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]


Full-duplex wireless: applications

- FD bi-directional setup:

- FD-enabled relaying:

- FD Cellular networking:
Ex. Use-Case: Wiretap Channel

- Example FD use-case: FD wiretap channel

Alice  

Bob  

Eavesdropper

- 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:

- Simplified model
  - Computational efficiency
Full-Duplex Transceiver Model

Receive chain

Rx

\( u_{in} \)

Self-interference channel:

\( e_{in} \)

Transmit chain

\( u_{out} \)

\( e_{out} \)

\( m \) : AWGN at the receiver

\( u_{in}, u_{out} \) : Intended received and transmitted signals

Proportional to the signal intensity

[DMBS:12], [DMBSR:12]

\[ e_{out} \sim \mathcal{C}\mathcal{N}\left(0, \kappa \text{diag}(\mathbb{E}\{u_{out}u_{out}^H\})\right) \]

\[ e_{in} \sim \mathcal{C}\mathcal{N}\left(0, \beta \text{diag}(\mathbb{E}\{u_{in}u_{in}^H\})\right) \]

FD Transceiver inaccuracy roots in

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


System Model: End-to-End Relay Link

- 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], …

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System Model: End-to-End Relay Link

- Received signal at the Relay:

\[ r_{in} = h_{sr} \sqrt{P_s} s + H_{rr} (u_{out} + e_{out}) + n_r + e_{in} \]

- Relay process:

\[ r_{supp} = r_{in} - H_{rr} u_{out}, \quad u_{out} := W r_{supp} \]

- Received signal:

\[ y = H_{rd} (W r_{supp} + e_{out}) + n_d, \quad \hat{s} = z^H y \]
Relay Operation: Single Antenna Setup

- Relay Tx Signal power where no inaccuracy exists:
  \[
  \mathbb{E}\{r_{\text{out}} r_{\text{out}}^*\} = |w|^2 \left( P_s |h_{sr}|^2 + M \right)
  \]
  Similar to the known HD formulation

- Relay Tx signal power in FD mode:
  \[
  \mathbb{E}\{r_{\text{out}} r_{\text{out}}^*\} = \frac{(\eta + 1) |w|^2 \left( P_s |h_{sr}|^2 + M \right)}{1 - |w|^2 \left( |h_{rr}|^2 \eta + (\gamma + 1) |\delta|^2 \right)}
  \]
  Distortion-free Relay Tx power
  Distortion-loop effect

  - No longer a quadratic function over \( w \)

- SENR maximization:
  \[
  \max \left( \text{SENR} = \frac{P_s |w|^2 |h_{sr}|^2}{(1+\eta)|w|^2 (P_s |h_{sr}|^2 + M) - P_s |h_{sr}|^2 \cdot |w|^2 + \ell} \right), \text{ s.t. } \mathbb{E}\{r_{\text{out},k} r_{\text{out},k}^*\} \leq P_{\text{max}}
  \]

  Unique optimum solution is obtained in closed form [TRCM:15]
Relay Operation: Multiple Antenna Setup

- Relay Tx covariance where no inaccuracy exists \((\kappa = \beta = 0)\)
  \[ Q := \mathbb{E}\{r_{\text{out}}r_{\text{out}}^H\} = W \left(P_s h_{sr} h_{sr}^H + \sigma_n^2 I\right) W^H \]

- Relay Tx signal power in FD mode:
  \[
  \text{vec}(Q) = \left( I - (W^* \otimes W) A \right)^{-1} (W^* \otimes W) a
  \]
  \[
  A := \beta S_D \left( H_{rr}^* \otimes H_{rr} \right) \left( I + \kappa S_D \right) + \kappa \left( H_{rr}^* \otimes H_{rr} \right) S_D, \\
  a := (I + \beta S_D) \text{vec}(P_s h_{sr} h_{sr}^H + \sigma_n^2 I_{Mr})
  \]

- Desired and error signal power at the destination:
  \[
  P_{\text{desired}} = \mathbb{E}\{|z^H H_{rd} W h_{sr} \sqrt{P_s s}|^2\}, \\
  P_{\text{error}} = P_{\text{tot}} - P_{\text{desired}}, \\
  P_{\text{tot}} = \mathbb{E}\{|z^H H_{rd} r_{\text{out}} + z^H n_d|^2\}
  \]

Our goal: SENR maximization
Performance Optimization: FD AF Relay

- **Optimization problem:**
  
  \[
  \max_{P_s, z, W} \frac{P_{\text{desired}}}{P_{\text{error}}} \\
  \text{s.t.} \quad Q \in \mathcal{H}, \quad \text{tr}(Q) \leq P_{r,\text{max}}, \quad P_s \leq P_{s,\text{max}}
  \]

- **Gradient projection**
  - Moving in SD direction
  - Projection into feasible region
  - Line search for stepsize (Armijo rule):
    \[
    \tilde{W}^{(\ell)} = \mathcal{P} \left( W^{(\ell)} + \tau \cdot \nabla W^* \left( \frac{P_{\text{desired}}}{P_{\text{error}}} \right) \right),
    \]
  - A local optimum solution is obtained

- Multiple initial points
- Optimal performance indicator BUT computationally complex
### Performance Optimization: FD AF Relay

- **Optimization problem:**

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

- **Iterative quadratic approximation**
  - Relay Tx covariance:
    \[
    Q^{(\ell)} \approx W^{(\ell)} \mathcal{R} \left( Q^{*(\ell-1)} \right) W^{(\ell)^H}
    \]
    \[
    \mathcal{R} \left( Q \right) : = P_s h_{sr} h_{sr}^H + \sigma_{nr}^2 I_{M_r} + \beta \text{diag} \left( P_s h_{sr} h_{sr}^H + \sigma_{nr}^2 I_{M_r} \right) \\
    + \beta \text{diag} \left( H_{rr} \left[ Q + \kappa \text{diag} \left( Q \right) \right] H_{rr}^H \right) + \kappa H_{rr} \text{diag} \left( Q \right) H_{rr}^H
    \]

  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 \( \mathbf{v}_{in}, \mathbf{v}_{out}, \mathbf{z} \)
Distortion loop effect

Channel Realizations:
- 100 channel realizations used
- Uncorrelated flat-fading, Gaussian
\[
\mathcal{E}\{|h_{rr}|\} = 0 \text{ dB}, \quad \mathcal{E}\{|h_{sr}|\} = \mathcal{E}\{|h_{rd}|\} = -30 \text{ dB}
\]

Setup:
\[M_d = M_t = M_r = 4\]

Noise condition:
\[\sigma_{nr}^2 = \sigma_{nd}^2 = 0.1\]

Power constraints:
\[P_{r,\text{max}} = P_{s,\text{max}} = 1\]

Observation
- Decoding gain
- Distortion loop awareness gain

End-to-end rate \textbf{vs.} distortion intensity
\(\kappa, \beta\) : 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!
References

References


AND MORE …
Relay Operation Analysis and Optimization

- **Performance optimization objective**

$$\begin{align*}
S_K, S_N & : \text{Set of all relays and destinations} \\
\mathcal{H}_k & : \text{Set of all feasible estimation errors} \\
A_k & : \text{Set of feasible } k\text{-th relay amplifications}
\end{align*}$$

$$\max_{k \in S_K, \ a_k \in A_k} \left\{ \min_{n \in S_N, \ \delta_k \in \mathcal{H}_k} \text{SENR}^{(n)}_k \right\}$$

- **Minimum end-to-end link quality (if relay } k \text{ is selected):**

$$\text{SENR}_k := \min_{n \in S_N, \ \delta_k \in \mathcal{H}_k} \text{SENR}^{(n)}_k = \frac{P_s \tilde{a}_k |h_{sr,k}|^2}{(1+\eta_k)\tilde{a}_k (P_s |h_{sr,k}|^2 + M_k)} - \frac{P_s |h_{sr,k}|^2 \cdot \tilde{a}_k + \ell_k}{1-\tilde{a}_k b_k}$$

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

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

\[
\text{SE} \tilde{\text{NR}}_k := \min_{n \in S_N, \delta_k \in \mathcal{H}_k} \text{SE} \tilde{\text{NR}}^{(n)}_k = \frac{P_s \bar{a}_k |h_{sr,k}|^2}{(1 + \eta_k) \bar{a}_k \left( P_s |h_{sr,k}|^2 + M_k \right) + P_s |h_{sr,k}|^2 \cdot \bar{a}_k + \ell_k}
\]

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

- Relay with highest optimal \( \text{SE} \tilde{\text{NR}}_k \) will be selected as active relay.

- Maximum feasible amplification

- \( r^* : \) Stationary point of SENR

- \( a_k^{lim} : \) Max. feasible \( |a_k|^2 \)

- 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