H} + \sigma_{\mathrm{nr}}^{2} \boldsymbol{I}_{M_{\mathrm{r}}}\right) \\ & + \beta \mathrm{diag}\left(\boldsymbol{H}_{\mathrm{rr}} \left[\boldsymbol{Q} + \kappa \mathrm{diag}\left(\boldsymbol{Q}\right)\right] \boldsymbol{H}_{\mathrm{rr}}^{H}\right) + \kappa \boldsymbol{H}_{\mathrm{rr}} \mathrm{diag}\left(\boldsymbol{Q}\right) \boldsymbol{H}_{\mathrm{rr}}^{H}\end{aligned}$$

➡ Turns the problem into an iterative QCQP

➡ Faster convergence

Distortion Loop Effect: FD AF vs. DF Relaying

- FD DF system



  - Tx power affects the residual SIC
  - BUT residual SIC power does not affect Tx power !

➡ **No distortion loop !**

➡ Good comparison benchmark

- Performance Optimization
  - Iterative convex optimization over $\boldsymbol{v}_{\text{in}}, \boldsymbol{v}_{\text{out}}, \boldsymbol{z}$

Distortion loop effect

Channel Realizations:

- 100 channel realizations used
- Uncorrelated flat-fading, Gaussian

$$\mathcal{E}\{|h_{\mathrm{rr}}|\} = 0\,\mathrm{dB},$$
$$\mathcal{E}\{|h_{\mathrm{sr}}|\} = \mathcal{E}\{|h_{\mathrm{rd}}|\} = -30\,\mathrm{dB}$$

Setup:

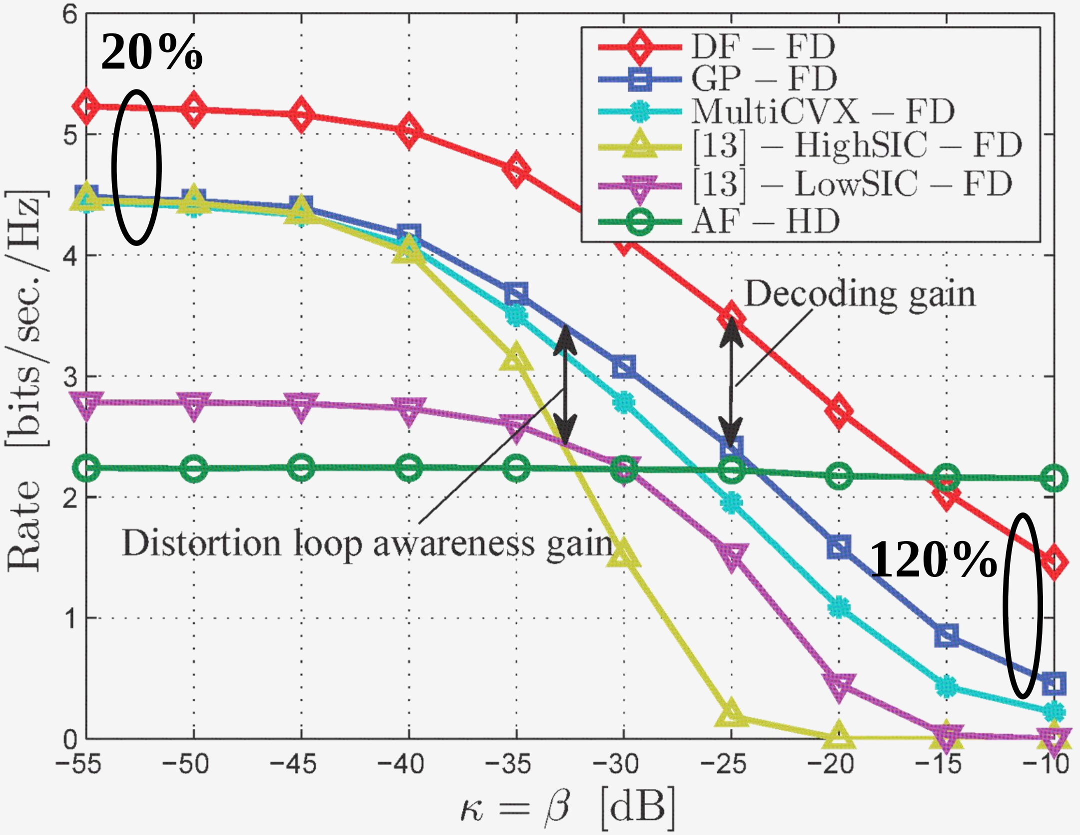
$$M_{\mathrm{d}} = M_{\mathrm{t}} = M_{\mathrm{r}} = 4$$

Noise condition:

$$\sigma_{\mathrm{nr}}^2 = \sigma_{\mathrm{nd}}^2 = 0.1$$

Power constraints:

$$P_{\mathrm{r,max}} = P_{\mathrm{s,max}} = 1$$



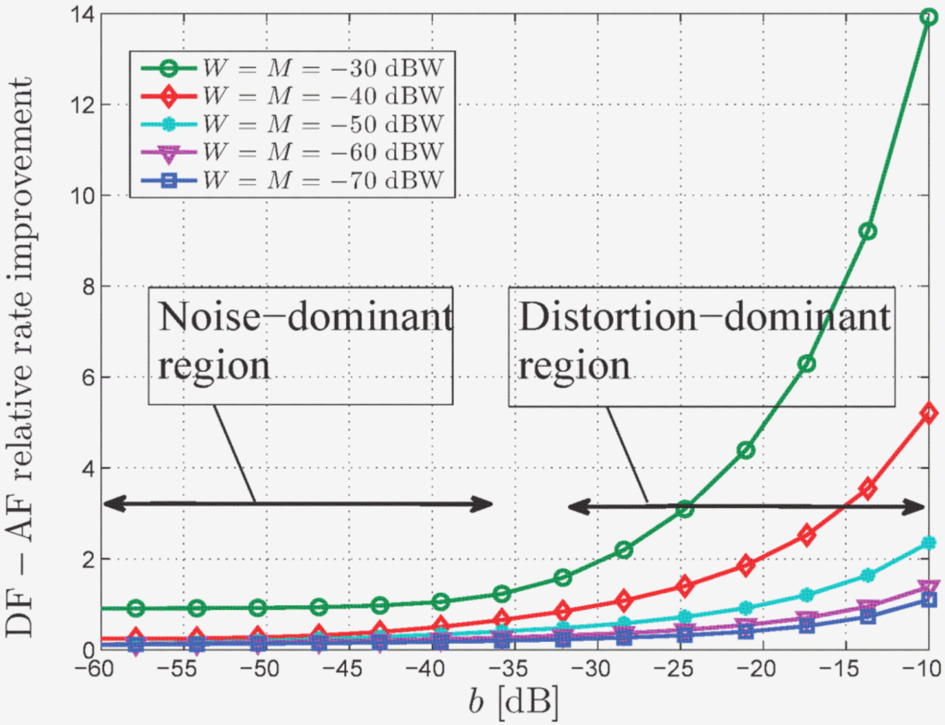
Observation

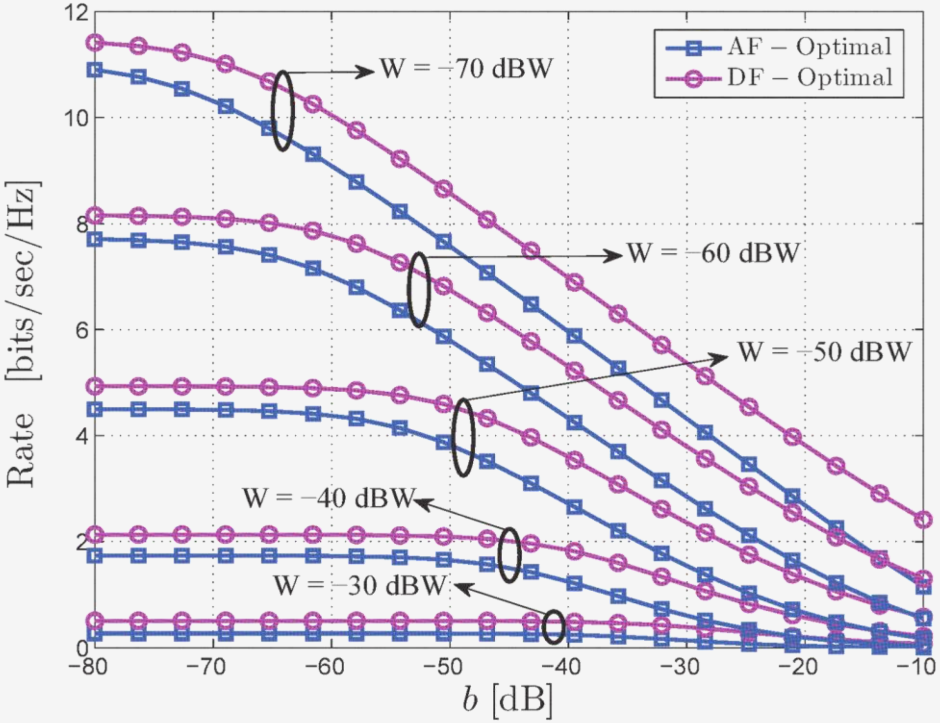
- Decoding gain
- Distortion loop awareness gain

End-to-end rate **vs.** distortion intensity

κ, β : Relay distortion coefficients

Distortion loop effect: AF vs. DF





Observation:

- Distortion loop dominates the relay performance for low dynamic range

b : collective distortion coefficient

$W = M$: noise variance

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Conclusion

- FD wireless communication
  - Tx and Rx at the same channel
- Improvements in spectral efficiency, latency, security, ..
- FD-AF relaying suffers from the **distortion loop**
- Effect of the distortion loop appears to be dominant when dynamic range is not high

Thanks for your attention!

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- **AND MORE …**

Relay Operation Analysis and Optimization

- Performance optimization objective

$\mathbb{S}_K, \mathbb{S}_N$: Set of all relays and destinations

$\mathcal{H}_k$: Set of all feasible estimation errors

$\mathcal{A}_k$: Set of feasible *k*-th relay amplifications

Destination index

$$\boxed{\max_{k \in \mathbb{S}_K,\, a_k \in \mathcal{A}_k} \left\{ \min_{n \in \mathbb{S}_N,\, \delta_k \in \mathcal{H}_k} \mathrm{SENR}_k^{(n)} \right\}}$$

Signal-to-Error+Noise-Ratio Relay index

- Minimum end-to-end link quality (if relay *k* is selected):

$$\widetilde{\mathrm{SENR}}_k := \min_{n \in \mathbb{S}_N,\, \delta_k \in \mathcal{H}_k} \mathrm{SENR}_k^{(n)} = \boxed{\frac{P_s \tilde{a}_k \left|h_{\mathrm{sr},k}\right|^2}{\frac{(1+\eta_k)\tilde{a}_k\left(P_s|h_{\mathrm{sr},k}|^2+M_k\right)}{1-\tilde{a}_k b_k} - P_s \left|h_{\mathrm{sr},k}\right|^2 \cdot \tilde{a}_k + \ell_k}}$$

where $\eta_k := \gamma_k + \beta_k + \beta_k\gamma_k,\ \ b_k := |\tilde{h}_{\mathrm{rr},k} + \delta_k^\star|^2 \eta_k + (\gamma_k + 1)|\delta_k^\star|^2,\ \ \ell_k := \max_{n \in \mathbb{S}_N} \left\{ W^{(n)} / |h_{\mathrm{rd},k}^{(n)}|^2 \right\},\ \ \tilde{a}_k := |a_k|^2$

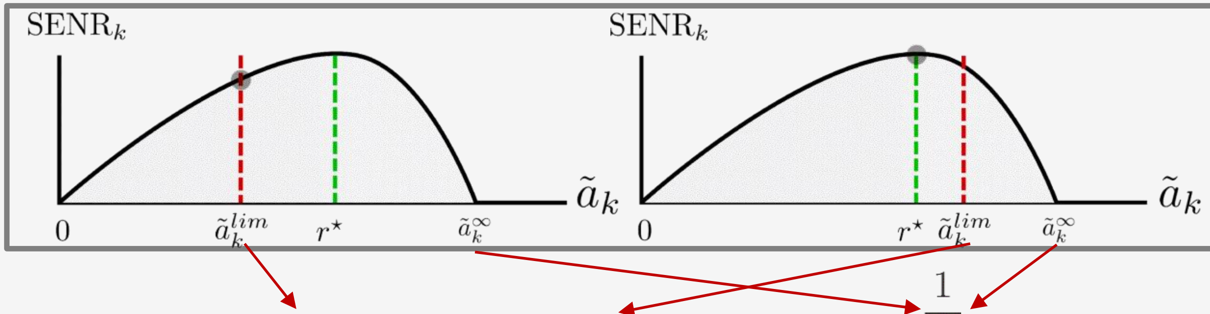
Collective distortion coefficient Weakest link indicator

- **Observation**:
  - Relay Tx power reaches infinity as $\tilde{a}_k \rightarrow \frac{1}{b_k}$,
  - Link quality approaches zero as $\tilde{a}_k \rightarrow 0$ and $\tilde{a}_k \rightarrow \frac{1}{b_k}$,
  - SENR value is positive and differentiable between these two values

Relay Operation Analysis and Optimization

$$\widetilde{\mathrm{SENR}}_k := \min_{n\in\mathbb{S}_N,\ \delta_k\in\mathcal{H}_k} \mathrm{SENR}_k^{(n)} = \frac{P_s\tilde{a}_k\left|h_{\mathrm{sr},k}\right|^2}{\frac{(1+\eta_k)\tilde{a}_k\left(P_s\left|h_{\mathrm{sr},k}\right|^2+M_k\right)}{1-\tilde{a}_k b_k} - P_s\left|h_{\mathrm{sr},k}\right|^2\cdot\tilde{a}_k + \ell_k}$$

- Taking derivative of $\widetilde{\mathrm{SENR}}_k$:
  - Exactly one maximum, r^*, exists in the relay stable region: $\tilde{a}_k \in [0, \frac{1}{b_k}]$
  - r^* is obtained in closed form!
  - Optimality is obtained by checking two possibilities



Maximum feasible amplification

$\frac{1}{b_k}$

r^* : Stationary point of SENR

a_k^{lim} : Max. feasible $|a_k|^2$

  - Relay with highest optimal $\widetilde{\mathrm{SENR}}_k$ will be selected as active relay.

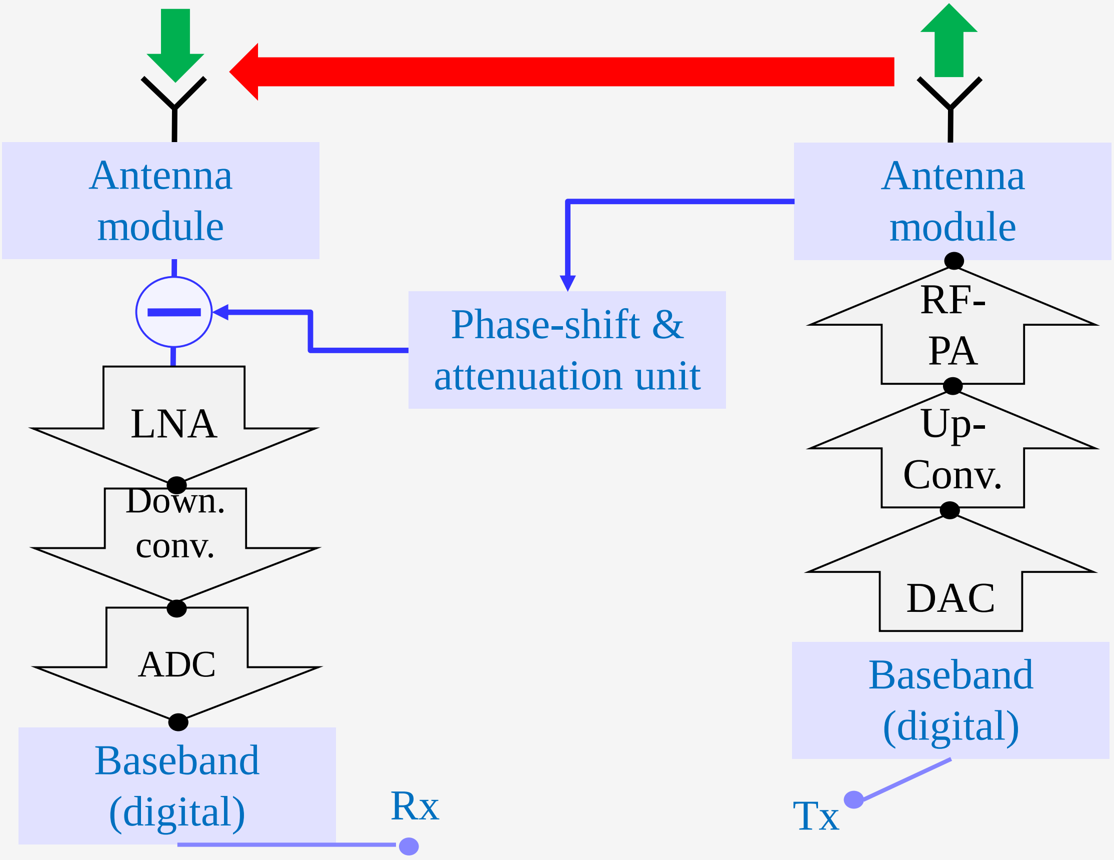
- Maximum relay amplification is not necessarily optimal!
- Distortion loop effect becomes dominant as relay power increases

Outline

- Full-duplex relaying
  - What is full-duplex wireless ?
  - Full-duplex amplify-and-forward relaying
- System model
  - FD-AF relay networks for multicast scenarios
  - FD transceiver operation
- Performance optimization
- **Simulation results**
- Conclusion

Self-interference cancellation

- ***Idea:*** to deal with overwhelming interference
  - suppress the main interference paths in RF
  - Reduce the rest in digital domain



- Copying the Tx signal in RF with phase shift and delay:
  - Stanford: BALUN technique [JCKBSSLK], [BMK]
- Challenge: Accurate phase-shift & attenuation is needed
- Around 110dB suppression is reported