Recent Advances in Full-Duplex Relaying

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- 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 (~ 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 \( \sim \frac{1}{3} \) 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)


References (published in 2010–2011)


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”!
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
The general purpose of a \textit{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).

- \textit{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.
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

- 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:
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 ± 100MHz operation band
  3. Multiple Rx and Tx antenna elements
- Building and measuring $4 \times 4$ array prototype

*Further details are provided in [H+]:
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

Average Physical Isolation

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

![Diagram showing isolation measurements]

- 20 dB 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

- 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**

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

- 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

![Graph showing the 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

- 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

![Graph showing Cancellation vs. Suppression](image)

- 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
  
  

- 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

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

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
  - full-duplex relay link:
    - Residual self-interference even after mitigation

\[
R_{\text{HD}} = \frac{1}{2} \log_2 \left( 1 + \frac{P_S}{P_N} \right)
\]

\[
R_{\text{FD}} = \log_2 \left( 1 + \frac{P_S}{P_I + P_N} \right)
\]

- 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
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

\[ \gamma_{LI} = \gamma_{SD} + 15 \text{ [dB]} \]

\[ p_R = p_* R \]

- 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

- 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

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

- 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?
**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 before A/D
- ~3-bit resolution for the signal of interest after digital cancellation and scaling
Example on Clipping Noise (4-bit A/D)

- ∼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!