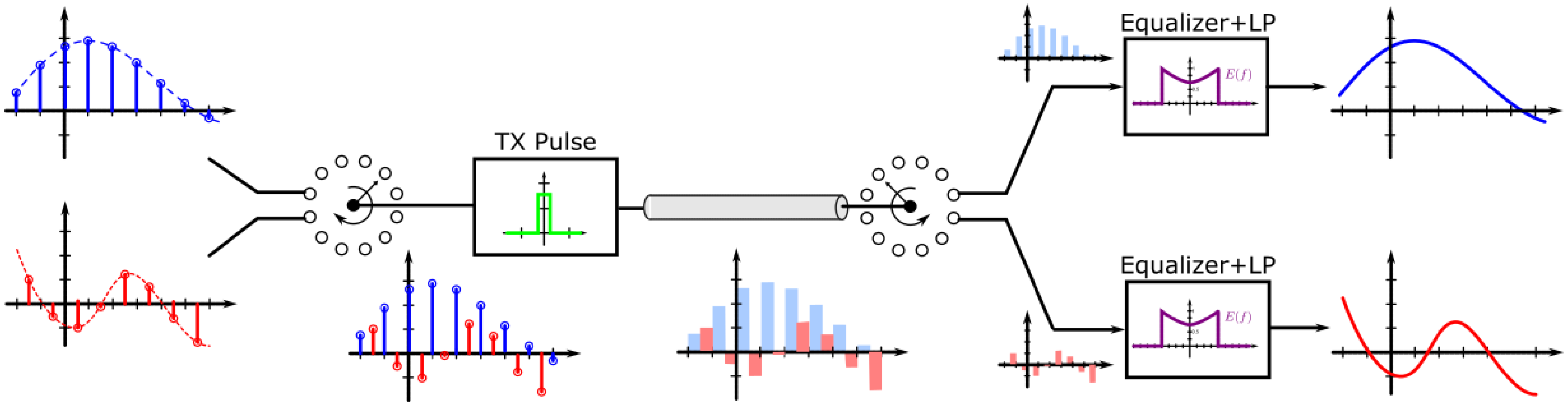
Recap from Week-5

- **Communication networks are often built as stars-of-stars**
- **Between local stars, multiple signals are multiplexed onto a single wire**

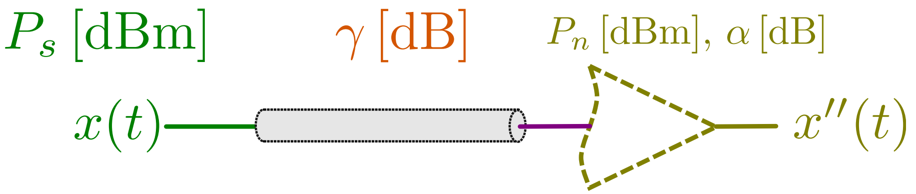
- **Pulse modulation is a straightforward way to “MUX” and “DE-MUX” provided that the bandwidth of the shared wire is sufficient (often the case)**



Recap from Week-5

- **Transmitting signals over long wires leads to attenuation and degrades the signal-to-noise ratio**

$$SNR''[dB] = P_s[dBm] + \gamma[dB] - P_n[dBm]$$



- **Periodic analog repeaters can not recover the SNR and even degrade SNR**

$$SNR''[dB] = \underbrace{P_s[dBm] + \gamma[dB] - P_n[dBm]}_{No\ repeaters} - 10\log_{10} N$$

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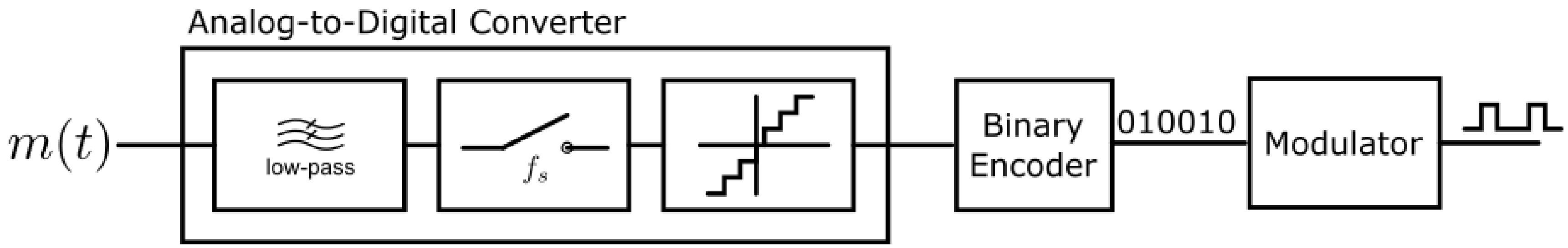
Quantization

Motivation: Binary Pulse Code Modulation (PCM)

- **Binary PCM: sends a sequence of pulses that encode a binary digits (0/1)**
  - PCM can be generalized to non-binary digits, but we will use the term for binary-PCM

- **Binary PCM transmission of an analog signal**
  1. Analog-to-digital conversion (filtering, sampling, quantization)
  2. Binary encoding as sequence of bits 0/1 (binary-PCM)
  3. Modulation: representing bits as waveform (baseband or RF as appropriate)



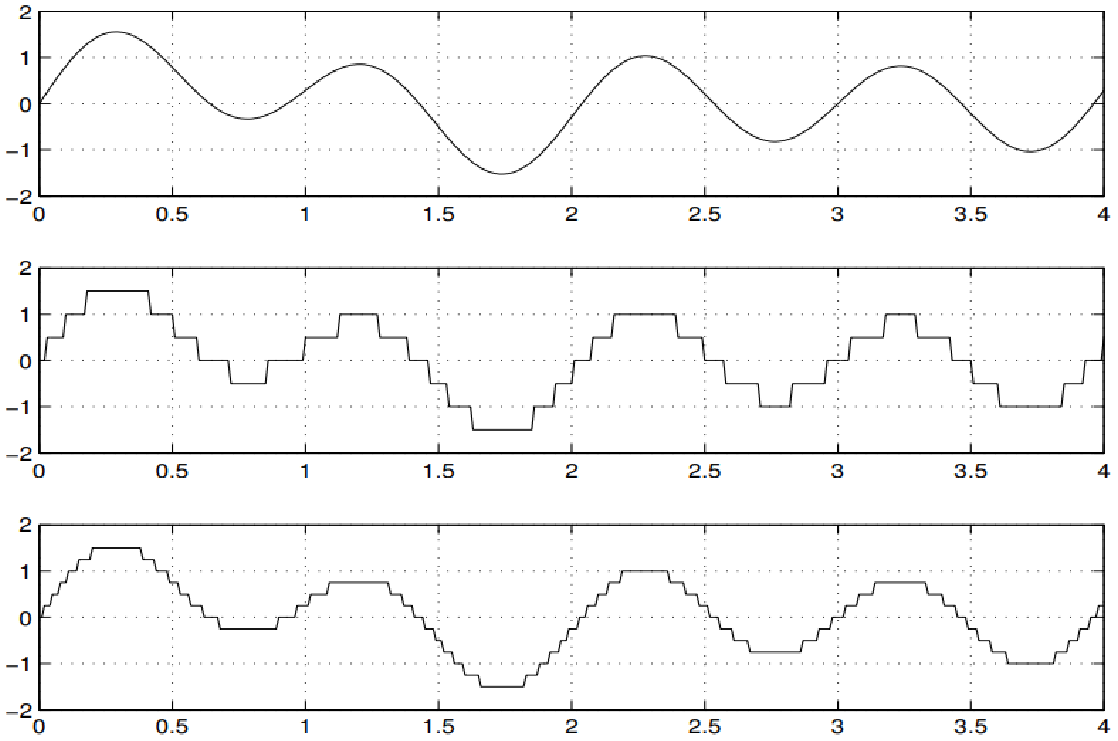
Quantization

- **Physical signals are analog. Hence $g(t) \in \mathbb{R}$ and $g[n] \in \mathbb{R}$**
- **To represent samples $g[n]$ in a digital computer, they must be quantized***
  - Quantized values are chosen from a finite set of symbols $\mathcal{Q}$
  - The number of symbols L in this set is called the cardinality of the set: $|\mathcal{Q}| = L$

- **In general, more quantization levels allow for a better representation of the signal, but also require more bandwidth for transmission**

$|\mathcal{Q}| = 7$

$|\mathcal{Q}| = 13$

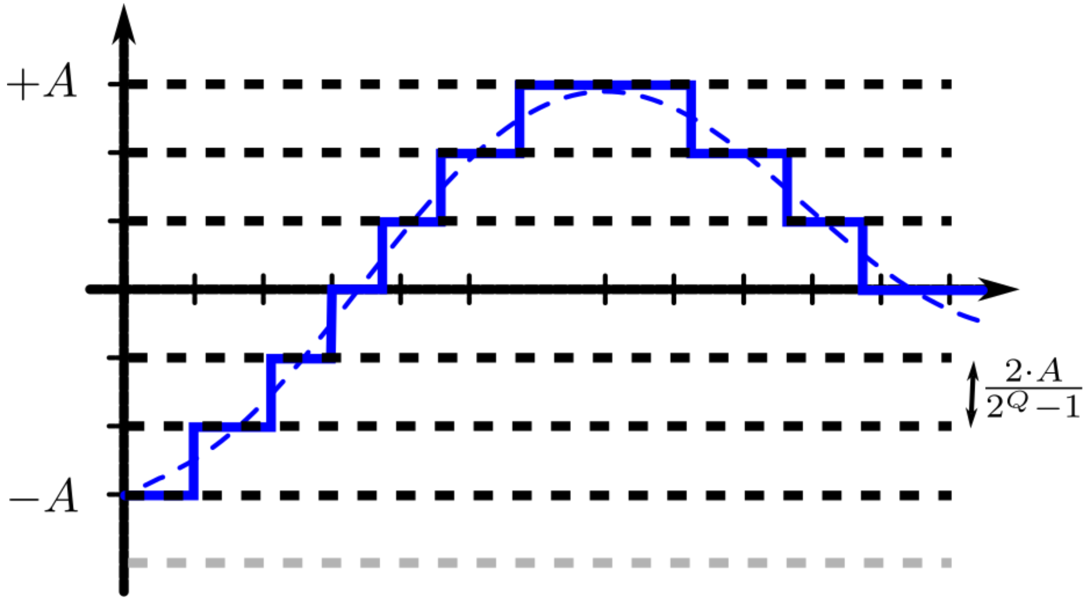


*Note that even floating-point numbers are quantized, just not uniform

Uniform Quantization

- **Computers typically represent quantized values as sequence of binary digits**
  - For efficient binary representation, **symbol sets** often **have power-of-two cardinality** $|\mathcal{Q}| = 2^Q$
  - For efficient computation, **we** often **use uniform quantization**

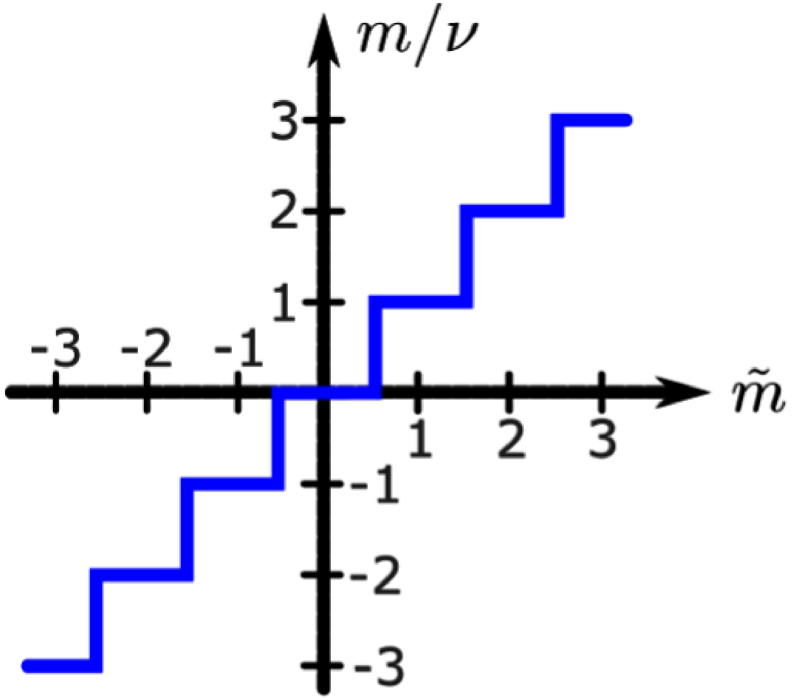
- **Signals with maximum and minimum values $\pm A$ are often DC free and symmetric around zero**
  - The range of such signals is $2A$
  - As signals are symmetric, **we** often **use only $2^Q - 1$** from 2^Q available **symbols** to have also a symmetric quantized range



*Note that even floating-point numbers are quantized, just not uniform

Uniform Symmetric Quantizer for Binary Symbols

- **Uniform symmetric quantizer maps values $\boldsymbol{m}[\boldsymbol{t}]$ to signed integers $\tilde{\boldsymbol{m}}[\boldsymbol{t}]$**
  - Bits per sample: Q
  - Effective number of levels: $2^Q - 1$
  - Signal range: $\pm A$
  - Quantization interval: $\nu = \frac{2 \cdot A}{2^Q - 1}$



$$\tilde{m}[t] = \begin{cases} -N & m[t] < -N\nu \\ n & \left(n - \frac{1}{2}\right)\nu \leq m[t] < \left(n + \frac{1}{2}\right)\nu \\ N & m[t] \geq N\nu \end{cases}$$

$$\boldsymbol{m}[\boldsymbol{t}] \in [-A, +A] \mapsto \tilde{\boldsymbol{m}}[\boldsymbol{t}] \in \left\{ -\frac{2^Q}{2} + 1, \dots, +\frac{2^Q}{2} - 1 \right\}$$

Uniform Quantizer Error (Maximum)

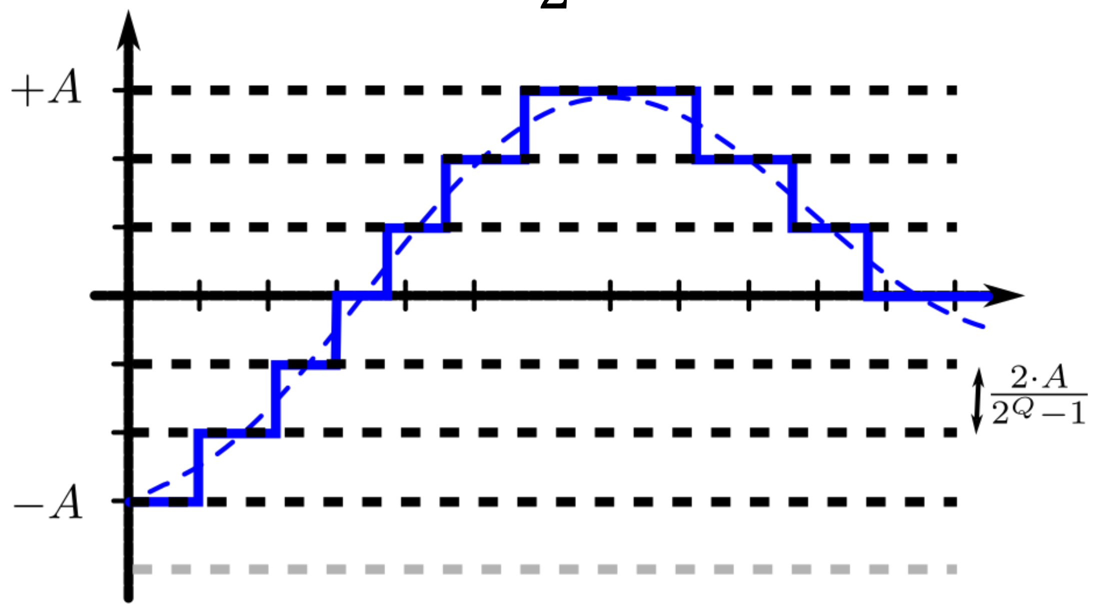
- **Quantizers are nonlinear time invariant systems**

$$\nu \approx \frac{A}{2^{Q-1}}$$

- **The maximum quantization error is**

$$\max_{m}\{|\tilde{m}\cdot\nu - m|\} = \frac{A}{2^{Q-1}} \approx \frac{A}{2^{Q}}$$

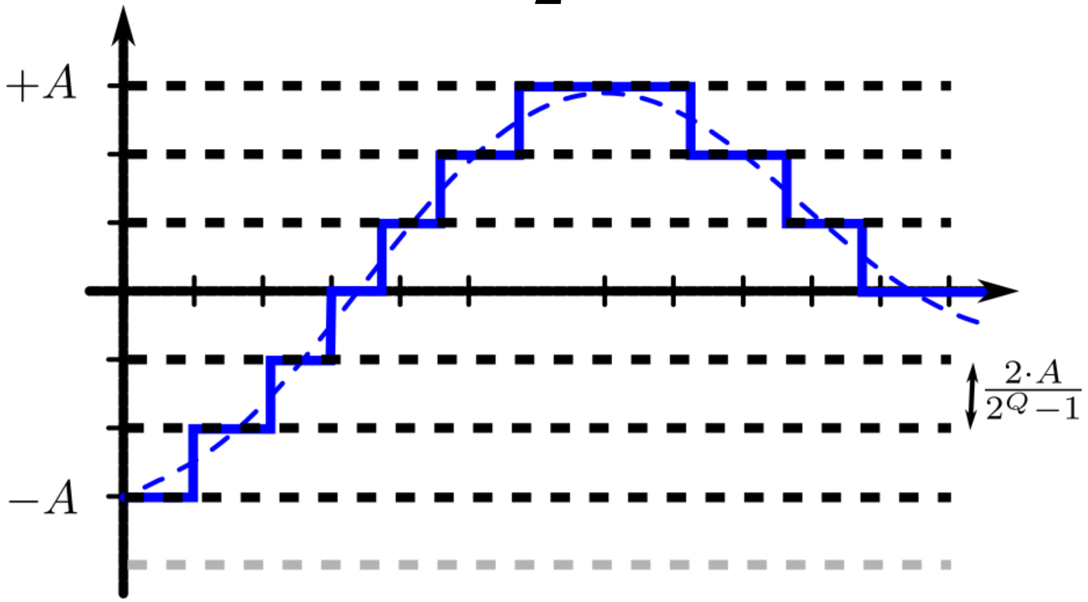
- **Accurate calculation of the mean squared quantization error is difficult**
  - Signal dependent non-linear function



Uniform Quantizer Error (Mean)

- **Quantizers are nonlinear time invariant systems**

$$\nu \approx \frac{A}{2^{Q-1}}$$



- **Accurate calculation of the mean squared quantization error is difficult**
  - Signal dependent non-linear function
- **Approximation of the mean squared quantization error:**
  - Assume that the signal is uniformly distributed between two quantization levels

$$MSE_Q = \frac{1}{\nu}\int_{-\frac{\nu}{2}}^{\frac{\nu}{2}} |x|^2\,dx = \frac{\nu^2}{12} = \frac{1}{12}\cdot\frac{A^2}{2^{2Q-2}} = \frac{1}{3}\cdot\frac{A^2}{2^{2Q}}$$

Signal-Quantization-Ratio (SQR)

- **For quantized signals we are interested in the Signal-to-Quantization Ratio**
  - Assuming that the signal power is proportional to A^2
  - Mean squared quantization error is given by $MSE_Q = \frac{1}{3} \cdot \frac{A^2}{2^{2Q}}$

$$SQR \propto \frac{A^2}{\frac{1}{3} \cdot \frac{A^2}{2^{2Q}}} \propto 2^{2Q}$$

$$SQR_{\mathrm{dB}} = c + Q \cdot \underbrace{2 \cdot \log_{10} 2}_{6\mathrm{dB}} = c + Q \cdot 6\mathrm{dB}$$

Increasing the resolution of the quantizer by 1-bit improves the SQR by 6dB

Signal Quality for Binary PCM

- **We assume that the transmission of the PCM signal is error free**
- **The quality is given by the number of bits we can use for a given channel**

- **Example: we have the following**
  - Audio signal $m(t)$ with bandwidth BW_m → Sampling rate $f_s = 2 \cdot BW_m$
  - Communication channel with bandwidth BW_{ch} → Bit rate $f_{bit} = 2 \cdot BW_{ch}$

$$Q_{max} = \frac{2 \cdot BW_{ch}}{2 \cdot BW_m} = \frac{BW_{ch}}{BW_m}$$

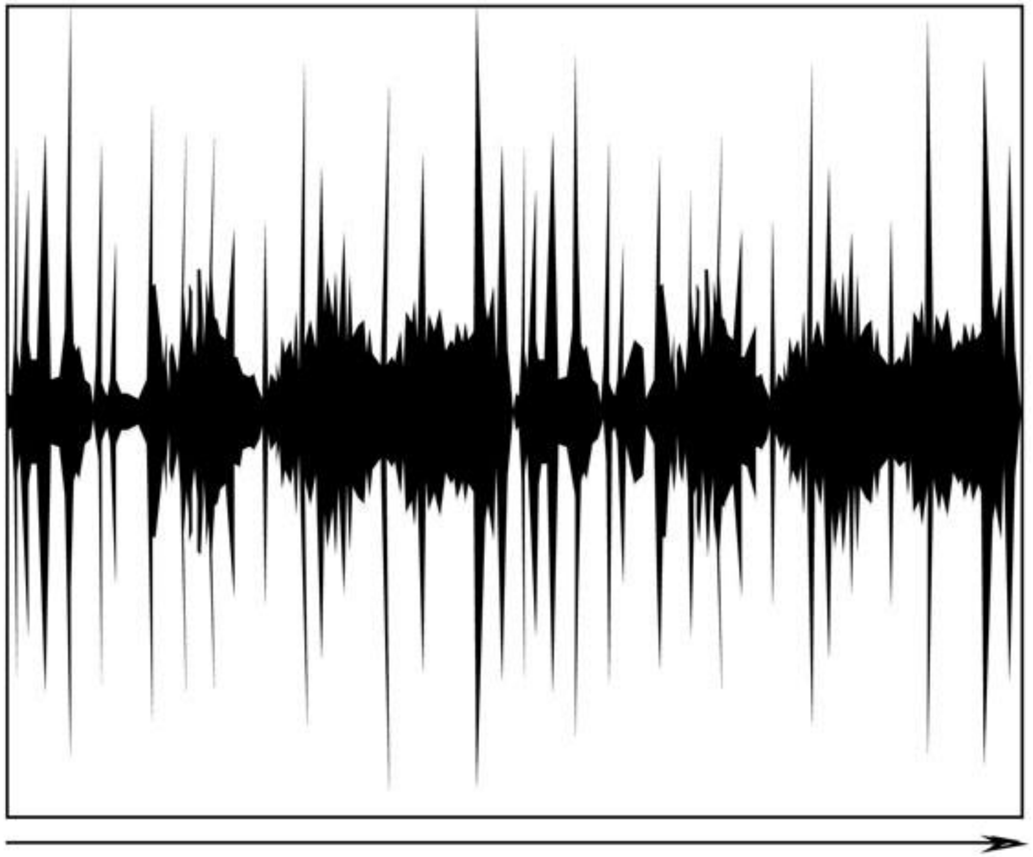
$$SQR_{\mathrm{dB}} = c + \frac{BW_{ch}}{BW_m} \cdot 6\mathrm{dB}$$

  - Increasing the communication channel BW by BW_m allows to increase the signal quality by $6\mathrm{dB}$

Quantization of Speech Signals

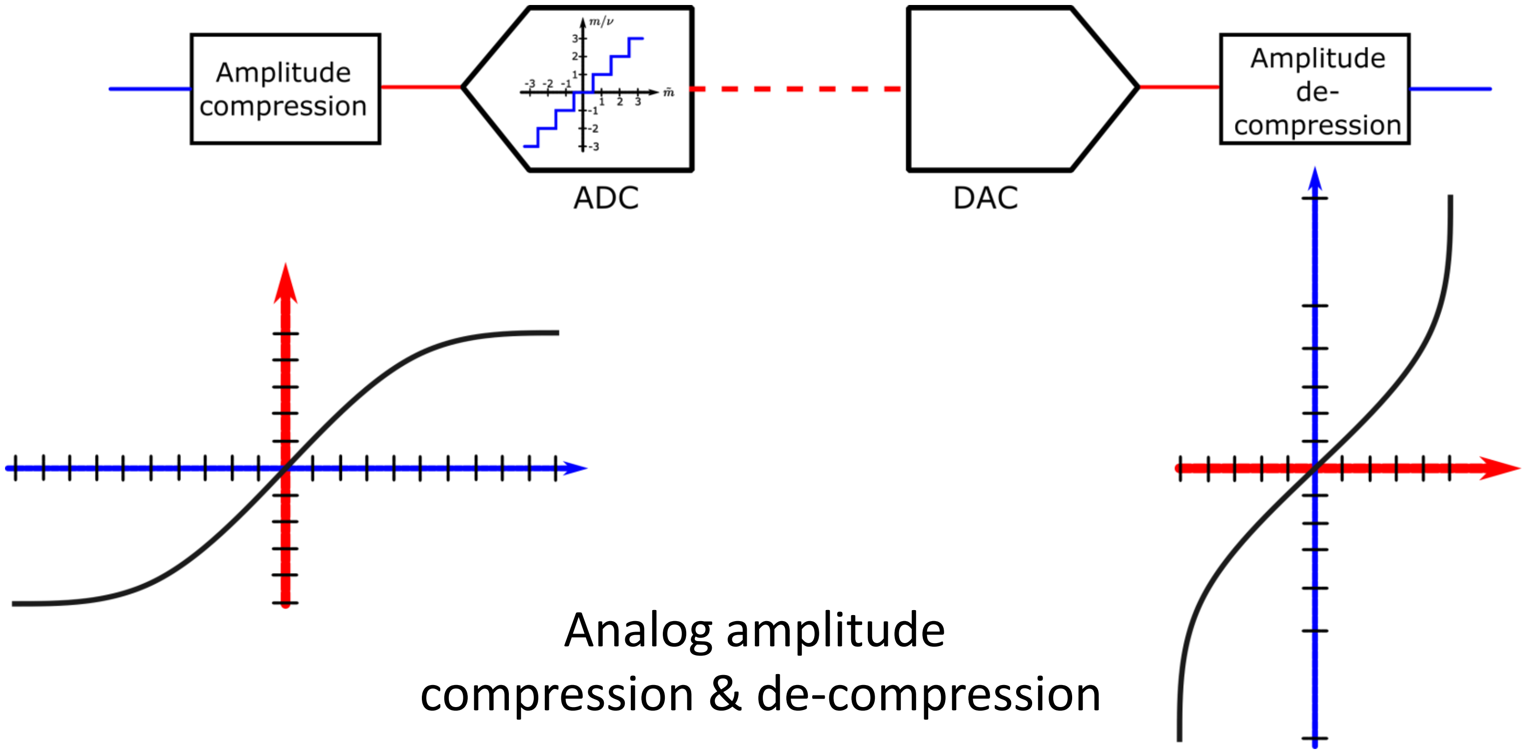
- **Linear quantization step size adapted to peak amplitude**
- **Linear quantization wastes resolution on large amplitudes**, where human hearing is less sensitive
- **Speech signals** are mostly low amplitude → **need better resolution near zero**
- **Solution:** Non-uniform quantization

Peak envelope of program signal over 20-second period



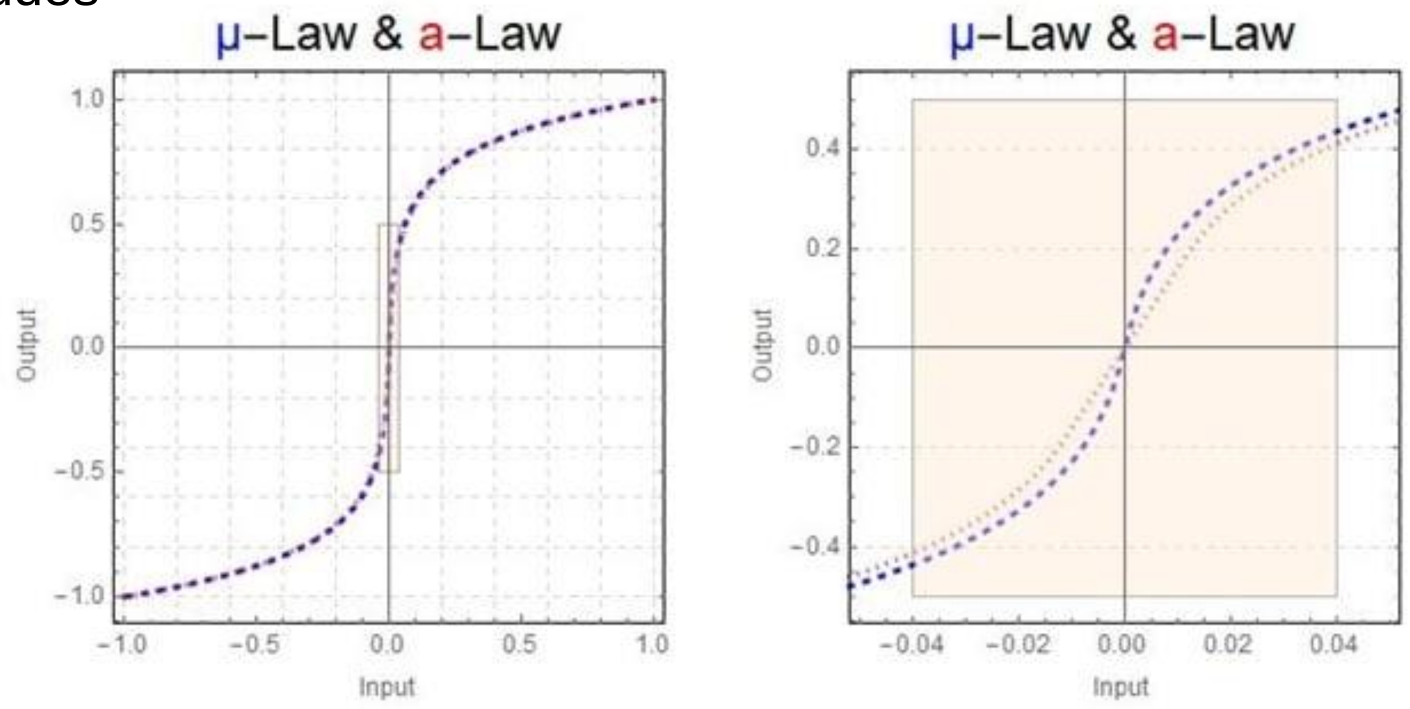
Non-linear Quantization with Amplitude Compression

- **Basic idea:** compress analog signal into a smaller range prior to quantization
  - Analog compression: prior to sampling & quantization
  - Digital compression: first sample with a high resolution, then compress and re-quantize



Non-linear Quantization: μ-Law and A-Law

- **Two popular compressions: μ-law and A-law with log-like behaviour**
  - Very similar, especially at high magnitudes
  - Slight differences for low magnitudes



- **U-Law (Noth America, Japan)**

$$F(x) = \text{sign}(x) \cdot \frac{\ln(1+\mu|x|)}{\ln(1+\mu)}, \ \mu = 255$$

- **A-Law (Europe, ITU-T global)**

$$F(x) = \begin{cases} \dfrac{A|x|}{1+\ln A} & |x| < \dfrac{1}{A} \\ \dfrac{1+\ln A|x|}{1+\ln A} & \dfrac{1}{A} \leq |x| \leq 1 \end{cases}, \ A = 87.6$$

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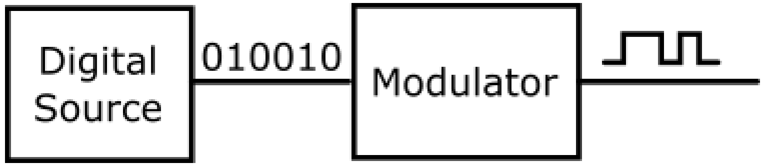
Digital Data Transmission & Error Rates in the Baseband

Week 5: Table of Contents

- **PCM Pulse Shapes and their Bandwidths**
- **Higher Order Digital PAM (M-PAM) for Higher Data Rates**
- **Applications**

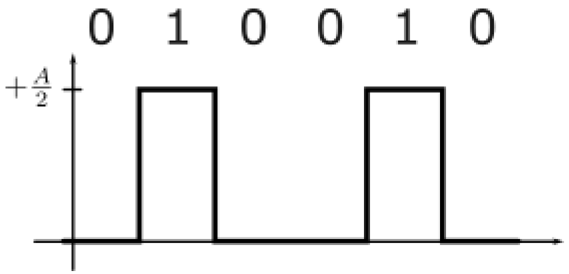
PCM Modulator: Unipolar vs. Bipolar

- **PCM encodes bits (0/1) into analog values, chosen from a binary alphabet**



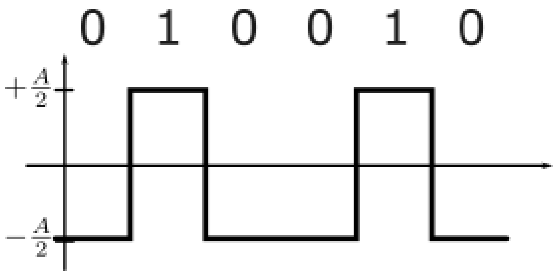
- **We distinguish between unipolar (only positive symbols) and bipolar (positive and negative, symmetric symbols) alphabets**
  - For reasons we will see later, we keep the “distance” between two symbols the same

Unipolar binary alphabet



$$\{0,1\} \longrightarrow \{0, A\}$$

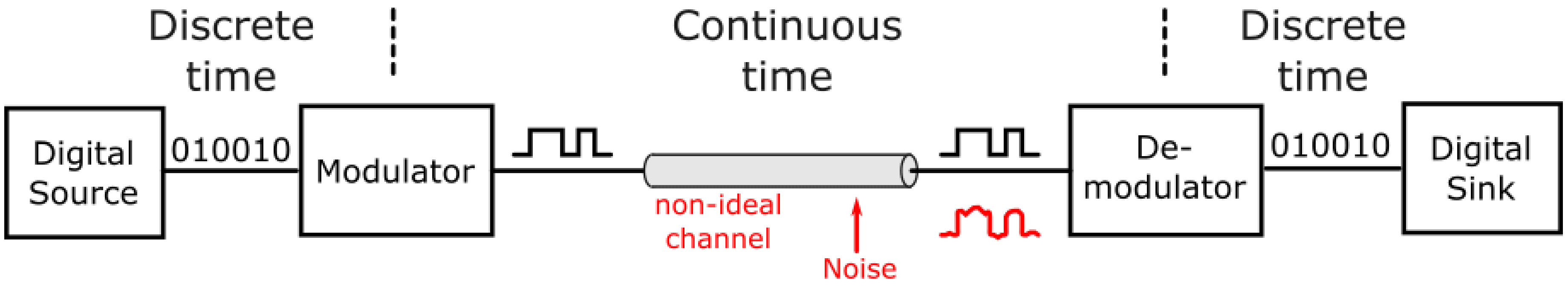
Bipolar binary alphabet



$$\{0,1\} \longrightarrow \left\{-\frac{A}{2}, +\frac{A}{2}\right\}$$

PCM Modulator: Pulse Shapes

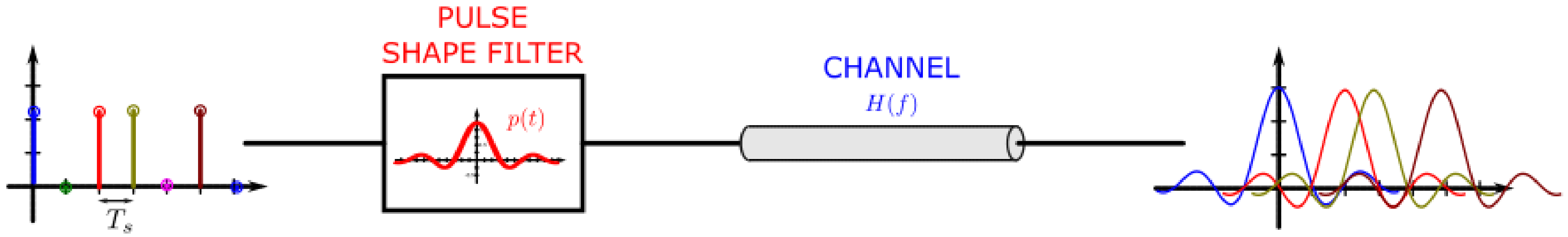
- **PCM transmits a series of bits over a continuous time / analog channel**
  - Transmitter: convert discrete time bits into bits as a series of continuous time pulses
  - Receiver: Recover the discrete time bits from the continuous time pulses through sampling



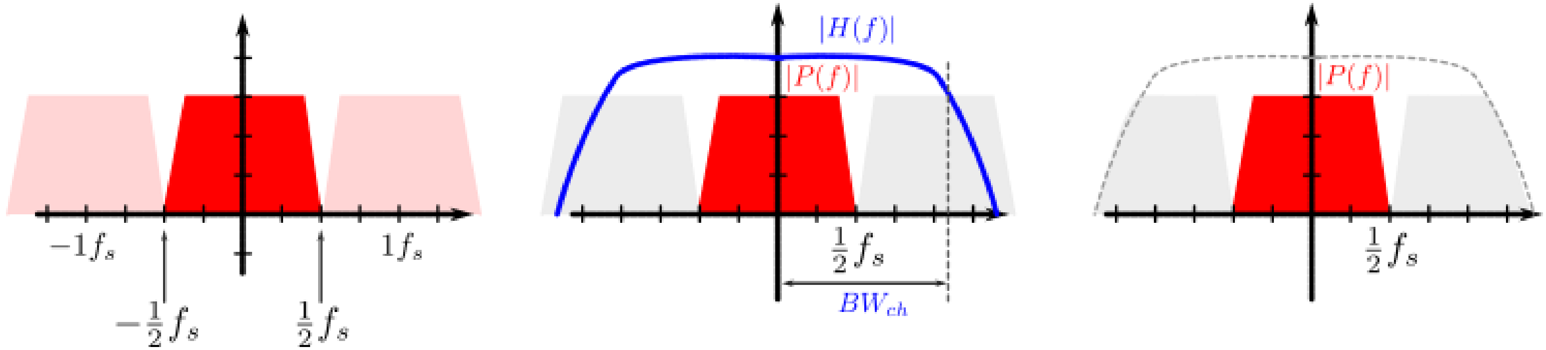
- **Transmission channel: distorts the signal by**
  - its typically low-pass frequency characteristics
  - adding noise (actually added at the receiver, but considered part of the channel)

PCM Modulator: Pulse Shapes

- **Conversion of discrete bits into a continuous time signal of “pulses” so that**
  - are not or almost not affected by the low-pass frequency characteristics of the channel
  - can be recovered easily (independently of each other) at the receiver



$$f_s = \frac{1}{T_s}: \text{BAUD Rate}$$

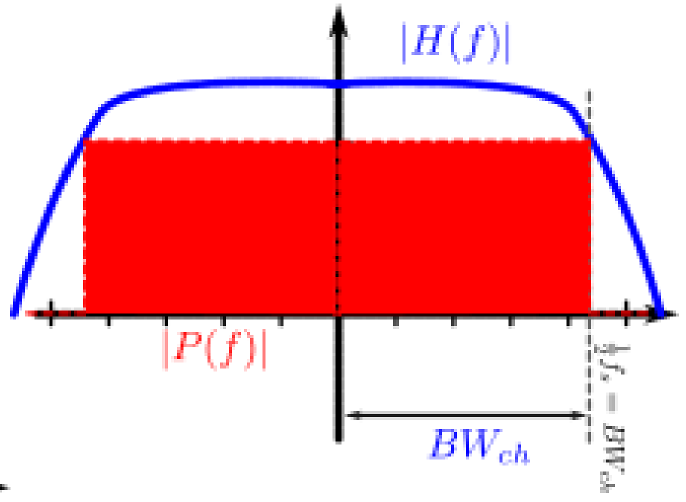


- **Choose pulse-shape filter and baud rate (sampling frequency) so that the fundamental spectrum of the signal is not affected by the low-pass channel**

$$f_s \leq 2 \cdot BW_{ch}$$

PCM Modulator: Ideal SINC Pulse

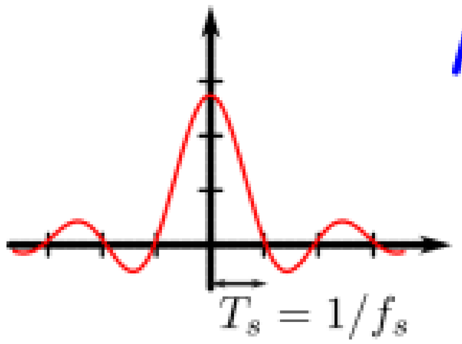
- **For $f_s = 2 \cdot BW_{ch}$ we need an ideal (brick-wall) pulse shape filter with the bandwidth of the channel**



$$P(f) = \Pi\left(\frac{f}{2 \cdot BW_{ch}}\right) = \Pi\left(\frac{f}{f_s}\right)$$

  - Pulse shape impulse response:

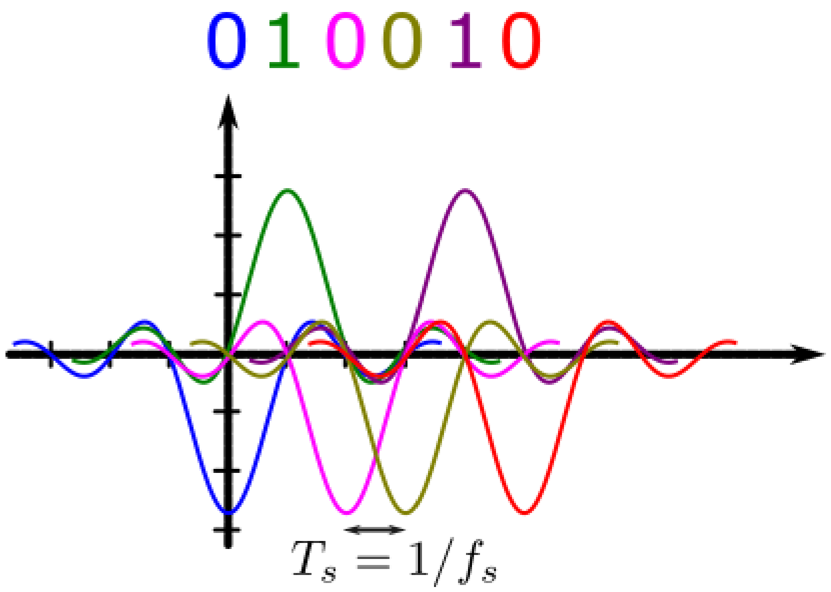
$$p(t) = \frac{\sin(\pi \cdot f_s \cdot t)}{\pi \cdot f_s \cdot t}$$



  - Data sequence with bipolar alphabet: $a_k \in \left\{-\frac{A}{2}, +\frac{A}{2}\right\}$

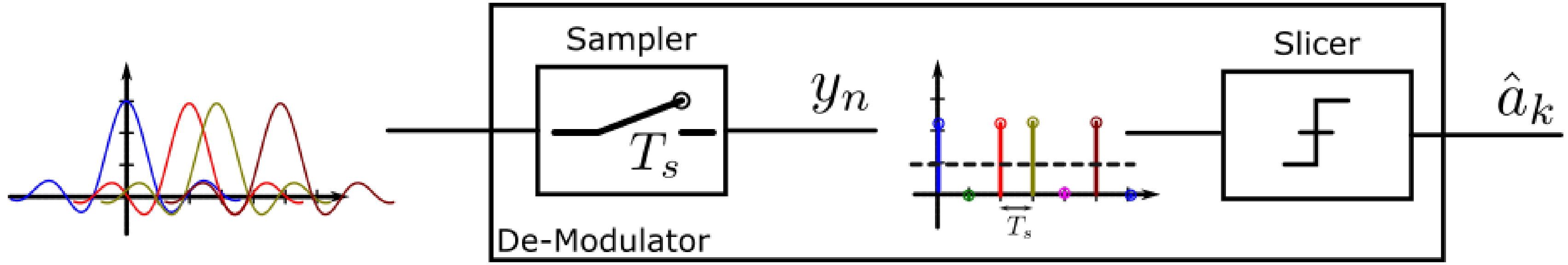
- **Received signal is the superposition of weighted transmit pulses delayed by $k \cdot T_s$**

$$y(t) = \sum_{k=-\infty}^{+\infty} a_k \cdot p(t - k \cdot T_s)$$

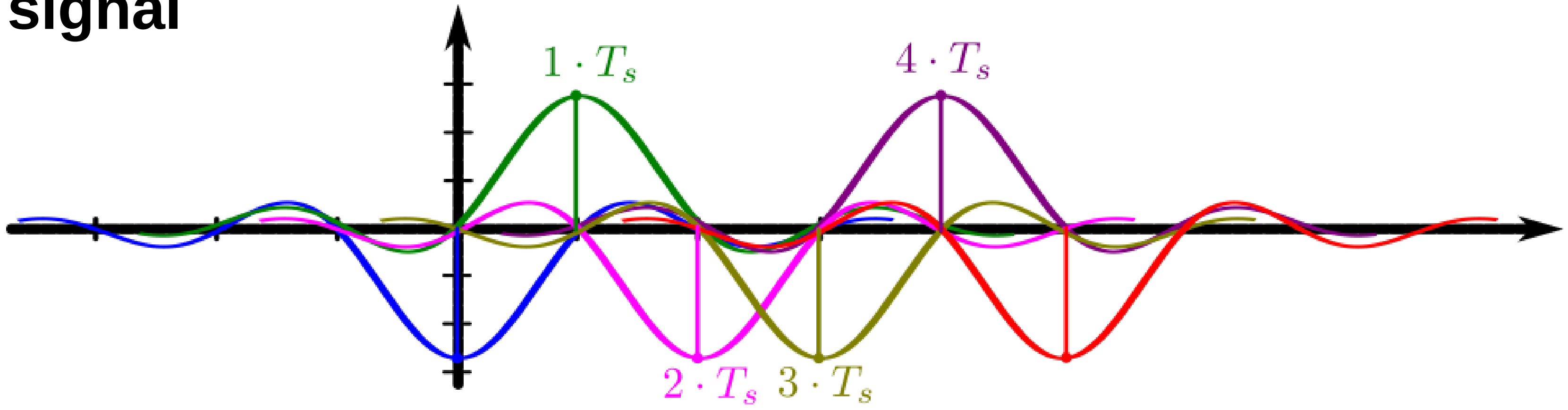


PCM Demodulation with SINC Pulse

- **Despite the overlap between Nyquist pulses, we can perfectly recover the original transmitted symbols by sampling at the right moment in time**



- **At $t = n \cdot T_s$, all overlapping symbols except one are zero and have no impact on the received signal**



PCM Demodulation with SINC Pulse

- **Despite the overlap between Nyquist pulses, we can perfectly recover the original transmitted symbols by sampling at the right moment in time**

- **Proof:**
  - Remember: $\frac{\sin(k\cdot\pi)}{k\cdot\pi} = \begin{cases} \mathbf{1} & \boldsymbol{k = 0} \\ \mathbf{0} & \boldsymbol{k \neq 0} \end{cases}$

$$y_k = y(t)\Big|_{t=k\cdot T_s} = \sum_{l=-\infty}^{+\infty} a_k \cdot \frac{\sin(\pi\cdot f_s\cdot(n-l)\cdot T_s)}{\pi\cdot f_s\cdot(n-l)\cdot T_s} =$$

$$+a_k \cdot \underbrace{\frac{\sin(\pi\cdot f_s\cdot(0)\cdot T_s)}{\pi\cdot f_s\cdot(0)\cdot T_s}}_{1} + \sum_{l\neq k} a_k \cdot \underbrace{\frac{\sin(\pi\cdot f_s\cdot(l-k)\cdot T_s)}{\pi\cdot f_s\cdot(l-k)\cdot T_s}}_{0}$$

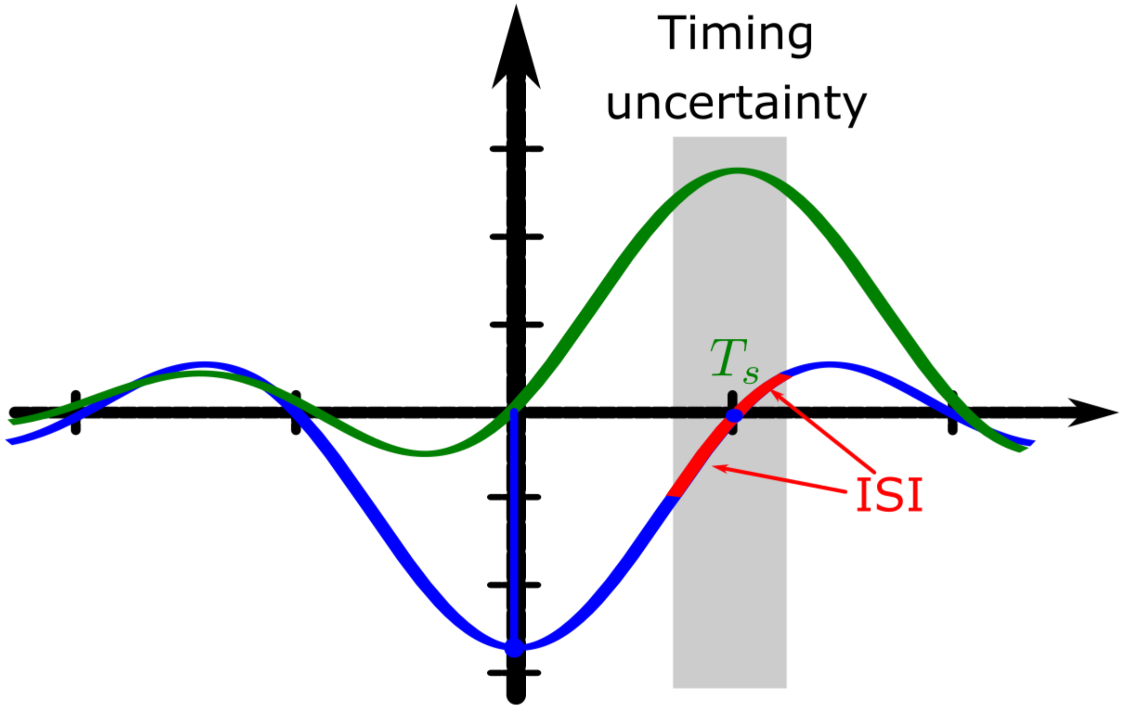
PCM with Non-Ideal SINC Pulses

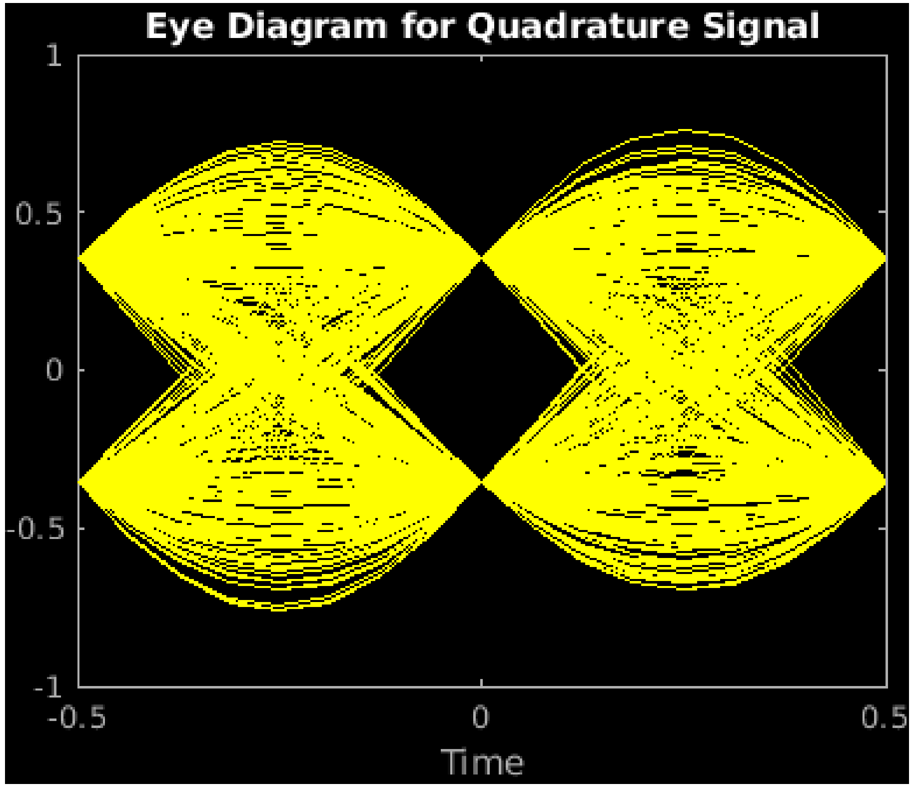
- **A SINC uses the available bandwidth in the best possible (optimal) way:**
  - For a given baud rate f_s, it uses the least possible bandwidth $BW_{ch} \geq f_s/2$
  - For a given channel bandwidth BW_{ch} it allows for the highest baud rate $f_s \leq 2 \cdot BW_{ch}$
- **Nevertheless, SINC pulses also have a practical disadvantage:**
  1. Any non-ideal sampling instant at the receiver leads to strong interference between symbols
  2. Cutting the tail impacts the spectrum (no longer an ideal brick-wall with strong spectral components far away from the intended bandwidth)

See next 2 slides

PCM with Non-SINC (non-ideal) Pulses

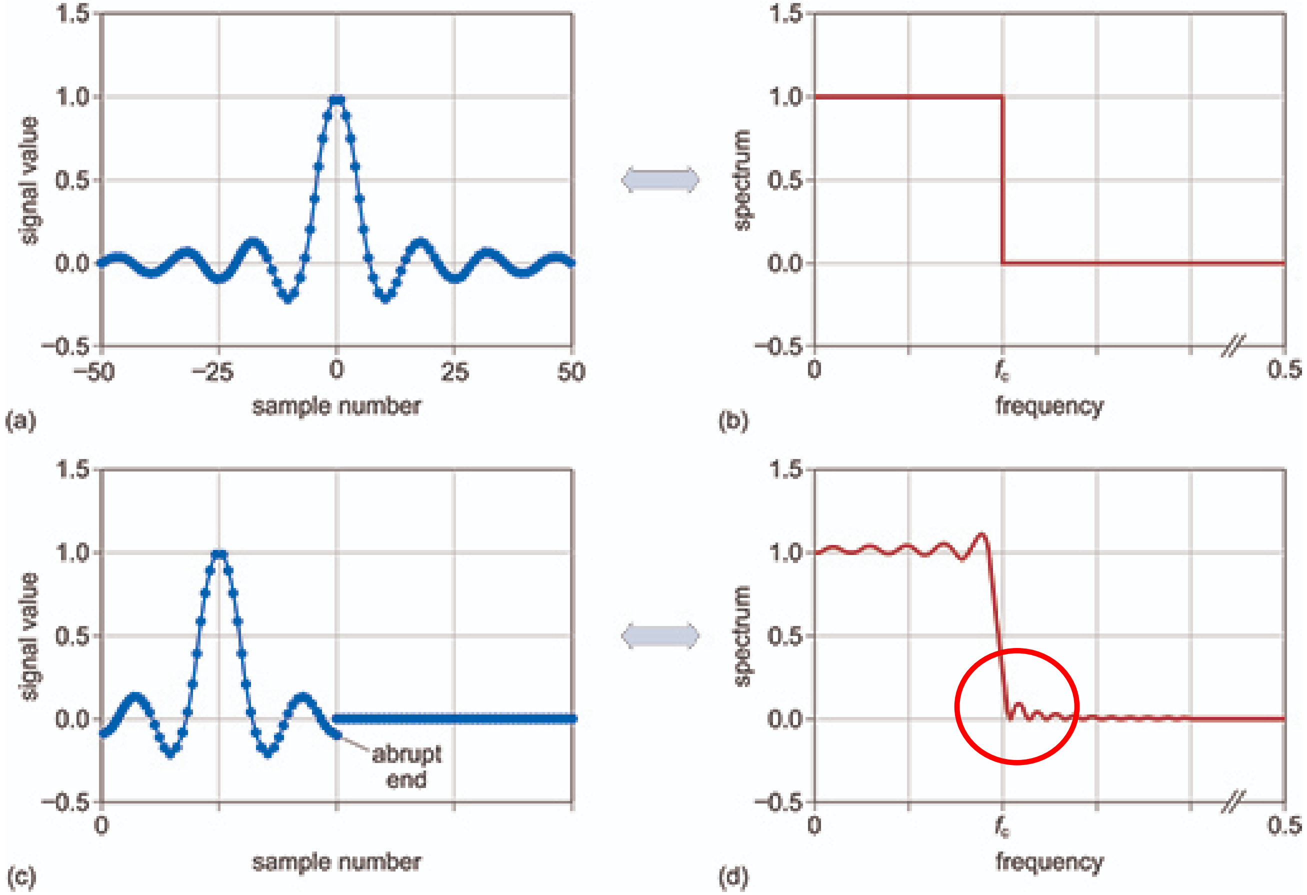
1. Any non-**ideal sampling instant at the receiver** leads to strong interference between symbols





PCM with Non-SINC (non-ideal) Pulses

2. Cutting the tail impacts the spectrum (no longer an ideal brick-wall with strong spectral components far away from the intended bandwidth)



Source: https://www.open.edu/openlearn/science-maths-technology/electronic-applications/content-section-3.7

Alternative (Non-Sinc) Pulse Shapes

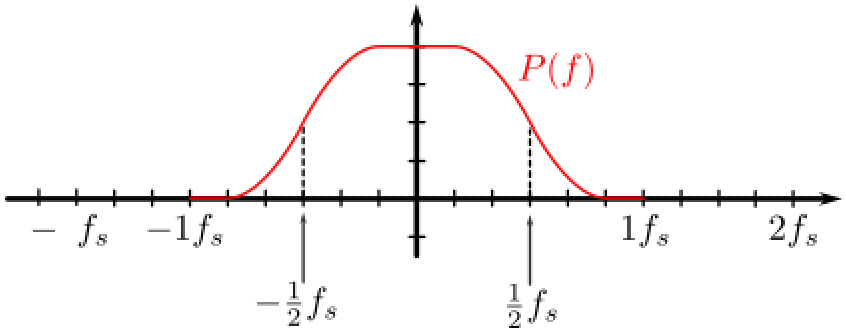
- **To achieve ISI free transmission, we actually only require:**

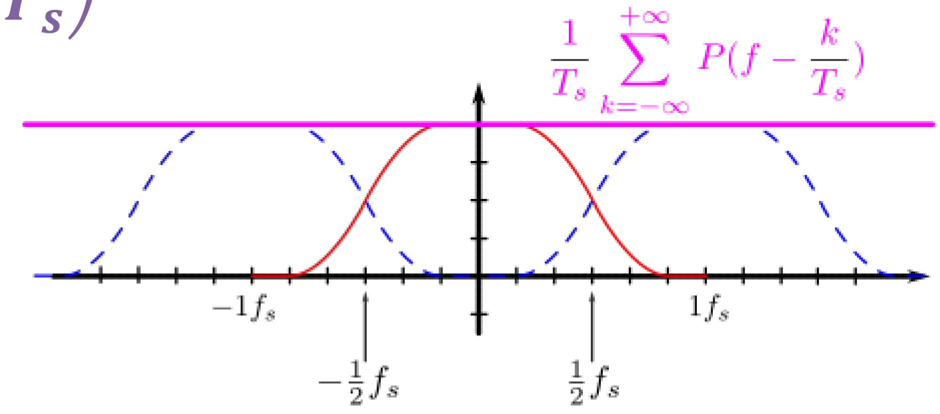
$$p(k \cdot T_s) = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases}$$

  - Any pulse with this criterion should be able to perfectly reconstruct the symbols a_k at $t = k \cdot T_s$

- **The 2nd Nyquist criterion defines such non-SINC pulses, that are ISI free, but have a BW that is greater than half the sampling frequency** $BW_p > \frac{f_s}{2}$

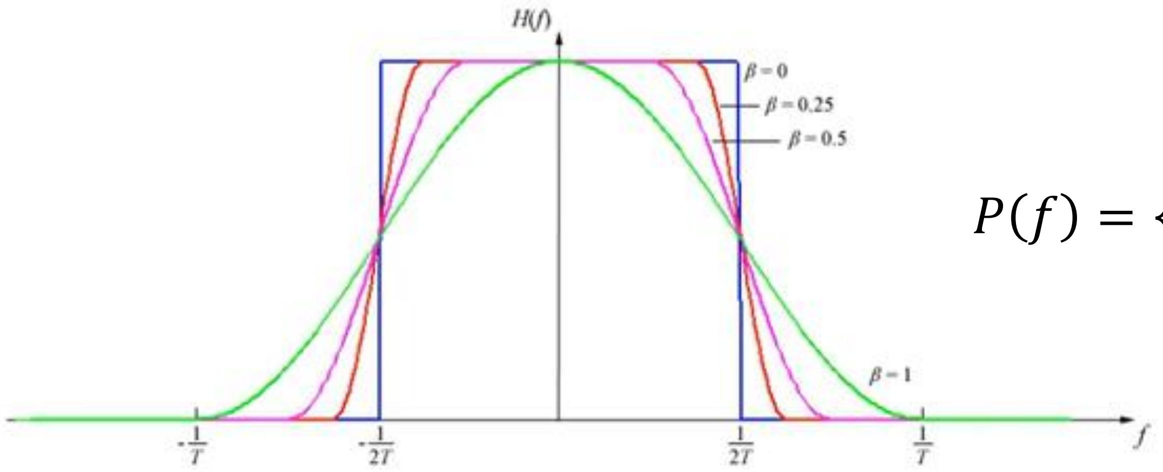
$$\sum_{k=-\infty}^{+\infty} P\left(f - \frac{k}{T_s}\right) = CONST.$$



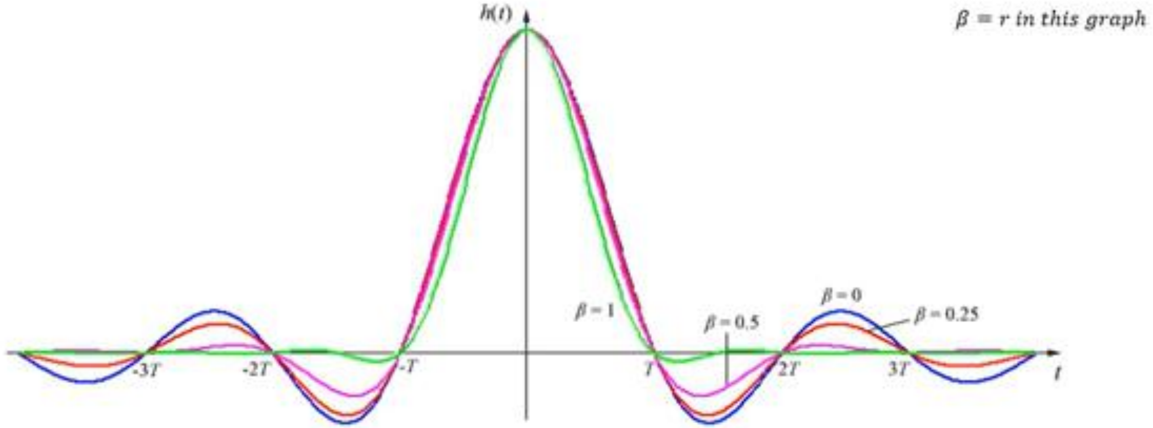


Raised Cosine Pulse (1)

- **The most famous Non-SINC pulse is the Raised Cosine Pulse**



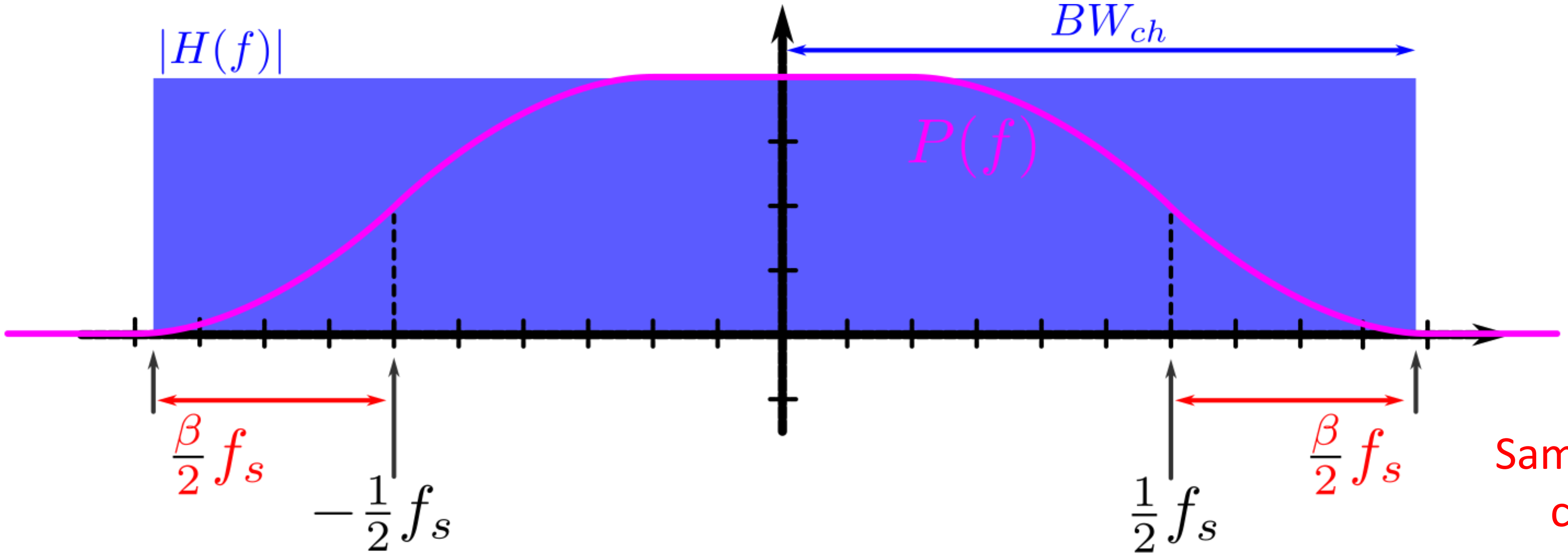
$$P(f) = \begin{cases} 1 & |f| < \frac{1-\beta}{2T_s} \\ \frac{1}{2}\left[1 + \cos\left(\frac{\pi T_s}{\beta}\left[|f| - \frac{1-\beta}{2T_s}\right]\right)\right] & \frac{1-\beta}{2T_s} < |f| \le \frac{1+\beta}{2T_s} \\ 0 & else \end{cases}$$



$$p(f) = \begin{cases} \frac{\pi}{4T_s}\,\mathrm{sinc}\,\frac{1}{2\beta} & t = \pm\frac{T}{2\beta} \\ \frac{1}{T_s}\,\mathrm{sinc}\,\frac{t}{T_s}\,\frac{\cos\left(\frac{2\beta t}{T_s}\right)}{1 - \left(\frac{2\beta t}{T_s}\right)^2} & else \end{cases}$$

Raised Cosine Pulse (2)

- **For $|f| > \frac{1+\beta}{2T_s} = \underbrace{\frac{1}{2T_s}}_{f_s/2} + \frac{\beta}{2T_s}$, there are no spectral components**
  - The first part $\frac{1}{2T_s}$ corresponds to the spectrum used by the ideal SINC filter
  - The second part $\frac{\beta}{2T_s}$ corresponds to the excess spectrum



$$\frac{1+\beta}{2} f_s < BW_{ch}$$

$$f_s < \frac{2 \cdot BW_{ch}}{1+\beta}$$

Sampling rate with a band-limited channel and Raised Cosine β

EPFL

Relationship Between Baud Rate and Bandwidth

	Maximum baud rate f_s, given a channel bandwidth BW_{ch}	Occupied spectrum BW given a baud rate f_s
Theoretical	$f_s = 2 \cdot BW_{ch}$	$BW = \frac{1}{2} f_s$
Realistic (rolloff β*)	$f_s = \frac{2}{1+\beta} \cdot BW_{ch}$	$BW = \frac{1+\beta}{2} f_s$

* Typical rolloff factors are $\beta = 0.6 - 0.8$

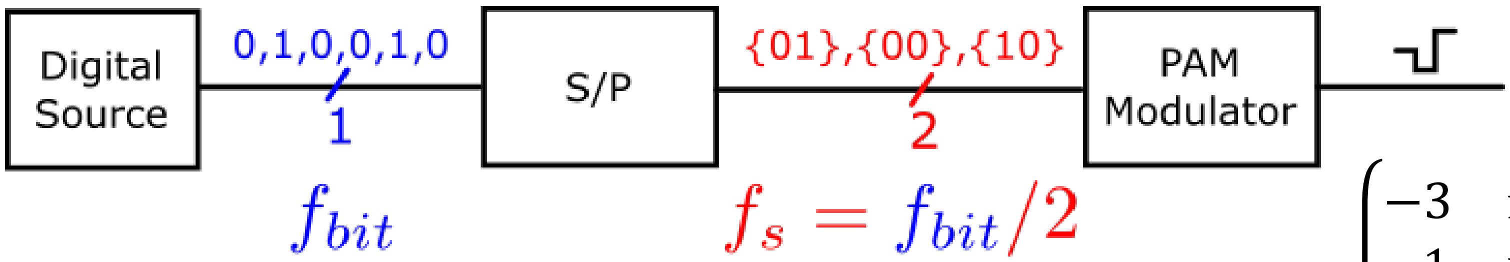
BW is the bandwidth that is occupied by the signal, regardless of if the channel supports it

Higher-Order Pulse Amplitude Modulation (M-PAM)

- **For a given bandwidth, the data rate with binary PCM is limited by the bandwidth as we send only 1 bit for every "symbol" (**$a_k \in \left\{-\frac{A}{2}, +\frac{A}{2}\right\}$**)**

- **Higher order symbol alphabets: grouping of multiple bits into one symbol**
  - Grouping of bits represented as serial-to-parallel (S/P) conversion

- **Example 4-PAM: grouping of 2 bits into one symbol with bit rate f_{bit} [bits/s]**



$$a_k \in \begin{cases} -3 & \text{message bits } 00 \\ -1 & \text{message bits } 01 \\ +1 & \text{message bits } 10 \\ +3 & \text{message bits } 11 \end{cases}$$

Efficiency: 2 bits / symbol

M-PAM Constellation Points & Alphabets

- **Grouping Q bits into one symbol increases the throughput Q-times, but requires an alphabet with $\mathrm{M} = 2^Q$ elements (levels)**

Information throughput per symbol

$$I_M = Q = \log_2 M$$

  - For a given baud-rate $\boldsymbol{f_s}$ we have $\boldsymbol{f_{bit}} = I_M \cdot \boldsymbol{f_s}$

- **Values that represent a combination of bits are called constellation points**
- **The set of constellation points $\mathcal{O}$ to represent groups of $Q = \log_2 M = \log_2|\mathcal{O}|$ bits is called a constellation alphabet**

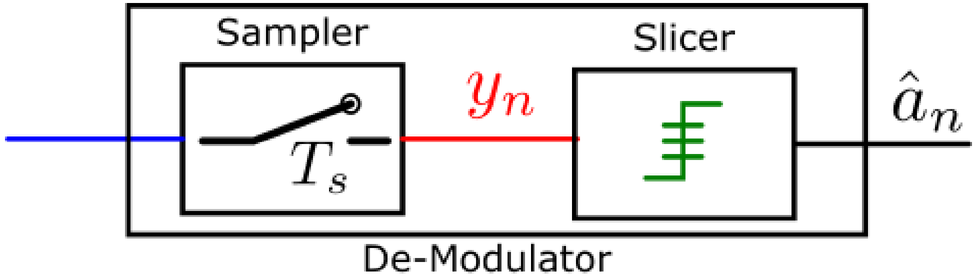
$$\boldsymbol{\mathcal{O} = \{x_0, x_1, x_2, \ldots, x_{M-1}\}}$$

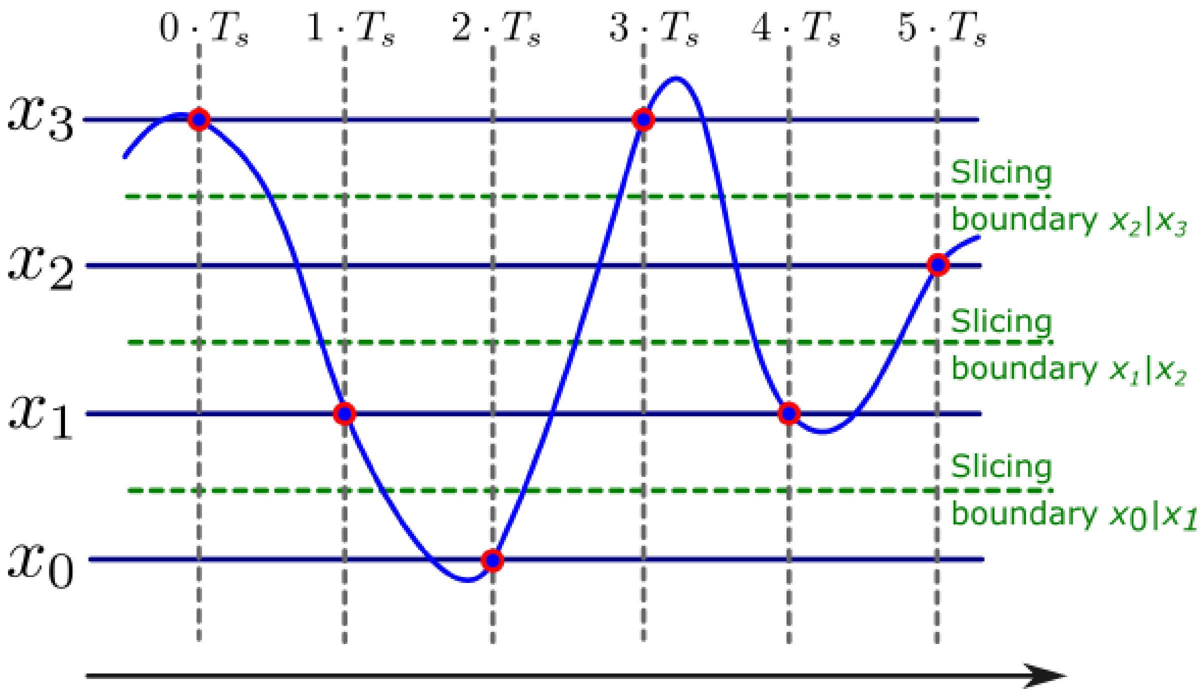
M-PAM Signal Reception w/o Noise

- **Consider a 4-PAM signal (received without noise and without attenuation)**

- **Demodulation**
  - **Sampler**: sample signal at the correct time instant to reveal the transmitted symbol without interference
  - **Slicer**: decide on the closest valid constellation point based on decision boundaries

$$a_m = k \text{ if } \left(y_n > \frac{x_m + x_{m-1}}{2}\right) \text{ and } \left(y_n < \frac{x_m + x_{m-1}}{2}\right)$$
$$x_{-1} = -\infty \,; x_M = +\infty$$





M-PAM Signal Power

- **As symbols are different, the power of each symbol may also be different**
  - Consider the power of the sampled signal: $P_n = |a_n|^2$

- **In general, we are mostly interested in the average signal power $\bar{P}_s$**
  - For a specific signal example (but with many samples)

$$\bar{P}_s = \lim_{N\to\infty} \frac{1}{N} \sum_{k=0}^{N-1} |a_k|^2$$

  - To be more general, it is reasonable to assume that the symbols $a_k \in \mathcal{O}$ are all equally likely

$$\Pr(a_k = x_i) = \frac{1}{N} \text{ for all } i = 0, \dots, M-1$$

$$\bar{P}_{\mathcal{O}} = \frac{1}{M} \sum_{m=0}^{M-1} |x_m|^2$$

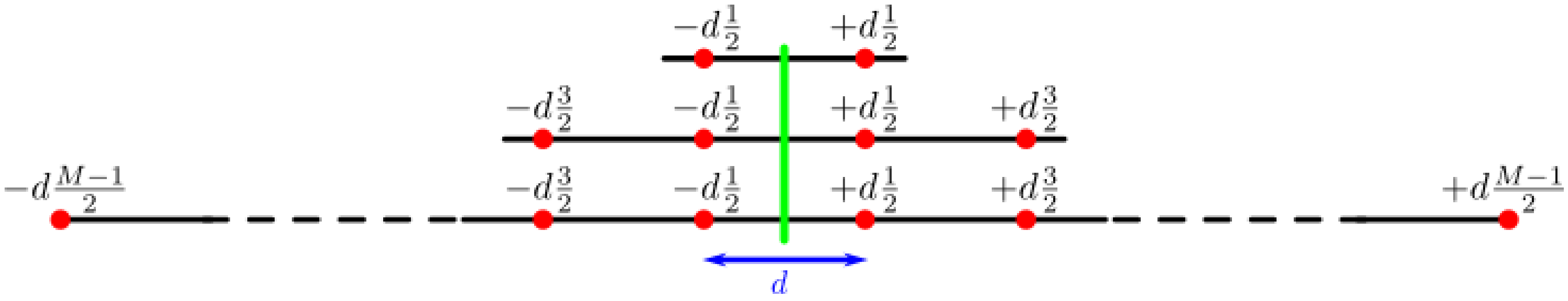
M-PAM Constellation Construction

- **Constructing a constellation involves two steps:**
  - Defining the values of the constellation points $\mathcal{O} = \{\boldsymbol{x_0}, \boldsymbol{x_1}, \boldsymbol{x_2}, \dots, \boldsymbol{x_{M-1}}\}$
  - Assigning a combination of bits to each constellation point

- **There are two strategies to define the values of the constellation points**
  - **Equal Distance** Construction: constellation points have same **distance $\boldsymbol{d}$** from their neighbours

$$x_{n+1} = x_n + d, n = 0, \dots, M-1, \text{given } x_0$$

Example: $x_0 = -\frac{M-1}{2} \rightarrow \mathcal{O} = \left\{\pm d\frac{1}{2}, \pm d\frac{3}{2}, \dots, \pm d\frac{M-1}{2}\right\}$



M-PAM Constellations Construction: Unit Power

- **Wireless systems: “average power” constrained by standards & regulations**
- **Unit Power** Construction: constellation points yield signal power of one $\bar{P}_s = 1$ while maintaining equal distance (defined by given power)

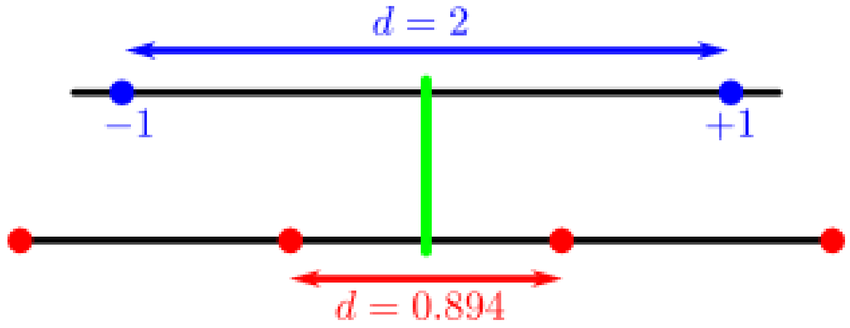
1. Start from equal distance construction with arbitrary distance d

$$x_{n+1} = x_n + d, n = 0, \dots, M-1, \text{given } x_0$$

$$\bar{P}_{\mathcal{O}} = \frac{1}{M} \sum_{m=0}^{M-1} |x_m|^2$$

2. Scale constellation points to achieve the desired average power level

$$\overline{x}_k = \frac{x_k}{\sqrt{\bar{P}_{\mathcal{O}}}} \quad ; \quad \overline{\mathcal{O}} = \{\overline{x}_0, \overline{x}_1, \overline{x}_2, \dots, \overline{x}_{M-1}\}$$



M-PAM Constellations Construction: Max. Amplitude

- **Wireline systems: circuit supply voltages define maximum amplitude**

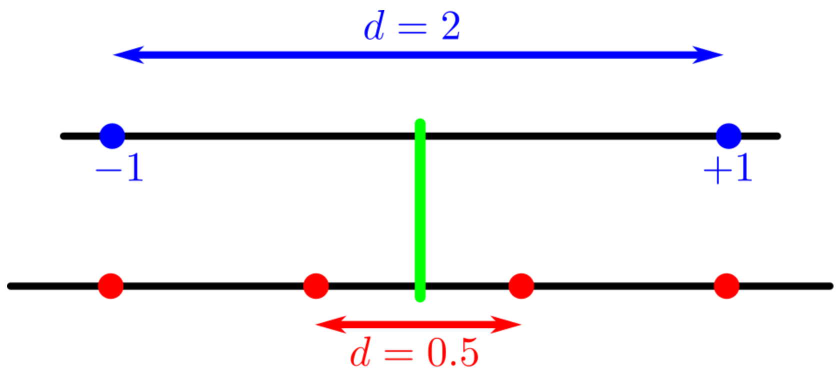
- **Maximum Amplitude** Construction: constellation points yield signal power of one $\bar{P}_s = 1$ while maintaining equal distance (defined by given power)

1. Start from equal distance construction with arbitrary distance d

$$x_{n+1} = x_n + d, n = 0, \dots, M-1, \text{given } x_0$$

2. Scale constellation points to achieve the desired average power level

$$\bar{x}_k = \frac{A}{M-1} x_k \quad ; \quad \bar{\mathcal{O}} = \{\bar{x}_0, \bar{x}_1, \bar{x}_2, \dots, \bar{x}_{M-1}\}$$



EE-432
Systeme de Telecommunication

Prof. Andreas Burg
Joachim Tapparel, Yuqing Ren, Jonathan Magnin

Applications

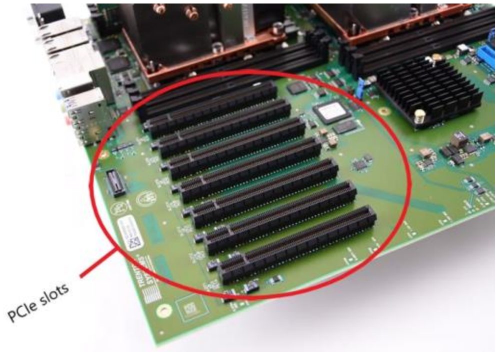
Applications of PCM Systems: Wireline

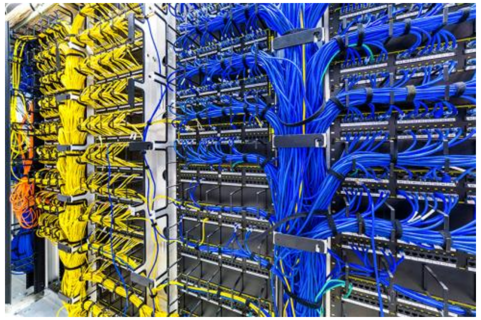
Telephone

USB

HDMI, Display Port, ...

Memory Interfaces

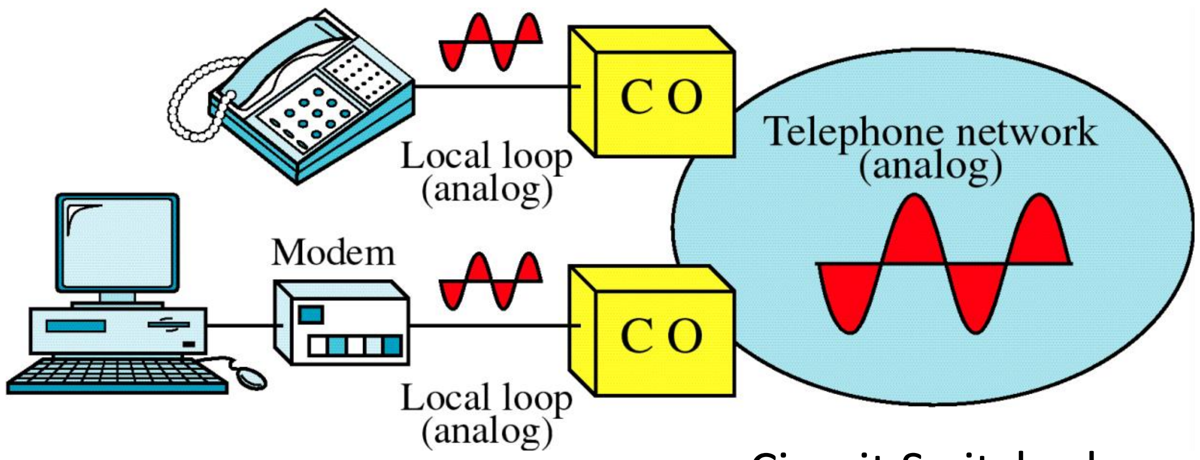




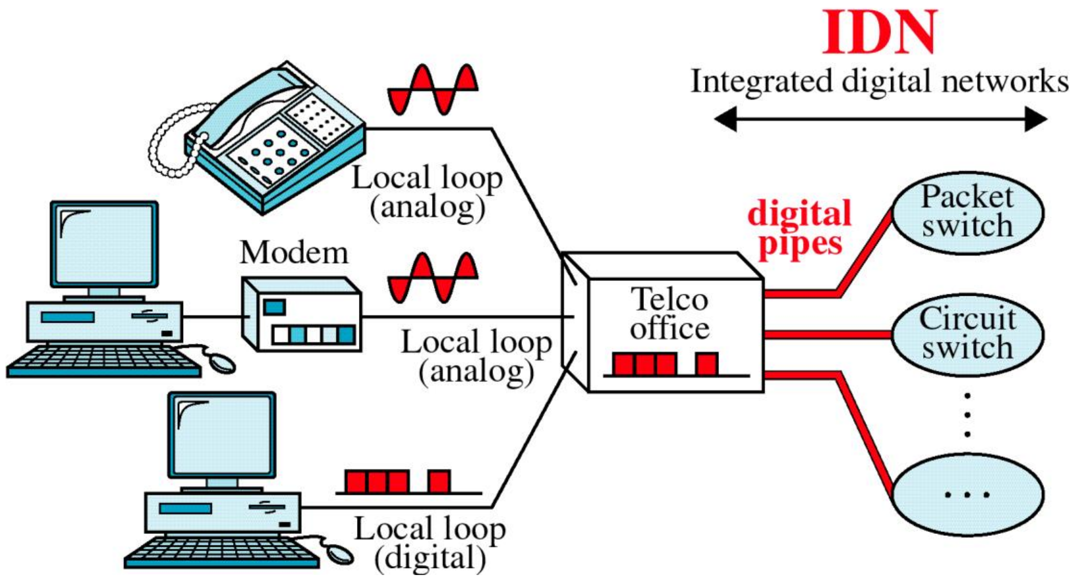
Computer Networks

ISDN Digital Telephony Motivation

- **Motivation in the late 1980s**
  - Increasing digitization of the global telephone network (with only local loop analog)
  - Increasing need for digital data communication over analog telephone network



Circuit Switched Network

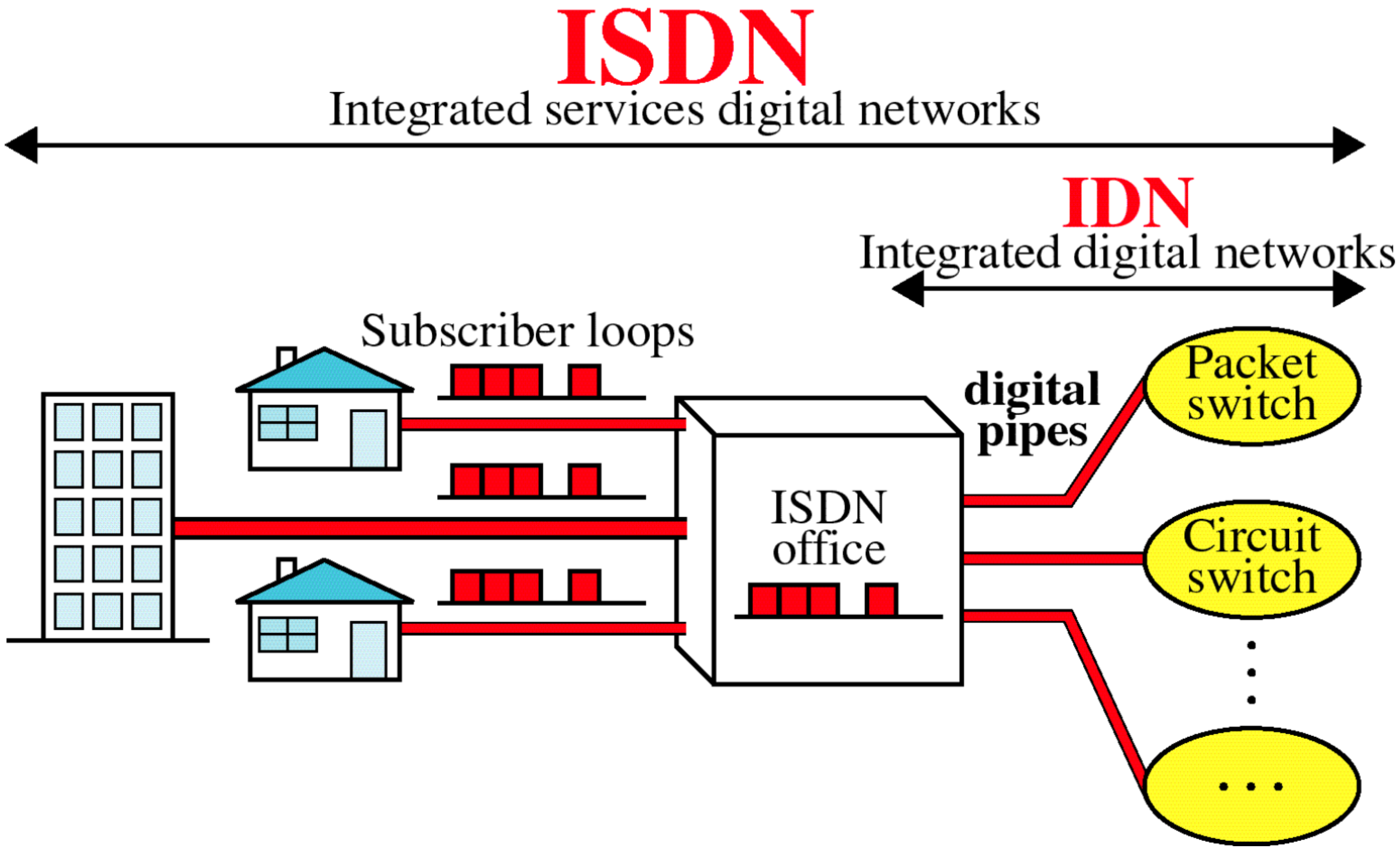


Packet Switched Network

- **Transition from analog local loop (end-user connection) to telephone network was inefficient. Need for new fully digital system**

ISDN Digital Telephony

- **ISDN: Integrated Services Digital Network**
  - Proposed in 1984, standardization completed in 1988, commercially available since 1992



Digital Telephone System: ISDN

- **ISDN:** Carry digitized voice using standard telephony bandwidth

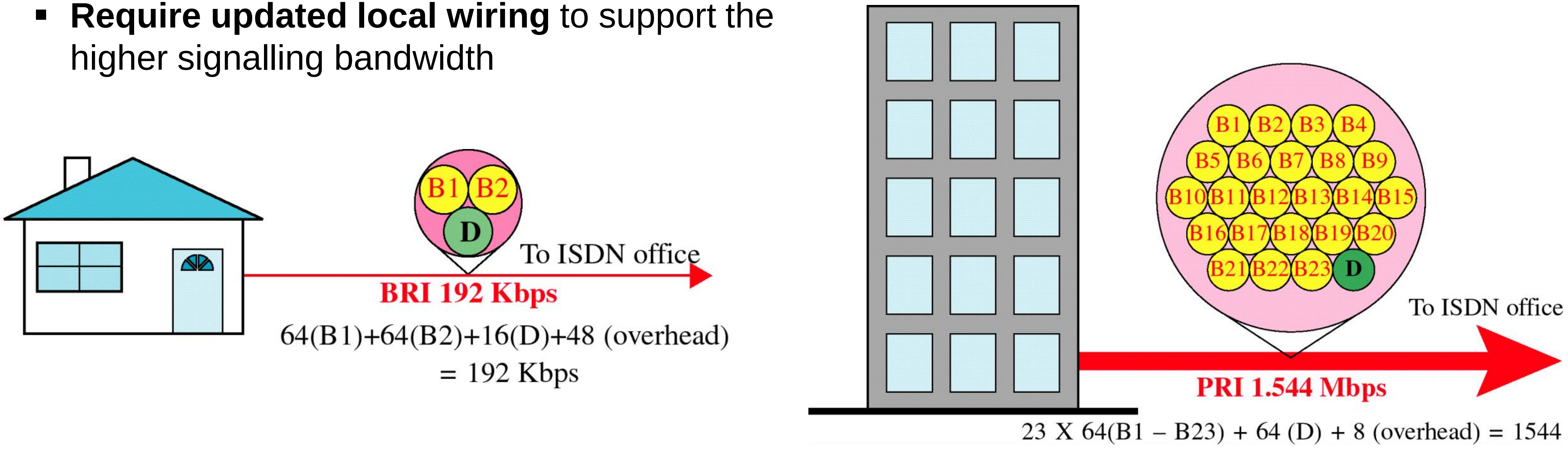
- **ISDN Voice Channels Bandwidth / Quantization:**
  - **Audio bandwidth**: ~300 Hz to 3400 Hz (speech-optimized passband)
  - **Nyquist rate**: To capture this bandwidth, the minimum sampling rate is 2 × 3400 = 6800 Hz
  - **Standard choice**: 8000 samples/second (8 kHz) is used in practice — the same rate as traditional PSTN systems.

  - Voice **quantization** with **8 bits/sample**
    - **Non-linear analog signal compression** based on A-law in Europe, μ-law in North America/Japan
    - No digital data compression

  - **64 kbps per voice channel** is referred to as a B-channel (Bearer channel) in ISDN
  - **Modulated using "2B1Q" (2 Binary 1 Quarternary) modulation (=4-PAM -3V,-1V,+1V,+3V)**

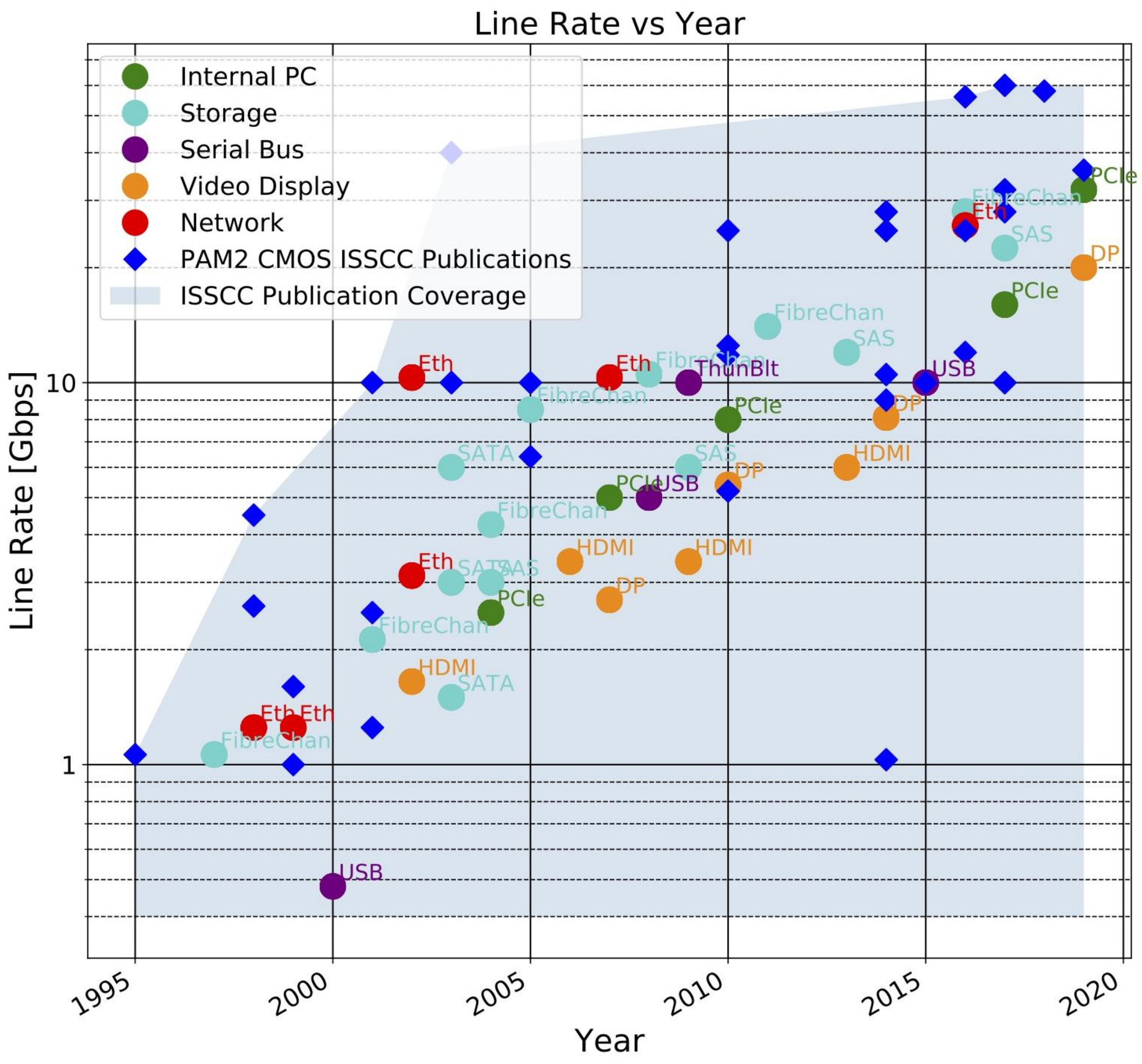
Digital Telephone System: ISDN

- **Basic Rate Interface (BRI):** residential and small-office customers
  - Two B-channels + one 16 Kbps D-channel (2B+D) and 48 Kbps of operating overhead
  - Can use the same **twisted-pair local loop** as analog network
- **Primary rate interface (PRI): business customers**
  - 23 B channels + one 64-kbps D channel and 8 kbps of overhead: 1.544 Mbps
  - **Require updated local wiring** to support the higher signalling bandwidth



SerDes High Speed Chip-to-Chip Links

- **High speed serial links are essential for many applications**
  - Optical Transmission: OC-192, OC-768, SONET
  - Internal PC: PCIe 1-5
  - Storage: Fibre Channel, SATA, SAS
  - Serial Bus: USB, Thunderbolt
  - Video Display: DisplayPort, HDMI



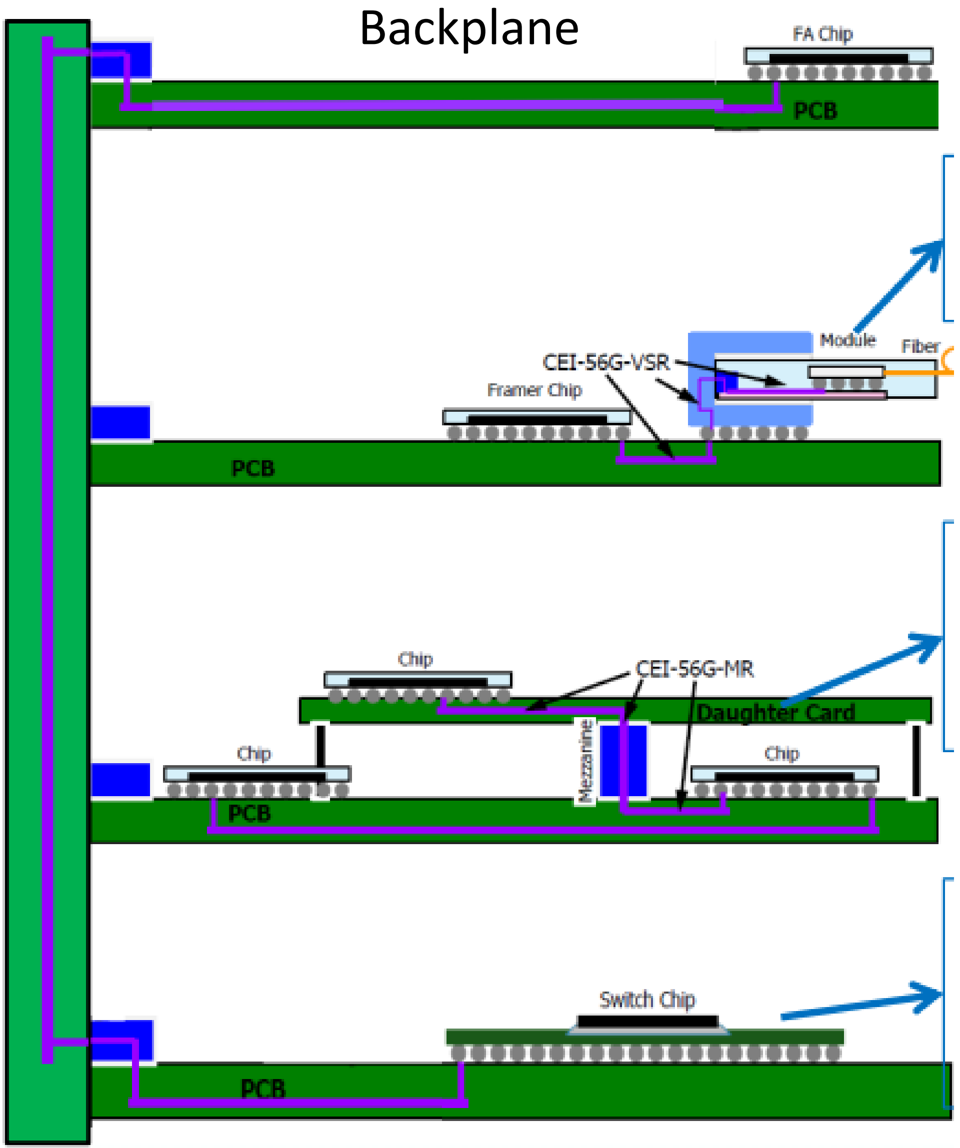
Ethernet

- **Purpose:** robust, and scalable method for local area communication (LAN)
  - Foundations developed in 1973
  - IEEE 802.3 standard since 1983 (10BASE5)

- **Evolution toward higher speed with** more parallel lanes, higher bandwidth, and higher order modulation

Standard	Data Rate	Modulation	Lanes	Baud rate	BW	Medium
10Base-T	10 Mbps	Machester	1	10	10 MHz	Twisted pair
100Base-T	100 Gbps	MLT-3 (PAM-3)	1	125	31.25 MHz	Cat 5
1000Base-T	1 Gbps	PAM-5	4	125	62.5 MHz	Cat 6
10GBase-T	10 Gbps	PAM-16	4	800	500 MHz	Cat 6A
25GBase-T	25 Gbps	PAM-16	4	2500	1250 MHz	Cat 8

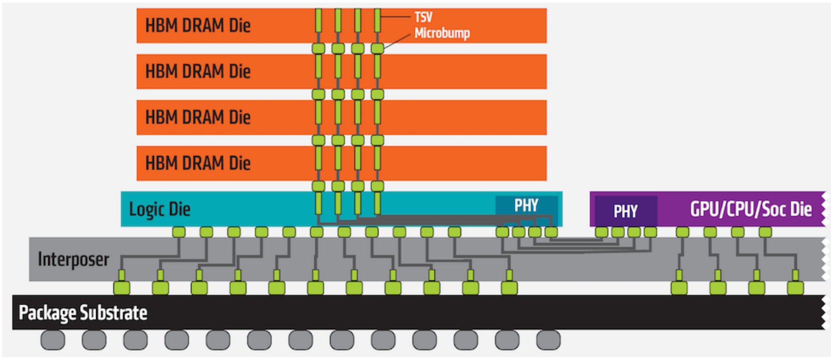
Chip-to-Chip Links in the Gbps Regime

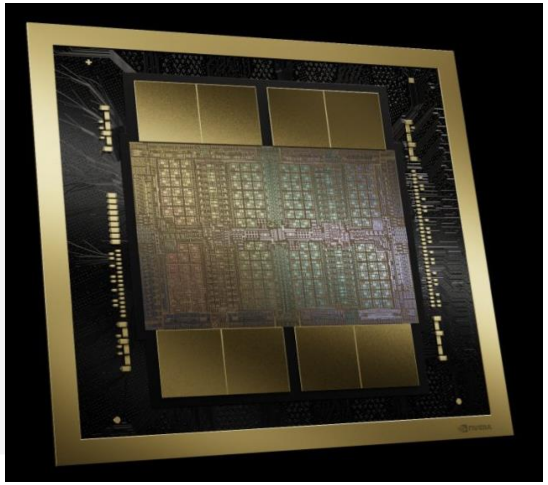


Memory Interfaces: moderate rate due to many parallel pins

Standard	Year	Baud Rate
DDR	1998	400 Mbaud
DDR 2	2003	400 – 1066 Mbaud
DDR 3	2007	800 – 2133 Mbaud
DDR 4	2014	1600 – 3200 Mbaud
DDR 5	2020	3200 – 6400 Mbaud

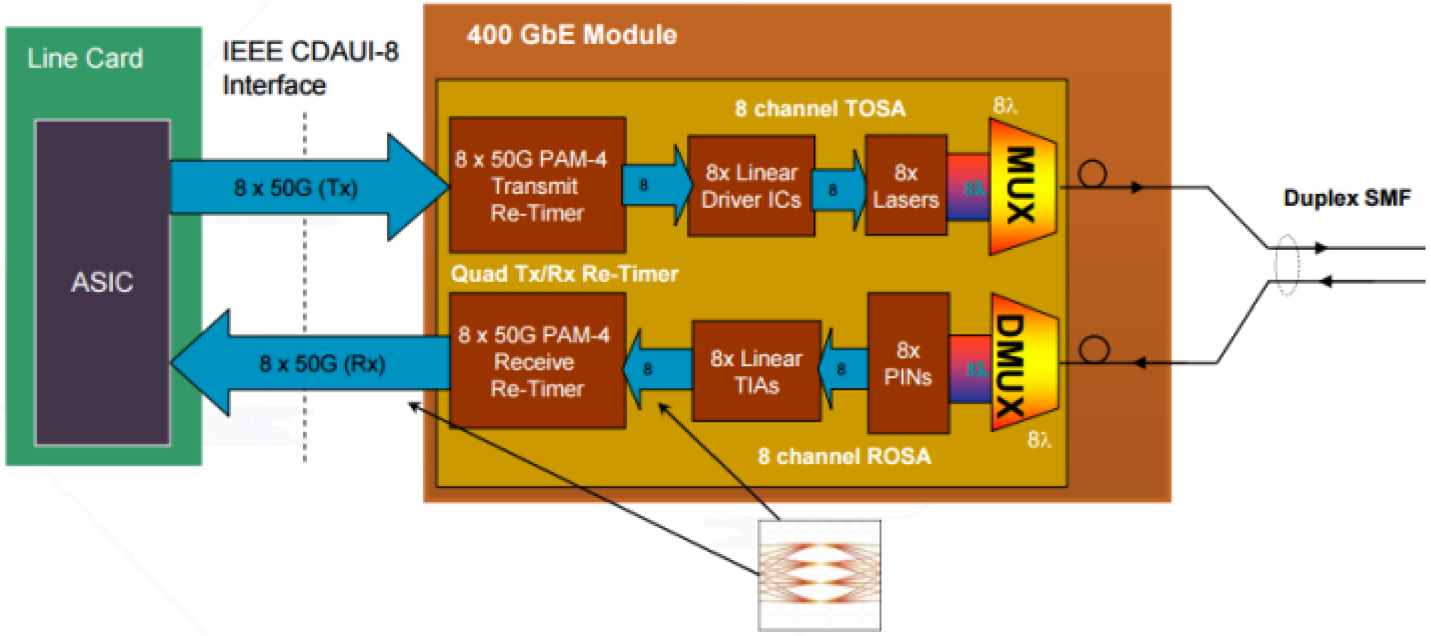
Memory Interfaces





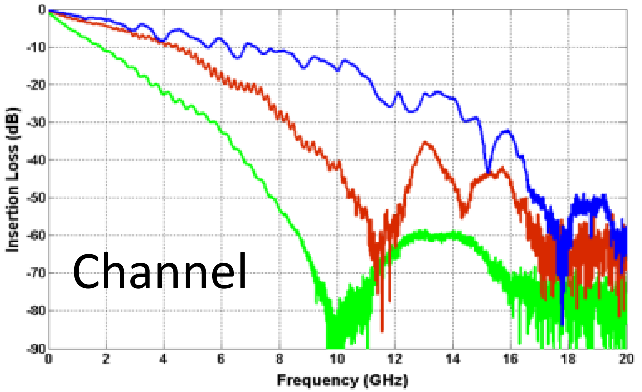
Line Card Interfaces

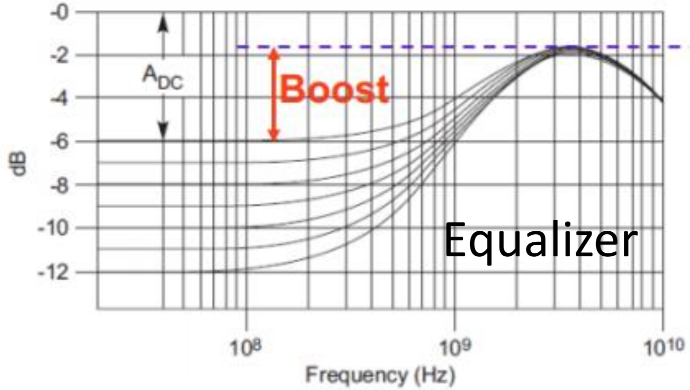
- **Interfaces to optical links are even more challenging**
  - Throughput in the 10s of Gbps per single pin

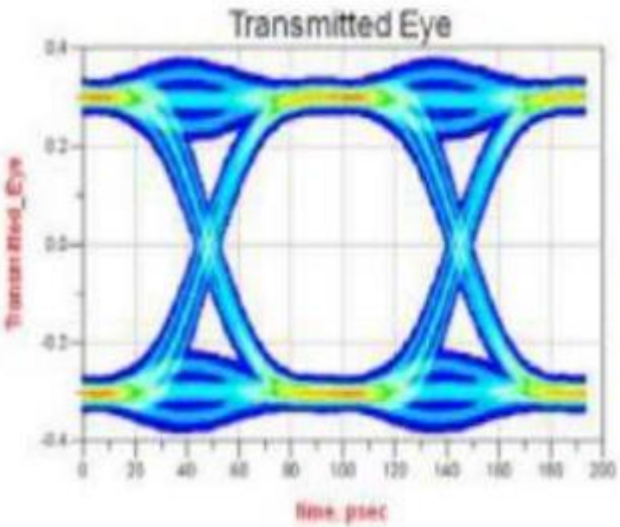


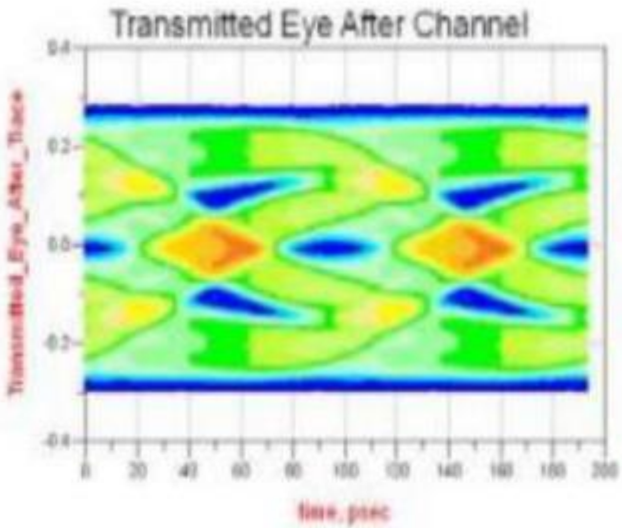
Serial Links Equalization

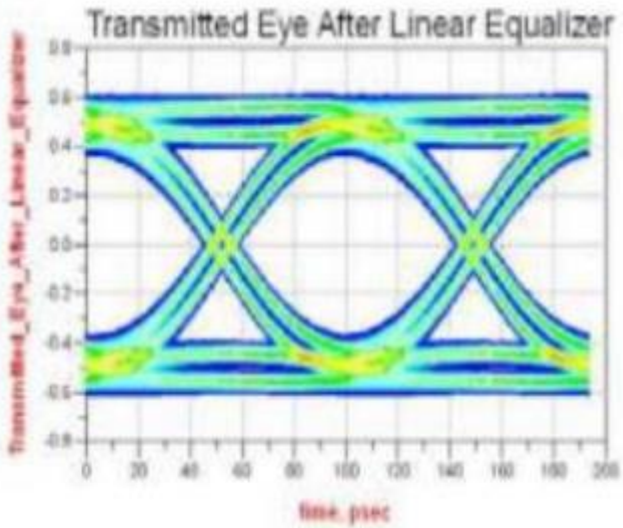
- **Chip-to-chip physical link has limited bandwidth: correction with equalization**





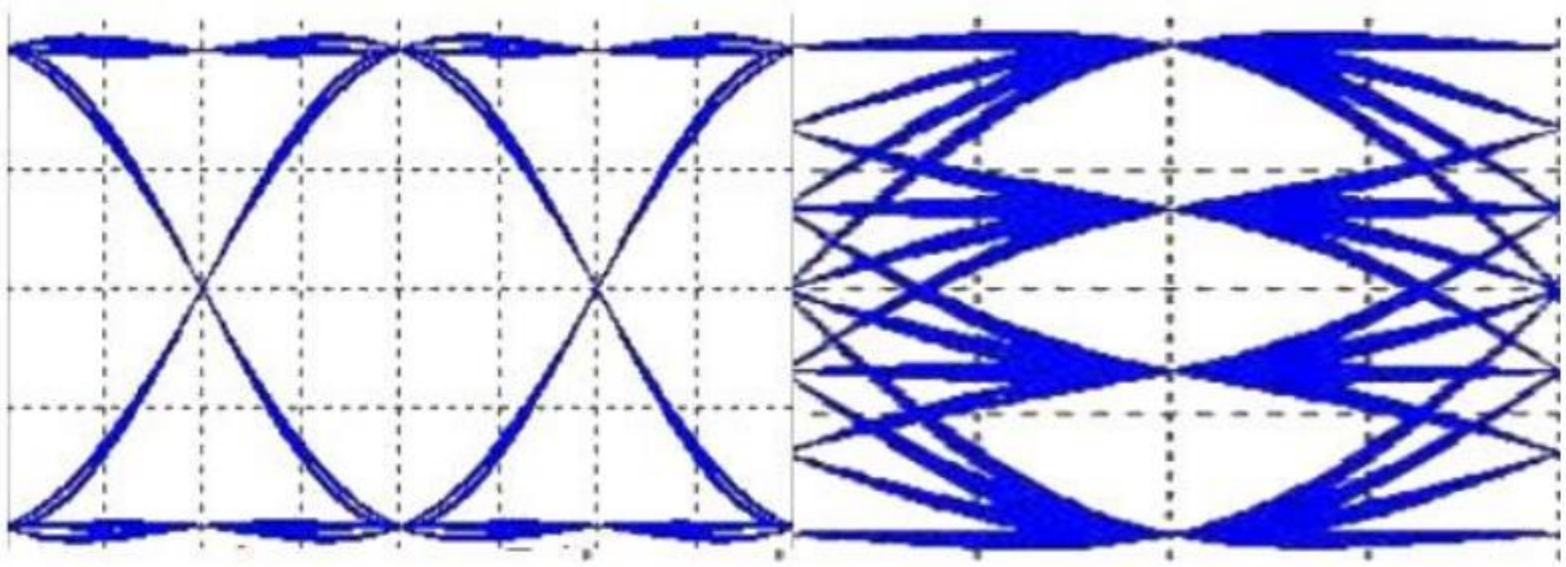






Serial Links with Higher PAM Order

- **Higher order PAM requires less bandwidth, but eye opening also reduces**

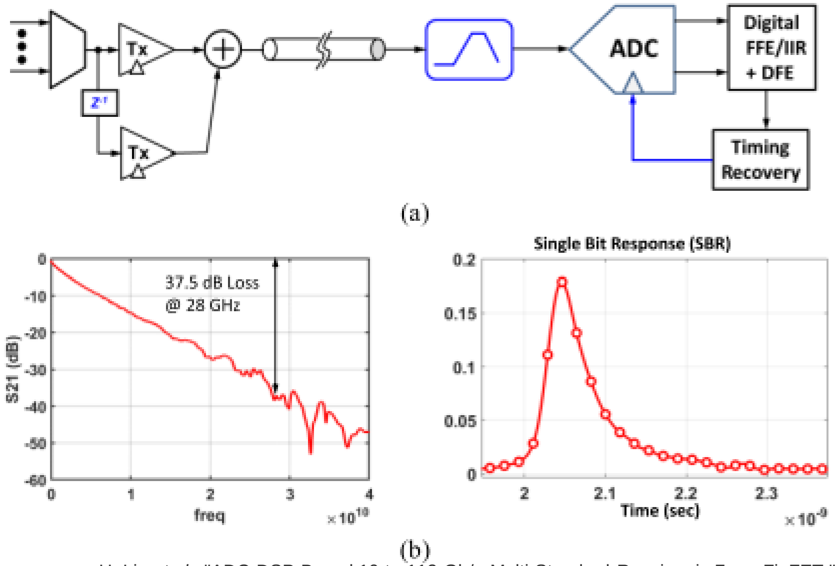


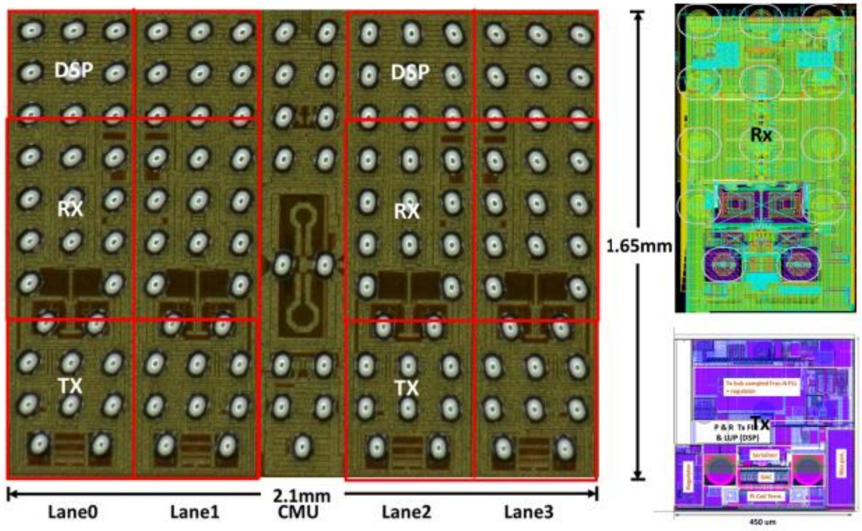
  - Eye height for PAM4 is 1/3 of that of PAM2, thus

$$\text{SNR loss} = 20 \cdot \log_{10}\left(\frac{1}{3}\right) \approx 9.5\ \text{dB}$$

Difficulty to Implement Advanced Receivers

- **Serial Links today can operate with Baud Rates in the 10s Gbps regime**
  - Signal processing mostly done in the analog domain
  - Digital signal processing only recently possible with very high-speed data converters





H. Lin *et al*., "ADC-DSP-Based 10-to-112-Gb/s Multi-Standard Receiver in 7-nm FinFET," in *IEEE Journal of Solid-State Circuits*, vol. 56, no. 4, pp. 1265-1277, April 2021, doi: 10.1109/JSSC.2021.3051109.