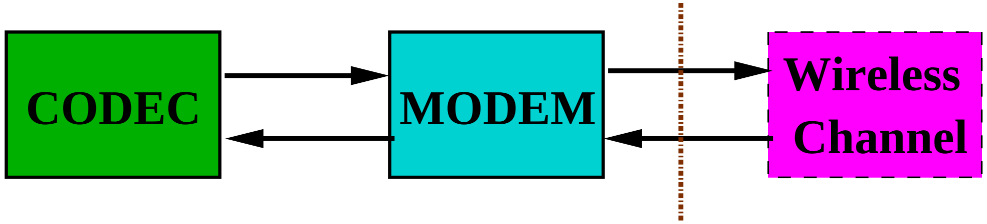
Revision of Wireless Channel

- Quick recap system block diagram



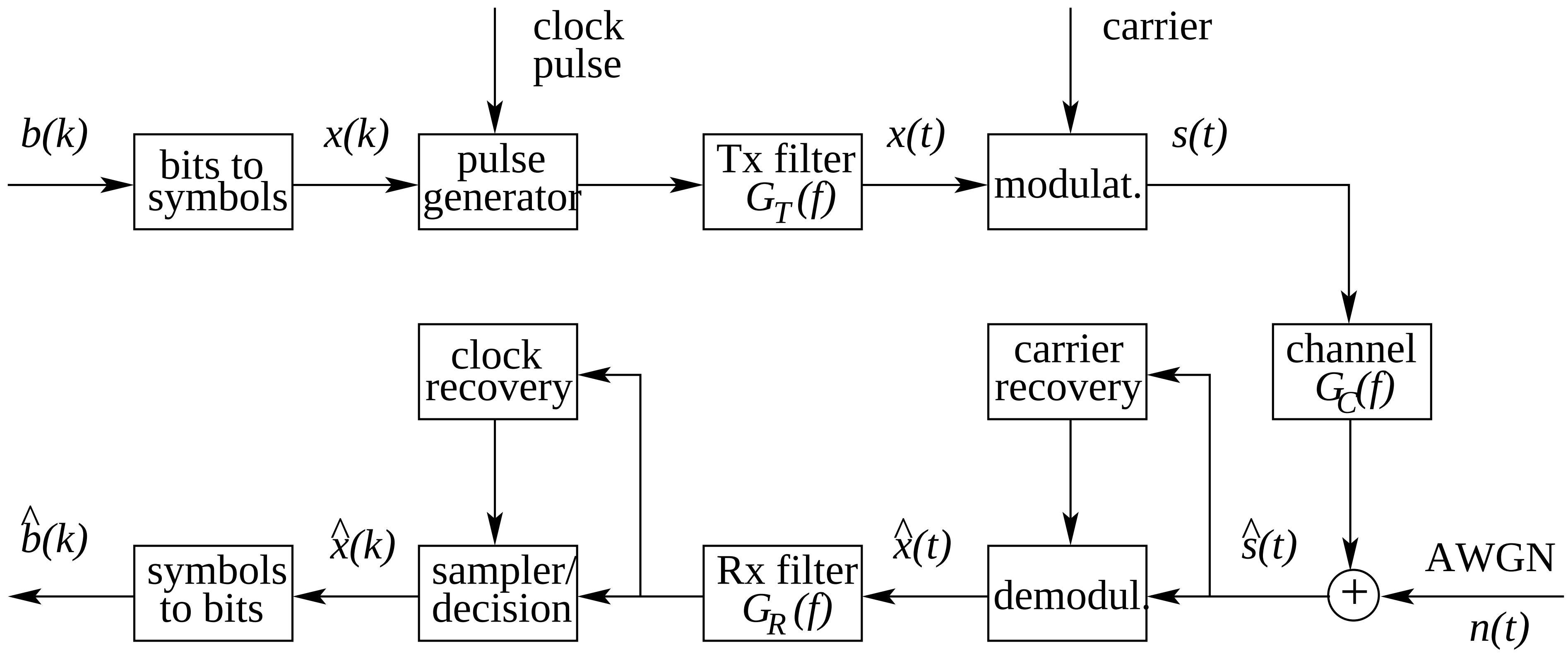
- Previous three lectures looked into **wireless mobile channels**
  - To understand mobile communication technologies, one needs a deep understand of **mobile communication media**
  - Two main sources of hostility in mobile media are **Doppler spread** and **multipath**
  - Many techniques developed are counter measures for **fading** and **frequency selective**

- Front end of transceiver is Modem, which faces hostile (fading and frequency selective) communication media

  Next six lectures we will have a look into Modem

Digital Modulation Overview

- Schematic of MODEM (modulation and demodulation) with its basic components:



- The purpose of MODEM: transfer the bit stream at certain rate over the communication medium reliably

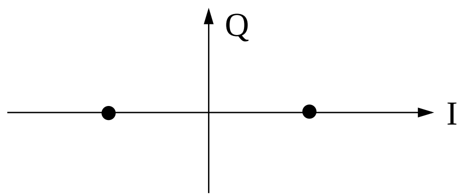
Constellation Diagram

- Digital **modulation signal** has finite states. This manifests in **symbol** (message) set: $\mathcal{M} = \{m_1, m_2, \cdots, m_M\}$, where each symbol contains $\log_2 M$ bits

- Or in modulation signal set: $\mathcal{S} = \{s_1(t), s_2(t), \cdots s_M(t)\}$. There is one-to-one relationship between two sets:

$$\mathcal{M} \overset{\text{modulation scheme}}{\longleftrightarrow} \mathcal{S}$$

- Example: BPSK, $M = 2$. Constellation diagram:



  Modulation signal set:

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t) \qquad s_2(t) = -\sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t)$$

- **Methods of modulation**: utilise amplitude, phase or frequency of carrier

Performance Measures

- Two key performance measures of a modulation scheme are power efficiency and bandwidth efficiency

- **Power efficiency** is expressed as the ratio of the signal energy per bit (E_b) to the noise PSD (N_0) required to achieve a given probability of error (say 10^{-4}):

$$\eta_P = \frac{E_b}{N_0} \qquad \text{Small } \eta_P \text{ is preferred}$$

- **Bandwidth efficiency** is defined as the ratio of the data bit rate R to the required RF bandwidth B_p:

$$\eta_B = \frac{R}{B_p} \ (\text{bps/Hz}) \qquad \text{Large } \eta_B \text{ is preferred}$$

- **Channel capacity** gives an upper bound of achievable bandwidth efficiency:

$$\eta_{B_{\max}} = \frac{C}{B_p} = \log_2(1 + \text{SNR})$$

Channel capacity of ideal channel with Gaussian signal used as upper limit for digital modulated signal

Modulation Schemes Classification

- According to pulse shaping techniques adopted
  - **Nyquist** pulse shaping: absolution bandwidth is finite, does not induce ISI

    These lead to bandwith efficient modulation schemes but are power inefficient, requiring expensive linear RF amplifier
  - **Non-Nyquist** pulse shaping: absolution bandwidth is infinite and can only be defined by e.g. 3 dB bandwidth, will induce certain level of ISI

    These lead to bandwith inefficient modulation schemes but are power efficient, only requiring inexpensive nonlinear RF amplifier

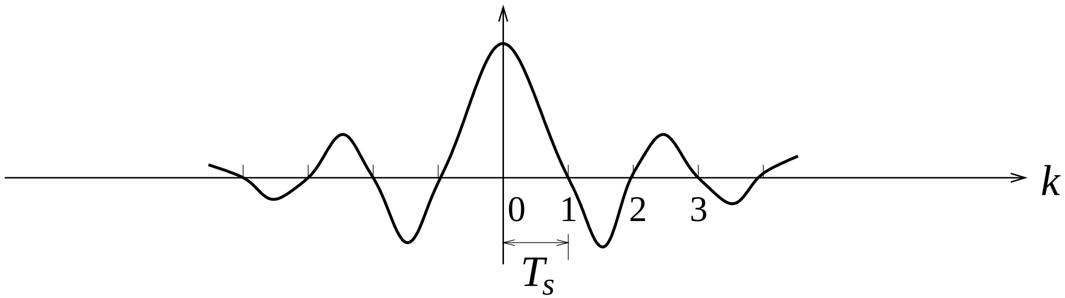
- Modulation schemes can be classified as linear or nonlinear

  Linear modulation is bandwidth efficient but power inefficient, nonlinear modulation is reverse
  - **Linear** modulation: RF signal amplitude varies linearly with modulating digital signal, e.g. QAM
  - **Nonlinear** modulation: RF signal amplitude does not vary linearly with modulating digital signal, e.g. constant envelope modulation

Nyquist Pulse Shaping

- **Nyquist criterion for zero ISI**: The impulse response of the baseband system $h_{eff}(t)$ must satisfy

$$h_{eff}(kT_s) = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases}$$



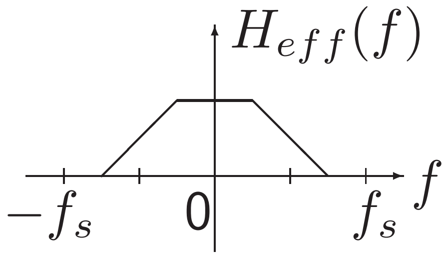
- Equivalently, the transfer function $H_{eff}(f)$ must satisfy

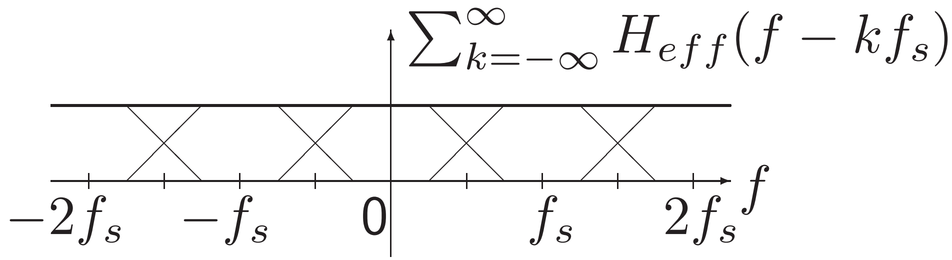
$$\sum_{k=-\infty}^{\infty} H_{eff}(f - kf_s) = \text{constant}, \ \text{for } |f| < \frac{f_s}{2}$$

where T_s is the symbol period and $f_s = \frac{1}{T_s}$ the symbol rate

Nyquist Pulse Shaping (continue)

- Illustration of condition for zero ISI, seeing from frequency domain:





- Note that $H_{eff}(f) = H_T(f)H_{Ch}(f)H_R(f)$. Assuming $H_{Ch}(f) = 1$, the transmit and receive filter pair provides the desired spectrum shape:

$$H_T(f)H_R(f) = H_{eff}(f)$$

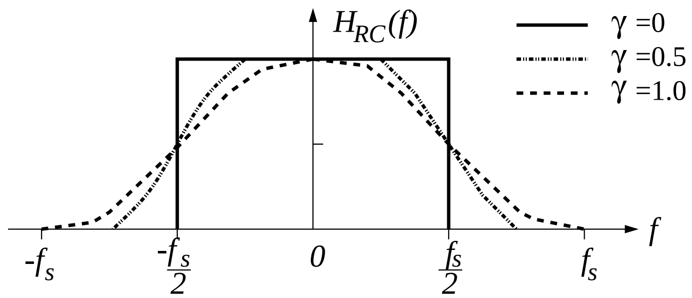
- The **minimum** required baseband **bandwidth** for zero ISI is $B_{\min} = \frac{f_s}{2}$, and this corresponds to the sinc pulse shaping

- Recall that given the baseband signal bandwidth B, the required RF bandwidth is $B_p = 2B$

Raised Cosine Pulse Shaping Filter

- The required baseband bandwidth $f_s/2 \le B \le f_s$, and the spectrum:

$$H_{RC}(f) = \begin{cases} 1 & |f| \le \frac{f_s}{2} - \beta \\ \cos^2\left(\frac{\pi}{4\beta}|f| - \frac{f_s}{2} + \beta\right) & \frac{f_s}{2} - \beta < |f| \le \frac{f_s}{2} + \beta \\ 0 & |f| > \frac{f_s}{2} + \beta \end{cases}$$



- where β is the extra bandwidth over the minimum $f_s/2$, and roll-off factor γ:

$$\gamma = \frac{\beta}{f_s/2} = \frac{B - f_s}{f_s} \quad \text{or} \quad B = \frac{f_s}{2}(1+\gamma)$$

- Raised cosine filter achieves zero ISI, but requires power inefficient linear amplifier

Example

- In GSM, the RF channel bandwidth is 200 kHz and the data rate is 270.833 kbps. The bandwidth efficiency is:

$$\eta_B = \frac{270.833}{200} \approx 1.4 \text{ bits}$$

For SNR=10 dB=10, such a channel has

$$\eta_{B\max} = \log_2(1+10) \approx 3.5 \text{ bits}$$

The bandwidth efficiency of GSM under the SNR=10 dB is only 40% of the limit:

$$\frac{\eta_B}{\eta_{B\max}} \approx 40\%$$

(Note: GSM uses 2 bits per symbol digital modulation scheme, so its channel capacity is smaller than ideal Gaussian signal. Thus actual GSM bandwidth efficiency is more than 40%)

- The symbol period is $T_s = 41.06$ μs and the raised cosine filter has a roll-off factor $\gamma = 0.35$. The filter (absolute) baseband bandwidth is

$$B = \frac{(1+\gamma)}{2T_s} = 16.44 \text{ kHz}$$

The require RF channel bandwidth is $B_p = 2B = 32.44$ kHz

Gaussian Pulse-Shaping Filter

- This is a non-Nyquist pulse shaping filter with the transfer function:

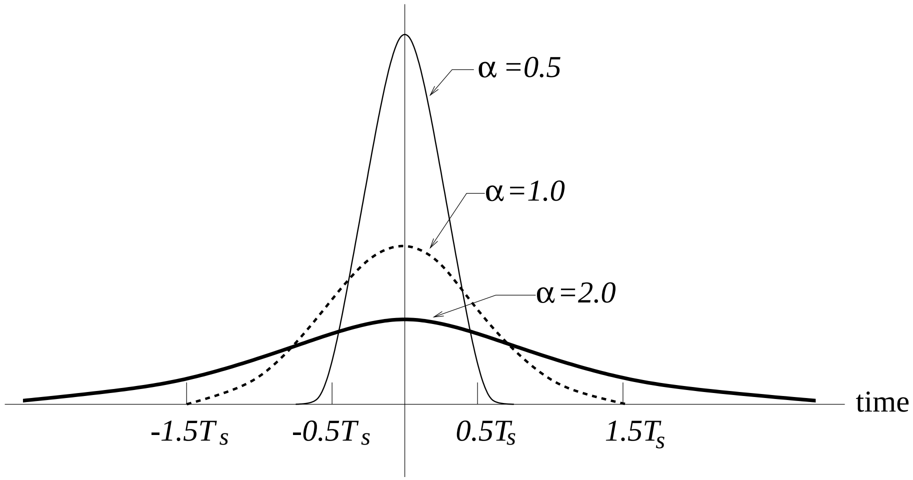
$$H_G(f) = \exp(-\alpha^2 f^2)$$

absolute bandwidth is infinity, α and 3-dB baseband bandwidth B satisfy

$$\alpha B = \frac{\sqrt{\ln 2}}{\sqrt{2}} = 0.5887$$

- Impulse response is:

$$h_G(t) = \frac{\sqrt{\pi}}{\alpha} \exp\left(-\frac{\pi^2}{\alpha^2} t^2\right)$$



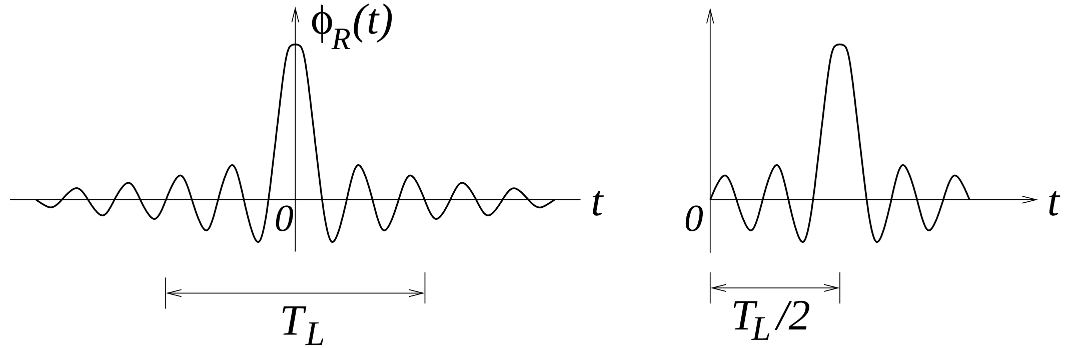
- This pulse shaping filter introduces ISI but only requires power efficient nonlinear amplifier: trade off is required between reducing RF bandwidth and increasing ISI

As α increases, required (3-dB) bandwidth decreases (Gaussian spectrum narrower) but ISI level increases (Gaussian time pulse wider)

Practical Implementation

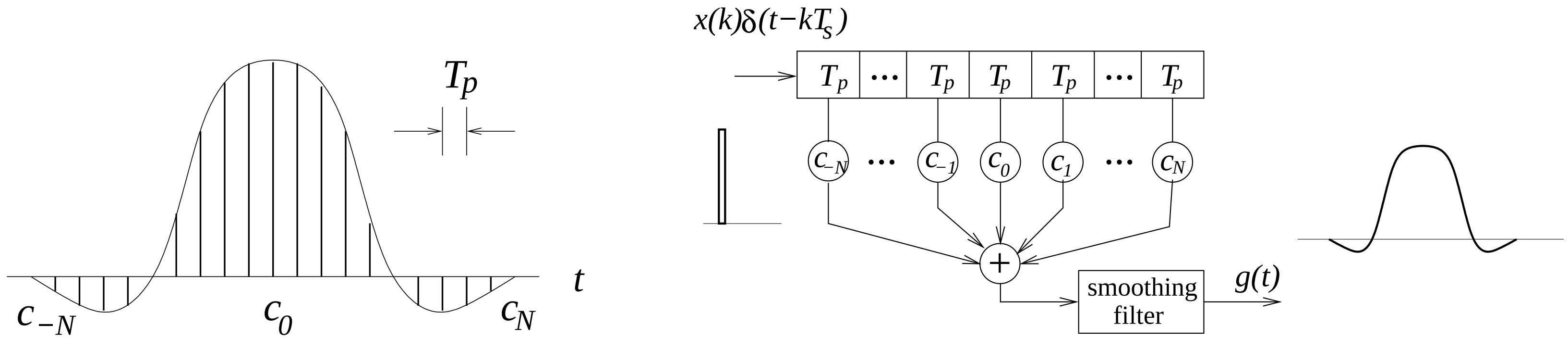
- Consider raised cosine pulse shaping filter

Truncate the infinite pulse to a finite but sufficient length and delay it



(a) truncate the pulse to length T_L (b) delay the truncated pulse

- Sampled values are obtained from the waveform of the truncated pulse and an FIR or transversal filter is used to realize the required Tx / Rx filters:



Summary

- Modulation overview: basic components of MODEM

  Symbol set (constellation diagram) /one-to-one/ modulation signal set

  Modulation methods: use amplitude, phase or frequency of carrier

  Performance measures: power efficiency and bandwidth efficiency, upper bound limit of bandwidth efficiency

- Pulse shaping:

  Nyquist pulse shaping: Nyquist criterion for zero ISI, minimum bandwidth for zero ISI, raised cosine (roll off factor) pulse shaping

  Non-Nyquist pulse shaping: Gaussian (α parameter) pulse shaping

  Practical implementation