Signal Processing for MultiGigabit Communication

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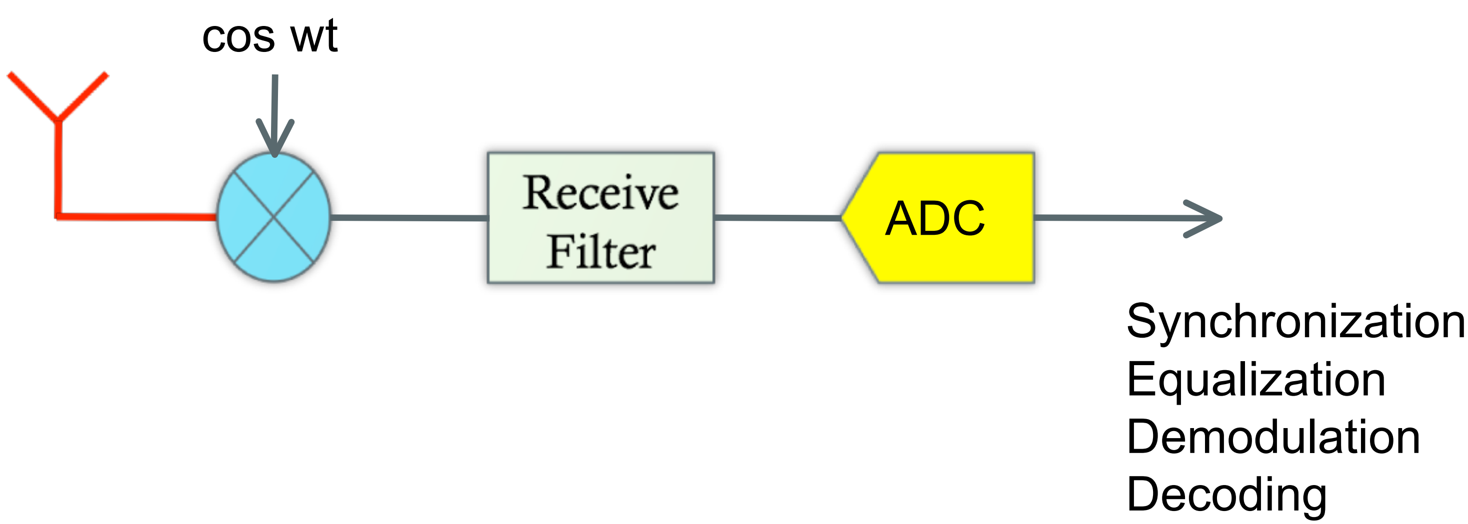
Moore's law in cellular/WLAN

Economies of scale from "all-digital" baseband have spurred massive growth



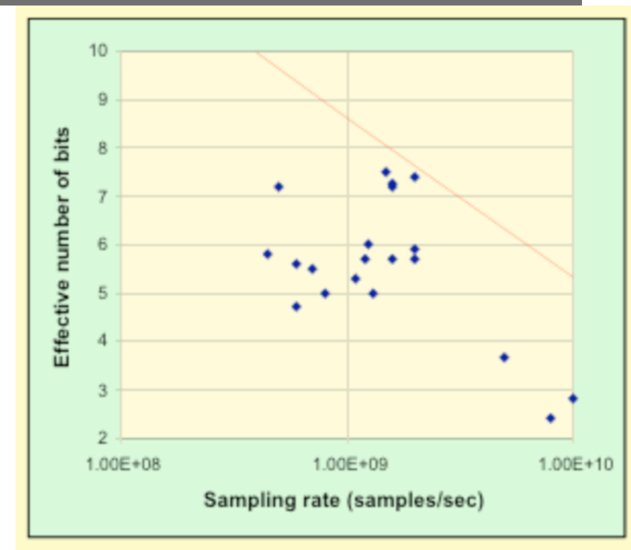
Can this scale to multiGigabit speeds?

MultiGigabit DSP: Moore's law continued?

- Ultrawideband
  - 3-10 GHz, unlicensed
  - Cluttered in-room environments
- Millimeter wave
  - 60 GHz unlicensed band: WPAN, WLAN, short-range outdoor
  - 70+ GHz semi-unlicensed point-to-point
  - Beamforming/MIMO are critical
- Optical communication
  - Coherent modulation, equalization
- Backplane
  - Cross-talk between massively parallel lines

The ADC Bottleneck

Difficult to get high speed, high precision, low power



* High-Speed ADC Survey, Lundberg, 2005

Sigma-Delta → SAR → Pipelined → Flash

Speed	100 KHz	10MHz	100MHz	1 GHz
Resolution	24 bit	18 bit	15 bit	8 bit
Power	1-10mW	10-100mW	100mW-1W	1-10W

ADC Survey by Le et al, IEEE Sig. Proc. Mag. Nov’05

All digital baseband with sloppy ADCs?

- Two complementary approaches
- Low-precision ADC
  - Small constellations, simple channels
  - Bottleneck: reduced information from 1-4 bits resolution
- Time-interleaved ADC
  - Large constellations, complex channels
  - Slower sub-ADCs in parallel
  - Bottleneck: mismatch

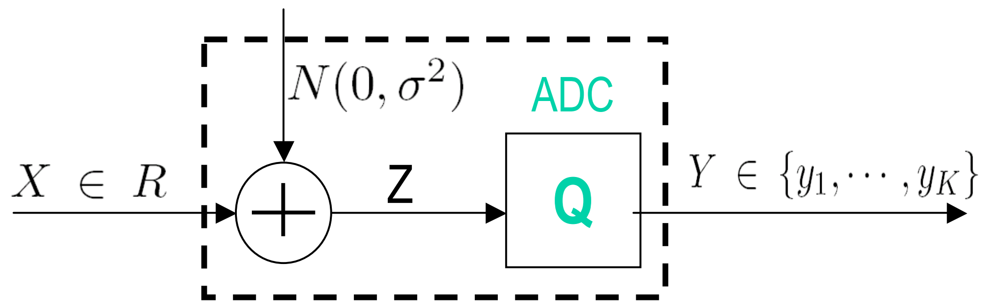
I. The Limits of Low-Precision ADC

Step 1: AWGN-QO Channel

- Linear modulation, AWGN, Nyquist sampling
- Ideal carrier and timing sync

$$Y = Q(X+N)$$

AWGN-*Quantized Output* Channel
(AWGN-QO)



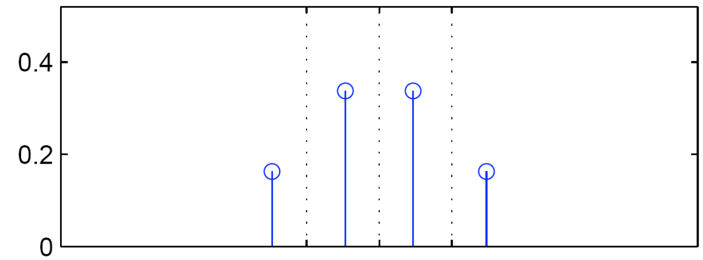
Shannon theory for AWGN-QO

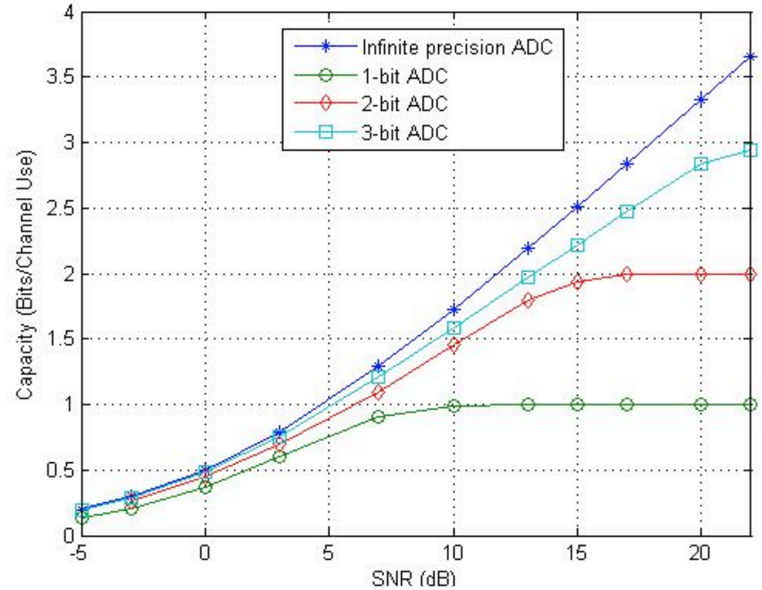
Capacity achievable with discrete input

At most K+1 points for K quantization bins
(K points appear to be enough)

Uniform PAM/ML decision boundaries near-optimal

10-15% reduction in spectral efficiency for moderate SNR





SNR(dB)	-20	-10	-5	0	3	7	10	15
1-bit optimal	0.0046	0.0449	0.1353	0.3689	0.6026	0.9020	0.9908	0.9974
2-bit optimal	0.0063	0.0613	0.1792	0.4552	0.6932	1.0981	1.4731	1.9304
2-bit benchmark	0.0049	0.0527	0.1658	0.4401	0.6868	1.0639	1.4086	1.9211

Encouraging results, but do they hold up for more realistic models?

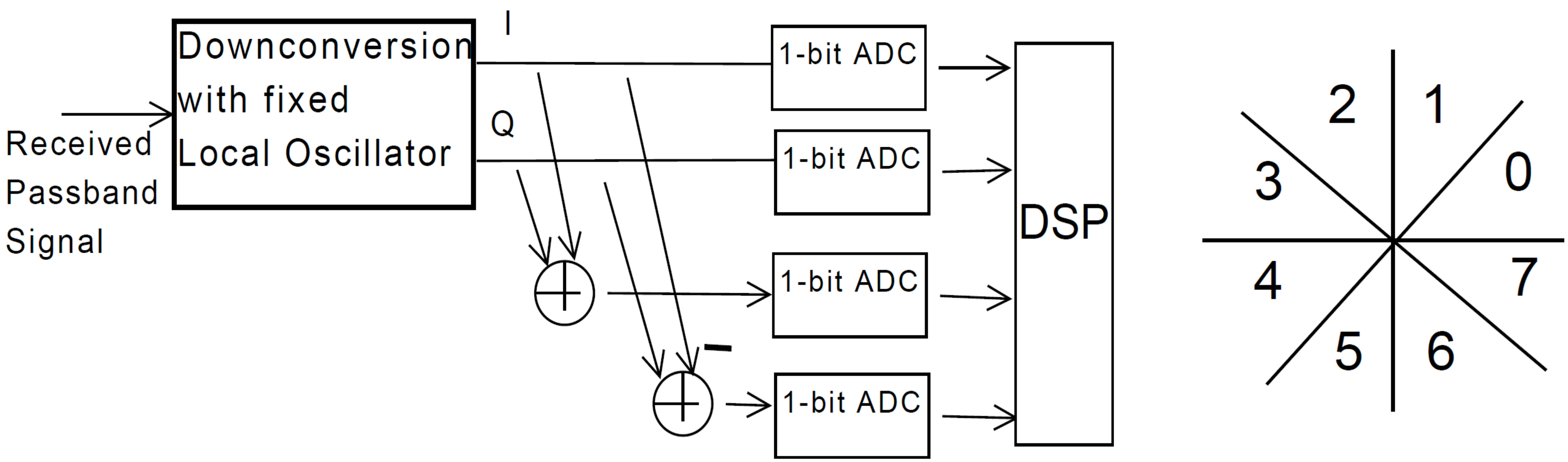
Step 2: No prior carrier sync

Quantized, block noncoherent, channel

$$Z_l = (S_l e^{j\phi} + N_l) \quad , \; l = 0, 1, \cdots, L-1$$

- Phase-only quantization implementable using 1-bit ADCs
  - significant power saving
  - no need for Automatic Gain Control (AGC)

Uniform 8-sector phase quantization

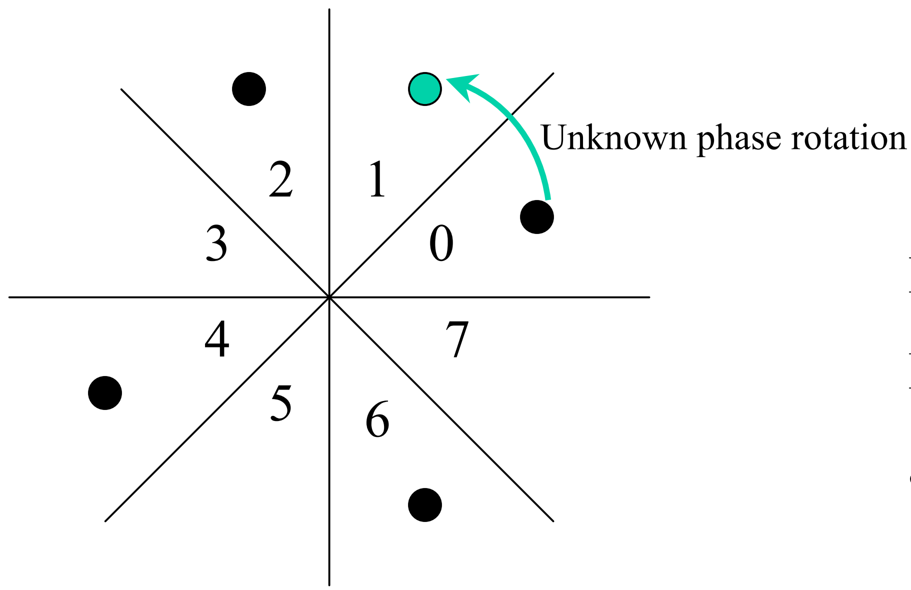


Symmetries in Input-Output Relationship

$$\mathsf{P}(\mathbf{z}|\mathbf{x},\phi) = \prod \mathsf{P}(z_l|x_l,\phi)$$

We begin by analyzing the symmetry in the individual symbol probabilities

QPSK with 8-sector phase quantization



M = 4

K = 8

a = K/M = 2

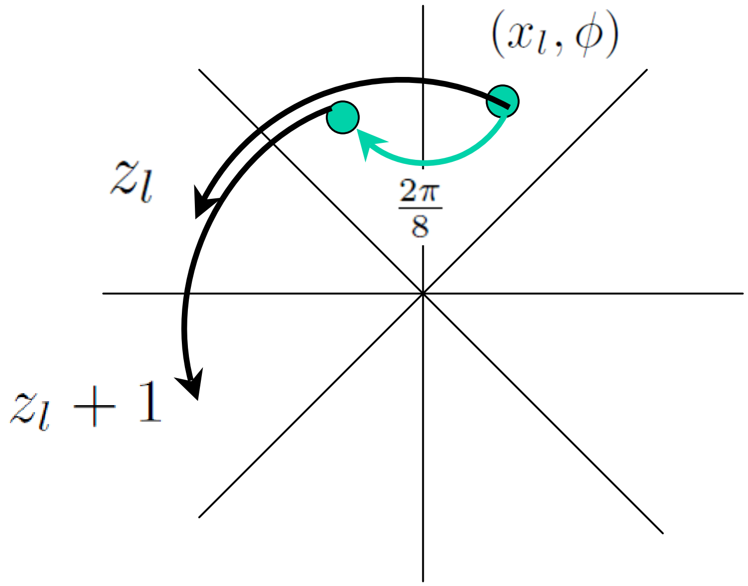
QPSK with 8-sector quantization

- Symmetries can be used to reduce complexity of capacity computations
  - Brute force computation exponential in block length

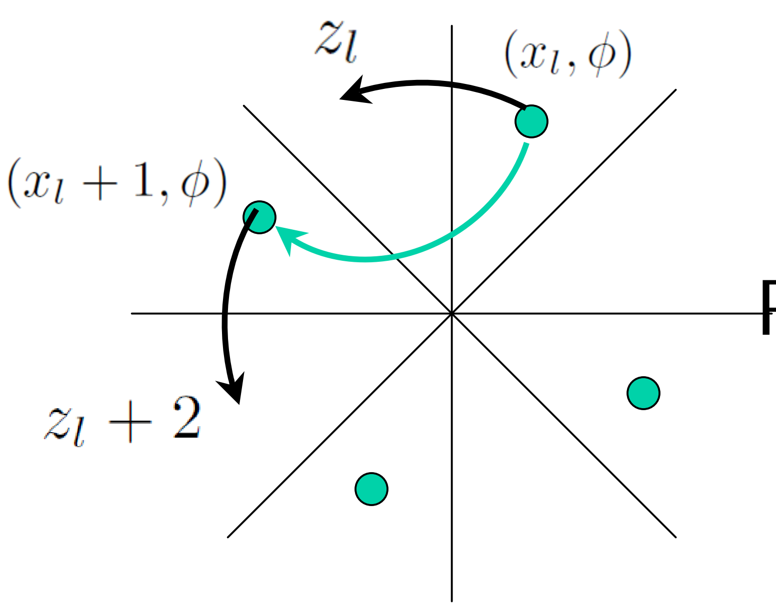
	L=3	4	5	6	7
Brute-force complexity	512	4096	32768	2.6*10e5	2.1*10e6
Low-complexity	15	43	99	217	429

- But symmetries also lead to poor performance
  - Two solutions to ML joint estimation of symbols and unknown phase for certain outputs

Symmetries in Input-Output Relationship



$$\mathsf{P}(z_l | x_l, \phi) = \mathsf{P}(z_l + 1 | x_l, \phi + \tfrac{2\pi}{K})$$



$$\mathsf{P}(z_l | x_l, \phi) = \mathsf{P}(z_l + a | x_l + 1, \phi)$$

Symmetries for block probabilities

$$\mathsf{P}(\mathbf{z}|\mathbf{x}) = \mathsf{P}(\mathbf{z}+\mathbf{1}|\mathbf{x})$$

invariance under cyclic shift

$$\mathsf{P}(\mathbf{z}) = \mathsf{P}(\mathbf{z}+\mathbf{1})$$

$$\mathsf{P}(\mathbf{z}|\mathbf{x}) = \mathsf{P}(\Pi\mathbf{z}|\Pi\mathbf{x})$$

invariance under permutation

$$\mathsf{P}(\mathbf{z}) = \mathsf{P}(\Pi\mathbf{z})$$

$$\mathsf{P}(\mathbf{z}|\mathbf{x}) = \mathsf{P}(\mathbf{z} \bmod a \mid \mathbf{x}-\mathbf{q})$$

$$\left(a = \frac{K}{M}, \mathbf{q} = \left\lfloor \frac{\mathbf{z}}{a} \right\rfloor\right)$$

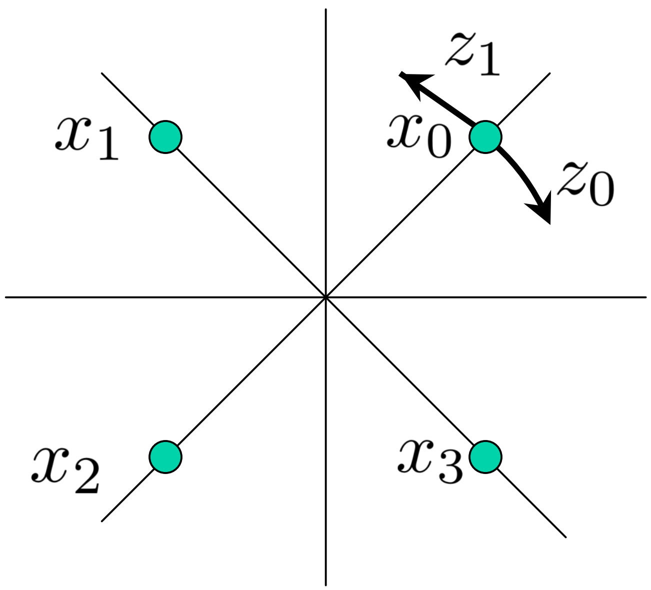
can restrict attention to only the first 'a' output symbols

$$\mathsf{P}(\mathbf{z}) = \mathsf{P}(\mathbf{z} \bmod a)$$

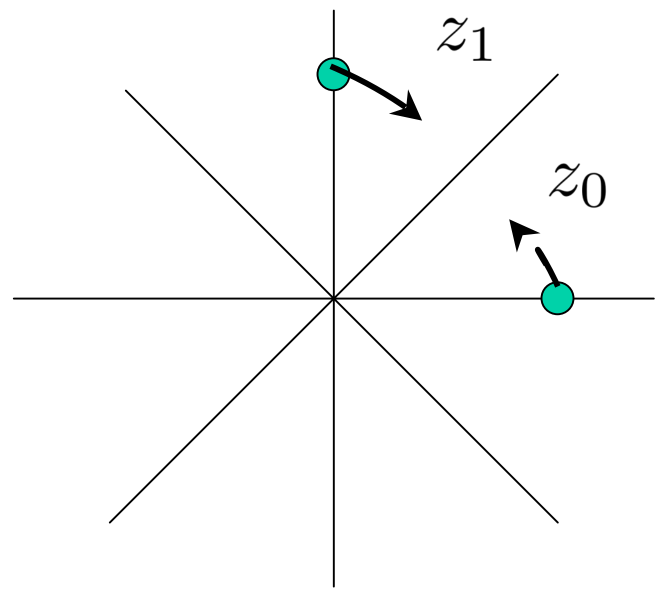
Ambiguity in noncoherent GLRT demodulator

$$\max_{\mathbf{x},\phi} \mathsf{P}(\mathbf{z}|\mathbf{x},\phi)$$

$$\max_{\phi} \mathsf{P}(z_1 z_0|x_0 x_0,\phi) = \max_{\phi} \mathsf{P}(z_1 z_0|x_0 x_3,\phi)$$

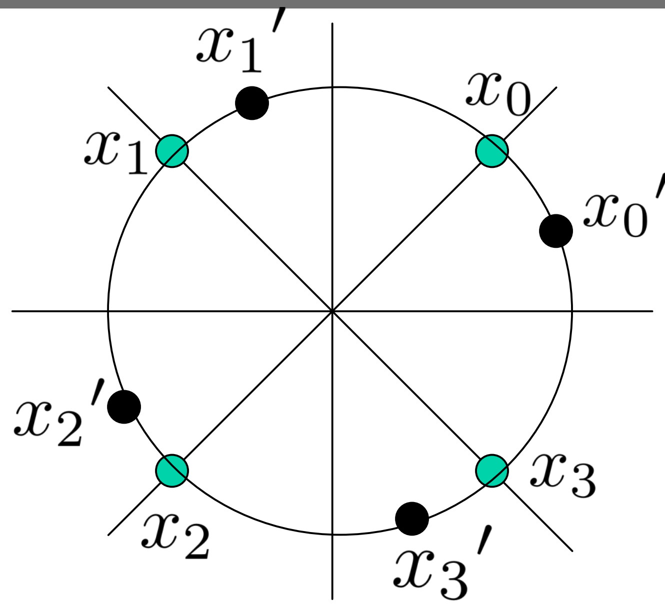


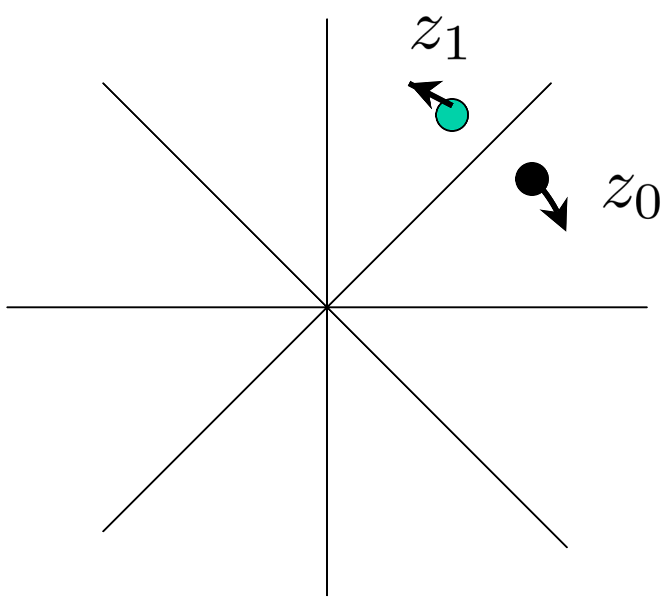
$$\mathsf{P}(z_1 z_0|x_0 x_0,\phi = 0)$$

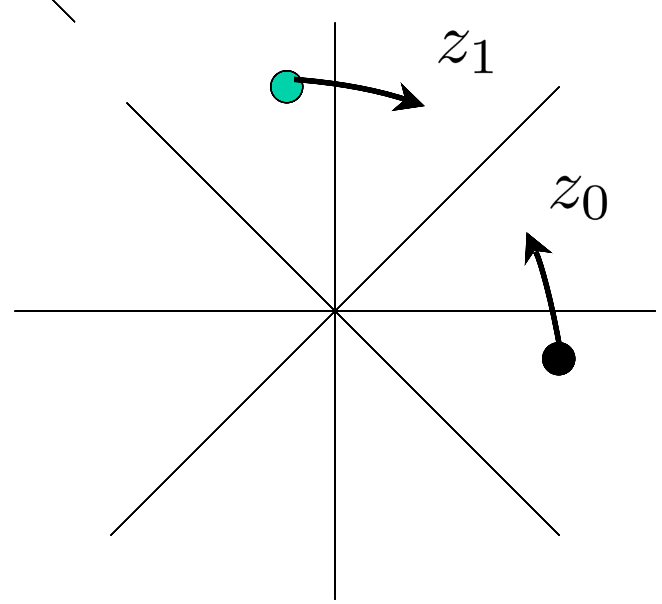


$$\mathsf{P}(z_1 z_0|x_0 x_3,\phi = \pi/4)$$

Dithering alleviates ambiguity

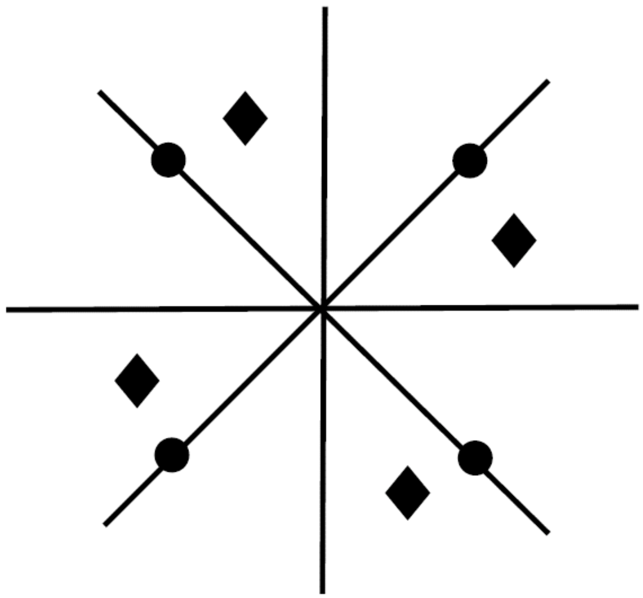


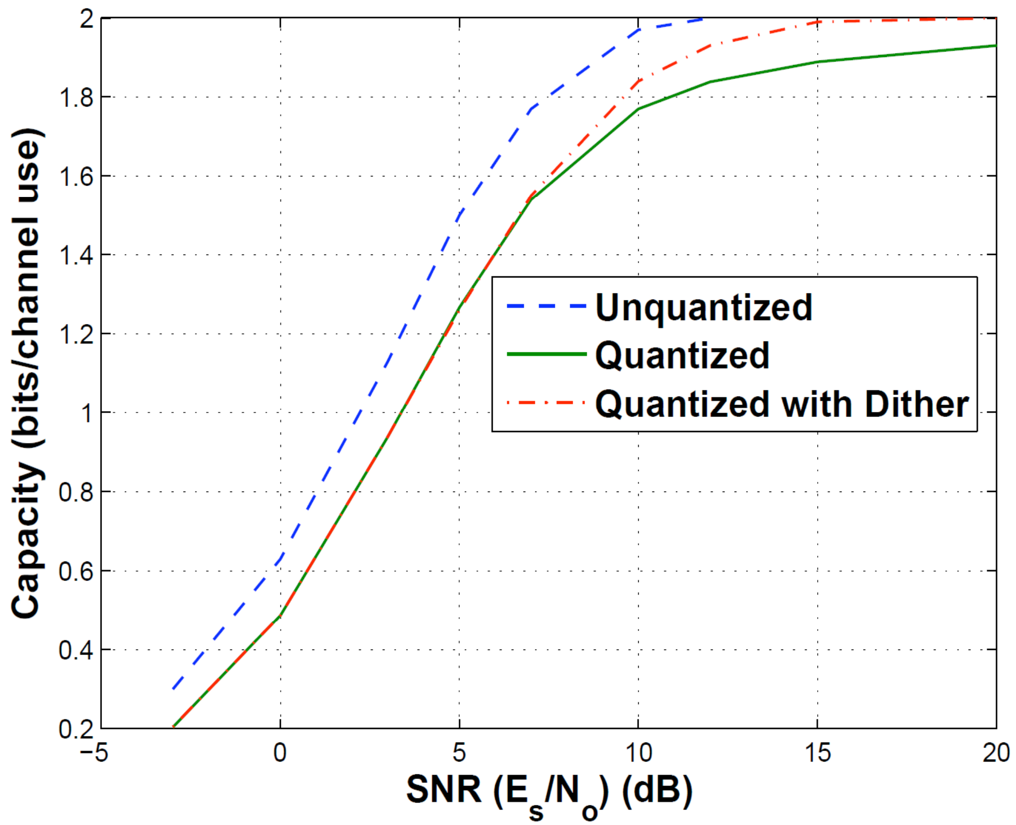




$$\max_{\phi} \mathsf{P}(z_1 z_0 | x_0 x_0', \phi) > \max_{\phi} \mathsf{P}(z_1 z_0 | x_0 x_3', \phi)$$

Dithering helps especially at high SNR



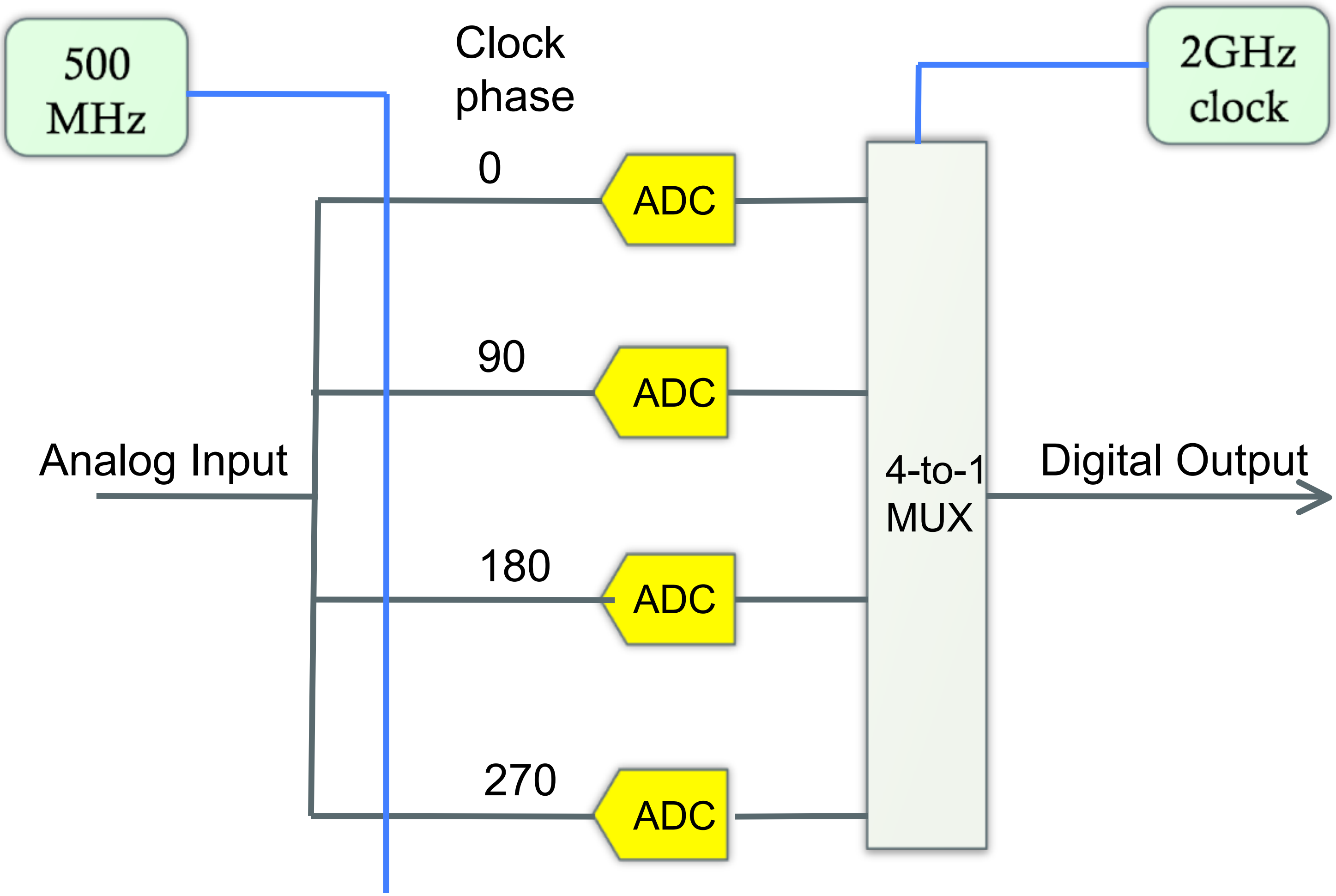


Take-aways on low-precision ADC

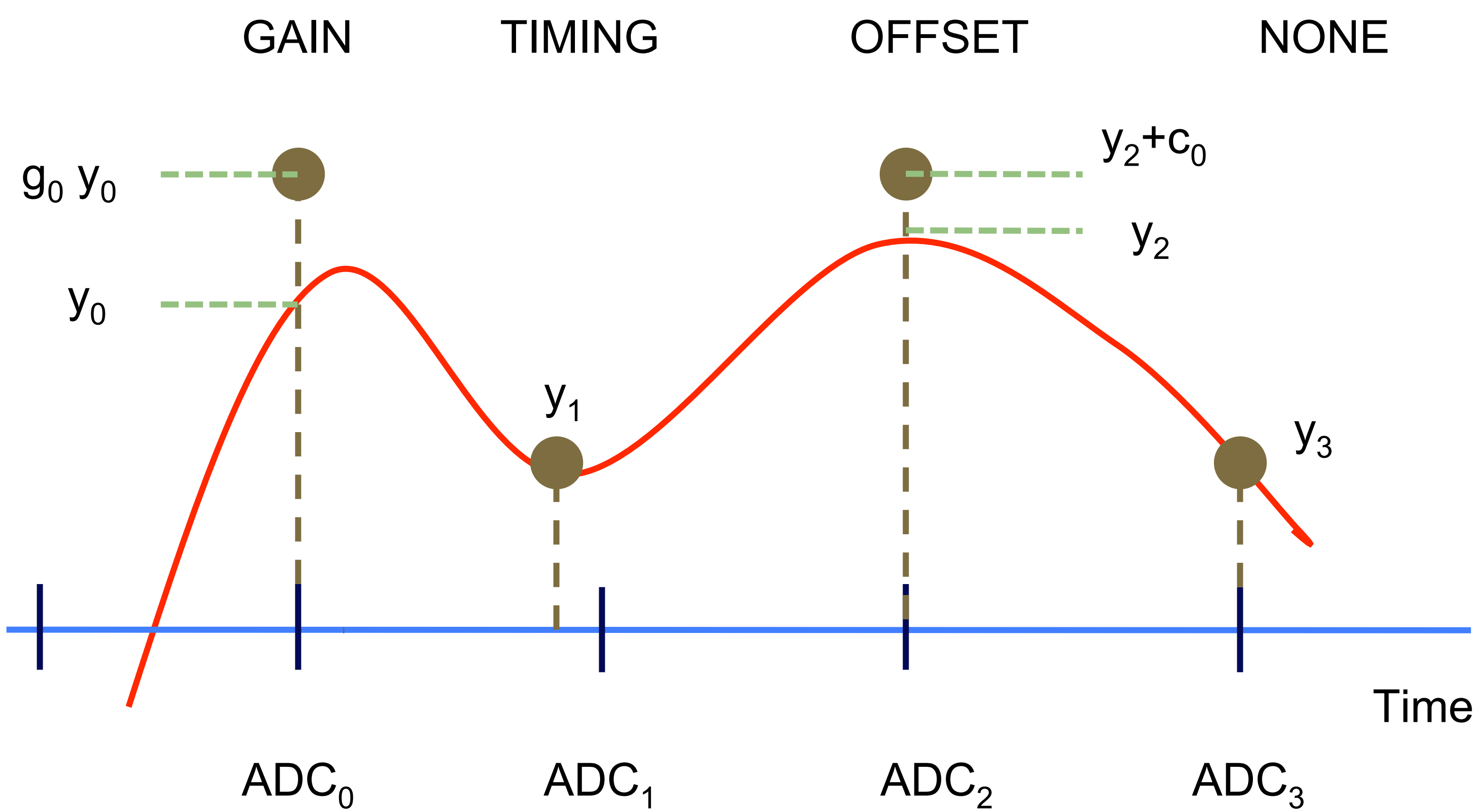
- Most theoretical issues regarding low-precision ADC remain open
  - Algorithms: timing sync, carrier sync
  - Shannon theory for models of increasing realism
  - Role of transmitter (dithering, precoding)
  - Possible to handle dispersive channels?

II. Time-interleaved ADCs in comm receivers

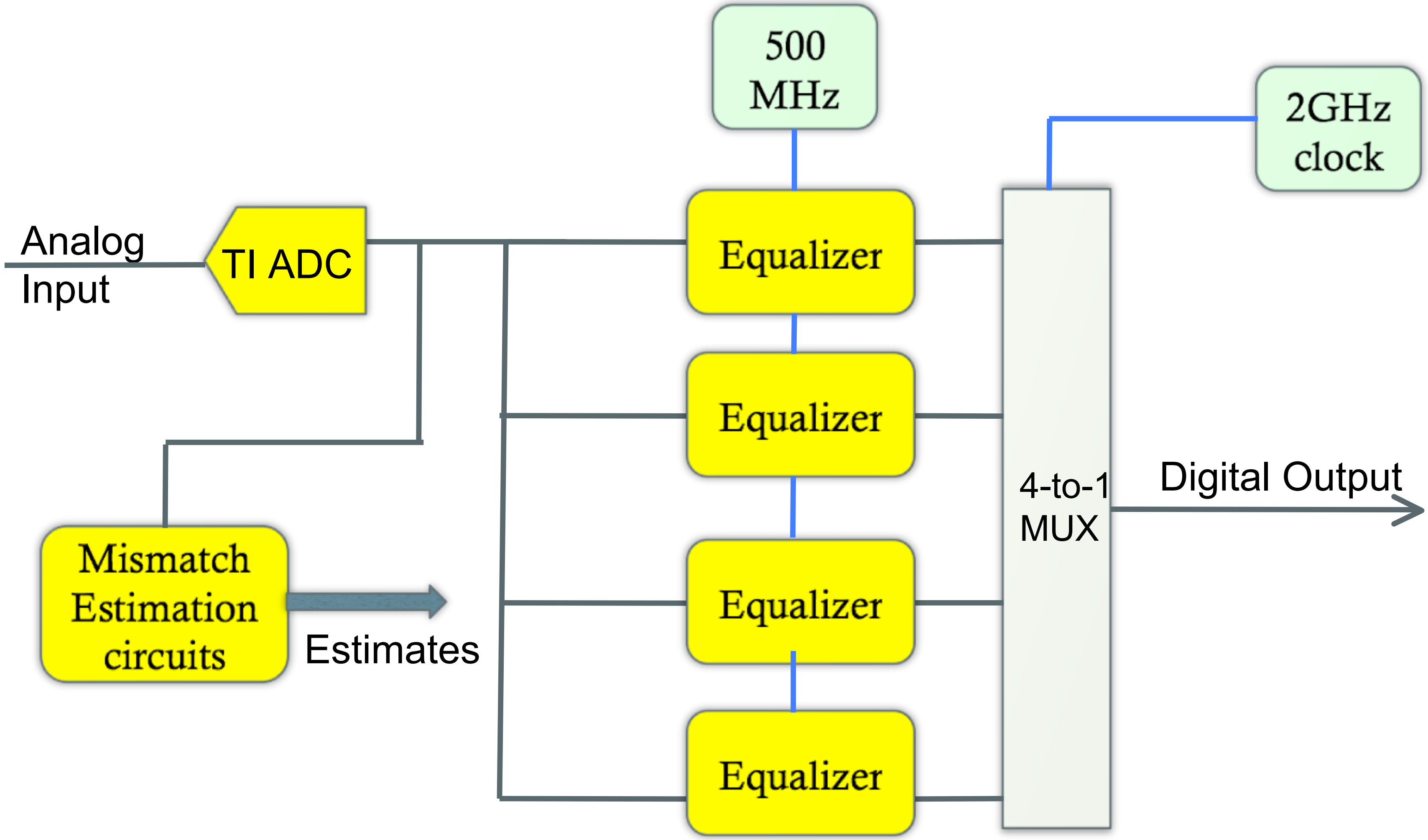
Time-interleaved ADC



TI-ADC performance limited by mismatch

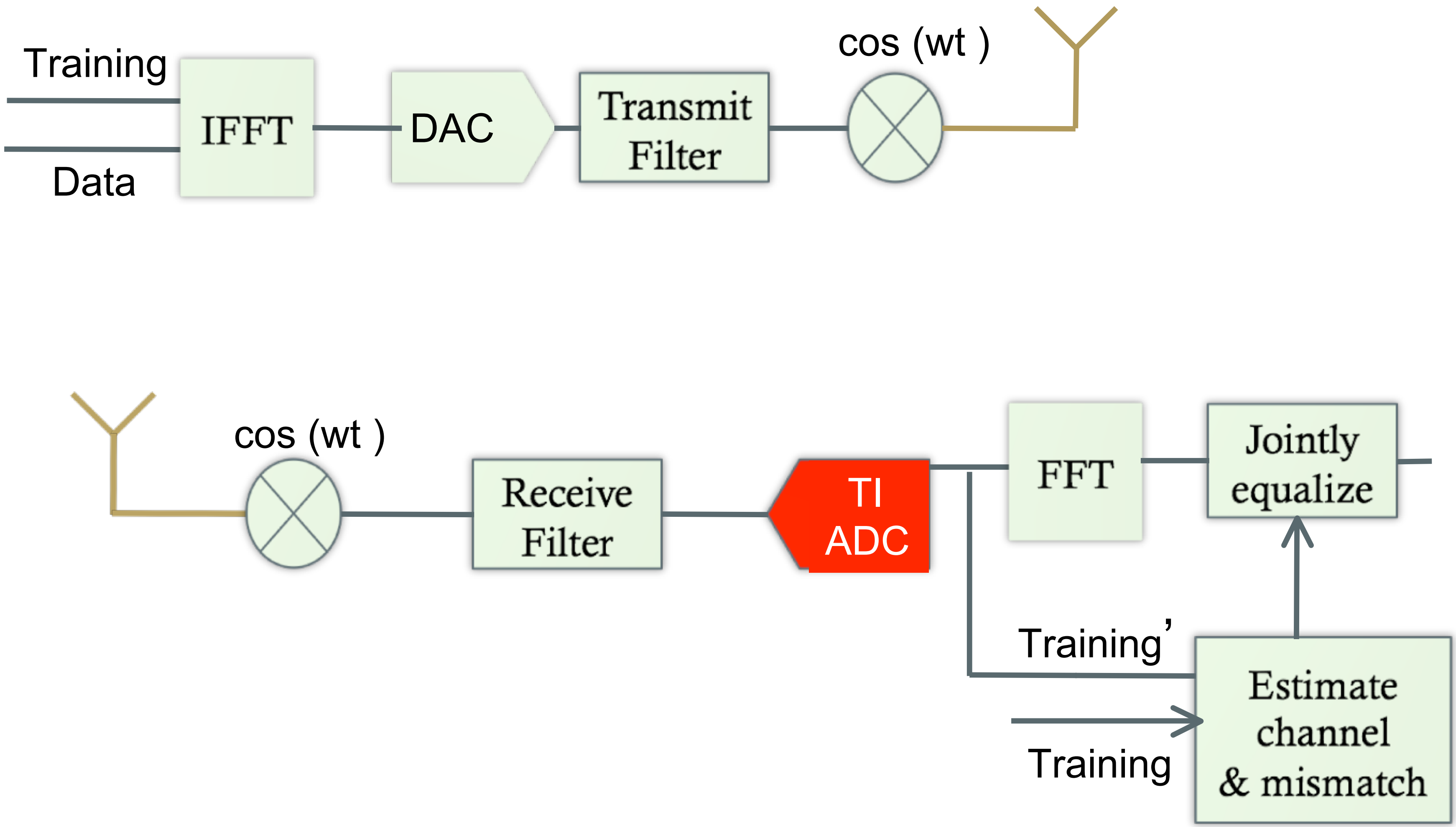


Conventional mismatch compensation



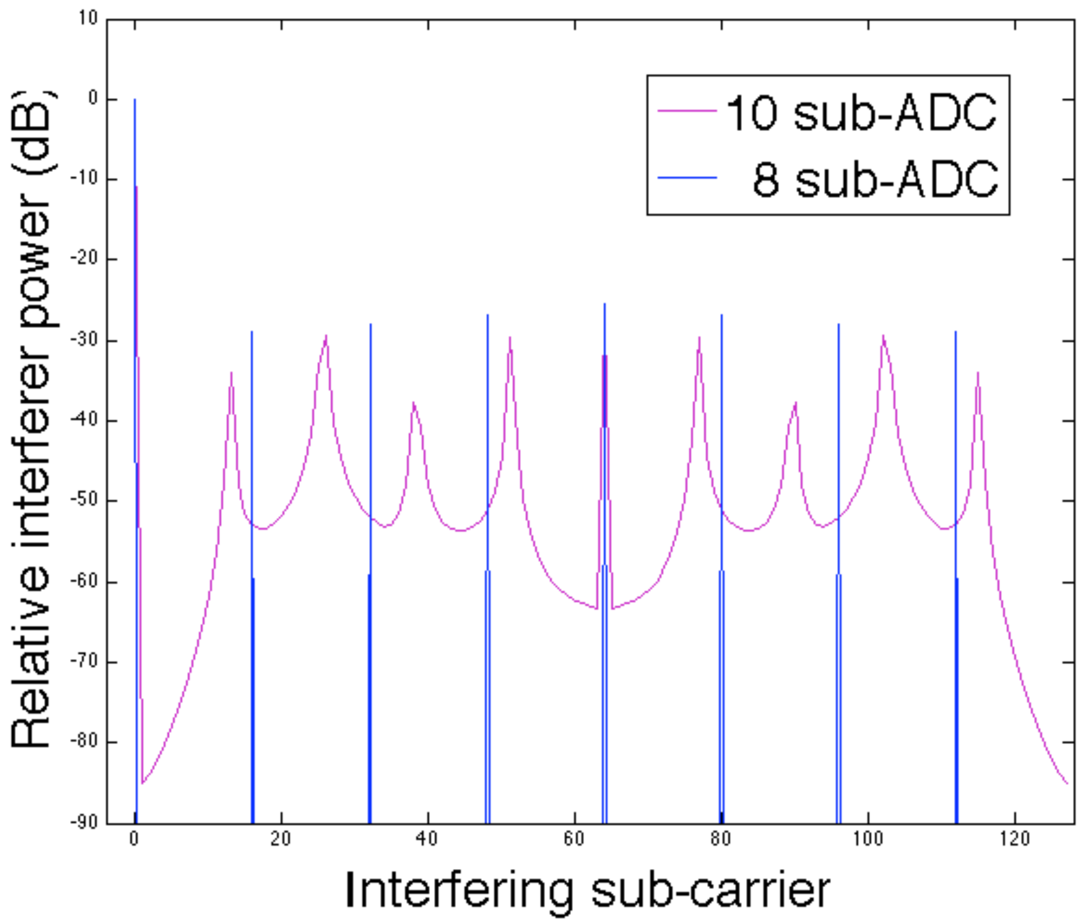
Much better performance/complexity tradeoffs by tailoring to application

Example: TI-ADC in OFDM reception



The Structure of Mismatch-induced Interference

If # sub-ADCs divides #subcarriers, then
inter-subcarrier interference limited to groups of size = # sub-ADCs

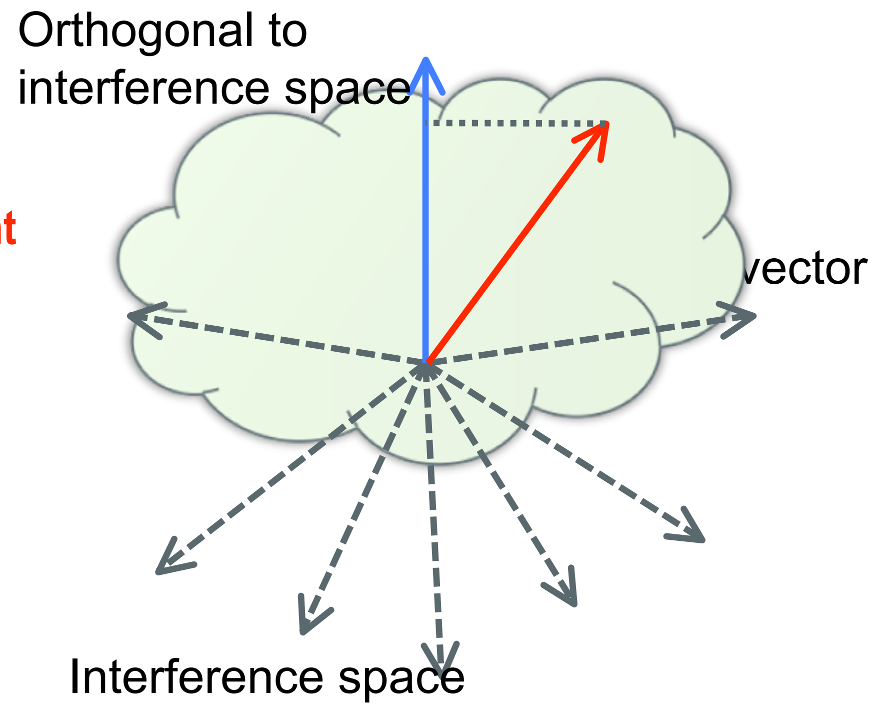


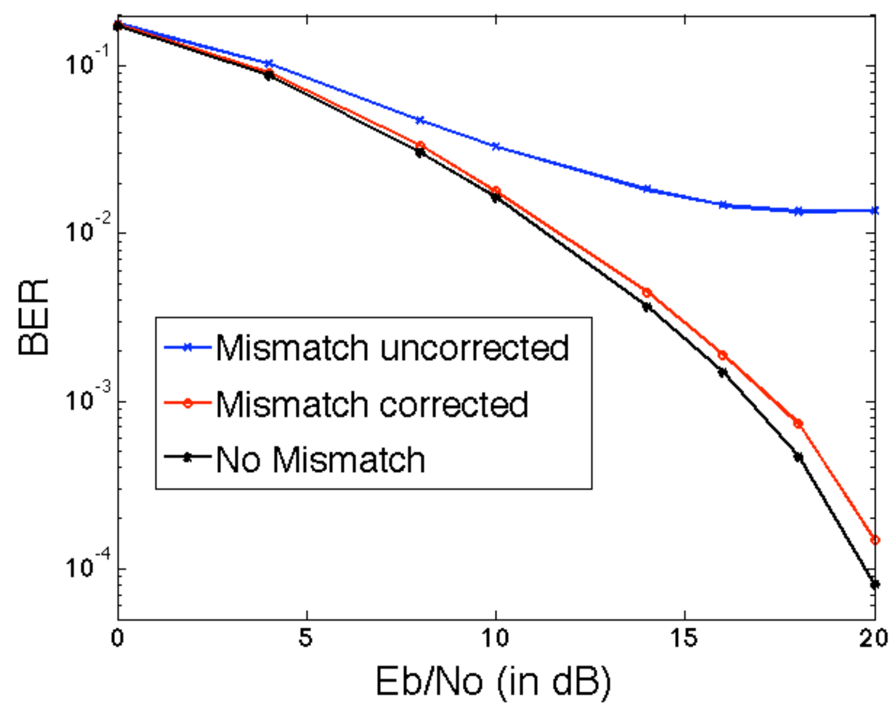
Signal at sub-carrier ‘0’ (total =128)

Zero-forcing equalization works well

Interference vectors quasi-orthogonal

ZF solution incurs minimal noise enhancement

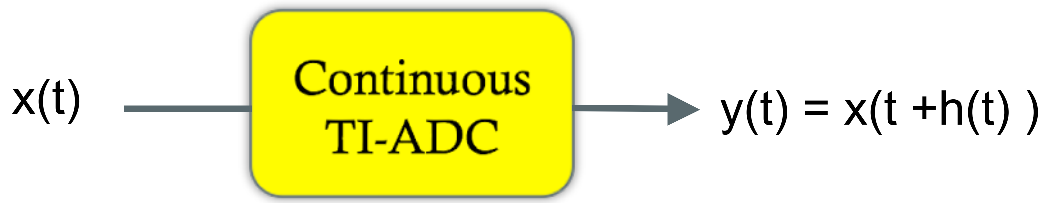




16-QAM, 8 sub-ADCs, 10% mismatch

Can we scale to a large # of sub-ADCs?

Key idea: time-frequency SVD, two dominant eigenmodes



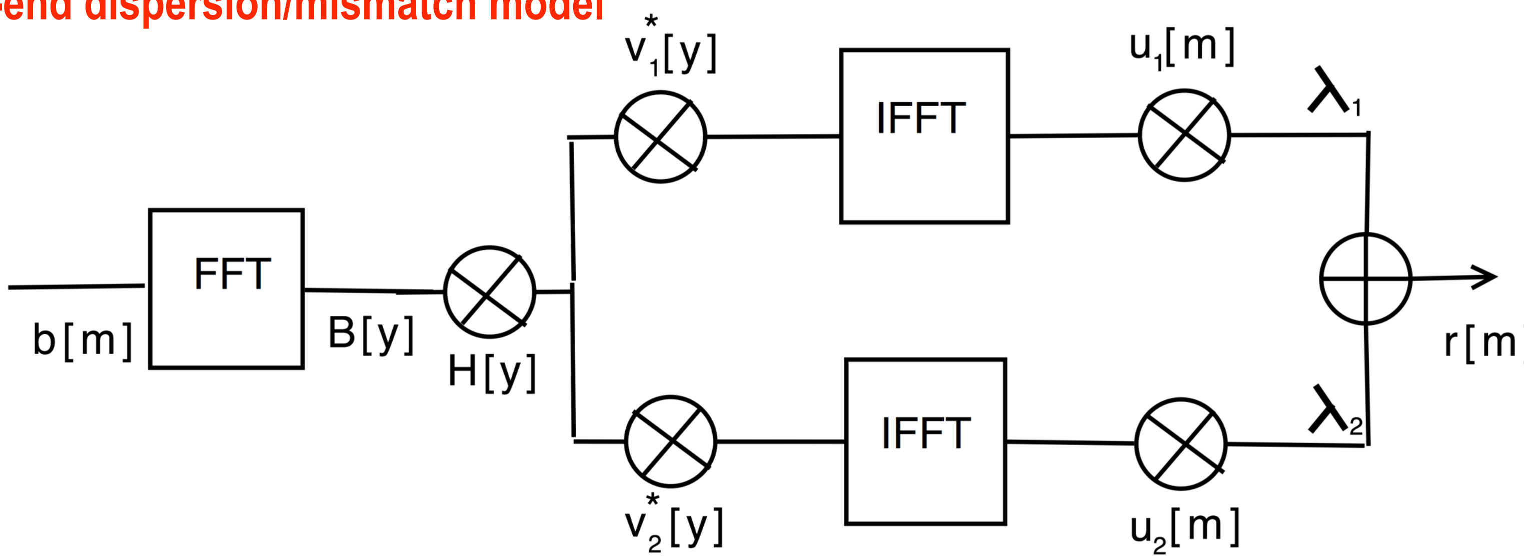
$$y(t) = \int_{-W}^{W} X(f) e^{j2\pi f t} e^{j2\pi f h(t)} df$$

$$e^{j2\pi f h(t)} = \sum_i \lambda_i f_i(t) g_i(f)$$

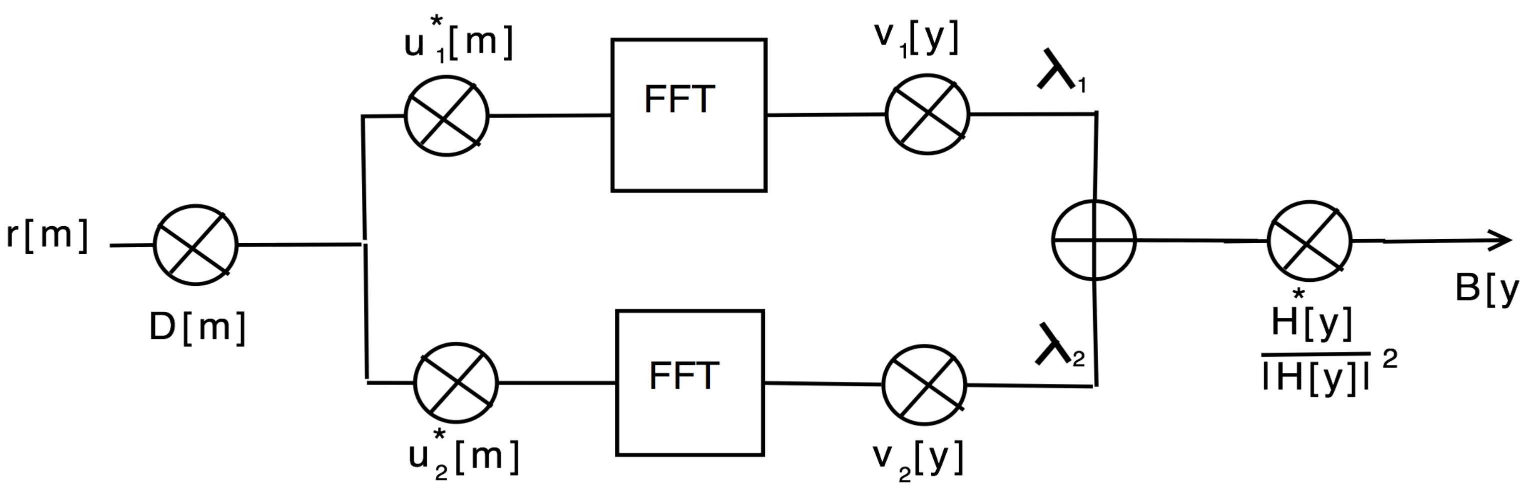
$$\text{Dominant eigenmodes } = \lceil 2\Delta W \rceil$$

ZF equalization based on two eigenmode approximation

End-to-end dispersion/mismatch model

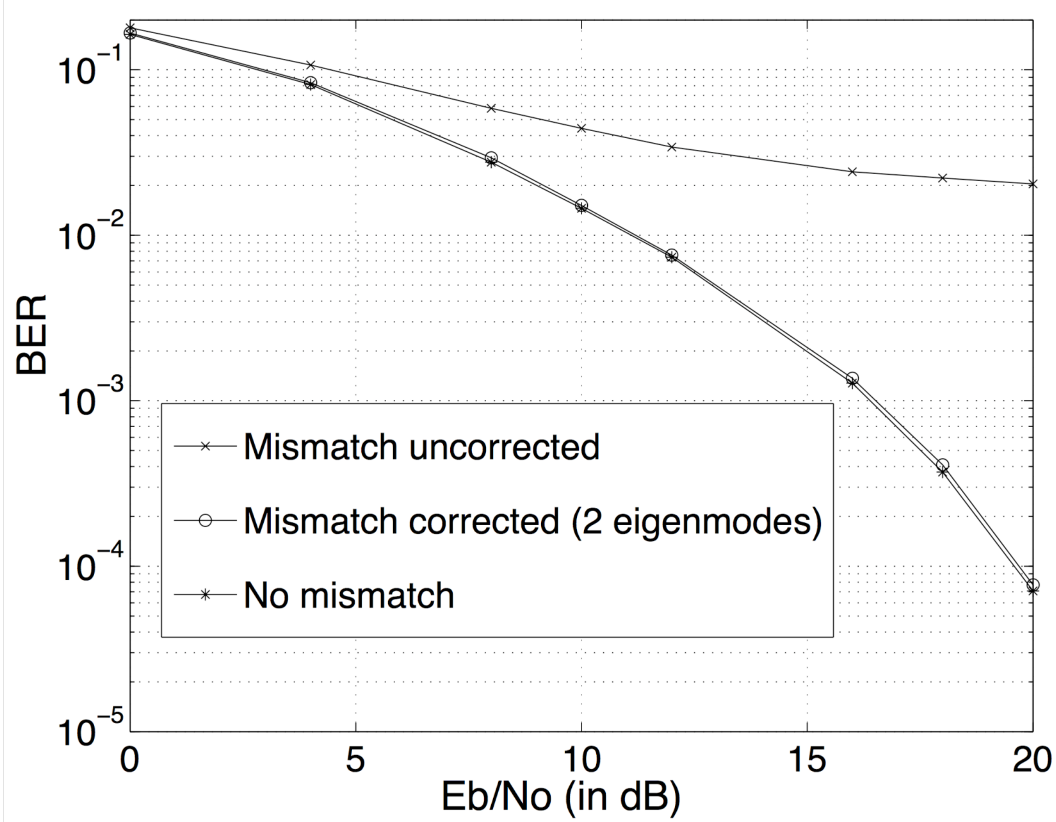


Equalization and mismatch compensation



Performance with 2-mode approximation

- 16 QAM, OFDM
- 32 parallel-ADCs
- 10% mismatch
- Perfect estimates



Take-aways on TI-ADC

- Zero-forcing mismatch correction works well for OFDM
- Two-eigenmode approximation scales well with # sub-ADCs
- Need to develop better theoretical understanding
  - Structure of mismatch-induced distortion
  - Scalability of mismatch and channel estimation
- Application to other settings of interest
  - Singlecarrier, MIMO
  - Generic TI-ADC design
- Transition to practice

Parting thoughts on multiGigabit comm

- Signal processing for multiGigabit communication requires new approaches
  - Mostly analog: short-term
  - Mostly digital with sloppy ADC: long-term
- Can we do robust design with low-precision ADC?
  - Performance limits: when is it a good idea?
  - Algorithms: redoing comm theory with a significant nonlinearity
- How far can we scale the TI-ADC approach?
  - Power/speed/precision tradeoffs
  - Algorithmic innovations
  - Fundamental understanding of mismatch