Aalto University
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Analog and Digital Self-interference Cancellation in Full-Duplex MIMO-OFDM Transceivers with Limited Resolution in A/D Conversion

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Introduction

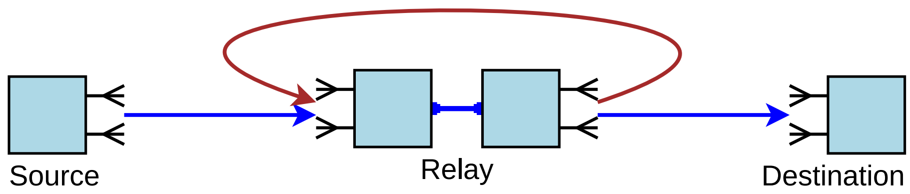
Asilomar — The Cradle of Full-Duplex Wireless

2007	T. Riihonen, R. Wichman, and J. Hämäläinen: "Co-phasing full-duplex relay link with non-ideal feedback information" was unsuccessful, presented later at IEEE ISWCS 2008
2008	T. Riihonen, S. Werner, J. Cousseau, and R. Wichman: "Design of co-phasing allpass filters for full-duplex OFDM relays"
2009	T. Riihonen, S. Werner, and R. Wichman: "Spatial loop interference suppression in full-duplex MIMO relays"
2010	M. Duarte and A. Sabharwal: "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results"
++++	P. Lioliou, M. Viberg, M. Coldrey, and F. Athley: "Self-interference suppression in full-duplex MIMO relays"
++++	T. Riihonen, S. Werner, and R. Wichman: "Residual self-interference in full-duplex MIMO relays after null-space projection and cancellation"
2011	B. P. Day, D. W. Bliss, A. R. Margetts, and P. Schniter: "Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range"
++++	E. Everett, M. Duarte, C. Dick, and A. Sabharwal: "Empowering full-duplex wireless communication by exploiting directional diversity"
++++	T. Riihonen, S. Werner, and R. Wichman: "Transmit power optimization for multiantenna decode-and-forward relays with loopback self-interference from full-duplex operation"
2012	Two special sessions and ten papers! The ultimate breakthrough for this research topic?

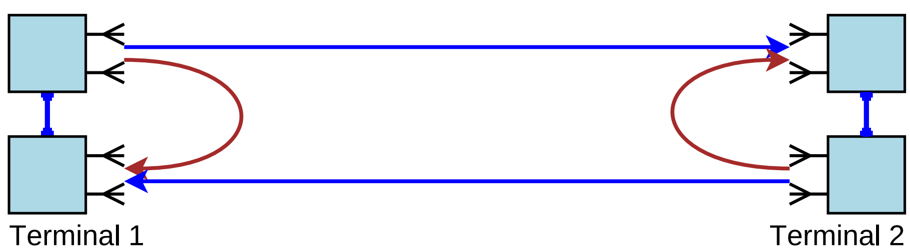
Full-Duplex Wireless: What? Why? When?

- *"Full-duplex"* wireless communication
  = systems where some node(s) may transmit (Tx) and receive (Rx) simultaneously on a *single* frequency band
- Progressive physical/link-layer *frequency-reuse* concept
  = up to double spectral efficiency at system level, if the significant technical problem of *self-interference* is tackled
- *Temporal symmetry* is needed to make the most of full duplex
  = Tx and Rx should use the band for the same amount of time
  - (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

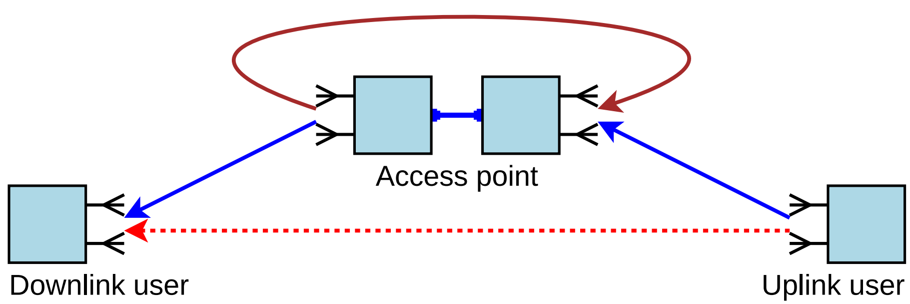
Full-Duplex Communication Scenarios



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

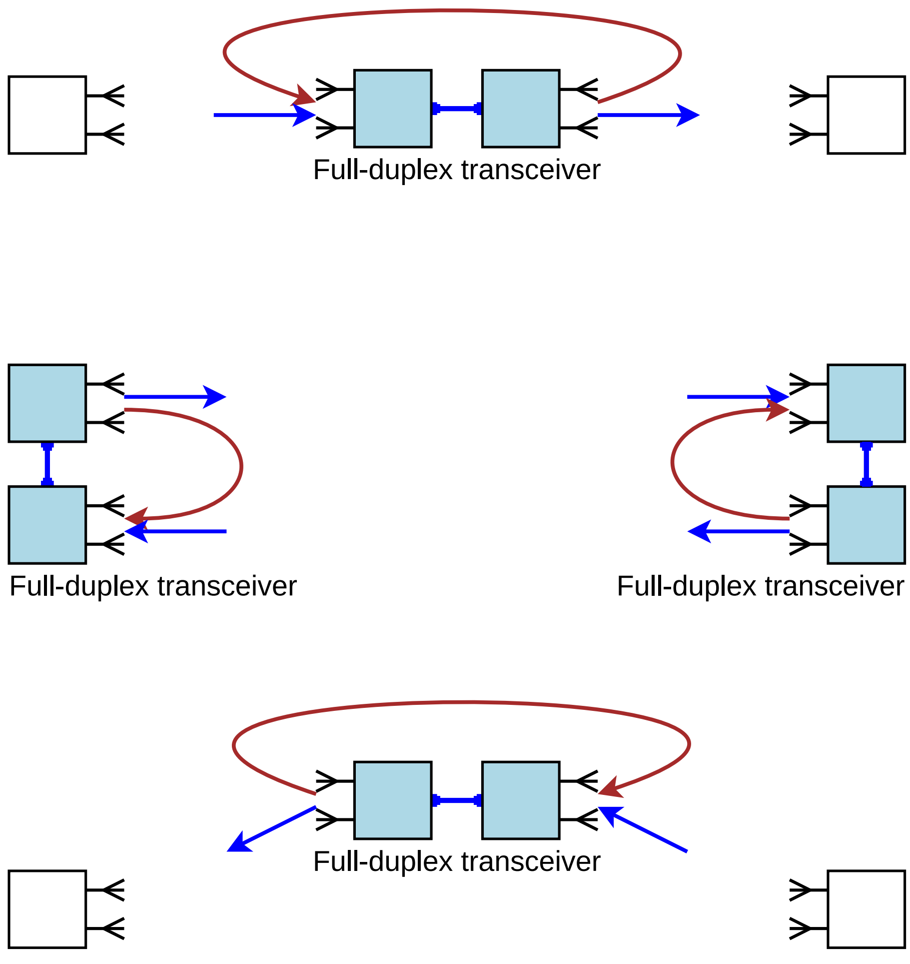


2) Bidirectional communication link between two terminals
   - Asymmetric traffic (maybe)
   - Symmetric channels (roughly)



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

Generic Full-Duplex MIMO Transceivers



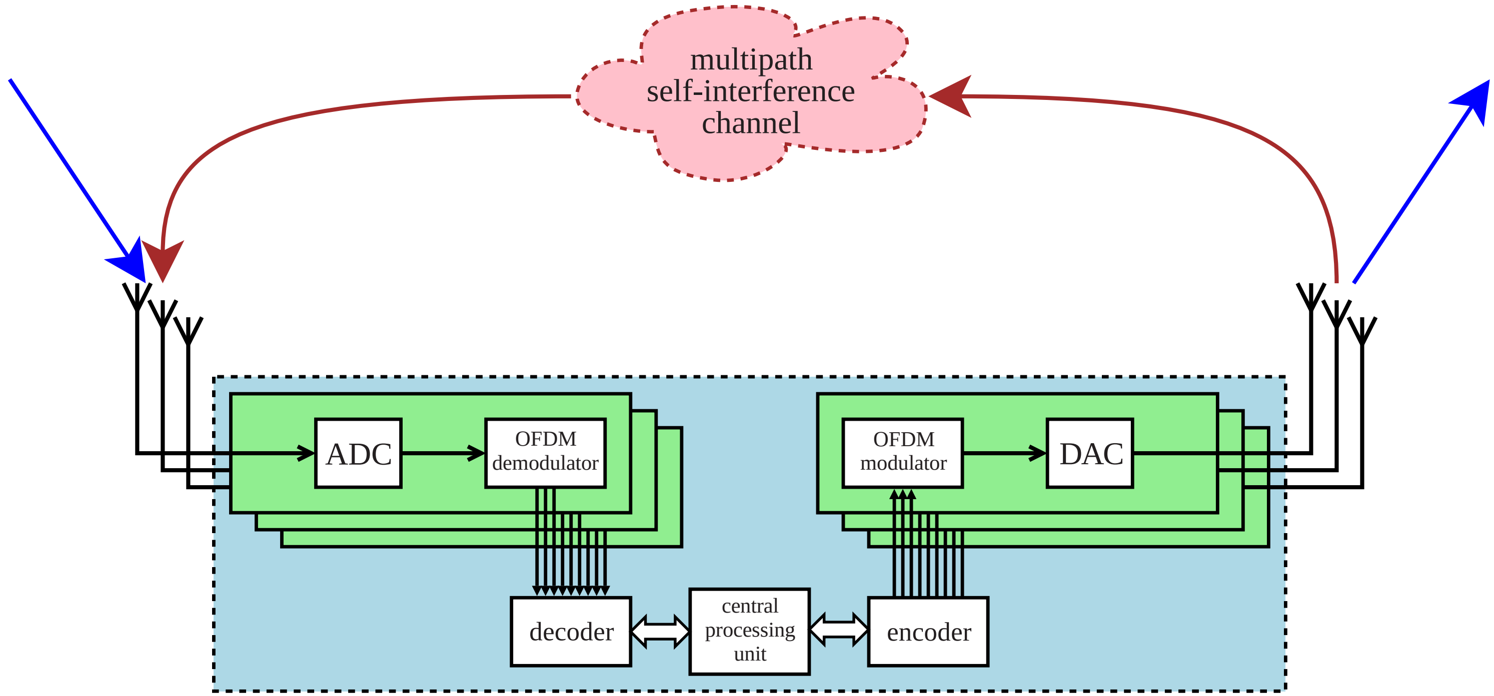
The basic building block
for more complex networks

- The benefits go beyond the physical layer!
- Will single-array full-duplex transceivers be viable some day?

In this work: OFDM signal

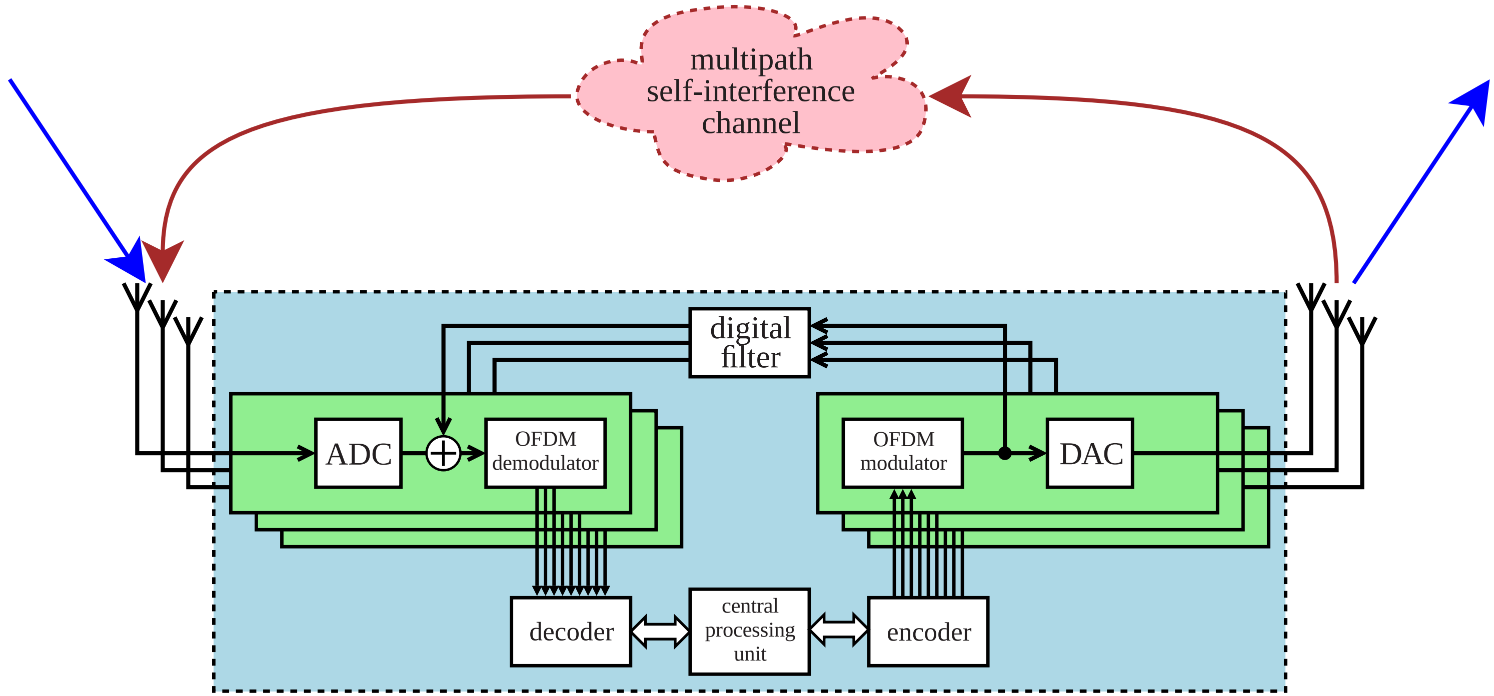
+ limited Rx dynamic range (= realistic A/D conversion)
  - ▷ b-bit quantization
  - ▷ adaptive gain control
+ analog- vs. digital-domain self-interference cancellation

Main Practical Problem: Limited Dynamic Range



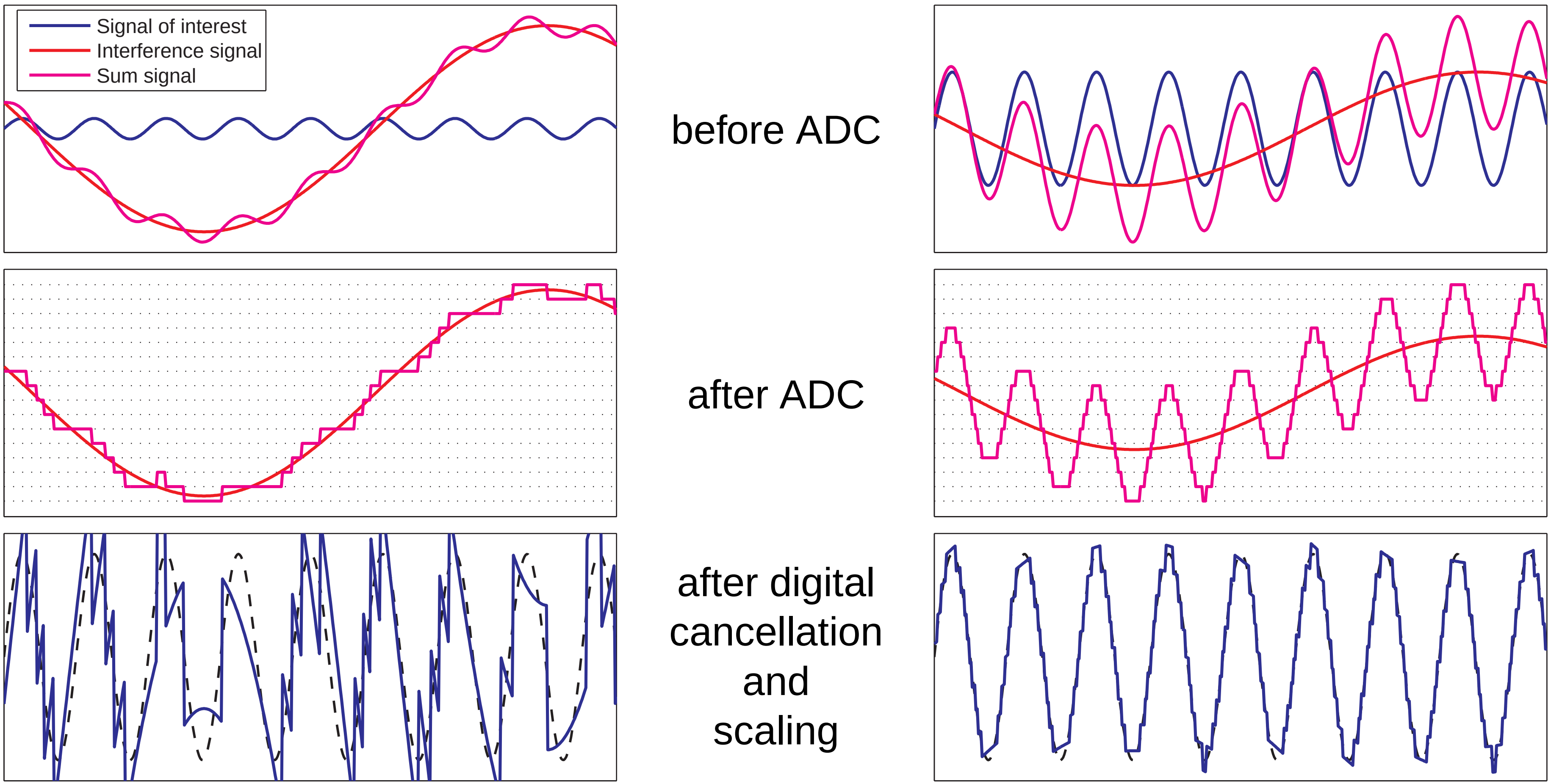
- Self-interference may be much stronger than the signal of interest
- Severe risk of saturating analog-to-digital converters (ADCs)
  - Quantization noise due to limited resolution
  - Clipping noise which is pronounced with OFDM
  - Bias in adaptive gain control (AGC) balancing above effects

Digital Cancellation (DC)



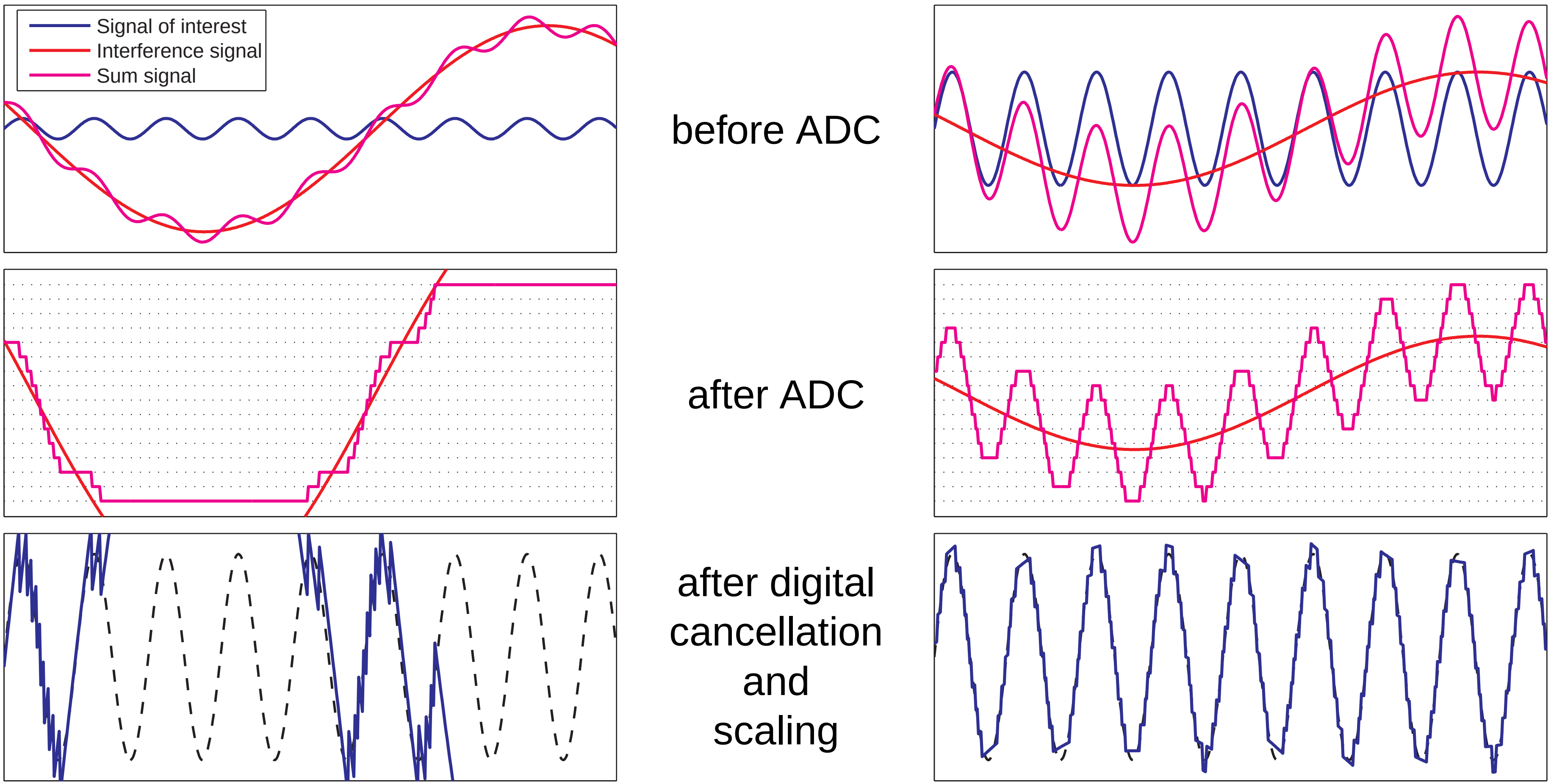
- Interference cancellation is a straightforward task in digital domain
  - ▷ The response of a digital cancellation filter can be adapted to match the frequency-selective self-interference channel
- But nothing can be done at this stage anymore if the signal of interest is already drowned in clipping-plus-quantization noise

Example on Quantization Noise $(b = 4)$



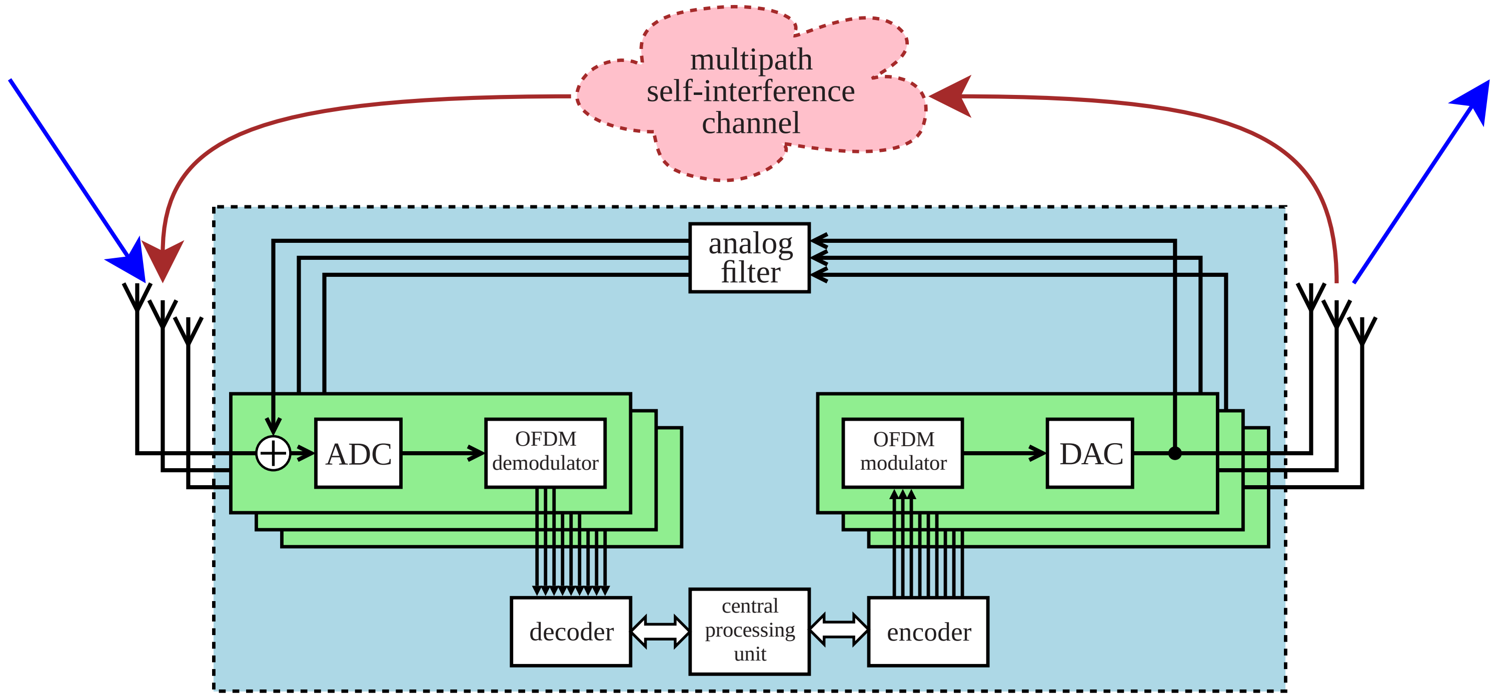
- ~ 1-bit resolution
  for the signal of interest
- ~ 3-bit resolution
  for the signal of interest

Example on Clipping Noise $(b = 4)$



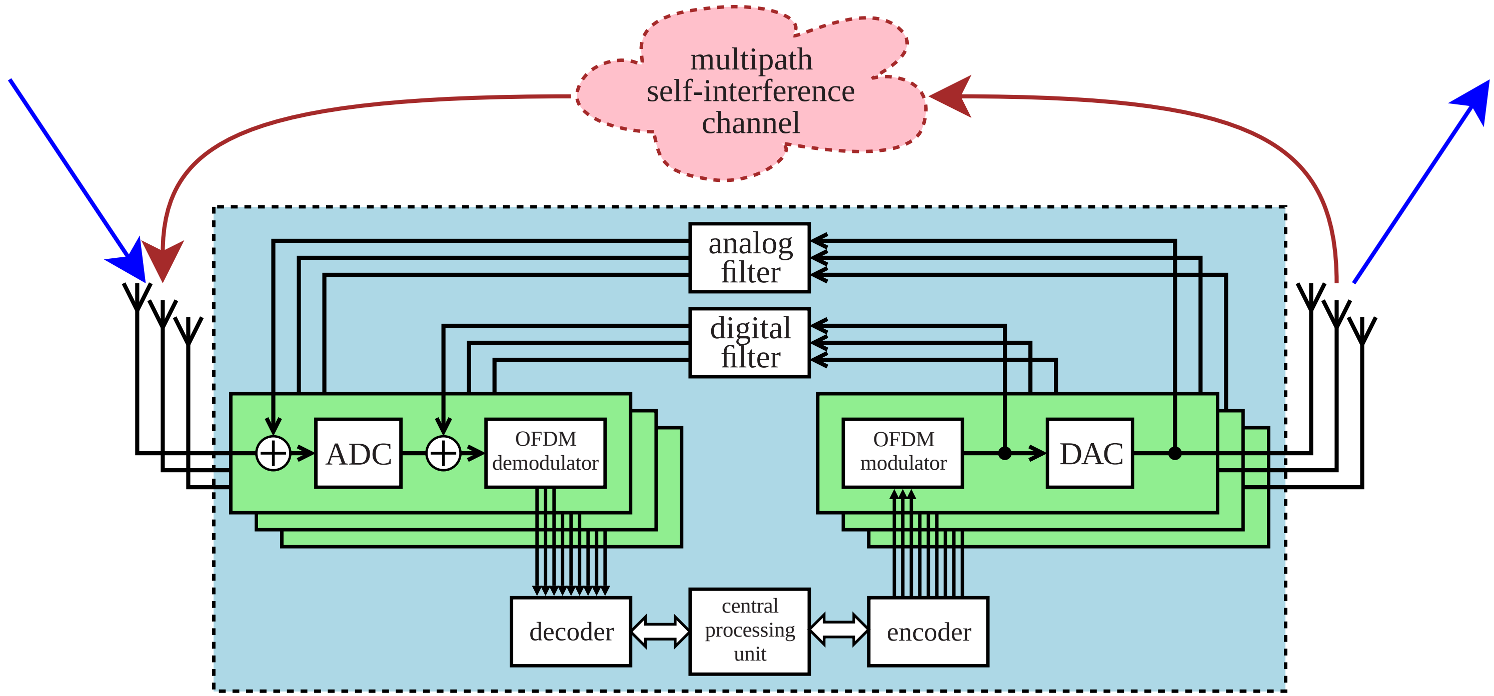
- ~ 2-bit *clipped* resolution for the signal of interest
- ~ 3-bit resolution for the signal of interest

Analog Cancellation (AC)



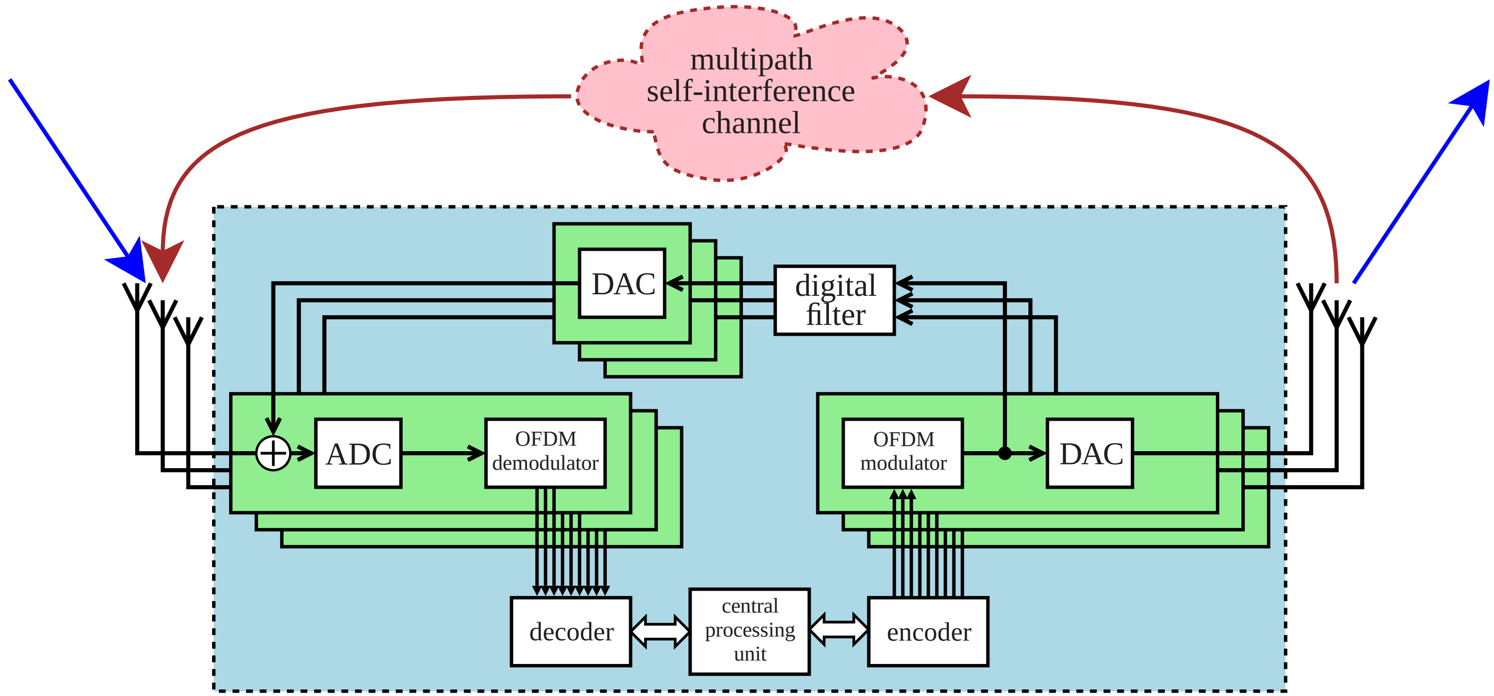
- It would be desirable to eliminate interference before ADCs
- But it is difficult and expensive to adapt the response of an analog filter to match the time- and frequency-selective MIMO channel
  - ▷ Typical implementation, simple phase shift and amplification in each branch, leaves significant residual interference

Combined Analog+Digital Cancellation (AC+DC)



- The obvious combination of analog- and digital-domain processing
  - ▷ If analog cancellation could sufficiently suppress the self-interference such that ADC saturation is avoided,
  - ▷ then digital cancellation would be able to efficiently eliminate the remaining self-interference

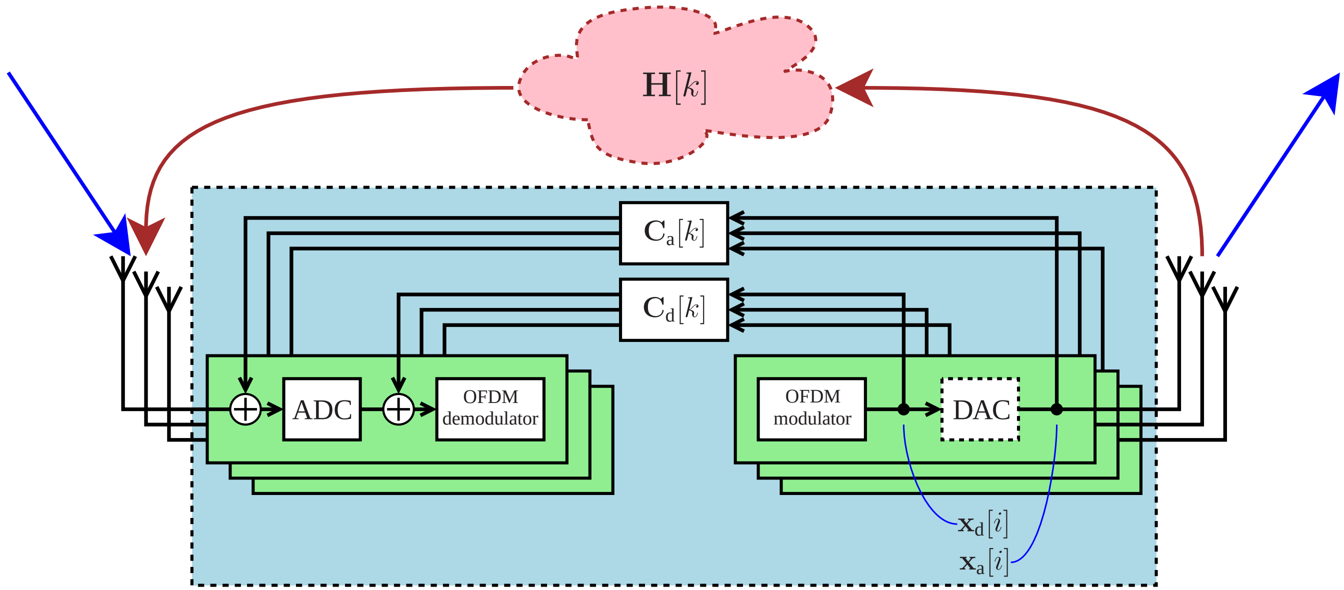
Hybrid Analog/Digital Cancellation (AC/DC)



- Smart design à la Duarte and Sabharwal (Asilomar 2010)
  - Pros: Circumvents the drawbacks of both AC and DC
  - Cons: Extra transmitter chain per each receive antenna
- Channel estimation errors and Tx nonlinearities limit performance

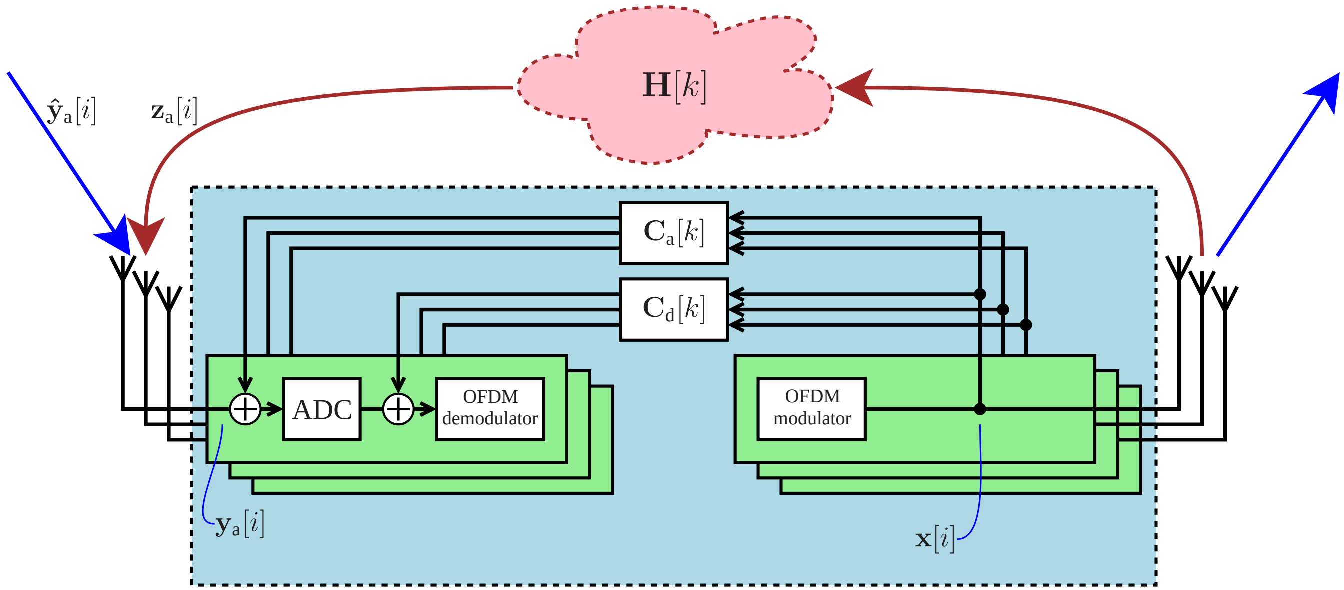
System Model

Transmitted Signals



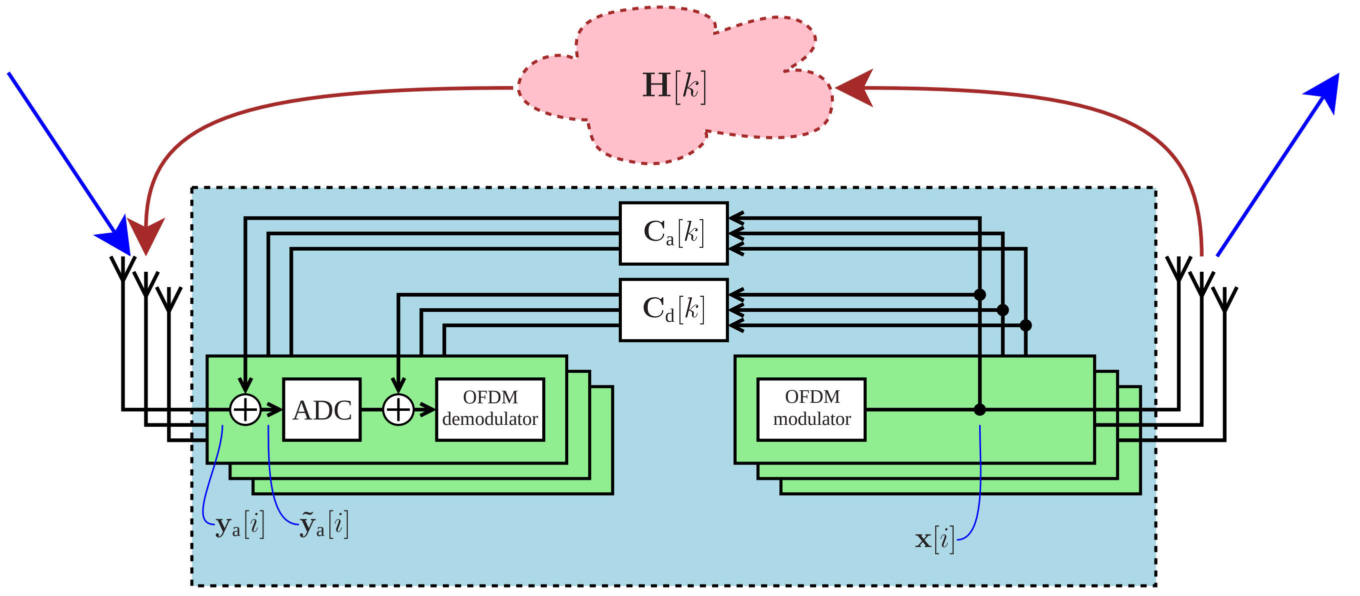
- The full-duplex transceiver tries to receive the signal of interest from a distant transmitter
- while simultaneously transmitting signal $\mathbf{x}[i] \in \mathbb{C}^{N_\mathrm{t} \times 1}$ to its own designated destination
  - Digital-to-analog converters (DACs) are now ideal: $\mathbf{x}_\mathrm{a}[i] \simeq \mathbf{x}_\mathrm{d}[i]$
- Gaussian-like OFDM signals are assumed throughout this study

Received Signals



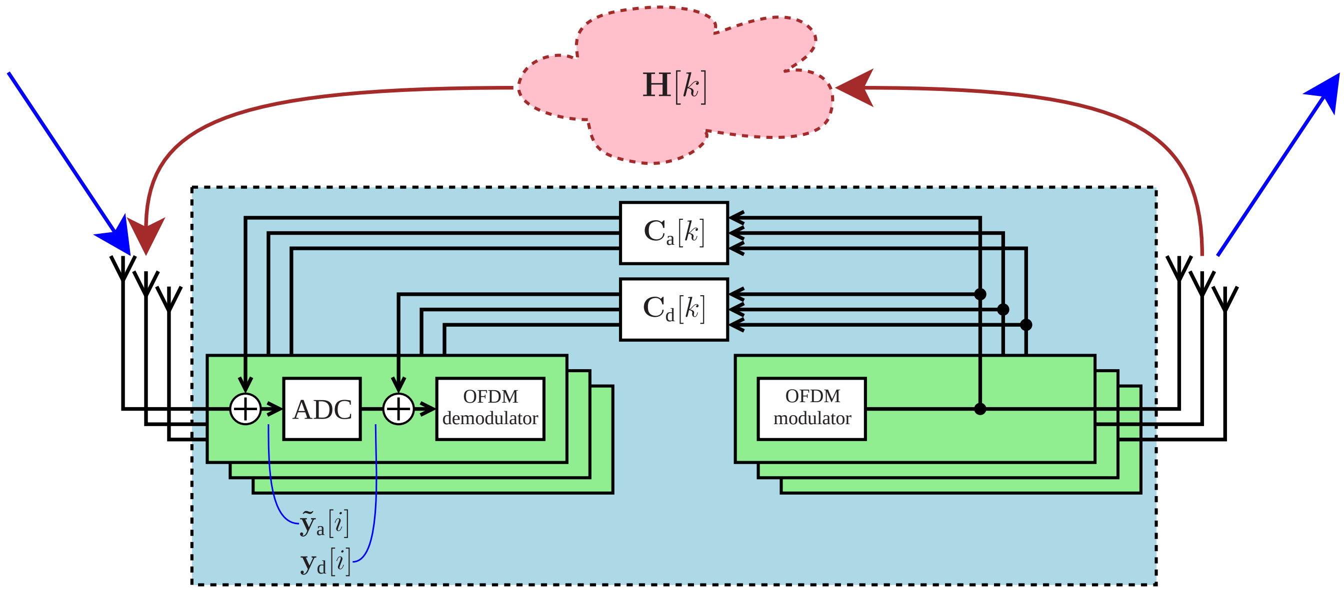
- Received analog composite signal: $\mathbf{y}_\mathrm{a}[i] = \hat{\mathbf{y}}_\mathrm{a}[i] + \mathbf{z}_\mathrm{a}[i] \in \mathbb{C}^{N_\mathrm{r} \times 1}$
  - the signal of interest is given by $\hat{\mathbf{y}}_\mathrm{a}[i] \in \mathbb{C}^{N_\mathrm{r} \times 1}$ and $P_\mathrm{S} = \mathcal{E}\{|\{\hat{\mathbf{y}}_\mathrm{a}[i]\}_m|^2\}$ denotes its power at the mth antenna
  - interference signal is given by $\mathbf{z}_\mathrm{a}[i] = \sum_{k=0}^{\infty} \mathbf{H}[k]\,\mathbf{x}[i-k] \in \mathbb{C}^{N_\mathrm{r} \times 1}$ and $P_\mathrm{I} = \mathcal{E}\{|\{\mathbf{z}_\mathrm{a}[i]\}_m|^2\}$ denotes its power at the mth antenna
- Multipath self-interference channel: $\mathbf{H}[k] \in \mathbb{C}^{N_\mathrm{r} \times N_\mathrm{t}},\ k = 0, 1, \ldots$

Analog Cancellation (AC)



- After analog cancellation: $\tilde{\mathbf{y}}_{\mathrm{a}}[i] = \hat{\mathbf{y}}_{\mathrm{a}}[i] + \tilde{\mathbf{z}}_{\mathrm{a}}[i]$
  - ▷ the signal of interest $\hat{\mathbf{y}}_{\mathrm{a}}[i]$ is not affected
  - ▷ residual interference signal becomes
    $\tilde{\mathbf{z}}_{\mathrm{a}}[i] = \sum_{k=0}^{\infty} (\mathbf{H}[k] + \mathbf{C}_{\mathrm{a}}[k])\, \mathbf{x}[i-k]$
- Analog cancellation filter: $\mathbf{C}_{\mathrm{a}}[k] \in \mathbb{C}^{N_{\mathrm{r}} \times N_{\mathrm{t}}}$, $k = 0, 1, \ldots$
  - ▷ for example $\{\mathbf{C}_{\mathrm{a}}[k]\}_{m,n} = \begin{cases} -\{\mathbf{H}[k]\}_{m,n}, & \text{if } k = \arg\max_{k'} |\{\mathbf{H}[k']\}_{m,n}|^2 \\ 0, & \text{otherwise} \end{cases}$

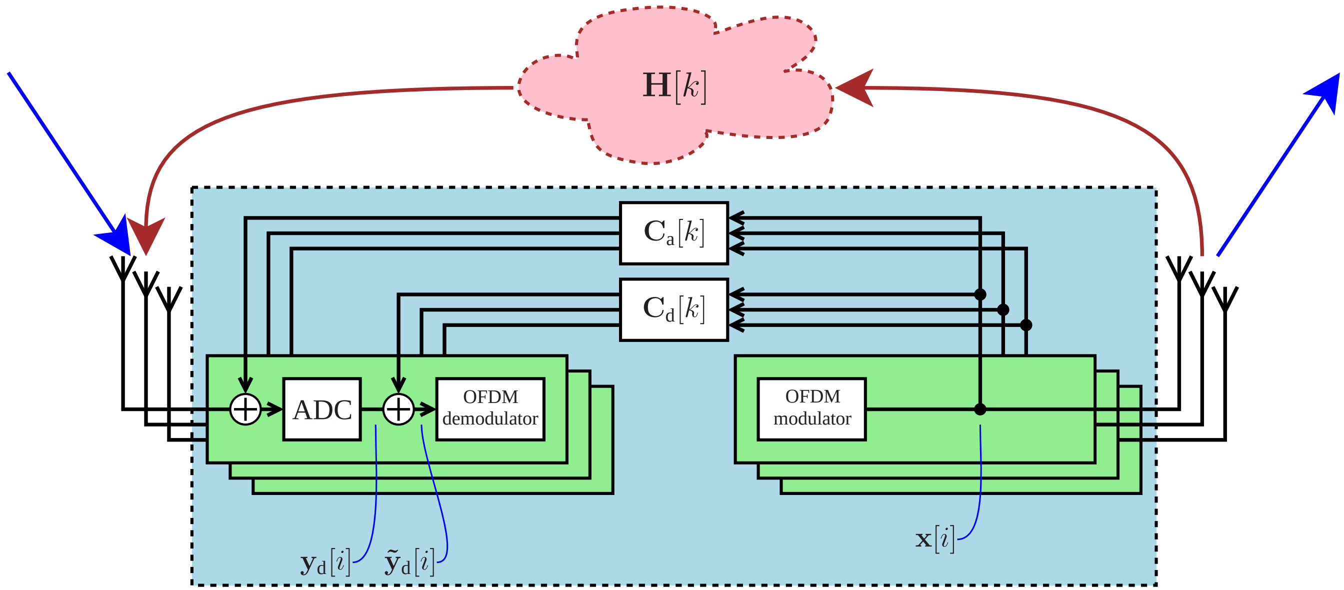
Analog-to-Digital Conversion (ADC)



- $2 \times N_{\rm r}$ ADCs: $\mathrm{Re}(\{\mathbf{y}_{\rm d}[i]\}_m) = \mathcal{Q}(\sqrt{g_m}\,\mathrm{Re}(\{\tilde{\mathbf{y}}_{\rm a}[i]\}_m))$

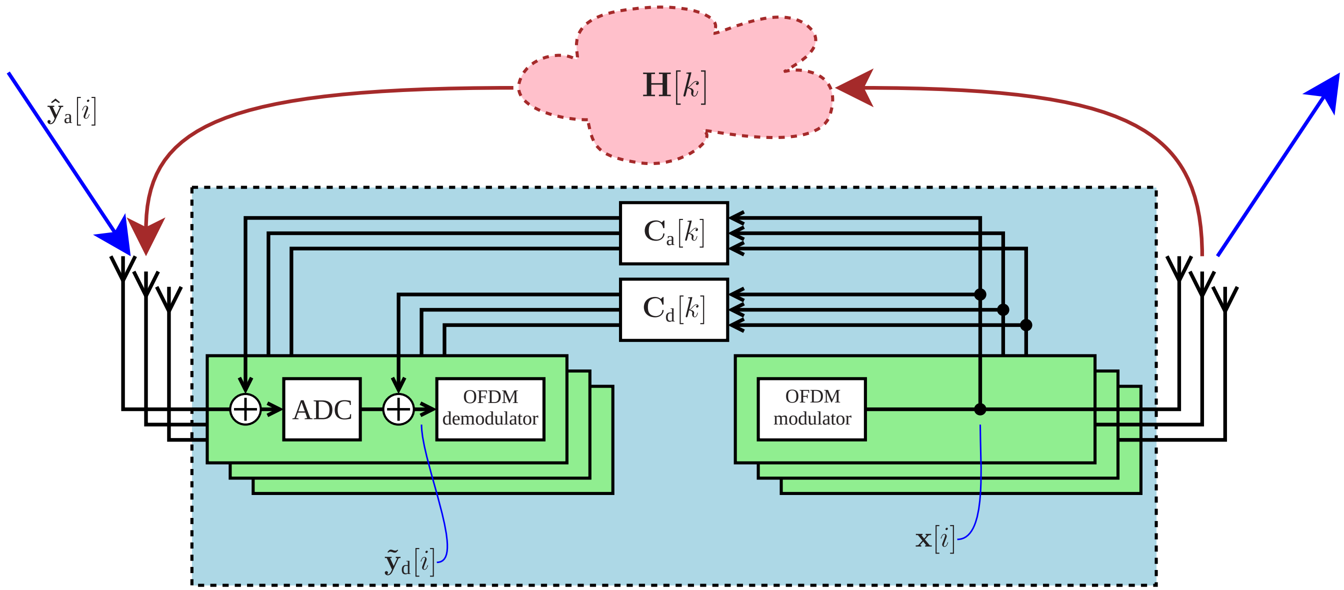
  $\mathrm{Im}(\{\mathbf{y}_{\rm d}[i]\}_m) = \mathcal{Q}(\sqrt{g_m}\,\mathrm{Im}(\{\tilde{\mathbf{y}}_{\rm a}[i]\}_m))$
  - ▷ AGC tunes variable gain amplifier (VGA) setting g_m to keep signal level within the fixed range of quantization block $\mathcal{Q}(\cdot)$
- The theory of non-linear memoryless devices: $\mathbf{y}_{\rm d}[i] = \mathbf{A}\tilde{\mathbf{y}}_{\rm a}[i] + \mathbf{n}[i]$
  - ▷ clipping-plus-quantization noise power is $P_{\rm N} = \mathcal{E}\{|\{\mathbf{n}[i]\}_m|^2\}$

Digital Cancellation (DC)



- After digital cancellation: $\tilde{\mathbf{y}}_{\mathrm{d}}[i] = \mathbf{A}\hat{\mathbf{y}}_{\mathrm{a}}[i] + \tilde{\mathbf{z}}_{\mathrm{d}}[i] + \mathbf{n}[i]$
  - ▷ interference signal is transformed from $\mathbf{z}_{\mathrm{d}}[i] = \mathbf{A}\tilde{\mathbf{z}}_{\mathrm{a}}[i]$ to $\tilde{\mathbf{z}}_{\mathrm{d}}[i] = \sum_{k=0}^{\infty}(\mathbf{A}(\mathbf{H}[k] + \mathbf{C}_{\mathrm{a}}[k]) + \mathbf{C}_{\mathrm{d}}[k])\,\mathbf{x}[i-k]$
  - ▷ clipping-plus-quantization noise term $\mathbf{n}[i]$ is not suppressed!
- Digital cancellation filter: $\mathbf{C}_{\mathrm{d}}[k] \in \mathbb{C}^{N_{\mathrm{r}} \times N_{\mathrm{t}}}$, $k = 0, 1, \ldots$
  - ▷ ideally $\mathbf{C}_{\mathrm{d}}[k] = -\mathbf{A}(\mathbf{H}[k] + \mathbf{C}_{\mathrm{a}}[k])$ if there is no estimation error

Complete Signal Model



- After putting everything together:

$$\tilde{\mathbf{y}}_{\mathrm{d}}[i] = \mathbf{A}\hat{\mathbf{y}}_{\mathrm{a}}[i] + \sum_{k=0}^{\infty}(\mathbf{A}(\mathbf{H}[k] + \mathbf{C}_{\mathrm{a}}[k]) + \mathbf{C}_{\mathrm{d}}[k])\,\mathbf{x}[i-k] + \mathbf{n}[i]$$

- Powers of signal components at the mth antenna:

$$\mathcal{E}\{|\{\tilde{\mathbf{y}}_{\mathrm{d}}[i]\}_m|^2\} = \alpha^2 P_{\mathrm{S}} + \mathcal{E}\{|\{\tilde{\mathbf{z}}_{\mathrm{d}}[i]\}_m|^2\} + P_{\mathrm{N}}$$

  where $\alpha = \{\mathbf{A}\}_{m,m}$

- SINR can be formulated after calculating $\mathcal{E}\{|\{\tilde{\mathbf{z}}_{\mathrm{d}}[i]\}_m|^2\}$

Analytical Results

Signal to Interference and Noise Ratio (SINR)

- The ratio of *desired* signal power to *residual* interference and *clipping-plus-quantization* noise power becomes

$$\gamma = \frac{\rho}{\frac{P_{\mathrm{S}}}{P_{\mathrm{I}}/\Delta_{\mathrm{a}}} + \rho/\Delta_{\mathrm{d}} + 1} \cdot \frac{P_{\mathrm{S}}}{P_{\mathrm{I}}/\Delta_{\mathrm{a}}} \quad \text{where} \quad \rho = \frac{\alpha^2 (P_{\mathrm{S}} + P_{\mathrm{I}}/\Delta_{\mathrm{a}})}{P_{\mathrm{N}}}$$

  - ▷ interference suppression due to cancellation:

$$\Delta_{\mathrm{a}} = \frac{\mathcal{E}\{|\{\mathbf{z}_{\mathrm{a}}[i]\}_m|^2\}}{\mathcal{E}\{|\{\tilde{\mathbf{z}}_{\mathrm{a}}[i]\}_m|^2\}} \quad \text{from AC}$$

$$\Delta_{\mathrm{d}} = \frac{\mathcal{E}\{|\{\mathbf{z}_{\mathrm{d}}[i]\}_m|^2\}}{\mathcal{E}\{|\{\tilde{\mathbf{z}}_{\mathrm{d}}[i]\}_m|^2\}} \quad \text{from DC}$$

  - ▷ signal-to-interference ratio (SIR):

$$\frac{P_{\mathrm{S}}}{P_{\mathrm{I}}} \quad \text{without cancellation}$$

$$\Delta_{\mathrm{a}} \frac{P_{\mathrm{S}}}{P_{\mathrm{I}}} \quad \text{after AC}$$

$$\Delta_{\mathrm{a}} \Delta_{\mathrm{d}} \frac{P_{\mathrm{S}}}{P_{\mathrm{I}}} \quad \text{after DC}$$

- A/D conversion affects SINR only through $\rho = \rho(\alpha, P_{\mathrm{N}}, P_{\mathrm{S}} + P_{\mathrm{I}}/\Delta_{\mathrm{a}})$
  - ▷ $\gamma \rightarrow \Delta_{\mathrm{a}} \Delta_{\mathrm{d}} \frac{P_{\mathrm{S}}}{P_{\mathrm{I}}}$ if dynamic range is *not* the limiting factor ($\rho \rightarrow \infty$)

SNR with Limited ADC Resolution

- The ratio of signal power to clipping-plus-quantization noise power after ADC, i.e., *dynamic range*: $\rho = \frac{\alpha^2(P_\mathrm{S}+P_\mathrm{I}/\Delta_\mathrm{a})}{P_\mathrm{N}} = \frac{\alpha^2 p}{g P_\mathrm{N}}$
  - ▷ AGC tunes VGA setting g such that normalized input power to the quantization block is constantly $p = g\left(P_\mathrm{S} + P_\mathrm{I}/\Delta_\mathrm{a}\right)$
- SINR is monotonically increasing in terms of dynamic range ρ:

$$\gamma = \frac{\rho}{\frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}}+\rho/\Delta_\mathrm{d}+1} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} \leq \Delta_\mathrm{a}\Delta_\mathrm{d}\frac{P_\mathrm{S}}{P_\mathrm{I}}$$

  - ▷ Thus, system design should always aim at maximizing ρ irrespective of P_S, P_I, Δ_a and Δ_d (as they do not affect ρ)
  - ▷ Signal type, ADC properties and p define ρ via α^2/g and P_N
    - OFDM transmission
    - Uniform quantization
    - ADC resolution
    - AGC bias

Dynamic Range for Uniform Quantization

- Input–output relation for uniform b-bit quantization ($Q = 2^b$):

$$\mathcal{Q}(y) = \begin{cases} 1, & \text{if } \frac{Q-2}{Q-1} < y \\ \frac{2q-2}{Q-1} - 1, & \text{if } \frac{2q-3}{Q-1} - 1 < y \leq \frac{2q-1}{Q-1} - 1 \\ -1, & \text{if } y \leq \frac{2-Q}{Q-1} \end{cases}$$

- After calculating α^2/g and P_{N} for OFDM signal:

$$\rho = \left[2\pi \frac{2\,\Phi\left(\frac{1}{\sqrt{p}}\frac{2-Q}{Q-1}\right) + \sum_{q=2}^{Q-1}\left(\frac{2q-2}{Q-1} - 1\right)^2 \left[\Phi\left(\frac{1}{\sqrt{p}}\left(\frac{2q-1}{Q-1} - 1\right)\right) - \Phi\left(\frac{1}{\sqrt{p}}\left(\frac{2q-3}{Q-1} - 1\right)\right)\right]}{\left(2\,e^{-\frac{1}{2p}\left(\frac{2-Q}{Q-1}\right)^2} + \sum_{q=2}^{Q-1}\left(\frac{2q-2}{Q-1} - 1\right)\left[e^{-\frac{1}{2p}\left(\frac{2q-3}{Q-1}-1\right)^2} - e^{-\frac{1}{2p}\left(\frac{2q-1}{Q-1}-1\right)^2}\right]\right)^2} - 1 \right]^{-1}$$

where $\Phi(\cdot)$ is the CDF of the standard normal distribution

- $\rho = \rho(b, p)$: The ADC affects achieved dynamic range (and SINR) only through its resolution and VGA setting (or AGC bias)

Numerical Results

Dynamic Range vs. VGA Setting

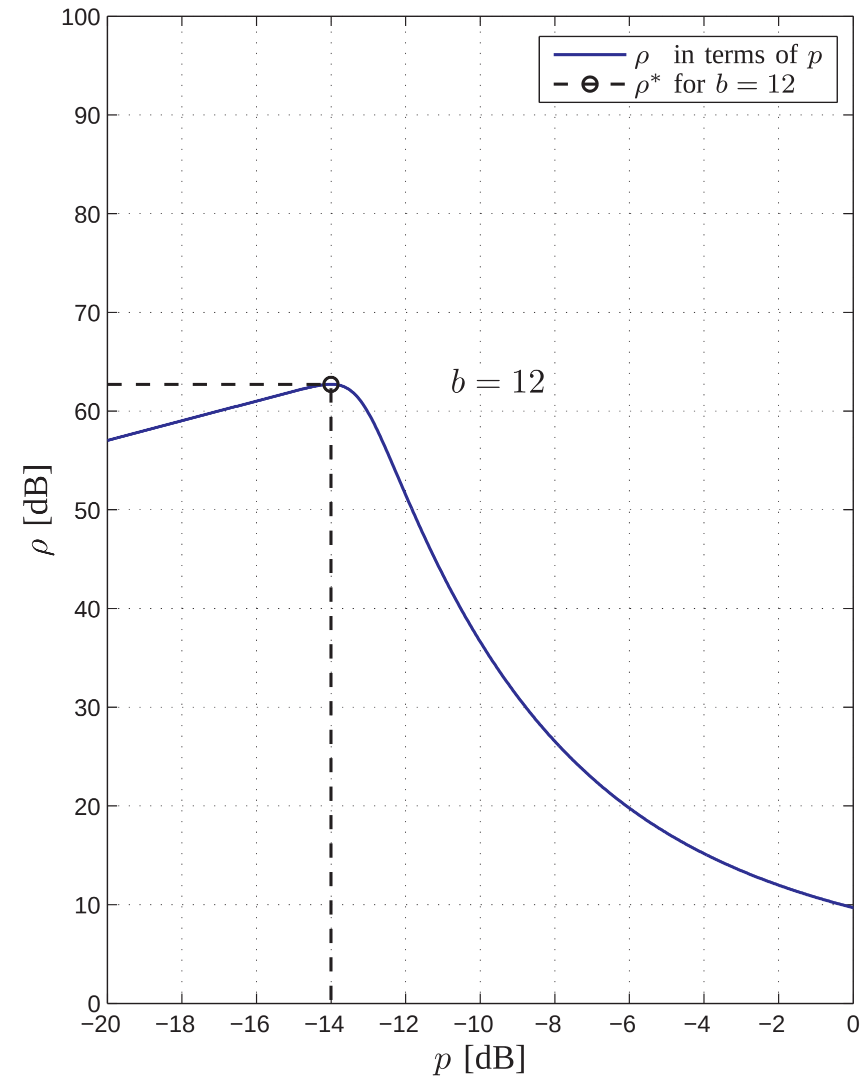
- Dynamic range can be maximized by proper AGC:

$$\rho^*(b) = \max_{p'} \rho(b, p')$$

  - ▷ results in maximal SINR with any P_S, P_I, Δ_a and Δ_d
- Optimal VGA setting yields

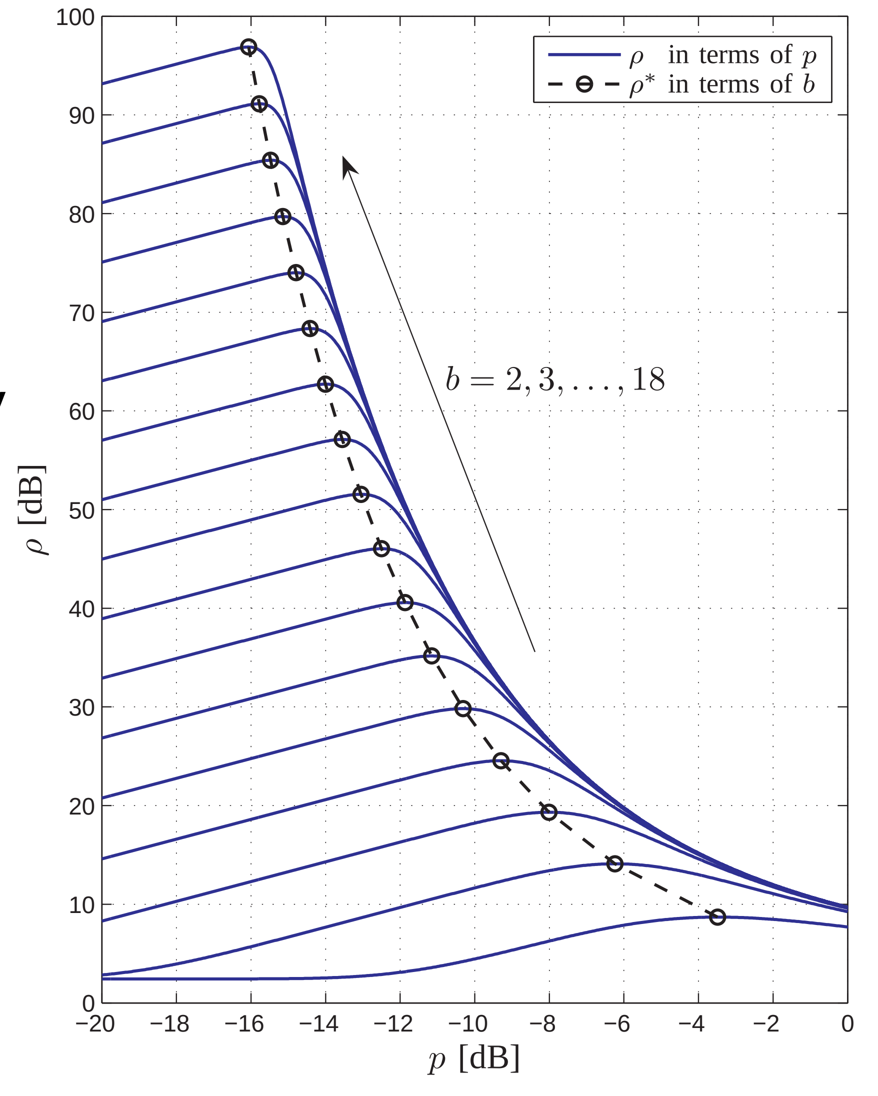
$$p = p^*(b) = \arg\max_{p'} \rho(b, p')$$

- AGC bias:
  - ▷ when $p < p^*(b)$, quantization dominates
  - ▷ when $p > p^*(b)$, clipping dominates

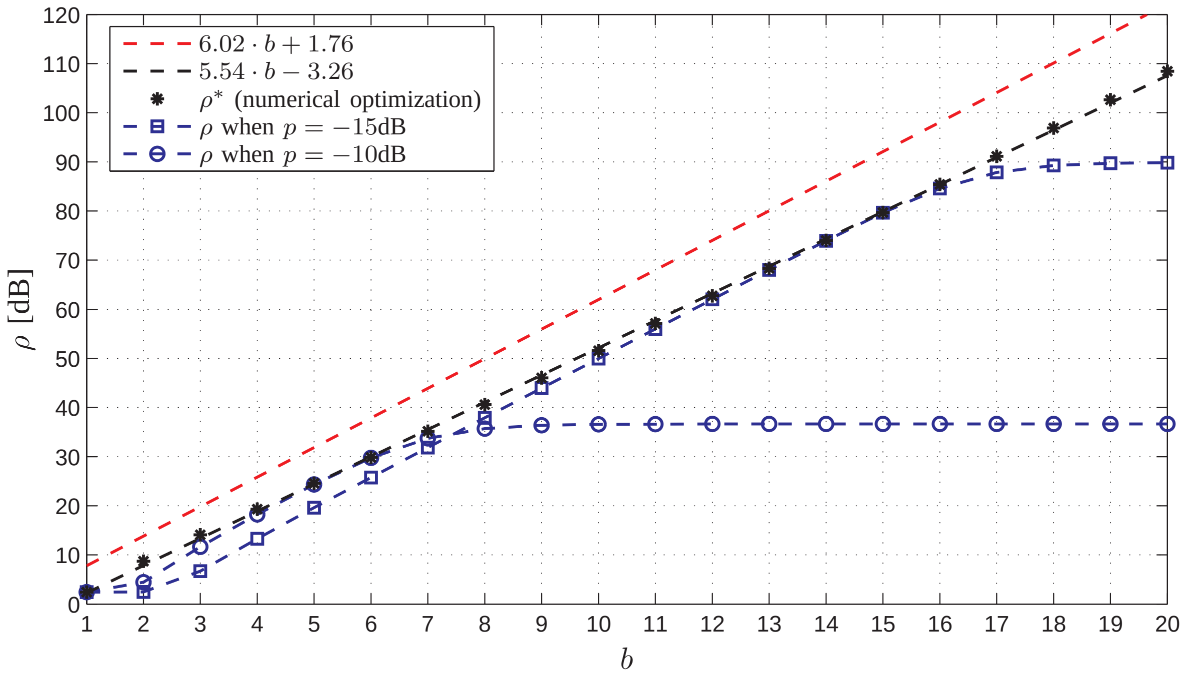


Optimal VGA Setting vs. ADC Resolution

- $\rho^*(b)$ increases in terms of b
  - ▷ Higher ADC resolution allows to trade off quantization noise level for lower clipping probability
- $p^*(b)$ decreases in terms of b
  - ▷ AGC should be designed by choosing VGA setting based on ADC resolution
  - ▷ Constant VGA setting would inevitably result in significant AGC bias and loss of dynamic range



Dynamic Range vs. ADC Resolution

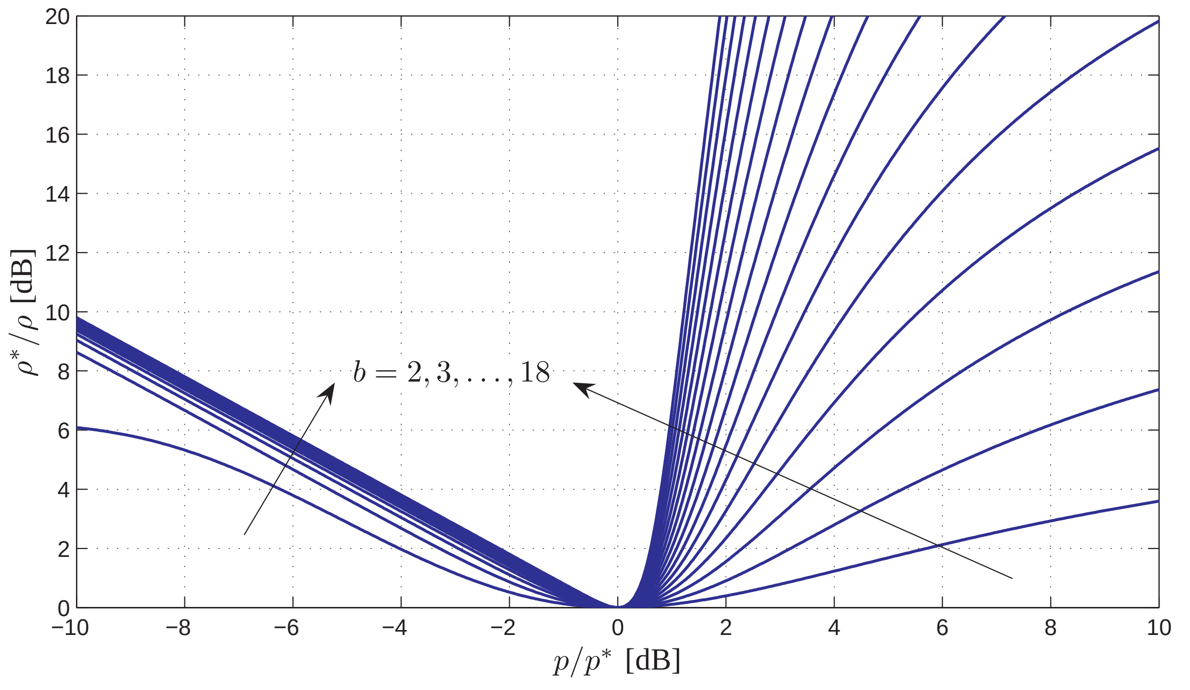


- Least-squares fit at $b = 1, 2, \ldots, 20$ shows almost linear relation:

$$\rho^*(b) \simeq 5.54 \cdot b - 3.26 \text{ [dB]}$$

- The classic rule-of-thumb, $6.02 \cdot b + 1.76$ [dB], is too optimistic
  - ▷ Not intended for OFDM signals, e.g., clipping neglected

Loss of Dynamic Range from AGC Bias



- The loss of dynamic range due to AGC bias is increased when the ADC resolution is increased
  - ▷ AGC bias may eat away the benefit of using better ADC
- Low VGA setting is a safe choice: linear loss in terms of AGC bias
- Too high VGA setting causes ADC saturation due to clipping

SINR vs. Dynamic Range (1)

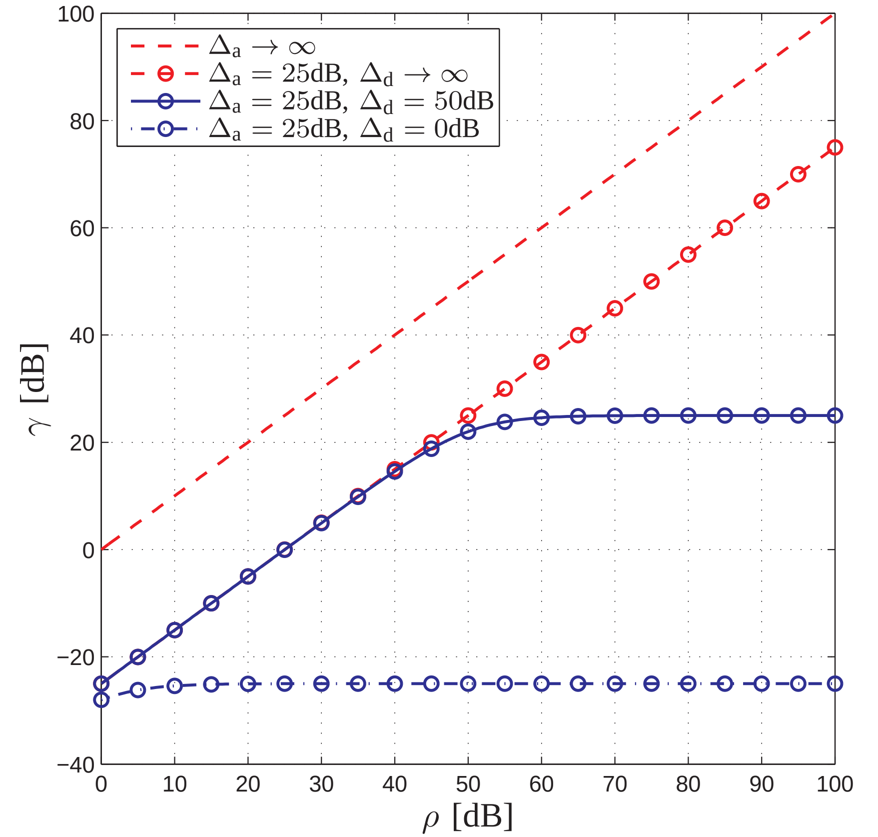
- Signal to interference and noise ratio (SINR) versus dynamic range ρ:

$$\gamma = \frac{\rho}{\frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} + \rho/\Delta_\mathrm{d} + 1} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}}$$

- On the right: Example when
  - ▷ SIR before AC $\frac{P_\mathrm{S}}{P_\mathrm{I}} = -50\mathrm{dB}$
- Tight bounds if $\Delta_\mathrm{a}\frac{P_\mathrm{S}}{P_\mathrm{I}} < 1$:

$$\gamma \leq \frac{\rho}{\frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} + 1} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} \leq \rho \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}}$$

$$\gamma \leq \frac{\rho}{\rho/\Delta_\mathrm{d} + 1} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} \leq \Delta_\mathrm{d} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}}$$



- Thus, $\gamma \approx \min\{\rho, \Delta_\mathrm{d}\} \cdot \Delta_\mathrm{a}\frac{P_\mathrm{S}}{P_\mathrm{I}}$ is a good approximation in practical situations with limited dynamic range (imperfect AC)

SINR vs. Dynamic Range (2)

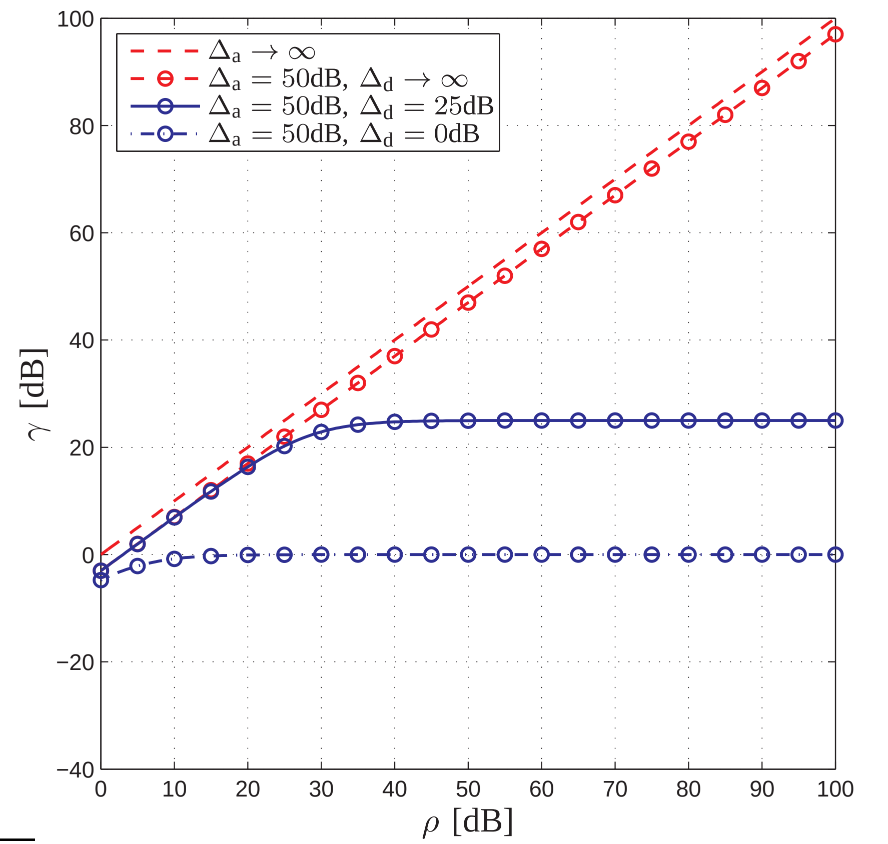
- Signal to interference and noise ratio (SINR) versus dynamic range ρ:

$$\gamma = \frac{\rho}{\frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} + \rho/\Delta_\mathrm{d} + 1} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}}$$

- On the right: Example when
  - SIR before AC $\frac{P_\mathrm{S}}{P_\mathrm{I}} = -50\mathrm{dB}$
- Tight bounds if $\Delta_\mathrm{a} \frac{P_\mathrm{S}}{P_\mathrm{I}} > 1$:

$$\gamma \leq \frac{\rho}{\frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} + \rho/\Delta_\mathrm{d}} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} \leq \rho$$

$$\gamma \leq \frac{\rho}{\frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} + \rho/\Delta_\mathrm{d}} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} \leq \Delta_\mathrm{d} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}}$$



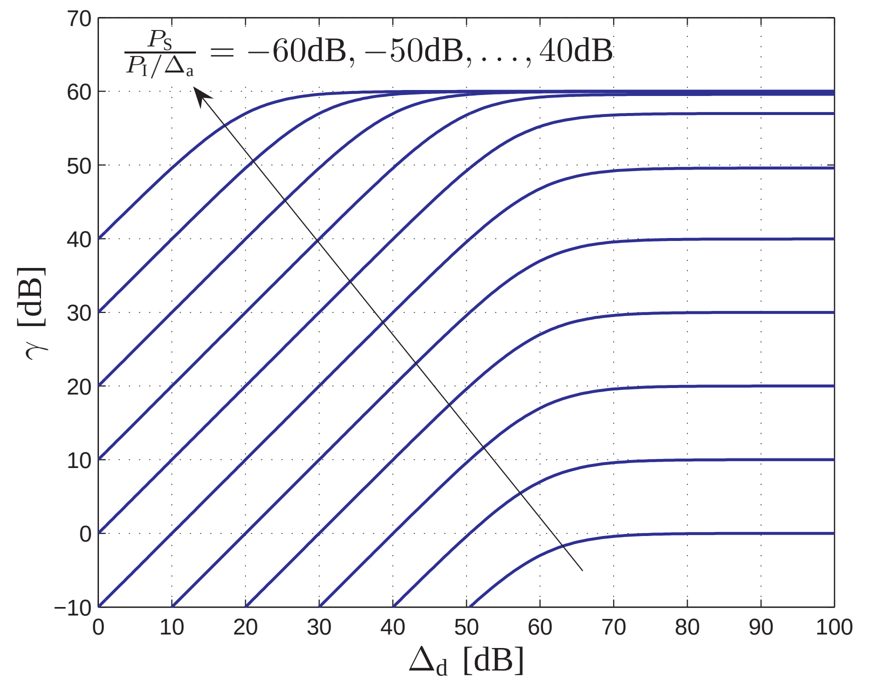
- Thus, $\gamma \approx \min\{\rho, \Delta_\mathrm{a}\Delta_\mathrm{d}\frac{P_\mathrm{S}}{P_\mathrm{I}}\}$ is a good approximation when analog cancellation works almost perfectly

SINR vs. Digital Cancellation

- Signal to interference and noise ratio (SINR) versus digital suppression Δ_d:

$$\gamma = \frac{\rho}{\frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}} + \rho/\Delta_\mathrm{d} + 1} \cdot \frac{P_\mathrm{S}}{P_\mathrm{I}/\Delta_\mathrm{a}}$$

- On the right: Example when
  - ▷ dynamic range $\rho = 60\mathrm{dB}$, e.g., 12-bit ADC resolution with small AGC bias ($3\mathrm{dB}$ loss of dynamic range)



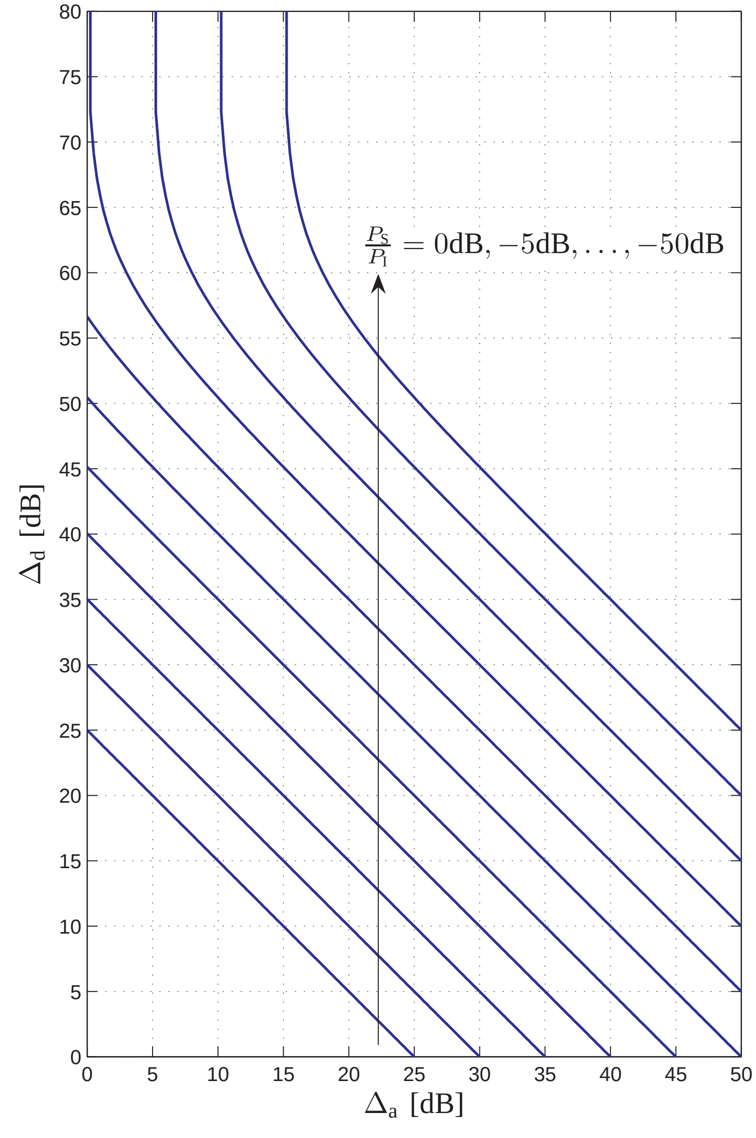
- SINR increases linearly in terms of digital suppression until performance is limited by the ADC dynamic range or imperfect analog cancellation

Suppression Requirements

- Minimal digital suppression needed to achieve $\gamma \geq \gamma_{\rm t}$:

$$\Delta_{\rm d} \geq \frac{\rho}{\frac{P_{\rm S}}{P_{\rm I}/\Delta_{\rm a}}\left(\frac{\rho}{\gamma_{\rm t}}-1\right)-1}$$

- On the right: Example when
  - ▷ dynamic range $\rho = 60\text{dB}$
  - ▷ target SINR $\gamma_{\rm t} = 25\text{dB}$
- Digital cancellation is efficient if target SINR $\gamma_{\rm t} \ll \rho$ (obviously) and SIR after AC $\Delta_{\rm a}\frac{P_{\rm S}}{P_{\rm I}} \geq \frac{\gamma_{\rm t}}{\rho}$
- Then requirement for combined analog and digital suppression becomes simply $\Delta_{\rm a}\Delta_{\rm d} \geq \frac{\gamma_{\rm t}}{P_{\rm S}/P_{\rm I}}$



Conclusion

Conclusion

- Wireless full-duplex: A progressive frequency-reuse concept!
  - ▷ Generic MIMO-OFDM transceivers considered herein
- Challenging implementation: strong self-interference combined with limited dynamic range, i.e., practical A/D conversion
  - ▷ Residual self-interference due to non-ideal cancellation
  - ▷ Quantization noise due to limited b-bit ADC resolution
  - ▷ Clipping noise due to high peak-to-average power ratio
- Analytical expressions for desired signal power to residual interference and clipping-plus-quantization noise power ratio
  - ▷ Optimal adaptive gain control for maximal dynamic range
  - ▷ Bias in variable gain amplifier setting
  - ▷ Analog vs. digital cancellation

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