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Rate–Interference Trade-off Between Duplex Modes in Decode-and-Forward Relaying

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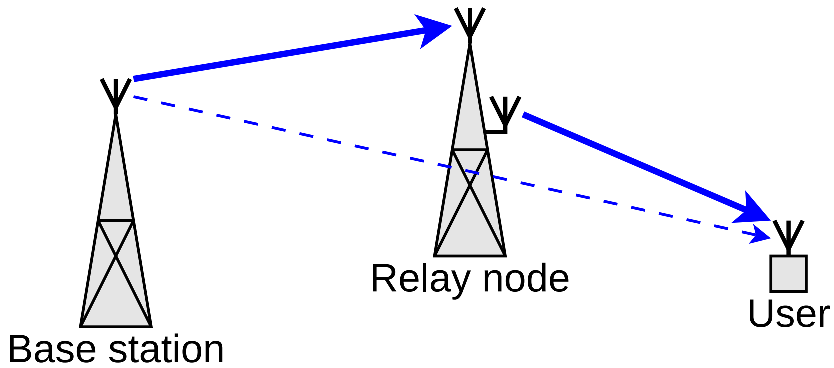
September 29, 2010
IEEE PIMRC'10, Istanbul, Turkey

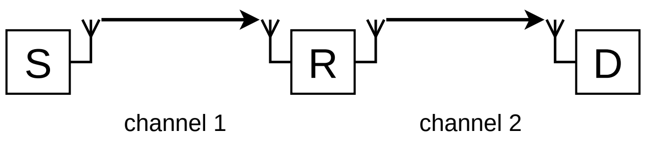
Introduction

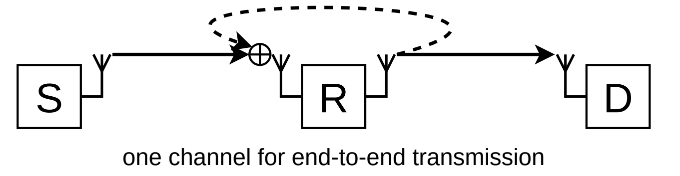
Background



- Focus: Relay-enhanced (coverage extension) cellular system
  - ▷ Two hops, strongly attenuated direct link
  - ▷ Fixed infrastructure-based relay node
  - ▷ Decode-and-forward (DF) protocol
- Goal: To study the tradeoff between link-level operation modes (half duplex vs. full duplex) in terms of spectral efficiency
- Disclaimer: Handheld/portable relays (such as those considered in *cooperative communication*) are not in the scope of our paper

Link-Level Operation Modes



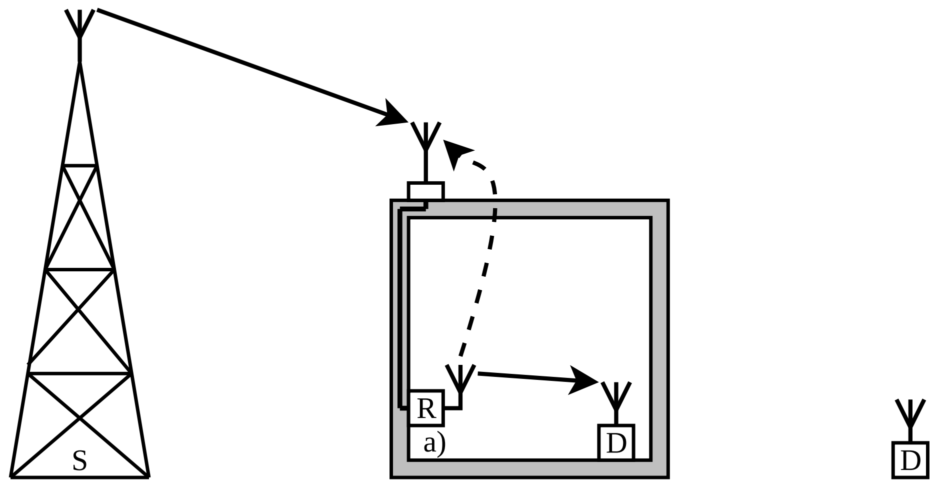


- Half duplex (HD)
  - ▷ Halved symbol rate
  - ▷ Cooperative communication
    - Possibly a single combined receive and transmit antenna

- Full duplex (FD)
  - ▷ Residual self-interference
  - ▷ Fixed infrastructure relays
    - Separated receive and transmit antennas
    - Interference mitigation

The rate–interference tradeoff between the duplex modes is essential for the design of infrastructure relay links

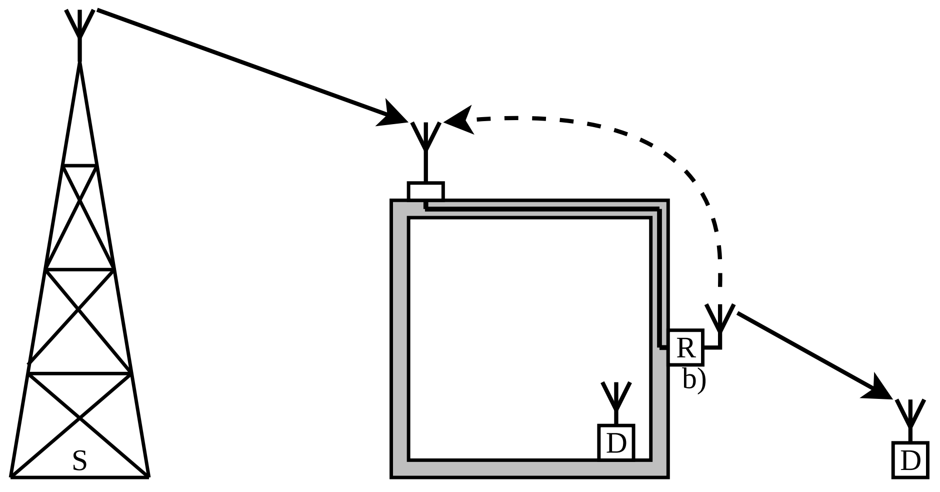
Typical Usage Scenarios for Full-Duplex Relays



- The relay receive antenna is at a rooftop to guarantee good quality for the input signal and to suppress the loopback channel
- The relay transmit antenna can be mounted

  a) inside a building to provide indoor coverage

Typical Usage Scenarios for Full-Duplex Relays



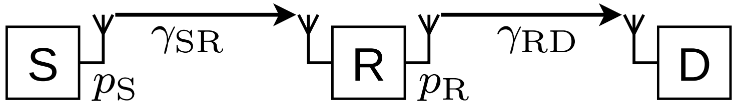
- The relay receive antenna is at a rooftop to guarantee good quality for the input signal and to suppress the loopback channel
- The relay transmit antenna can be mounted

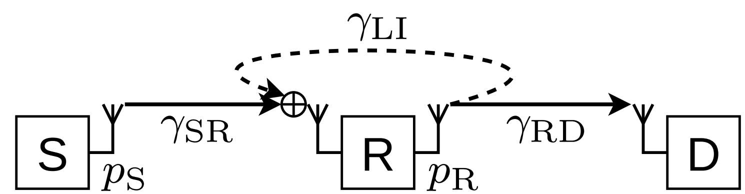
  b) on an exterior wall to fill a coverage gap between buildings

Instantaneous Capacity

Instantaneous Capacity

- Instantaneous channel SNRs: γ_{SR}, γ_{RD}, γ_{LI}
- Normalized transmit powers: p_{S}, p_{R}
- The rate–interference tradeoff in terms of instantaneous capacity





– Capacity with the half-duplex mode:

$$\mathcal{C}_{\mathrm{HD}} = \frac{1}{2} \log_2 \left(1 + \min\left\{p_{\mathrm{S}}\gamma_{\mathrm{SR}}, p_{\mathrm{R}}\gamma_{\mathrm{RD}}\right\}\right)$$

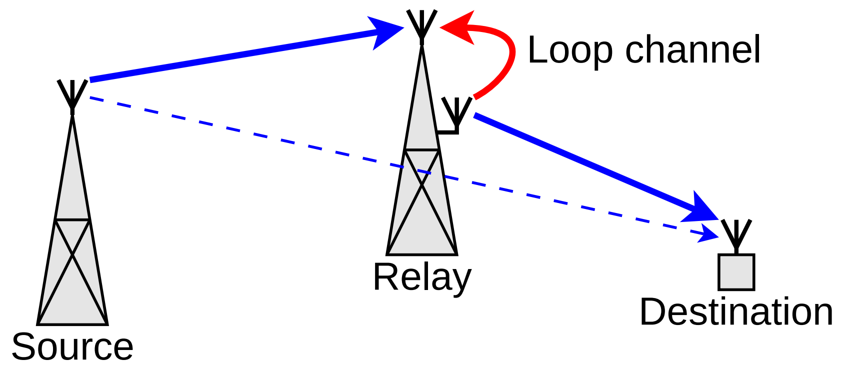
– Capacity with the full-duplex mode:

$$\mathcal{C}_{\mathrm{FD}} = \log_2 \left(1 + \min\left\{\frac{p_{\mathrm{S}}\gamma_{\mathrm{SR}}}{p_{\mathrm{R}}\gamma_{\mathrm{LI}}+1}, p_{\mathrm{R}}\gamma_{\mathrm{RD}}\right\}\right)$$

Novel aspect in our work: The tradeoff explicitly accounts for the residual loop interference remaining after practical cancellation

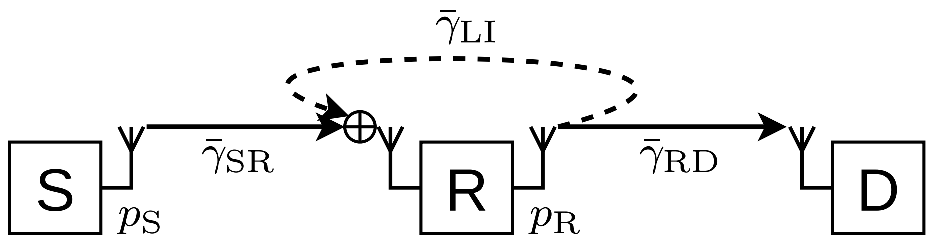
Average Capacity

Channel Models



- The source and the relay are fixed nodes
  - ▷ Static source–relay (SR) channel: $\gamma_{\mathrm{SR}} = \bar{\gamma}_{\mathrm{SR}}$
  - ▷ Static *residual* loop interference (LI) channel: $\gamma_{\mathrm{LI}} = \bar{\gamma}_{\mathrm{LI}}$
- The destination is a mobile terminal without line-of-sight
  - ▷ Rayleigh relay–destination (RD) channel: $\gamma_{\mathrm{RD}} \sim \mathrm{Exp}\left(1/\bar{\gamma}_{\mathrm{RD}}\right)$
- Coverage extension and gap-filling scenarios
  - ▷ Direct link only increases noise level at the destination

Full-Duplex Mode



- Average capacity with the full-duplex mode

$$\bar{C}_{\mathrm{FD}} = \int_0^\infty \log_2\left(1+\min\left\{\frac{p_{\mathrm{S}}\bar{\gamma}_{\mathrm{SR}}}{p_{\mathrm{R}}\bar{\gamma}_{\mathrm{LI}}+1}, p_{\mathrm{R}}s\right\}\right) f_{\gamma_{\mathrm{RD}}}(s)ds$$

$$= \frac{e^{\frac{1}{p_{\mathrm{R}}\bar{\gamma}_{\mathrm{RD}}}}\left[E_1\left(\frac{1}{p_{\mathrm{R}}\bar{\gamma}_{\mathrm{RD}}}\right) - E_1\left(\frac{p_{\mathrm{S}}\bar{\gamma}_{\mathrm{SR}}+p_{\mathrm{R}}\bar{\gamma}_{\mathrm{LI}}+1}{p_{\mathrm{R}}\bar{\gamma}_{\mathrm{RD}}(p_{\mathrm{R}}\bar{\gamma}_{\mathrm{LI}}+1)}\right)\right]}{\log_e(2)}$$

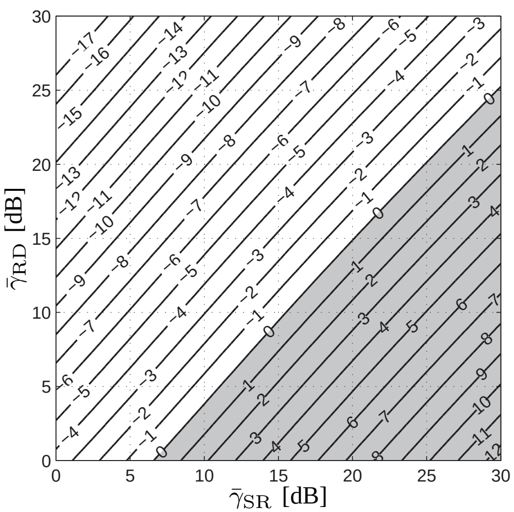
- The transmit powers can be optimized

Transmit Power Optimization for the FD Mode

- The maximum source transmit power is optimal: $p_{\mathrm{S}} = 1$
- Maximum relay transmit power: $p_{\mathrm{R}} = 1$
  - Average capacity denoted by $\bar{\mathcal{C}}_{\mathrm{FD1}}$
- Optimized relay transmit power:

$$p_{\mathrm{R}} = p_{\mathrm{R}}^{*} = \arg \max_{0 \leq p_{\mathrm{R}} \leq 1} \bar{\mathcal{C}}_{\mathrm{FD}}$$

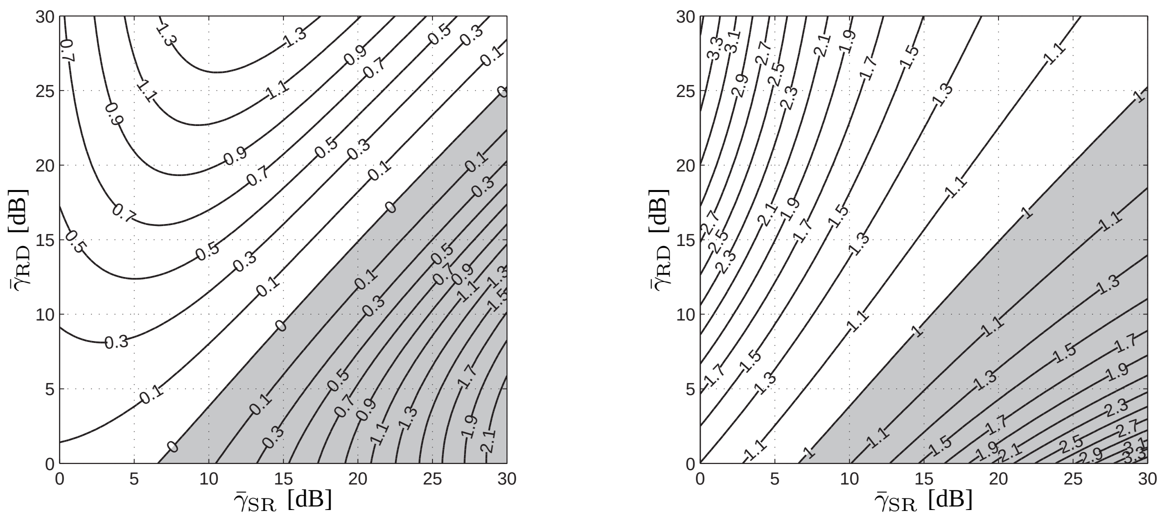
  - Average capacity denoted by $\bar{\mathcal{C}}_{\mathrm{FD2}}$
  - The figure plotted with $\bar{\gamma}_{\mathrm{LI}} = 6$dB



(a) p_{R}^{*} [dB]

The Benefit of Transmit Power Optimization

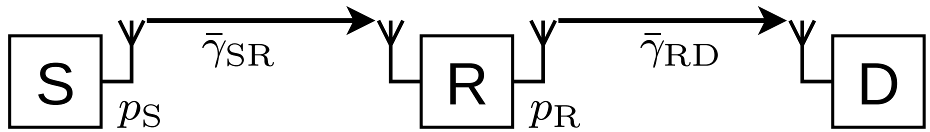
- For $\bar{\gamma}_{\mathrm{LI}} = 6$dB:



(a) $\bar{\mathcal{C}}_{\mathrm{FD2}} - \bar{\mathcal{C}}_{\mathrm{FD1}}$ [bit/s/Hz] (b) $\bar{\mathcal{C}}_{\mathrm{FD2}}/\bar{\mathcal{C}}_{\mathrm{FD1}}$

- Transmit power optimization can both save energy and significantly improve capacity (especially when $\bar{\gamma}_{\mathrm{SR}} \ll \bar{\gamma}_{\mathrm{RD}}$)
- When $\bar{\gamma}_{\mathrm{SR}} \gg \bar{\gamma}_{\mathrm{RD}}$, capacity would be improved by allowing larger maximum transmit power

Half-Duplex Mode



- Average capacity with the half-duplex mode ($\bar{\gamma}_{\mathrm{LI}} = 0$)

$$\begin{aligned}\bar{\mathcal{C}}_{\mathrm{HD}} &= \frac{1}{2}\int_0^{\infty} \log_2\left(1 + \min\left\{p_{\mathrm{S}}\bar{\gamma}_{\mathrm{SR}}, p_{\mathrm{R}}s\right\}\right) f_{\gamma_{\mathrm{RD}}}(s)ds \\ &= \frac{e^{\frac{1}{p_{\mathrm{R}}\bar{\gamma}_{\mathrm{RD}}}}\left[E_1\left(\frac{1}{p_{\mathrm{R}}\bar{\gamma}_{\mathrm{RD}}}\right) - E_1\left(\frac{p_{\mathrm{S}}\bar{\gamma}_{\mathrm{SR}}+1}{p_{\mathrm{R}}\bar{\gamma}_{\mathrm{RD}}}\right)\right]}{2\log_e(2)}\end{aligned}$$

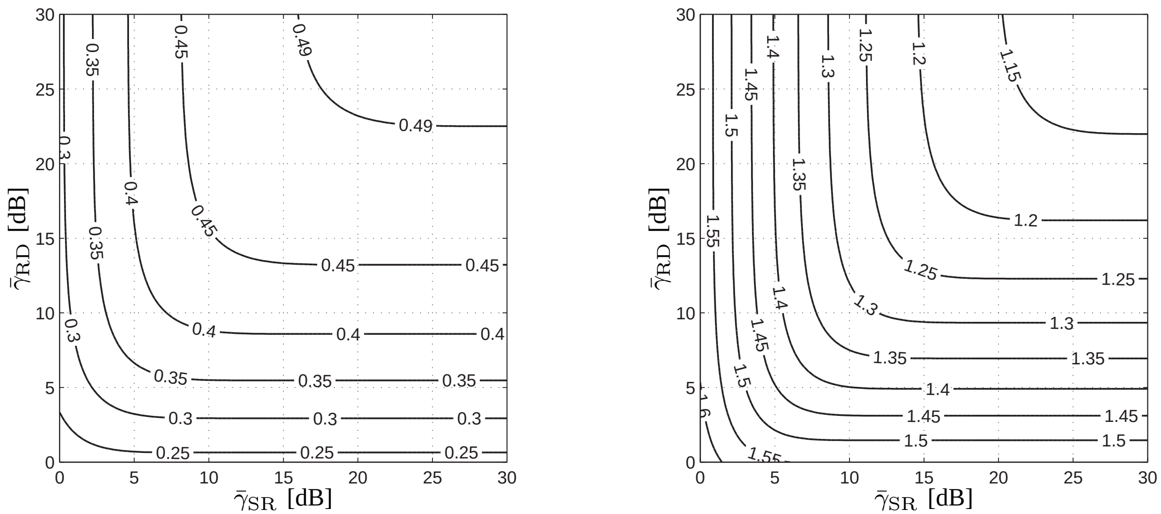
- Two schemes for normalizing transmit powers

Transmit Power Normalization for the HD Mode

- Normalization of the individual transmit powers: $p_{\mathrm{S}} = p_{\mathrm{R}} = 1$
  - Average capacity denoted by $\bar{\mathcal{C}}_{\mathrm{HD1}}$
  - Both modes set the same maximum transmit power during each channel use
  - Fair comparison in terms of the transmitter architecture

- Normalization of the total system transmit power: $p_{\mathrm{S}} = p_{\mathrm{R}} = 2$
  - Average capacity denoted by $\bar{\mathcal{C}}_{\mathrm{HD2}}$
  - The HD mode can use double power during each channel use if the total system transmit power is the same in both modes
  - Fair comparison in terms of the system power usage

Comparison of the Normalization Schemes



(a) $\bar{\mathcal{C}}_{\mathrm{HD2}} - \bar{\mathcal{C}}_{\mathrm{HD1}}$ [bit/s/Hz]

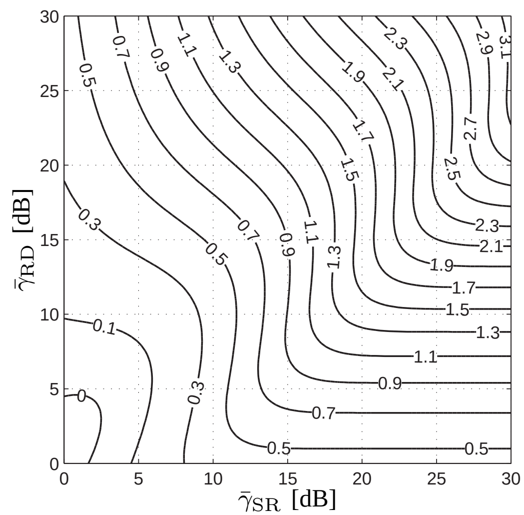
(b) $\bar{\mathcal{C}}_{\mathrm{HD2}} / \bar{\mathcal{C}}_{\mathrm{HD1}}$

- The 2nd normalization scheme results in 0.3–0.45bit/s/Hz higher capacity in the practical SNR range due to 3dB higher transmit powers
  - Small compared to the 50% loss due to the pre-log factor
- $\bar{\mathcal{C}}_{\mathrm{HD2}} - \bar{\mathcal{C}}_{\mathrm{HD1}} < 0.5$bit/s/Hz

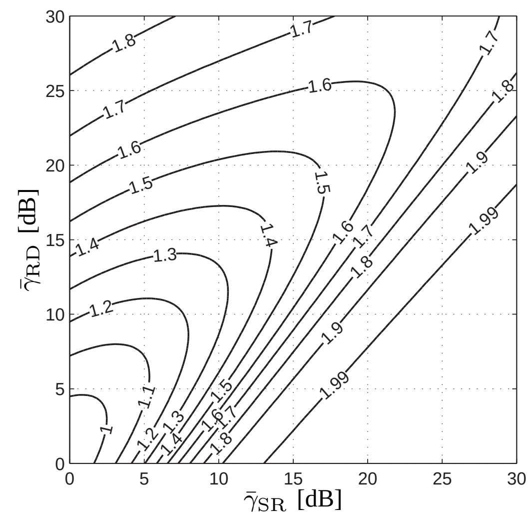
Capacity Comparisons

Full-Duplex vs. Half-Duplex

- For $\bar{\gamma}_{\mathrm{LI}} = 6$dB:



(a) $\bar{C}_{\mathrm{FD2}} - \bar{C}_{\mathrm{HD1}}$ [bit/s/Hz]

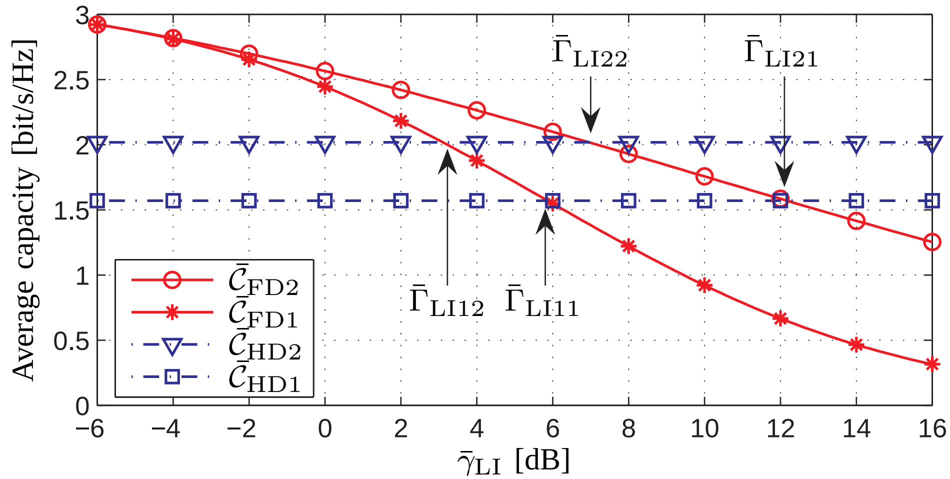


(b) $\bar{C}_{\mathrm{FD2}} / \bar{C}_{\mathrm{HD1}}$

- The full-duplex mode offers *some* capacity improvement over the half-duplex mode with all practical SNR values
- In the mid-SNR range, the full-duplex mode results in *significant* gain
- The half-duplex mode is better only when the channel SNRs are low

Break-Even Loop Interference Levels

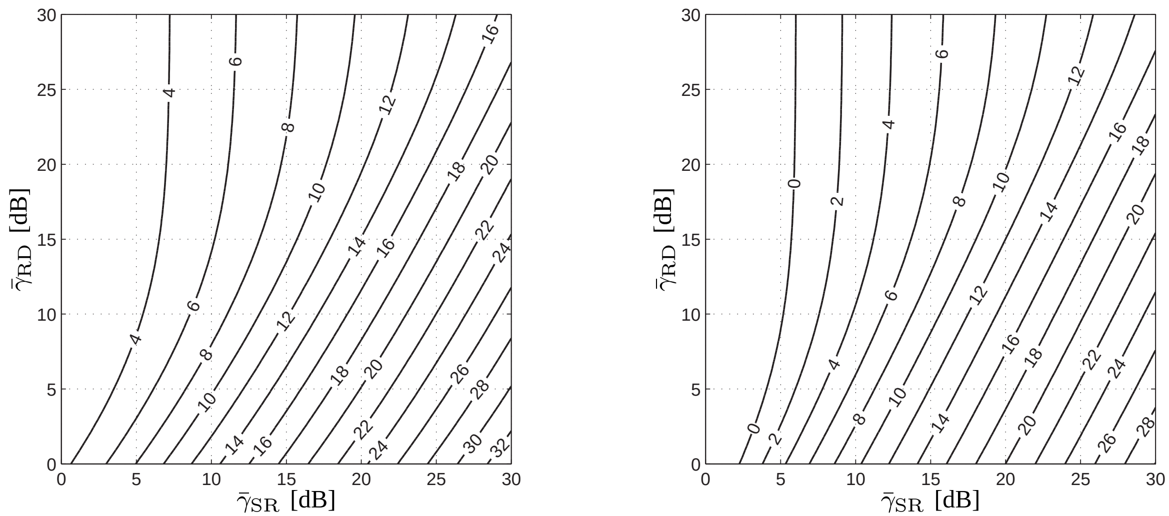
- For $\bar{\gamma}_{\mathrm{SR}} = 10$dB, $\bar{\gamma}_{\mathrm{RD}} = 15$dB:



- The full-duplex mode achieves better capacity than the half-duplex mode when the loop interference level is low
- . . . and vice versa when the loop interference level is high
- Break-even loop interference: $\bar{\mathcal{C}}_{\mathrm{FD}i} \geq \bar{\mathcal{C}}_{\mathrm{HD}j}$ if and only if $\bar{\gamma}_{\mathrm{LI}} \leq \bar{\Gamma}_{\mathrm{LI}ij}$

Using Maximum Transmit Power in the FD mode

- $\bar{\mathcal{C}}_{\mathrm{FD1}} \geq \bar{\mathcal{C}}_{\mathrm{HD}j}$ if and only if $\bar{\gamma}_{\mathrm{LI}} \leq \bar{\Gamma}_{\mathrm{LI1}j}$

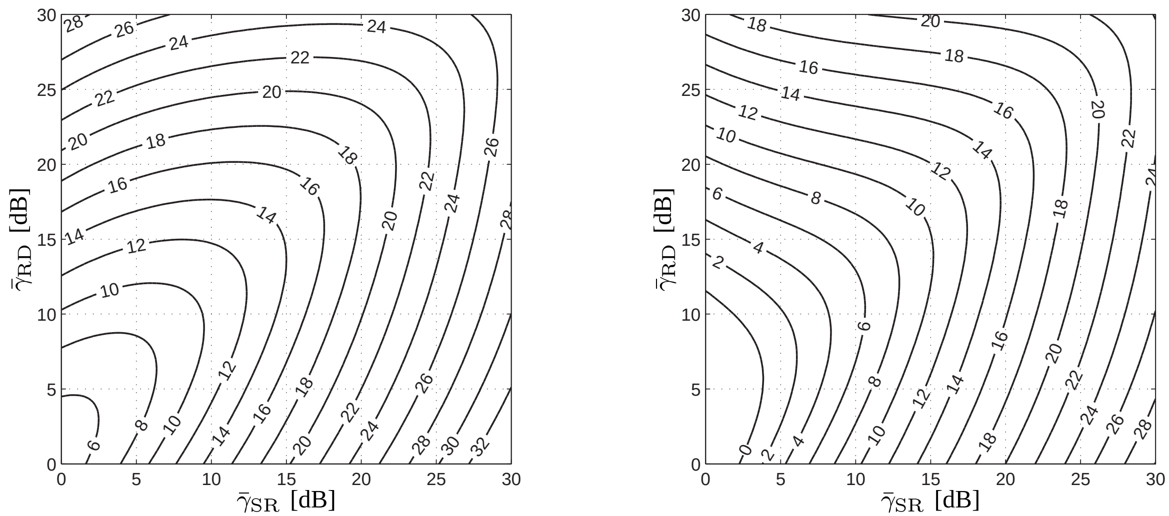


(a) $\bar{\Gamma}_{\mathrm{LI11}}$ [dB] (b) $\bar{\Gamma}_{\mathrm{LI12}}$ [dB]

- The power of the residual loop interference can generally be reasonably high, and still the FD mode achieves better capacity than the HD mode
- 2–4dB lower break-even levels with the 2nd normalization

Using Optimized Transmit Power in the FD mode

- $\bar{\mathcal{C}}_{\mathrm{FD2}} \geq \bar{\mathcal{C}}_{\mathrm{HD}j}$ if and only if $\bar{\gamma}_{\mathrm{LI}} \leq \bar{\Gamma}_{\mathrm{LI2}j}$



(a) $\bar{\Gamma}_{\mathrm{LI21}}$ [dB] (b) $\bar{\Gamma}_{\mathrm{LI22}}$ [dB]

- Transmit power optimization affects significantly the tradeoff to the advantage of the full-duplex mode
- These levels seem to be attainable for infrastructure-based relays

Conclusion

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- The choice between full-duplex and half-duplex operation modes presents a fundamental rate–interference trade-off
  - The choice can be rationalized in terms of residual self-interference remaining after imperfect cancellation
  - Capacity analysis
    - Capacity improvement due to the full-duplex mode
    - Break-even loop interference levels
    - The effect of loop interference in the full-duplex mode can be minimized by optimizing the relay transmit power
  - It may be better to allow some interference with the full-duplex mode than to reduce the symbol rate by using two time slots for eliminating the loop interference with the half-duplex mode

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