Aalto University
School of Electrical Engineering

Recent Advances in Full-Duplex Relaying

Taneli Riihonen

Department of Signal Processing and Acoustics

Center of Excellence in Smart Radios and Wireless Research

Aalto University School of Electrical Engineering, Finland

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Presenter: Taneli Riihonen

- Master of Science, Helsinki University of Technology (TKK), Finland, 2006
  - ▷ Received the McKinsey Award for the best graduating student (only one among all 1007 M.Sc. degrees completed at TKK during that year)
  - ▷ Currently wrapping up D.Sc. thesis at Aalto University
- Productive (co-)author in scientific publications
  - ▷ $15/38$ published journal/conference papers, some under review
- Dedicated (co-)supervisor for younger students
  - ▷ 8 M.Sc. theses completed, 1 currently in progress
  - ▷ 2 D.Sc. theses in progress (and collaboration with many others as a co-author)
- Diligent and punctual reviewing service for the community
  - ▷ Regularly since 2008: so far ~ 200 papers ($\sim 1/1$ journals/confs.)
  - ▷ Exemplary Reviewer 2012 for IEEE Communications Letters
- Looking for a postdoc position abroad to grow academically and personally

Agenda

- Overview of the presenter's work on *full-duplex relaying* in 2008–2011 which constitutes $\sim 1/3$ of his upcoming dissertation
- Tutorial to essential aspects that need to be considered when introducing full-duplex operation into multihop relaying systems
- The basis for seminal research: *loopback self-interference*!
  - ▷ Mitigation techniques and evaluation of their performance
  - ▷ The feasibility of full-duplex relaying in the presence of *residual* self-interference, i.e., comparison to half duplex
  - ▷ Merging full duplex with MIMO and OFDM techniques
- The results were originally published in multiple conference and journal papers [1]–[12] (see the next two slides)

References (published in 2009)

[1] T. Riihonen, S. Werner, and R. Wichman, “Comparison of full-duplex and half-duplex modes with a fixed amplify-and-forward relay,” in *Proc. IEEE Wireless Communications and Networking Conference*, Apr. 2009.

[2] T. Riihonen, S. Werner, R. Wichman, and J. Hämäläinen, “Outage probabilities in infrastructure-based single-frequency relay links,” in *Proc. IEEE Wireless Communications and Networking Conference*, Apr. 2009.

[3] T. Riihonen, S. Werner, and R. Wichman, “Optimized gain control for single-frequency relaying with loop interference,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 2801–2806, Jun. 2009.

[4] T. Riihonen, S. Werner, R. Wichman, and E. Zacarias B., “On the feasibility of full-duplex relaying in the presence of loop interference,” in *Proc. 10th IEEE Workshop on Signal Processing Advances in Wireless Communications*, Jun. 2009.

[5] T. Riihonen, K. Haneda, S. Werner, and R. Wichman, “SINR analysis of full-duplex OFDM repeaters,” in *Proc. 20th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Sep. 2009.

[6] T. Riihonen, S. Werner, and R. Wichman, “Spatial loop interference suppression in full-duplex MIMO relays,” in *Proc. 43rd Annual Asilomar Conference on Signals, Systems, and Computers*, Nov. 2009.

References (published in 2010–2011)

[7] T. Riihonen, S. Werner, and R. Wichman, "Rate-interference trade-off between duplex modes in decode-and-forward relaying," in *Proc. 21st IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Sep. 2010.

[8] T. Riihonen, S. Werner, and R. Wichman, "Residual self-interference in full-duplex MIMO relays after null-space projection and cancellation," in *Proc. 44th Annual Asilomar Conference on Signals, Systems, and Computers*, Nov. 2010.

[9] T. Riihonen, A. Balakrishnan, K. Haneda, S. Wyne, S. Werner, and R. Wichman, "Optimal eigenbeamforming for suppressing self-interference in full-duplex MIMO relays," in *Proc. 45th Annual Conference on Information Sciences and Systems*, Mar. 2011.

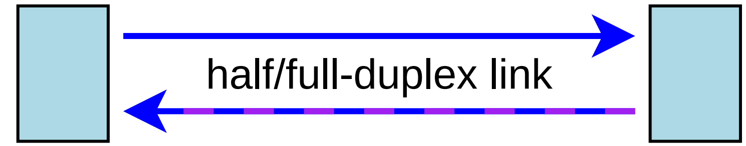
[10] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Transactions on Wireless Communications*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.

[11] T. Riihonen, S. Werner, and R. Wichman, "Transmit power optimization for multiantenna decode-and-forward relays with loopback self-interference from full-duplex operation," in *Proc. 45th Annual Asilomar Conference on Signals, Systems, and Computers*, Nov. 2011.

[12] T. Riihonen, S. Werner, and R. Wichman, "Mitigation of loopback self-interference in full-duplex MIMO relays," *IEEE Transactions on Signal Processing*, vol. 59, no. 12, pp. 5983–5993, Dec. 2011.

Introduction

Old Terminology



- Recommendation ITU-R V.662-2 (1993), or Wikipedia:

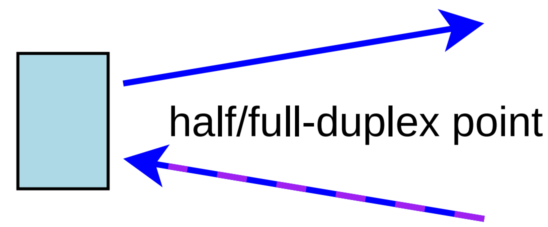
half duplex — "Designating or pertaining to a method of operation in which information can be transmitted in either direction, but not simultaneously, between two points."

full duplex — "Designating or pertaining to a mode of operation by which information can be transmitted in both directions simultaneously between two points."

- Ambiguity problems
  - ▷ What is the level of abstraction, e.g., considered OSI layer?
  - ▷ May the two directions use different transmission media?
  - ▷ What if communication involves more than two points?

... and even ITU itself characterizes the terms as "deprecated"!

New Terminology



- Herein, we shall adopt the following revised definitions:

half duplex — "Designating or pertaining to a mode of operation by which information can be transmitted to and from a point in two directions, but not simultaneously on the same physical channel."

full duplex — "Designating or pertaining to a mode of operation by which information can be transmitted to and from a point in two directions simultaneously on the same physical channel."

- Unambiguous and suitable for discussing modern topics
  - ▷ Focus on the operation mode of any transceiver instead of bidirectional communication between exactly two points
  - ▷ Physical-layer perspective creates a link to spectral efficiency

... and it is not only me who already understands the terms like this

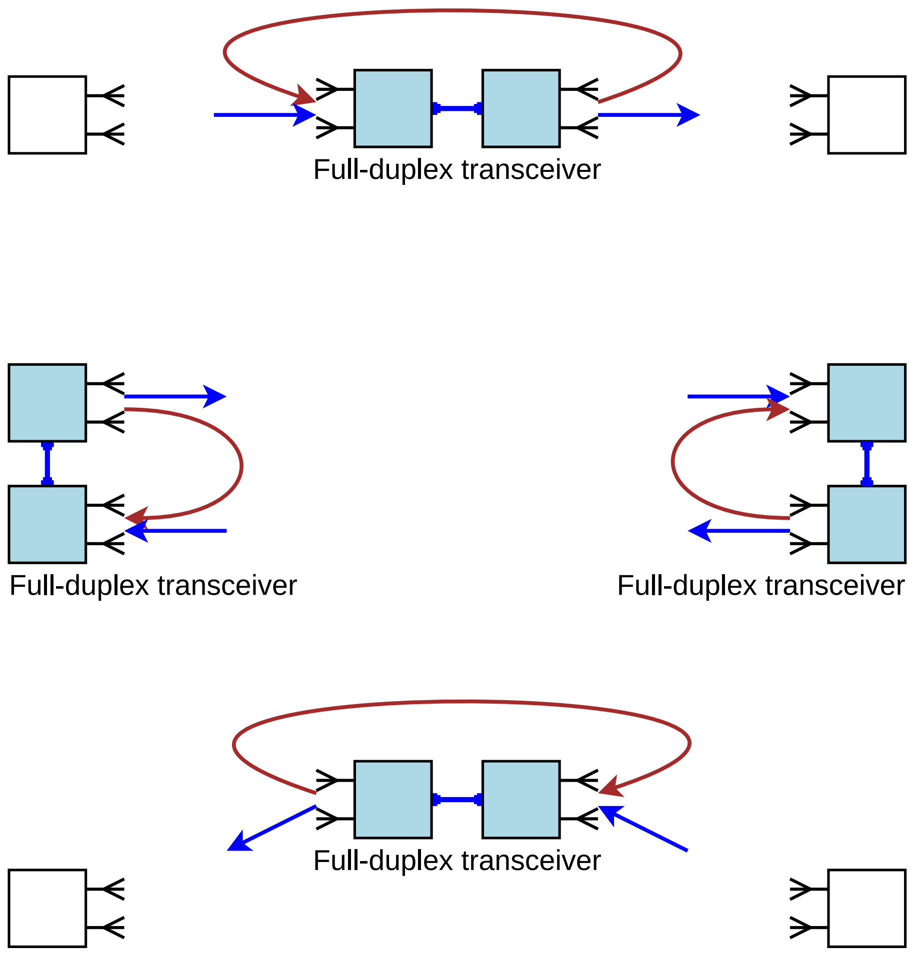
Hot Emerging Topic: Full-Duplex Wireless

- Systems where some node(s) operate in the full-duplex mode
- Sometimes descriptively referred to as single-frequency "*simultaneous transmit and receive*" (STAR)
- Progressive physical/link-layer *frequency-reuse* concept

  = up to double spectral efficiency at a system level, if the significant technical problem of *self-interference* is tackled

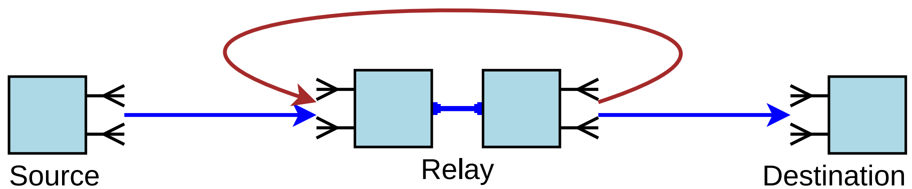
- Transmission and reception should use the band for the same amount of time to make the most of full duplex
  - ▷ (a)symmetry of traffic pattern, i.e.,
    requested rates in the two simultaneous directions
  - ▷ (a)symmetry of channel quality, i.e.,
    achieved rates in the two simultaneous directions

Full-Duplex Radio Transceivers

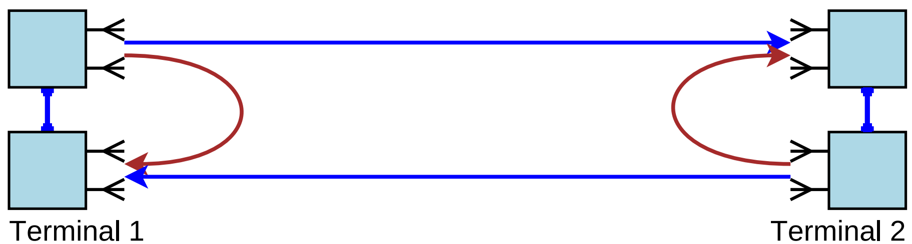


- Basic building blocks for more complex networks
- The benefits go beyond the physical layer!
  - e.g., simultaneous spectrum sensing and transmission
- Will single-array (or -antenna) full-duplex transceivers be viable some day?
  - Our study is not limited to the dual-array case although it is assumed

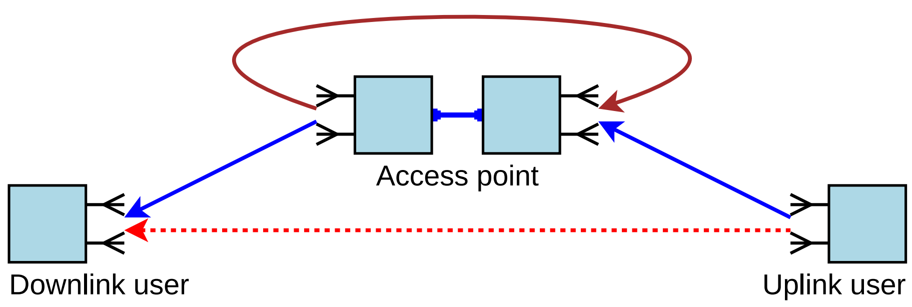
Full-Duplex Communication Scenarios



1) Multihop relay link
   - Symmetric traffic
   - Asymmetric channels
   - Direct link may be useful

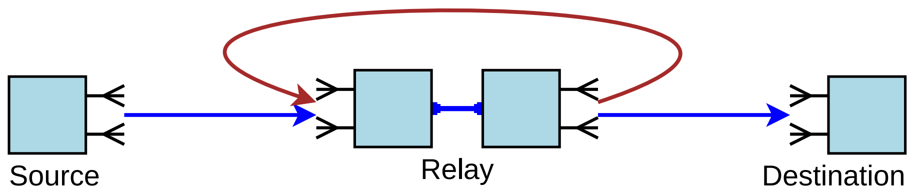


2) Bidirectional communication link between two terminals
   - Asymmetric traffic (typically)
   - Symmetric channels (roughly)



3) Simultaneous down- and uplink for two half-duplex users
   - Asymmetric traffic
   - Asymmetric channels
   - Inter-user interference!

Full-Duplex Relaying



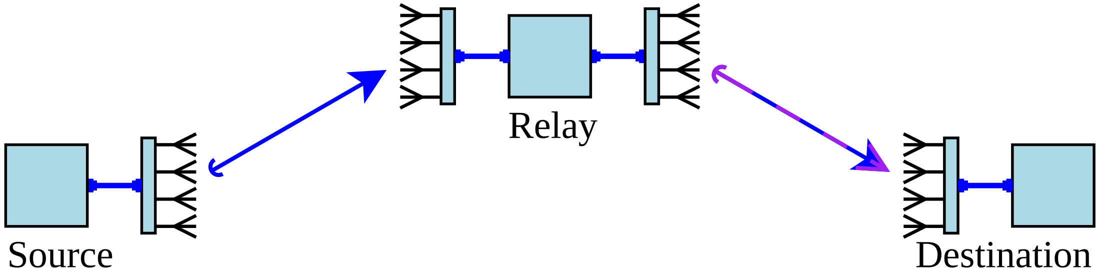
- Multihop relay link
  - ▷ Symmetric traffic
  - ▷ Asymmetric channels
  - ▷ Direct link may be useful

Agenda

- Tutorial to essential aspects that need to be considered when introducing full-duplex operation into multihop relaying systems
- The basis for seminal research: *loopback self-interference*!
  - ▷ Mitigation techniques and evaluation of their performance
  - ▷ The feasibility of full-duplex relaying in the presence of *residual* self-interference, i.e., comparison to half duplex
  - ▷ Merging full duplex with MIMO and OFDM techniques

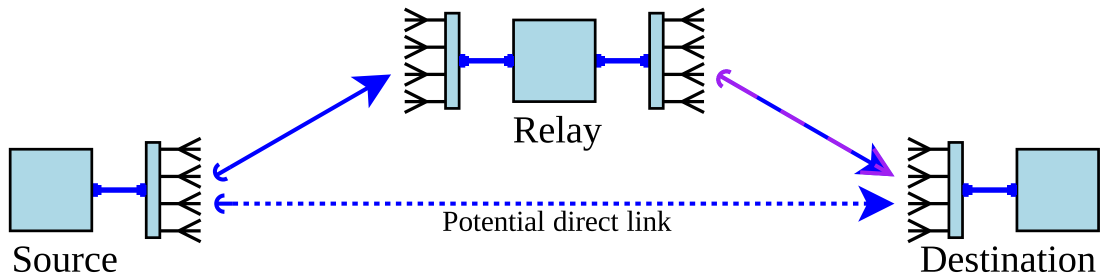
Full-Duplex Relaying

Relaying



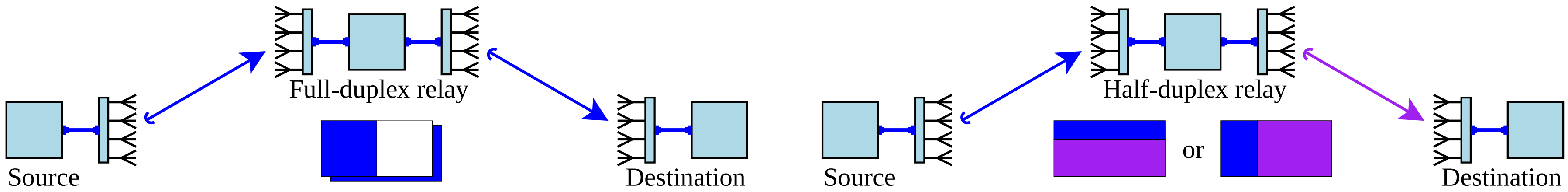
- The general purpose of a *relay node* is to forward signals from a source transmitter to a destination receiver
  - ▷ Other network topologies are also possible, e.g., with multiple hops or parallel relays
  - ▷ Common protocols: amplify-and-forward (AF), decode-and-forward (DF)
- *Full-duplex relays* exploit STAR such that source–relay and relay–destination links share one physical channel
  - ▷ can be more sophisticated than simple on-channel repeaters

Direct Link



- Two different applications for relays:
  a) *coverage extension* where the relay is deployed because the direct link is weak
  b) *diversity improvement* where transmission from both the relay and the source is strong (on average) at the destination
- The former is more potential application for full-duplex relays
  - ▷ Half-duplex relaying can offer maximum diversity gain
  - ▷ Rate/SNR gain of full-duplex relaying becomes marginal with a strong direct link: simple switching works well

Inherent Symmetry: Advantage for Full Duplex



- Full duplex can ideally render up to double spectral efficiency when compared to conventional half-duplex operation
  - ▷ Largest gains are achieved when simultaneous transmissions occupy the channel for the same amount of time
- Relay links are good candidates for adopting the full-duplex mode because their traffic pattern is inherently symmetric:
  - ▷ Equal *requested* source–relay and relay–destination data rates to avoid data overflow or underflow in the relay
  - ▷ Unequal *achieved* data rates due to channel imbalance

Mitigation of Loopback Self-interference

Mitigation of Loopback Self-interference (Refs)

- The following discussion mainly originates from

  [12] T. Riihonen, S. Werner, and R. Wichman, "Mitigation of loopback self-interference in full-duplex MIMO relays," *IEEE Transactions on Signal Processing*, vol. 59, no. 12, pp. 5983–5993, Dec. 2011.

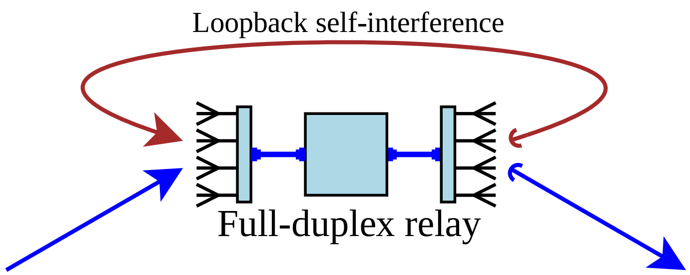
- Related results are available also in conference papers:

  [6], [8], [9], [11]

- Measurement data on prototype antenna arrays by courtesy of colleagues from Department of Radio Science and Engineering:

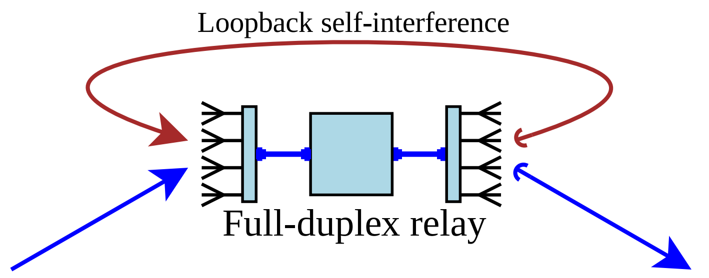
  [H+] K. Haneda, E. Kahra, S. Wyne, C. Icheln, and P. Vainikainen, "Measurement of loop-back interference channels for outdoor-to-indoor full-duplex radio relays," in *Proc. 4th European Conference on Antennas and Propagation*, Apr. 2010.

Loopback Self-interference



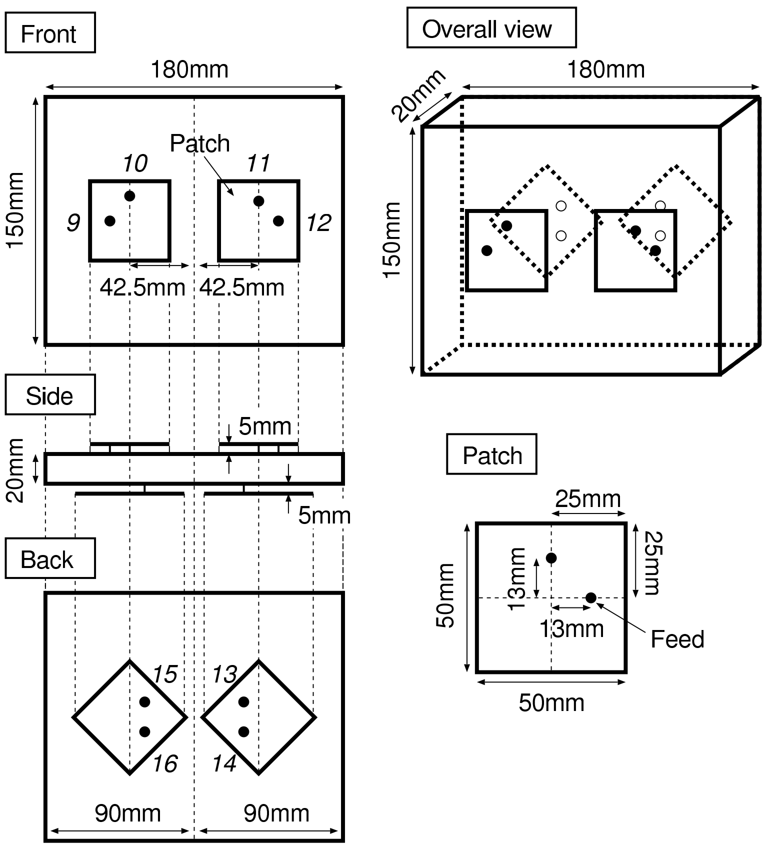
- Full-duplex operation is possible only after tackling a significant technical challenge: unavoidable *self-interference*
  - ▷ Huge difference in power levels (interference vs. desired signal)
- Full duplex is adopted first for fixed infrastructure nodes and later (maybe) for small portable, or even handheld, radios
  - ▷ Initially, the concept of full-duplex relaying is different from cooperative communication among mobile nodes where time-division half-duplex operation is the baseline assumption
- Next: self-interference mitigation techniques

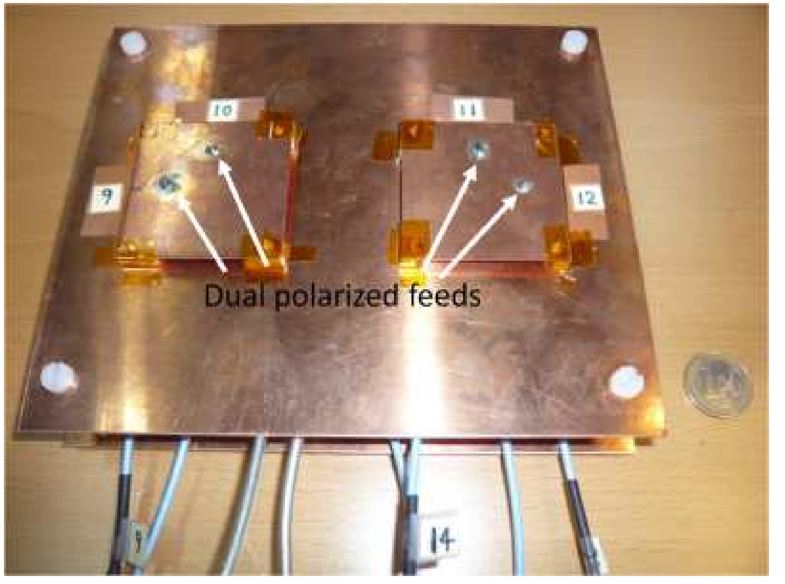
Passive Physical Isolation



- State-of-the-art devices require two separate antenna arrays: one for receiving and the other for transmitting
  - ▷ Mainly antenna design and placement problems: directivity, back-to-back coupling, distance, obstacles
  - ▷ But using two arrays is useful for relaying in general since the source and the destination are located at different directions
- In (future?) single-array devices, all physical isolation is provided by a circulator: mainly an electronics design problem
- Next: measured physical isolation with prototype antenna arrays

Experimental Antenna Arrays for Full-Duplex MIMO Relay*

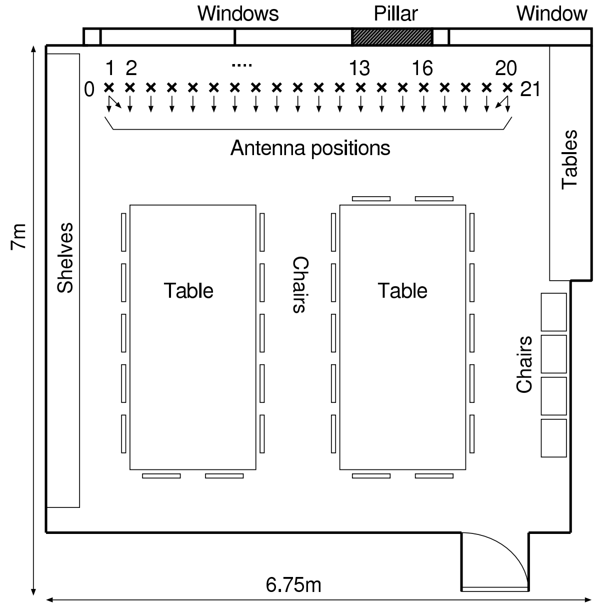


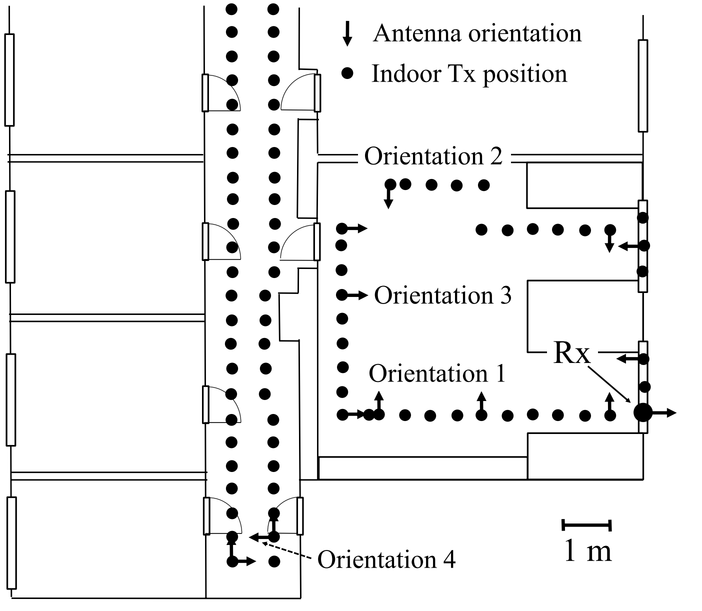


- Design goals:
  1. Compact size but high isolation
  2. 2.6GHz $\pm$ 100MHz operation band
  3. Multiple Rx and Tx antenna elements
- Building and measuring 4×4 array prototype

* Further details are provided in [H+]:
K. Haneda et al., “Measurement of loop-back interference channels for outdoor-to-indoor full-duplex radio relays,” April 2010.

Channel Measurement Campaign for Outdoor-to-Indoor Relaying Scenarios*





Compact array configuration

- Arrays attached side-by-side (2cm)
- Small box like a Wi-Fi router
- Several positions next to windows

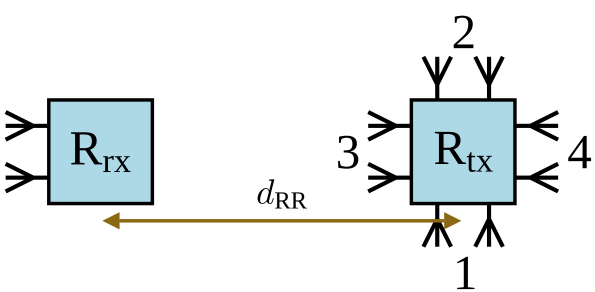
Separate array configuration

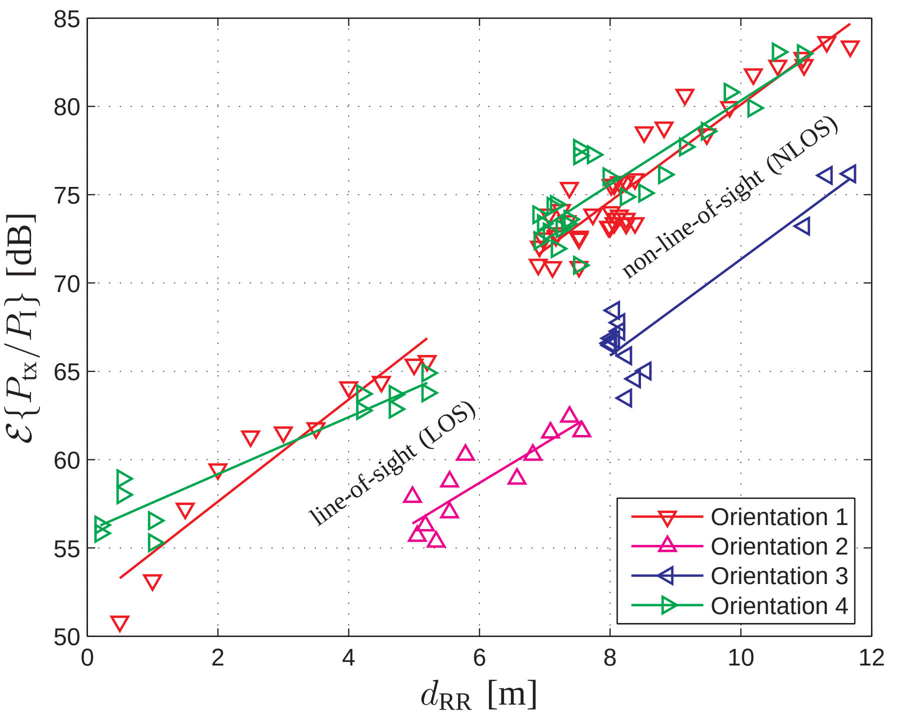
- Four Tx antenna orientations
- LOS: Tx in the same room as Rx
- NLOS: Tx in the adjacent corridor

* Further details are provided in [H+]:
K. Haneda et al., “Measurement of loop-back interference channels for outdoor-to-indoor full-duplex radio relays,” April 2010.

Average Physical Isolation

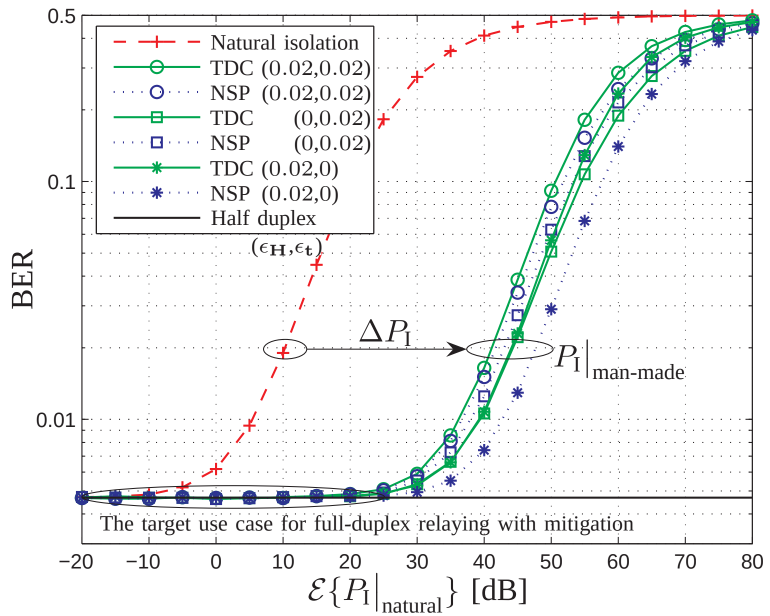
- For compact array configuration, measured isolation is 36.2dB
- For separate array configuration, isolation is directly proportional to antenna separation (2–3dB/m)





- 20dB isolation from window glass for separate array configuration
- Mere physical isolation may not be sufficient which gives motivation for active mitigation by signal processing

Objective for Active Mitigation

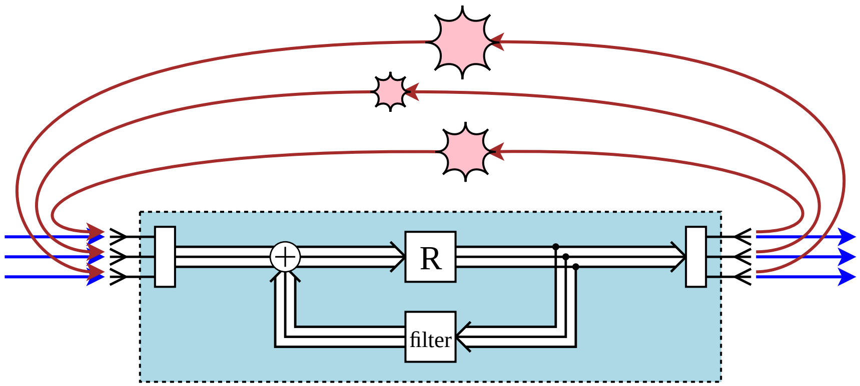


bit-error rate in a DF relay vs. physical isolation

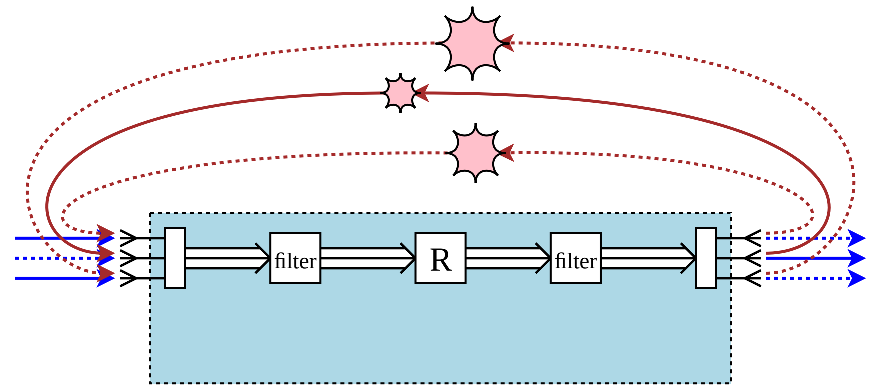
- Transparent minimization of self-interference: the relay protocol can operate as in the half-duplex mode but at double symbol rate
  - ▷ Mitigation becomes separated from the protocol design and the schemes are applicable with all kinds of protocols

Active Mitigation

Time-domain cancellation:

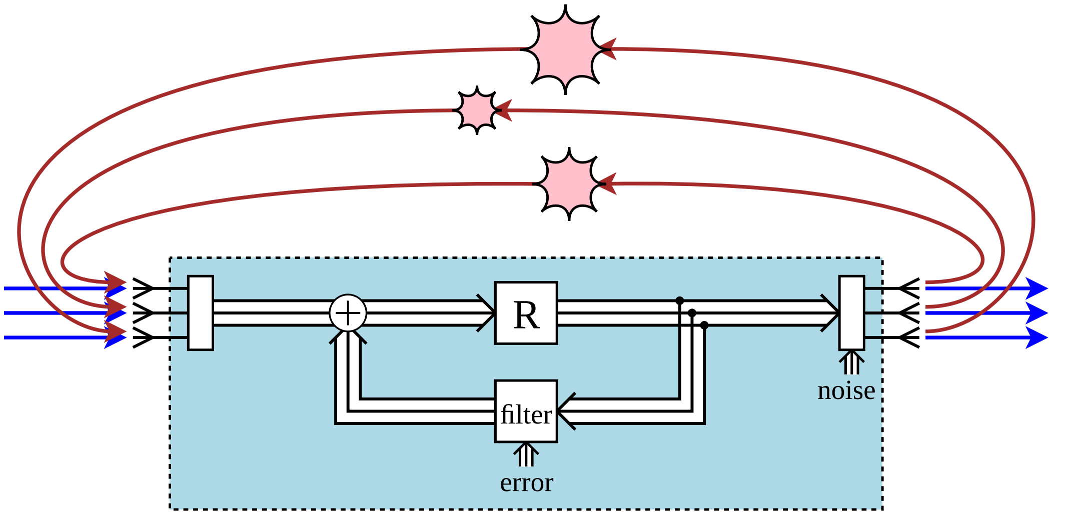


Spatial-domain suppression:



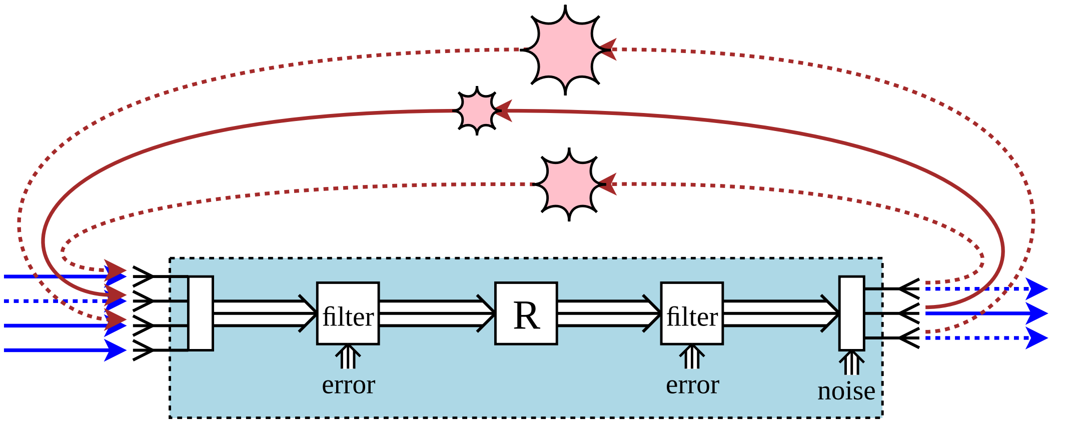
- Two main techniques for active self-interference mitigation
  - ▷ **Cancellation**: time-domain filtering in feedback path
  - ▷ **Suppression**: spatial-domain filtering in feedforward path
- Both schemes could ideally eliminate all self-interference
- Cancellation is a rather straightforward task while suppression can be implemented in various ways

Imperfect Side Information



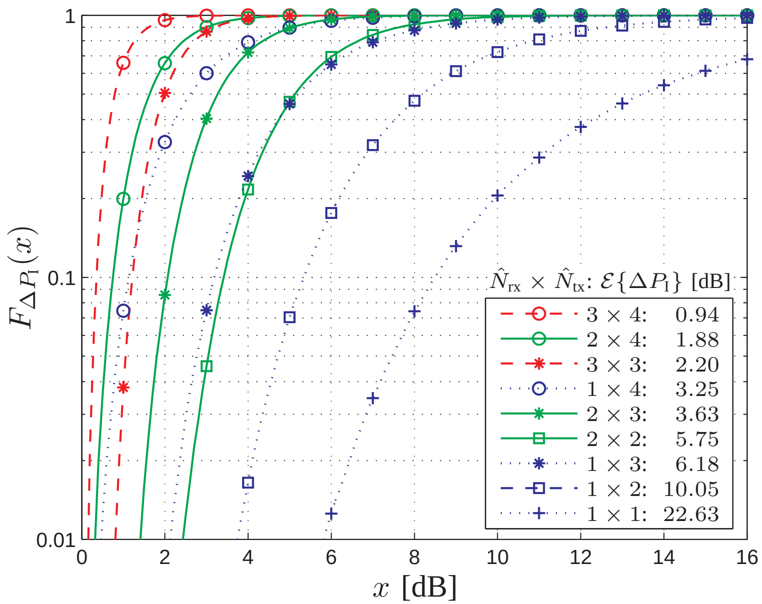
- In practice, self-interference cannot be perfectly eliminated
  - ▷ Channel estimation error in filter design
  - ▷ Transmit-side noise due to non-ideal electronics (the actual transmitted signal is not known)
- Sufficient physical isolation and analog pre-cancellation are also required to cope with limited dynamic range at the receive side

Spatial-Domain Suppression

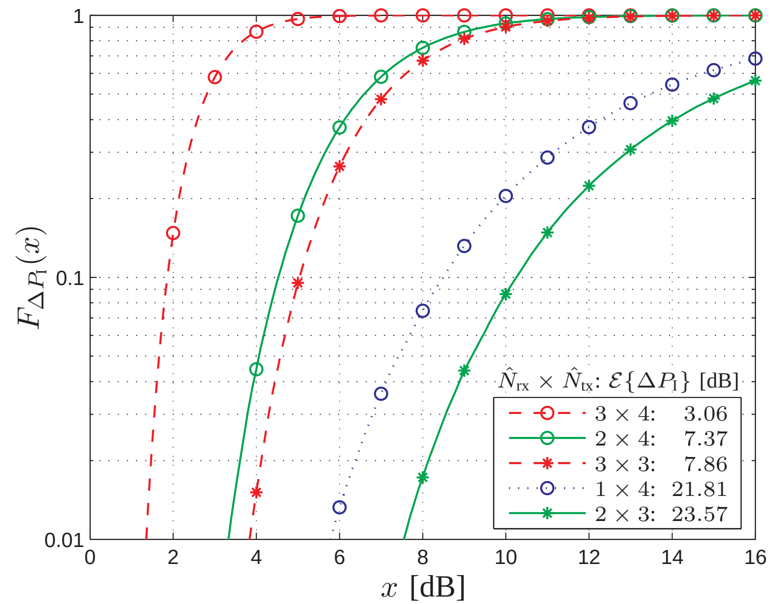


- Next: evaluating the main variations of suppression
  - antenna selection (AS)
  - beam selection (BS)
  - null-space projection (NSP)
  - minimum mean square error (MMSE) filtering
- In some cases, it may be beneficial to combine time-domain cancellation with spatial-domain suppression

Antenna vs. Beam Selection



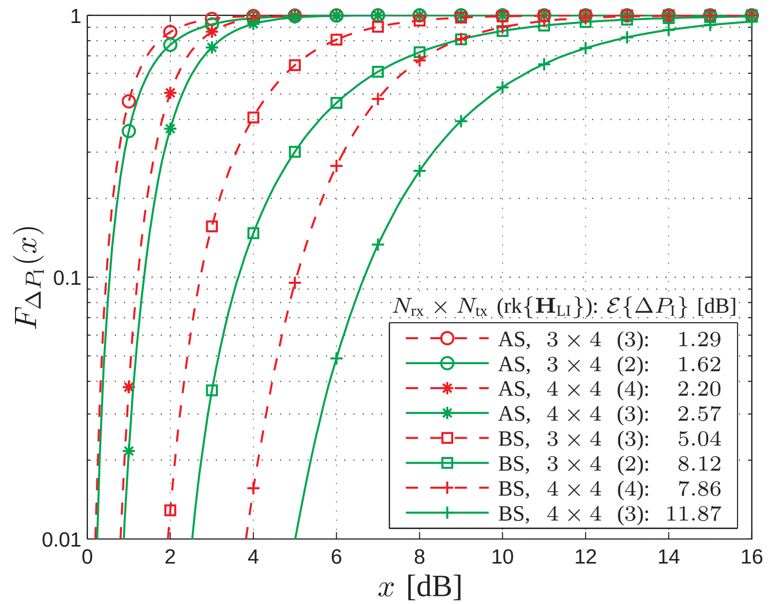
antenna selection (AS)



beam selection (BS)

- Ideal side information; four receive and transmit antennas
- AS improves isolation significantly only in the single-stream case
  - BS is reduced to null-space projection (NSP) and eliminates self-interference completely if less than five streams are used

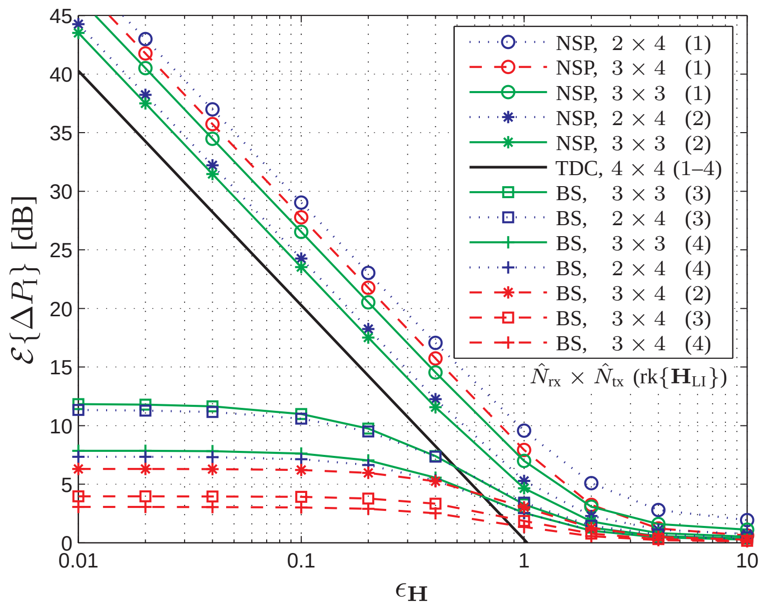
Rank of Loopback Channel



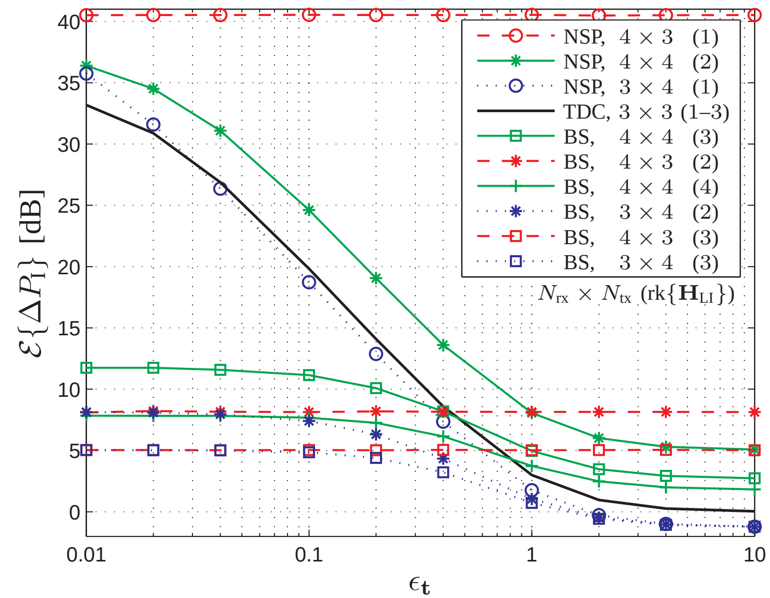
ideal side information; three receive and transmit antennas

- Spatial-domain suppression can benefit from low channel rank
  - ▷ Beam selection (BS) directs the self-interference energy to the weakest eigenmodes which include the null space
- Time-domain cancellation (not shown) would not be affected at all

Imperfect Side Information



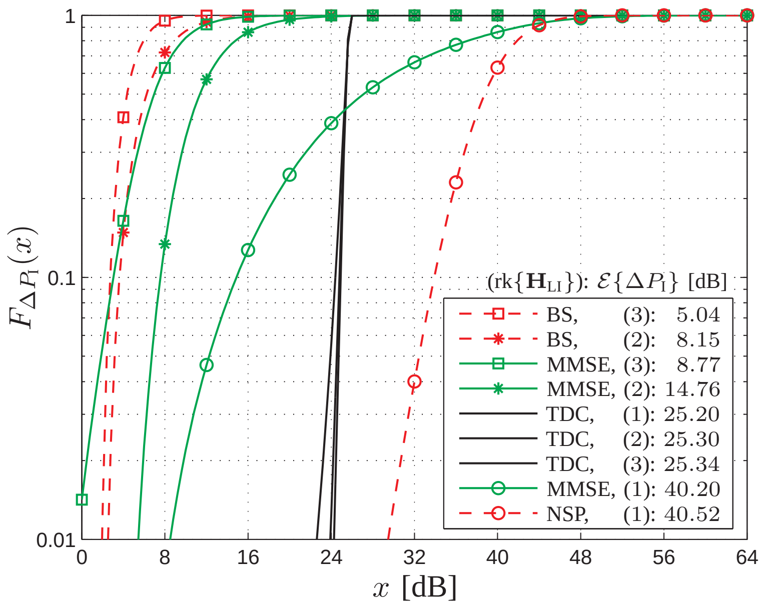
channel estimation error



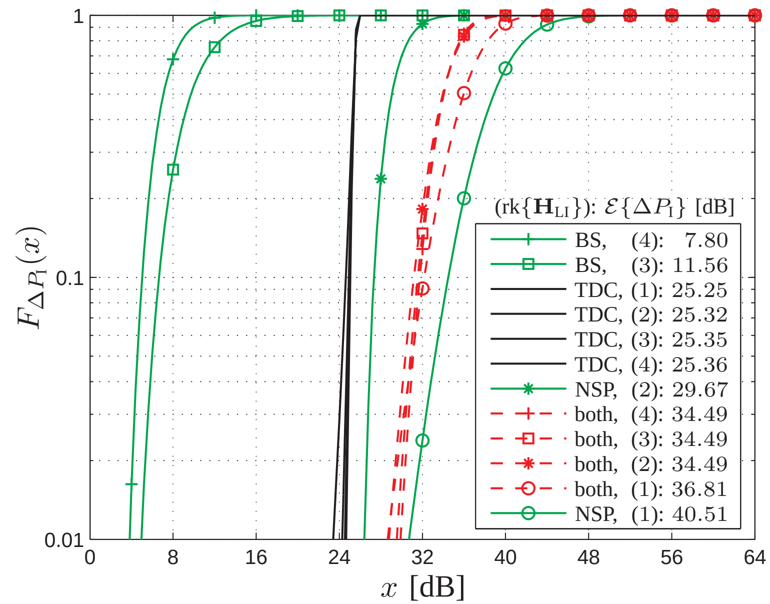
transmit-side noise

- Additional isolation from BS is limited with ideal side information
  - ▷ Imperfect side information determines the additional isolation achieved with NSP or time-domain cancellation (TDC)
- NSP can be made immune to transmit-side noise

Cancellation vs. Suppression



minimum MSE filtering



combined time/spatial-domain mitigation

- Loopback channel rank defines which scheme is preferable
- The combination of TDC and suppression offers better performance than either alone, except when rank-deficient loopback channel enables the usage of NSP

Transmit Power Adaptation

Transmit Power Adaptation (Refs)

- The following discussion mainly originates from

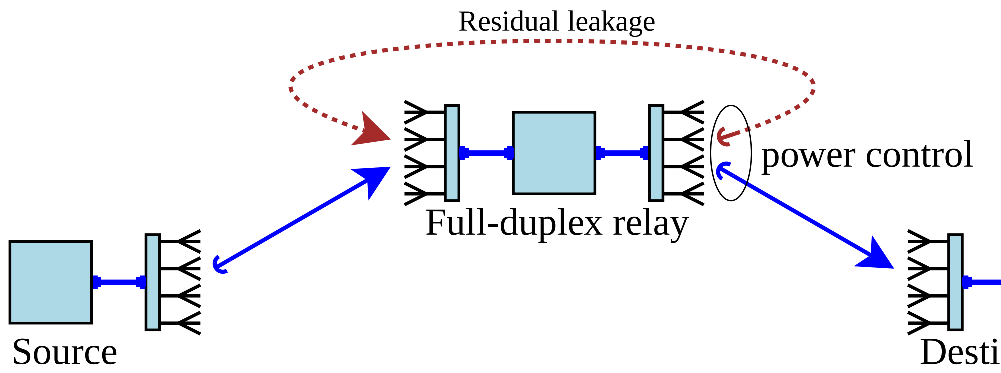
  [3] T. Riihonen, S. Werner, and R. Wichman, “Optimized gain control for single-frequency relaying with loop interference,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 2801–2806, Jun. 2009.

  [10] T. Riihonen, S. Werner, and R. Wichman, “Hybrid full-duplex/half-duplex relaying with transmit power adaptation,” *IEEE Transactions on Wireless Communications*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.

- Related results are available also in conference papers:

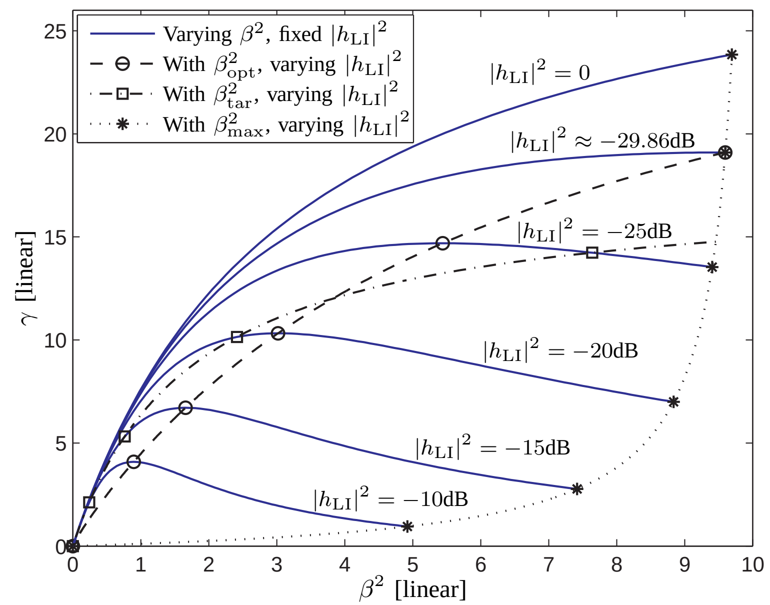
  [4], [5], [7], [11]

Transmit Power Adaptation



- In practice, there will always be *residual* self-interference after applying all means of mitigation
- Fortunately, transmit power adaptation can still exploit the channel imbalance caused by residual interference
  - In principle, the relay should appropriately lower its own transmit power if the first hop is the bottleneck of the system
- Win–win solution: energy savings can be achieved while performance is also optimized

Example with Amplify-and-Forward Protocol



end-to-end SINR vs. relay gain

- The end-to-end signal-to-interference and noise ratio (SINR) starts to decrease when increasing relay gain beyond the optimal point
  - Relay should use its maximum allowed transmit power only in the case of low residual self-interference

Full Duplex vs. Half Duplex

Full Duplex vs. Half Duplex (Refs)

- The following discussion mainly originates from

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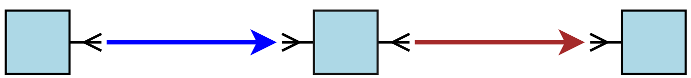
- Related results are available also in conference papers:

  [1], [4], [7], [11]

- In articles [2] and [3], our results focus on the full-duplex mode, but the analysis itself could be also used for comparison purposes

Fundamental Rate–Interference Trade-off

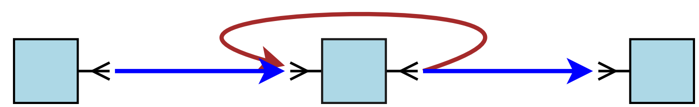
- Determining the ultimate feasibility of full-duplex relaying in the presence of *residual* self-interference. In principle,
  - ▷ half-duplex relay link:



Reduced symbol rate due to two allocated channels

$$\mathcal{R}_{\mathrm{HD}} = \frac{1}{2} \log_2 \left(1 + \frac{P_{\mathrm{S}}}{P_{\mathrm{N}}} \right)$$

  - ▷ full-duplex relay link:



Residual self-interference even after mitigation

$$\mathcal{R}_{\mathrm{FD}} = \log_2 \left(1 + \frac{P_{\mathrm{S}}}{P_{\mathrm{I}} + P_{\mathrm{N}}} \right)$$

- Should the system choose to operate with
  a) loss of end-to-end symbol rate (half duplex), or
  b) loss of S(I)NR due to self-interference (full duplex)?

Full- or Half-Duplex (... or Direct Transmission)?

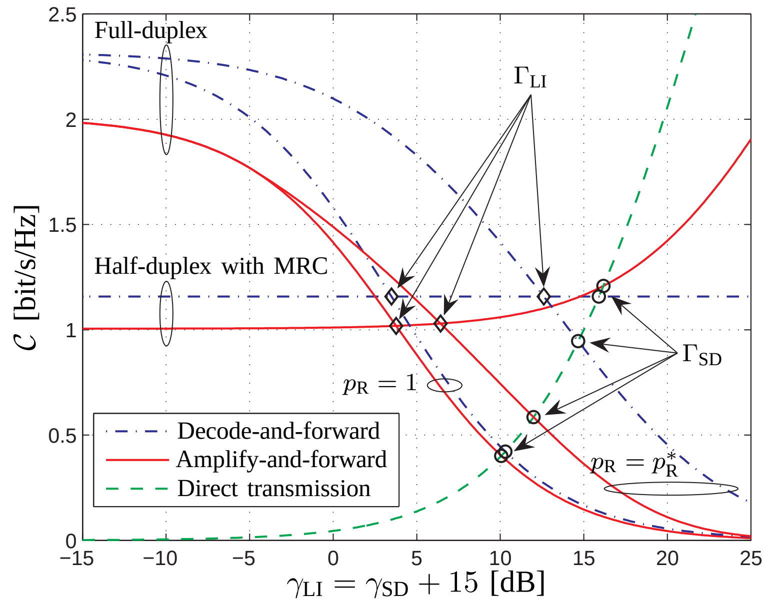
- Rate–interference trade-off: choosing between
  - ▷ full-duplex (FD) relaying with residual self-interference
    - Direct link treated as interference at the destination
    - With and without transmit power adaptation
  - ▷ half-duplex (HD) relaying
    - Maximum ratio combining (MRC) for the direct and relayed transmissions at the destination
  - ▷ direct transmission (DT)
    - The same (full) symbol rate as with FD relaying but low channel SNR on average (coverage extension)
- The comparison yields switching boundaries between the modes according to channel imbalance

Instantaneous Channel State Information

Let us next consider the case of deterministic (static) channels

- This represents, for example, a snapshot of the system within channel coherence time in a slow-fading environment
- Instantaneous channel state information (channel SNRs) for
  - ▷ choosing the proper mode
  - ▷ transmit power adaptation (with FD)
  - ▷ maximum ratio combining (with HD)
- Metric for the comparison: instantaneous transmission rate
  - ▷ The analysis can be completely conducted in terms of closed-form expressions (see the papers)

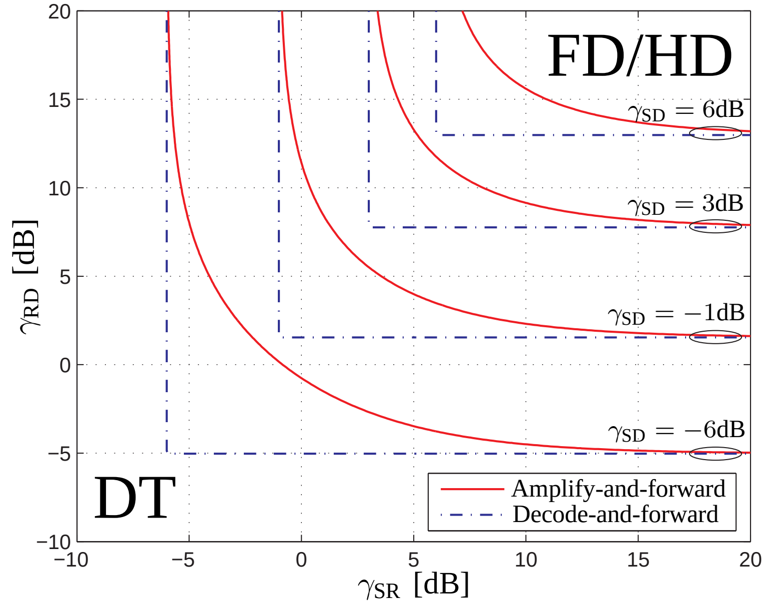
Instantaneous Switching Boundaries



instantaneous transmission rates

- Full-duplex (FD) relaying is preferred with low self-interference
  - Transmit power adaptation extends the range further
- Pure direct transmission (DT) is preferred with a strong direct link and MRC gives little benefit for half-duplex (HD) relaying

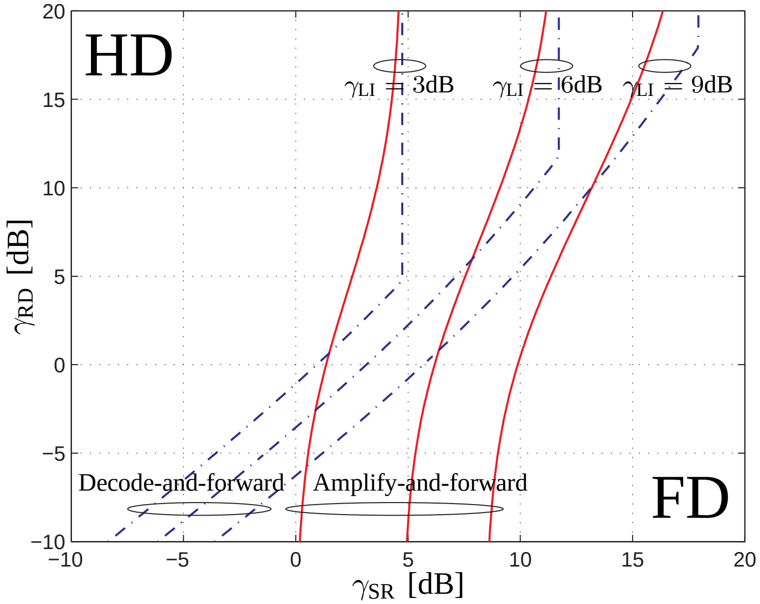
Direct Transmission vs. Relaying



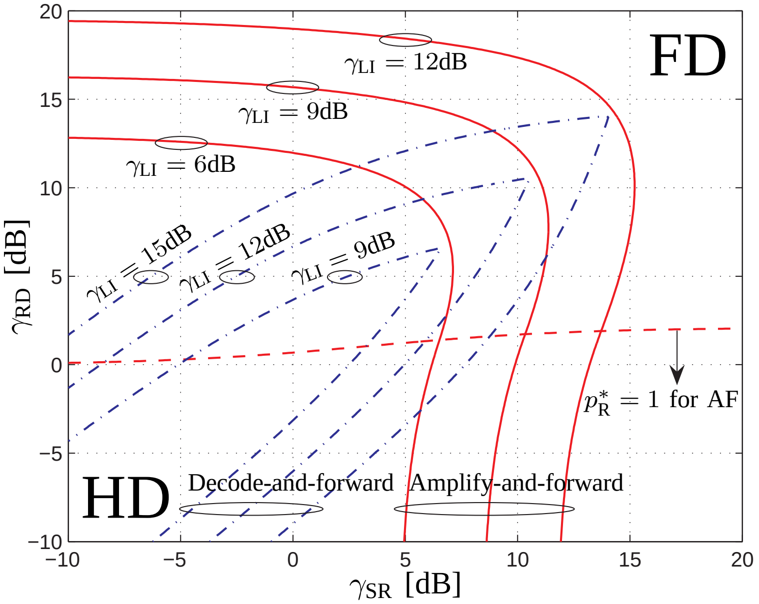
switching boundaries

- FD relaying is suitable for the scenario of *coverage extension*
  - ▷ When the direct link exists in fortunate fading states, the relay is not momentarily needed at all
- Simple switching yields also good *diversity improvement*

Full-Duplex vs. Half-Duplex Relaying



without transmit power adaptation



with transmit power adaptation

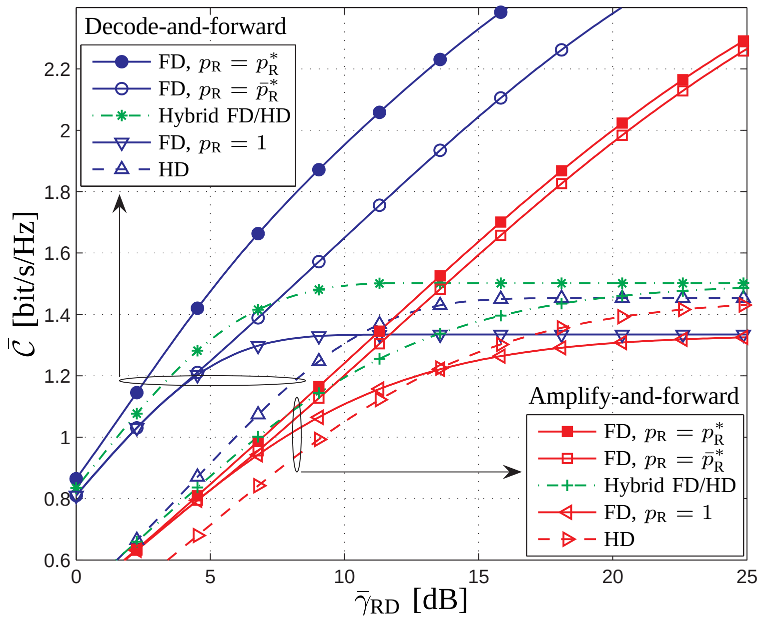
- Instead of adhering to any mode at early design stage, it is advantageous to implement *hybrid full-duplex/half-duplex relaying*, i.e., opportunistic switching between the modes, because the rate–interference trade-off favors them alternately during operation

Statistical Channel State Information

Let us then consider the case of fading channels

- Fixed infrastructure relay node for coverage extension
  - ▷ Static link between the base station and the relay
  - ▷ Rayleigh-fading link between the relay and a mobile user
- Statistical channel state information (average channel SNRs) for
  - ▷ choosing the proper mode
  - ▷ transmit power adaptation (with FD)
- Metric for the comparison: average transmission rate
  - ▷ The actual rate expressions can be calculated in a closed form but switching boundaries and transmit power adaptation need numerical look-up tables (see the papers)

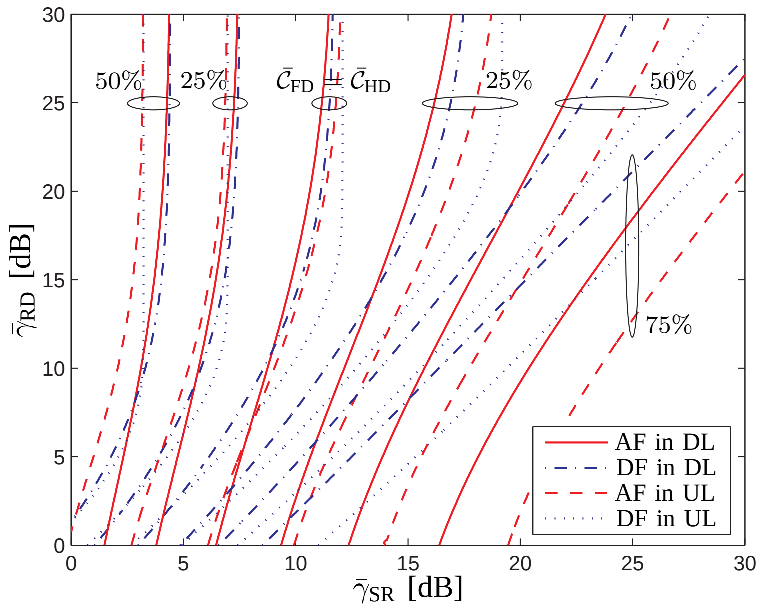
Statistical Switching Boundaries



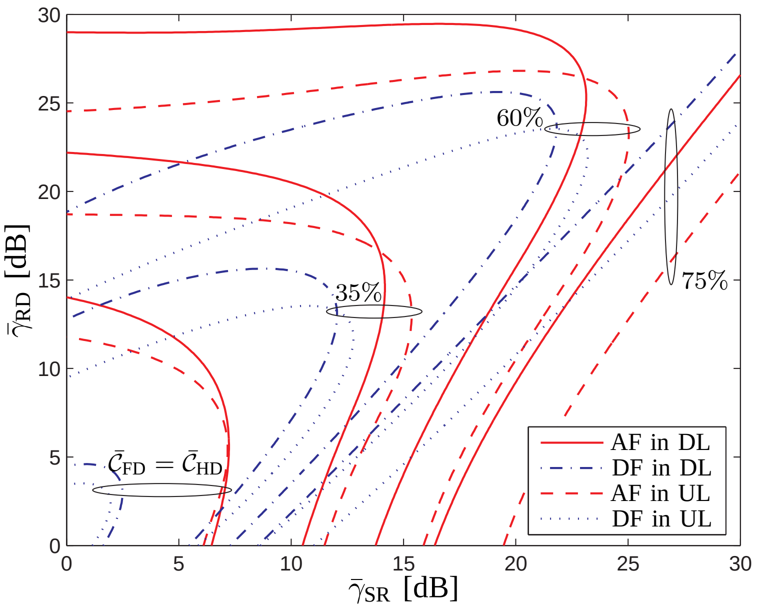
average transmission rates

- Statistical mode switching and transmit power adaptation yield rather good performance with much lower signaling overhead
  - Hybrid FD/HD relaying (instantaneous switching) gives the largest gains near statistical switching boundaries

Full-Duplex vs. Half-Duplex Relaying



without transmit power adaptation



with transmit power adaptation

- Illustrating downlink (DL) vs. uplink (UL) transmission
  - ▷ self-interference in a mobile channel vs. in a fixed channel
- Rate is significantly improved by choosing the proper mode which is typically FD when using transmit power adaptation

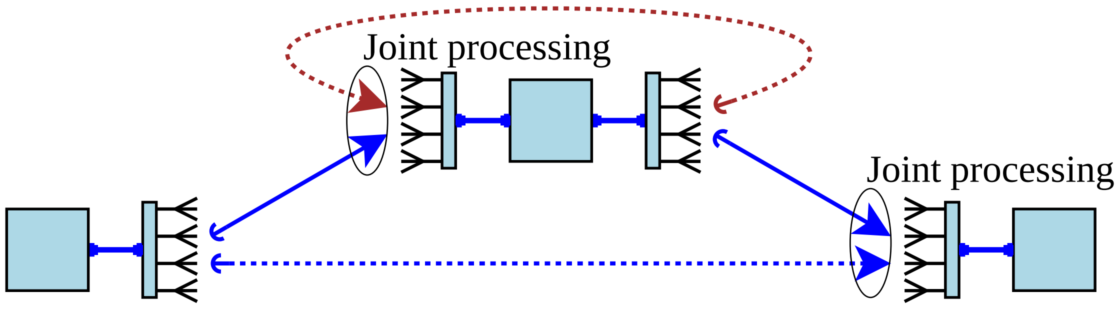
Conclusion

Conclusion

- Wireless full duplex: A progressive frequency-reuse concept!
- Herein: overview of recent work on *full-duplex relaying*
- Essential aspects that need to be considered when introducing full-duplex operation into multihop relaying systems
  - ▷ Loopback self-interference
  - ▷ Mitigation techniques and evaluation of their performance
    - physical isolation
    - time-domain cancellation
    - spatial-domain suppression
    - transmit power adaptation
  - ▷ Rate–interference tradeoff: the feasibility of full-duplex relaying in the presence of *residual* self-interference
- ... and how is all this related to OFDM mentioned in the beginning?

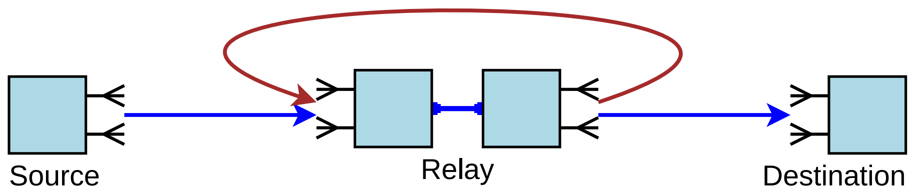
Future Work

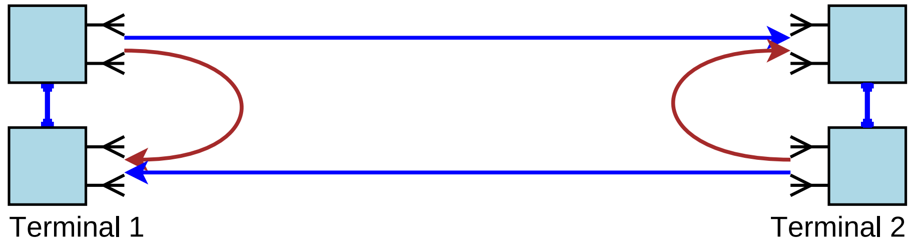
Joint Signal and Interference Processing

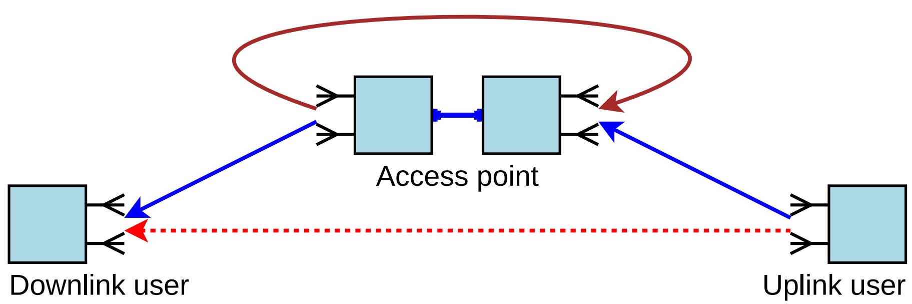


- Herein: “transparent” self-interference mitigation schemes
  - ▷ Any existing relaying protocol could be used
  - ▷ But the joint design of mitigation and a specific protocol would probably bring performance gains
- Herein: simple switching between direct transmission and relaying
  - ▷ Direct link is regarded as interference when using the relay
  - ▷ The destination could apply signal processing techniques to separate and constructively combine the superimposed signals from the source and the relay

Extensions to Other Full-Duplex Scenarios







Full-duplex communication

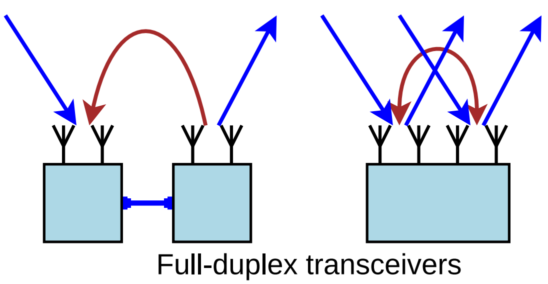
1) Multihop relay link
2) Bidirectional communication
3) Simultaneous down- and uplink

Other potential uses for STAR

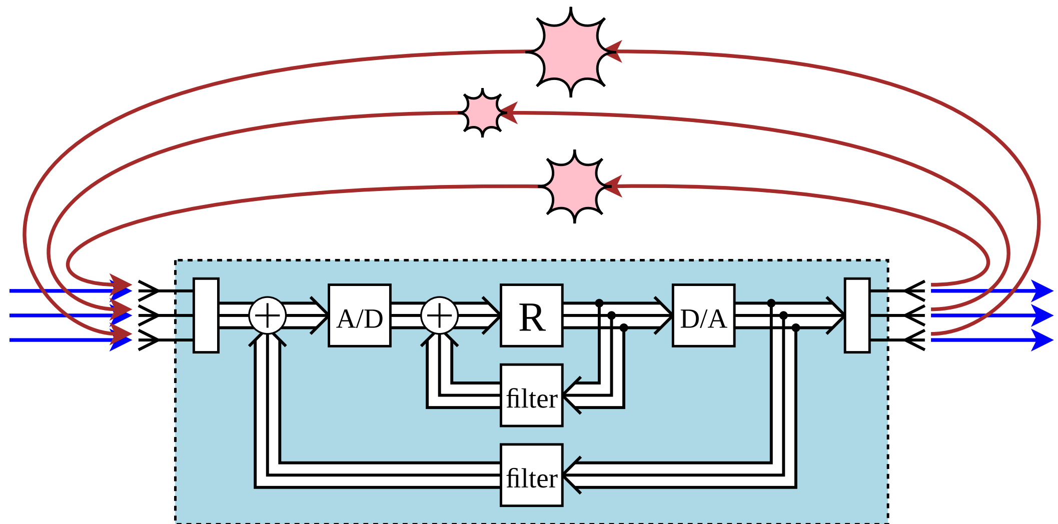
- medium access control
- cognitive radios

Generic full-duplex radios

- improved isolation and mitigation

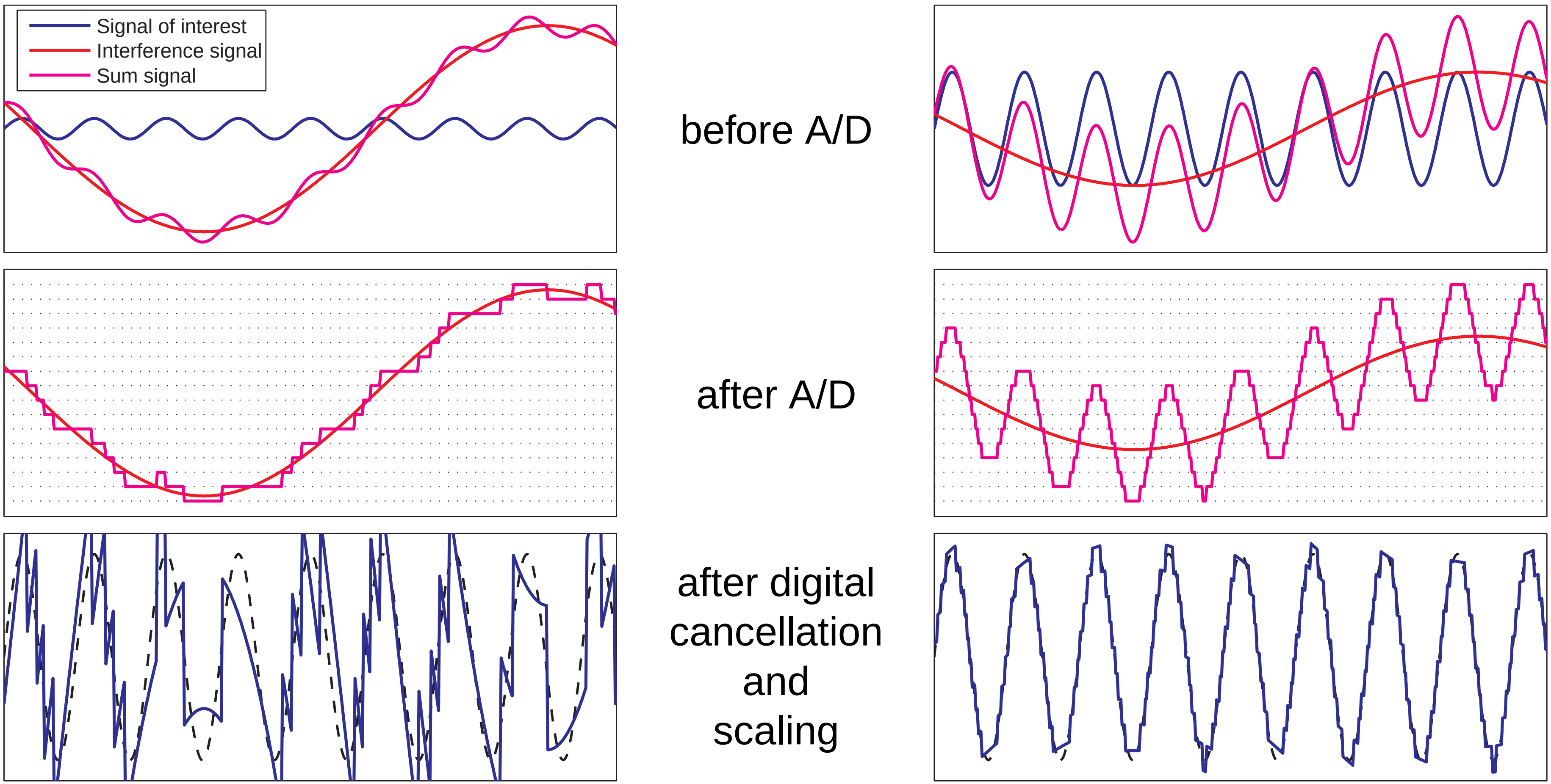


Limited Receiver Dynamic Range



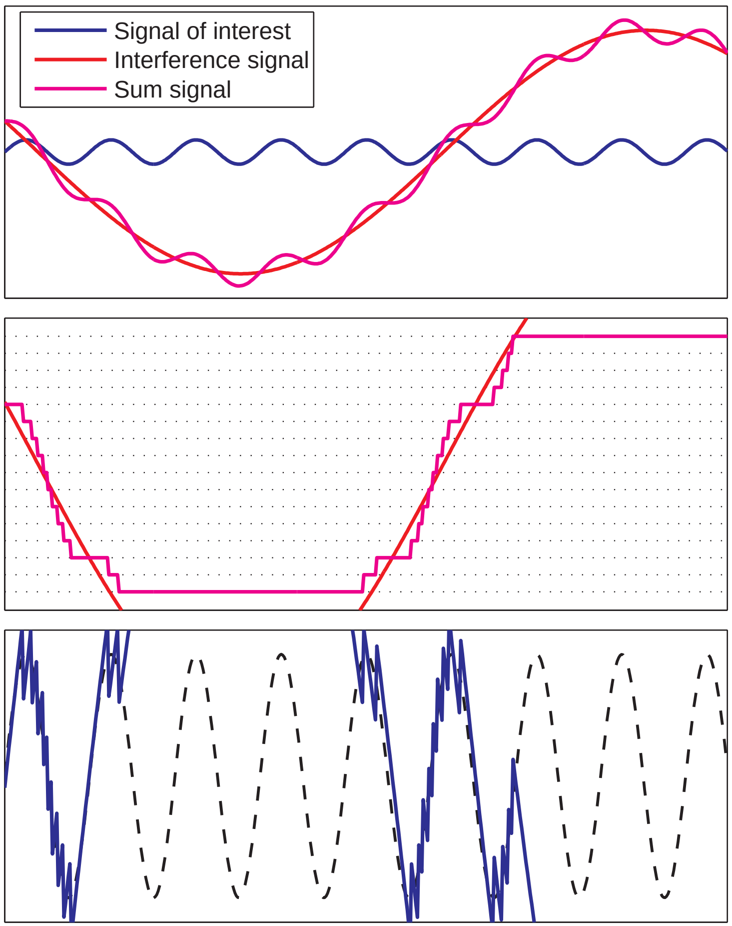
- Severe risk of saturating analog-to-digital (A/D) converters
  - ▷ quantization noise due to limited resolution
  - ▷ clipping noise which is pronounced with OFDM
- Digital cancellation is useless if dynamic range is not sufficient
- It is difficult and expensive to adapt the response of an analog filter to match the time- and frequency-selective MIMO channel

Example on Quantization Noise (4-bit A/D)



- ~ 1-bit resolution for the signal of interest
- ~ 3-bit resolution for the signal of interest

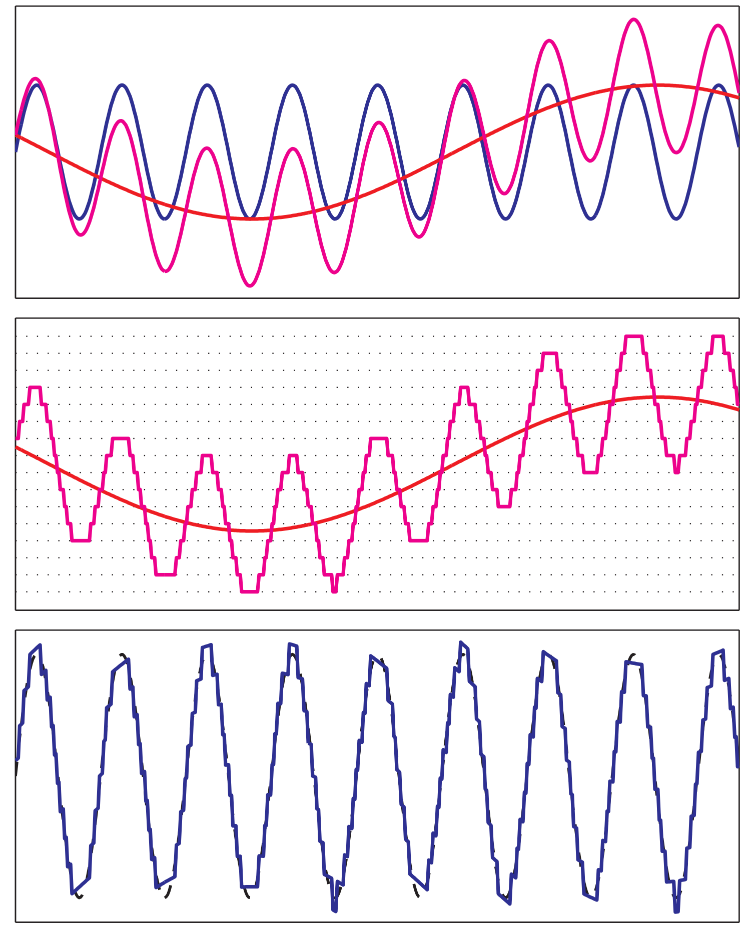
Example on Clipping Noise (4-bit A/D)



before A/D

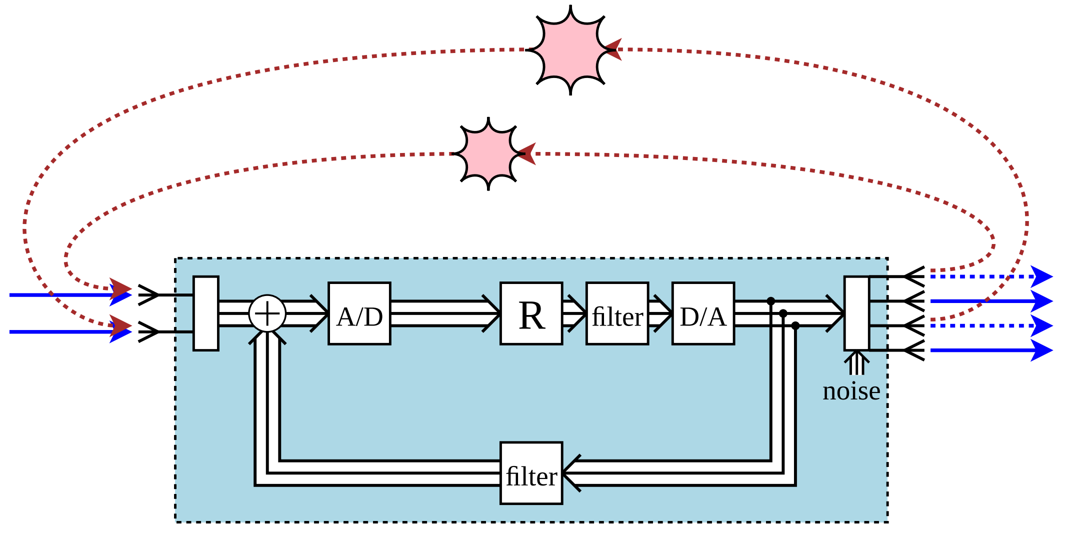
after A/D

after digital cancellation and scaling



- ~ 2-bit *clipped* resolution for the signal of interest
- ~ 3-bit resolution for the signal of interest

Mitigation in Analog Domain



- Self-interference should be minimized before A/D conversion
  - ▷ Physical isolation is an antenna design problem
  - ▷ Analog cancellation is an electronics design problem
- Transmit-side beamforming can eliminate the interference "on-the-air" before it even reaches the receiver front-end
  - ▷ A digital signal processing problem!

Aalto University
School of Electrical
Engineering