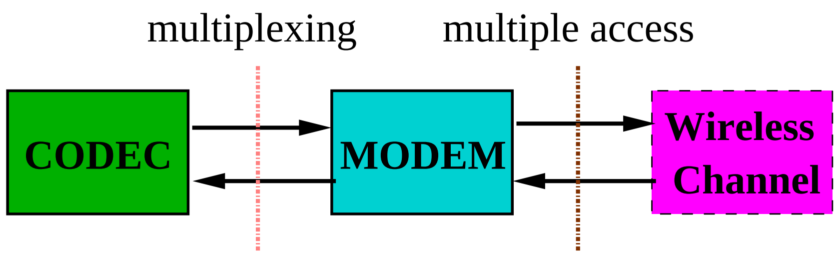
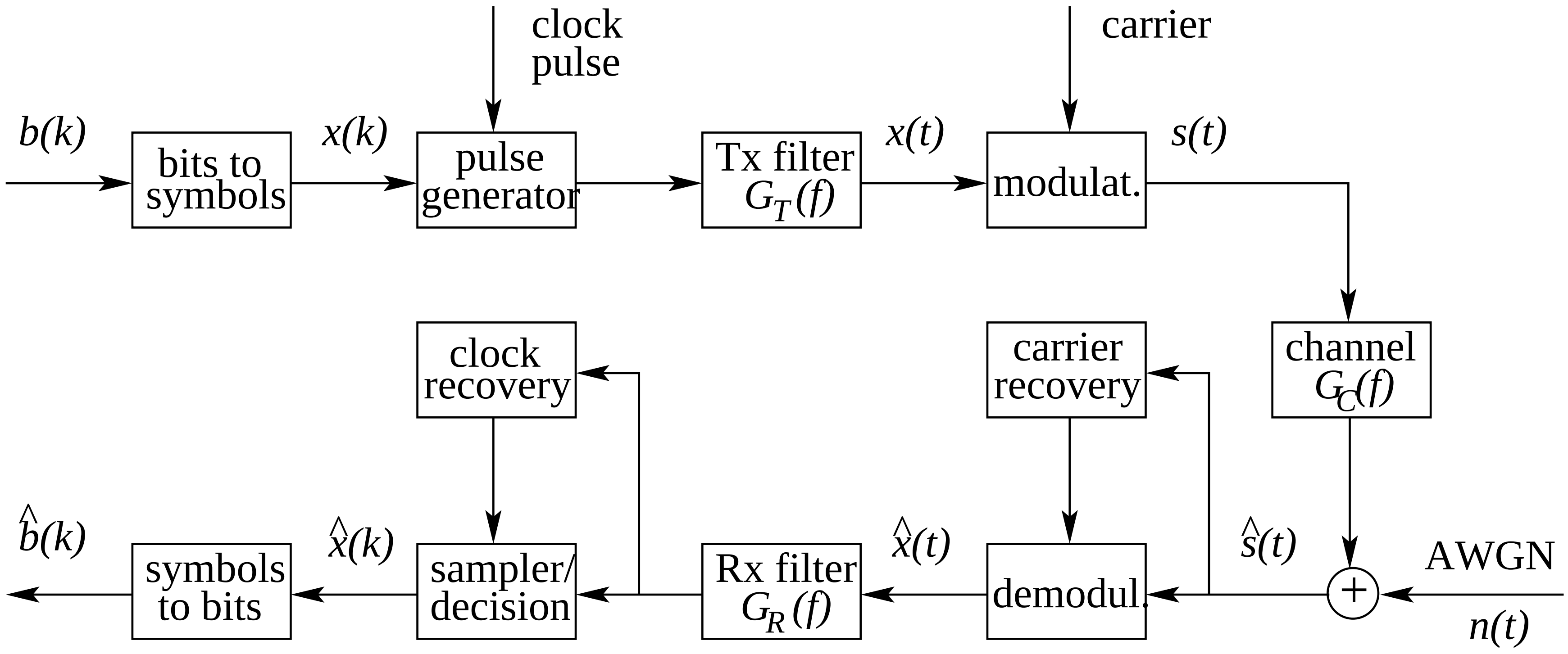
Revision of Previous Six Lectures

- Previous six lectures have concentrated on Modem, under ideal AWGN or flat fading channel condition
- Important issues discussed need to be revised, and they are summarised in Revisions before each lecture





- We have not yet discussed carrier recovery for QAM and clock recovery for multilevel signalling $\Rightarrow$ this lecture, as well as some other issues

Carrier Recovery for QAM

- Recall that **carrier recovery** operates in RF receive signal, which in QAM case contains in-phase and quadrature components
  - **Time-2** carrier recovery **does not work** for quadrature modulation
  - This is because I and Q branches have equal average signal power, square RF signal $r(t)$ leads to low RF signal level
- More specifically, simply consider the squared $r(t)$:

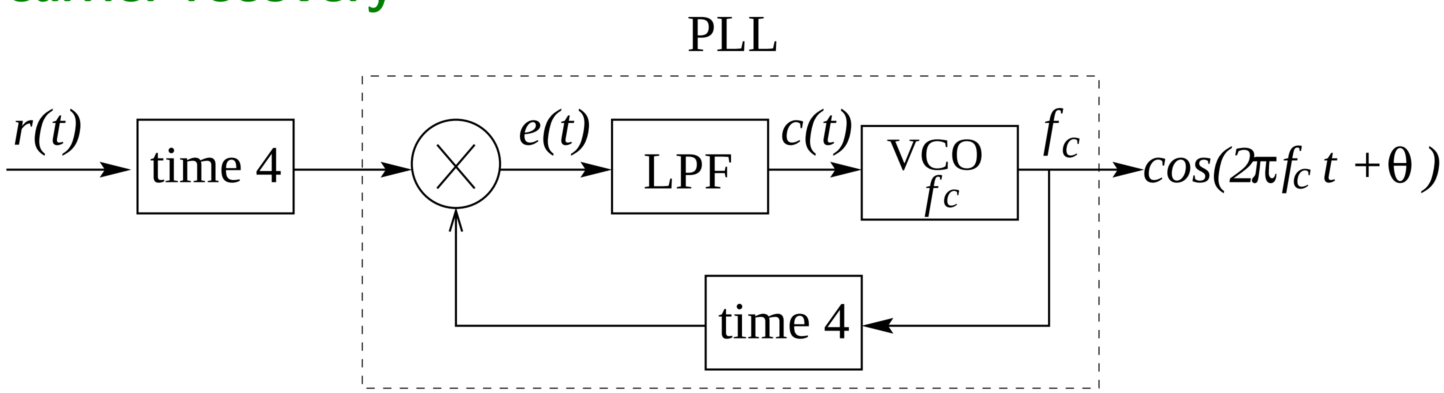
$$\begin{aligned} r^2(t) &= (a_R(t)\cos(\omega_c t + \phi) + a_I(t)\sin(\omega_c t + \phi))^2 \\ &= \frac{1}{2}a_R^2(t)(1 + \cos(2\omega_c t + 2\phi)) + \frac{1}{2}a_I^2(t)(1 - \cos(2\omega_c t + 2\phi)) \\ &\quad + a_R(t)a_I(t)\sin(2\omega_c t + 2\phi) \end{aligned}$$

  - $a_R^2(t)\cos(2\omega_c t + 2\phi)$ and $-a_I^2(t)\cos(2\omega_c t + 2\phi)$ almost cancel out on average
  - $a_R(t)a_I(t)$ has very low correlation, thus last term is almost zero on average
- Therefore, the baseband signals $a_R^2(t)$ and $a_I^2(t)$ dominate, and the carrier could not be recovered from $r^2(t)$

Time-4 Carrier Recovery for QAM

- Raising to 4th power works: as this generates significant component $\cos(4(\omega_c t + \theta))$ at $4\omega_c$, and in theory dividing this component by 4 gets carrier $\cos(\omega_c t + \theta)$

- **Time-4 carrier recovery**



  - As VCO operates at f_c not $4f_c$, feedback must raised to 4th power
  - PLL does not operate at $4f_c$: high frequency electronics more expensive and harder to build

- After carrier recovery, clock recovery operates in I or Q baseband signals
  - For 4QAM, I or Q is 2-ary (BPSK). Thus, time-2, early-late and zero-crossing clock recovery schemes all work for 4QAM

Clock Recovery for High-Order QAM

- Time-2 clock recovery: for 16QAM or higher, it does not work satisfactorily
  - I or Q are multilevel (e.g. I or Q of 16QAM: -3,-1,+1+3), and the symbol-rate component is less clear in the squared signal
- Early-late clock recovery: for 16QAM or higher, it also works less satisfactorily
  - Squared waveform peaks do not always occur every sampling period, and worst still half of the peaks have wrong polarity
- Zero-crossing clock recovery: for 16QAM or higher, it also works less satisfactorily
  - Only some of zero crossings occur at middle of sampling period, and logic circuit is required to adjust sampling instances correctly
- Synchroniser clock recovery: works well for QAM but requires extra bandwidth
  - Synchroniser clock recovery is usually applied in initial link synchronisation
  - During data communication phase, alternative synchronisation required

Why E-L not Work for High-Order QAM

E-L Scheme for 16QAM example:

- Left graph: the middle symbol represents the symbol period in which peak detection is attempted
- Right graph: the sampling instance is early

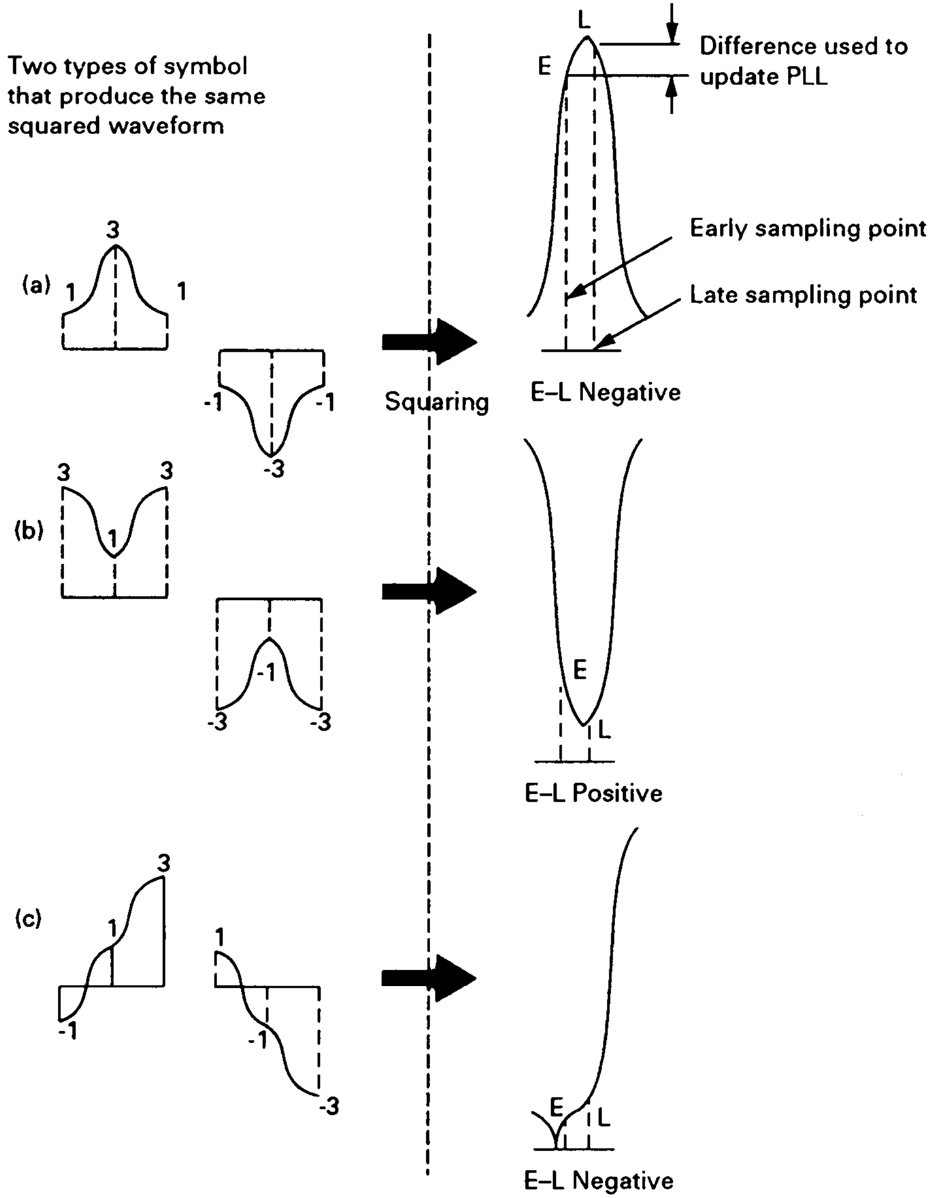
○ If sampling instance is early

(a) $E - L < 0 \rightarrow$ early, correct decision
(b) $E - L > 0 \rightarrow$ late, wrong decision
(c) $E - L < 0 \rightarrow$ early, correct decision

○ If sampling instance is late

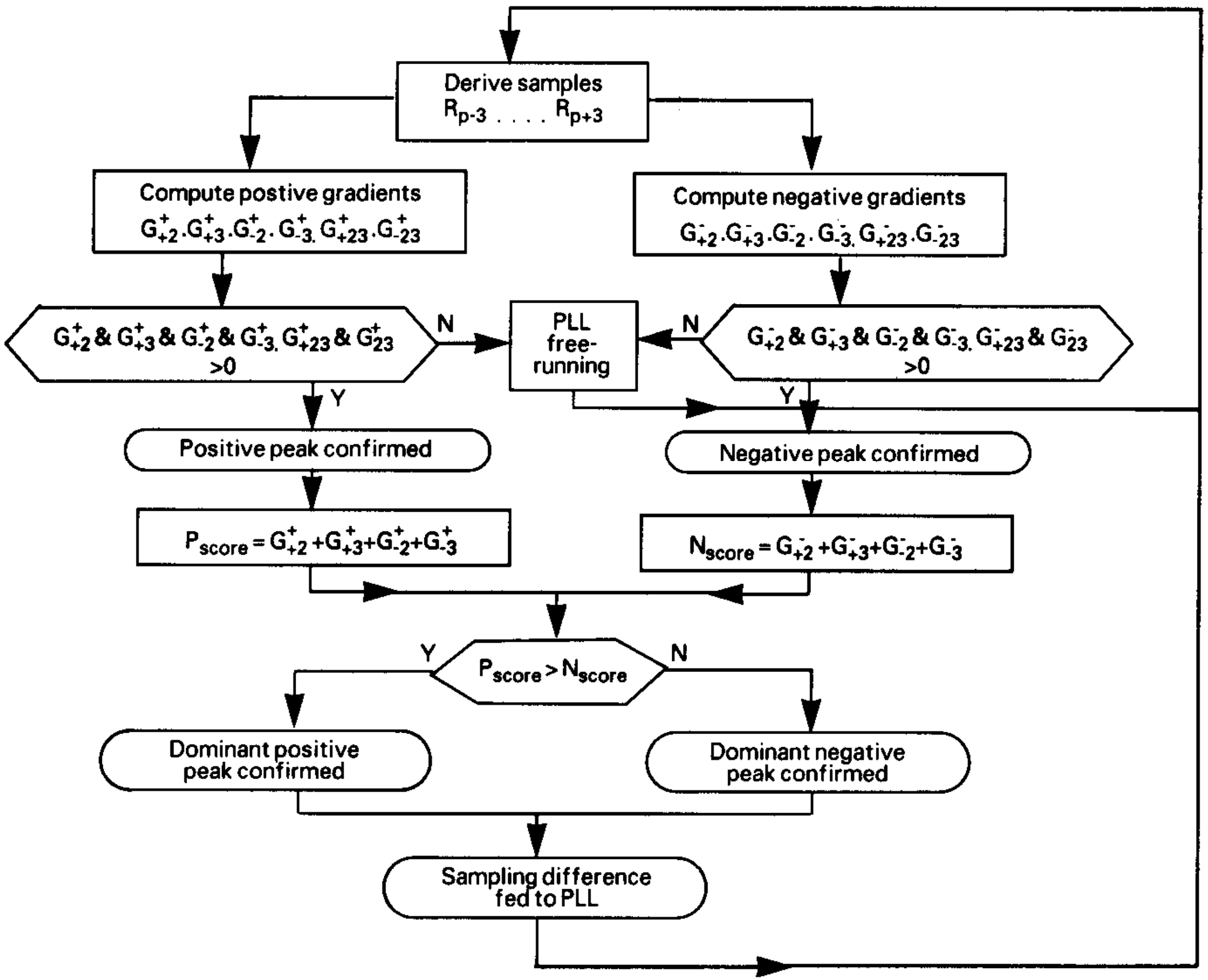
(a) $E - L > 0 \rightarrow$ late, correct decision
(b) $E - L < 0 \rightarrow$ early, wrong decision
(c) $E - L < 0 \rightarrow$ early, wrong decision

○ Thus $E - L$ Scheme has 50% wrong polarity



Modified Early-Late Clock Recovery

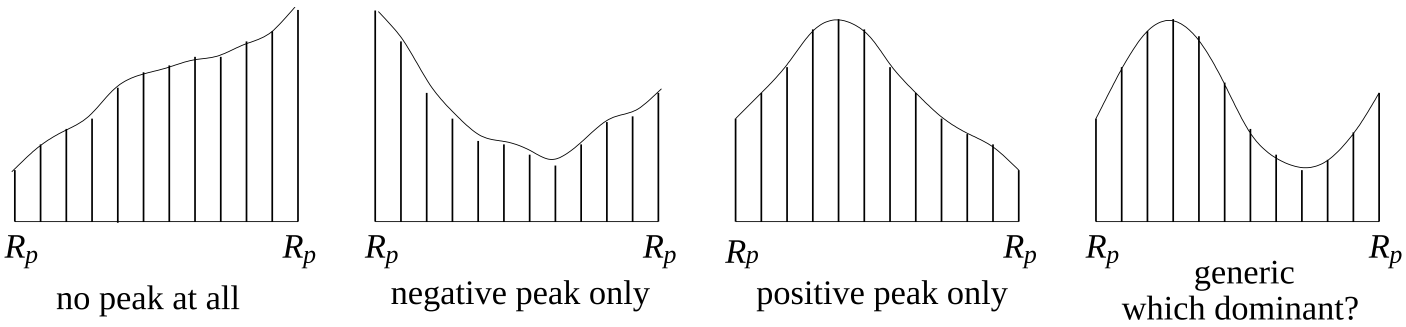
- As previous slide shows, there are three cases of squared waveform: (a) positive peak, (b) negative peak, (c) no peak
- To make scheme work, key is:
  - **Decision rules** for updating sampling instance using difference between E and L should be **different for cases (a) and (b)**
  - In case of **no peak**, it is better **no updating** at all, as 50% of times will be wrong
- Modified E-L scheme adopts oversampling in one symbol period, say, n samples $\{R_i\}_{i=1}^n$, instead of just two samples E and L



- It detects which of (a), (b) and (c) cases occurs and take corresponding action

Modified E-L Clock Recovery (continue)

- For convenience, we will use R_p to denote either the **maximum** or the **minimum** of $\{R_i\}_{i=1}^{n}$
  - ◇ If Max R_p is at either end, no positive peak
  - ◇ If Min R_p is at either end, no negative peak
  - ◇ If Max R_p is at one end and Min R_p at the other end, no peak at all and do nothing (PLL free run)



- How to find positive and/or negative peaks

gradients for confirming positive peak

$$G^{+}_{+2} = R_p - R_{p+2},\; G^{+}_{+3} = R_p - R_{p+3}$$
$$G^{+}_{-2} = R_p - R_{p-2},\; G^{+}_{-3} = R_p - R_{p-3}$$
$$G^{+}_{+23} = R_{p+2} - R_{p+3}$$
$$G^{+}_{-23} = R_{p-2} - R_{p-3}$$

gradients for confirming negative peak

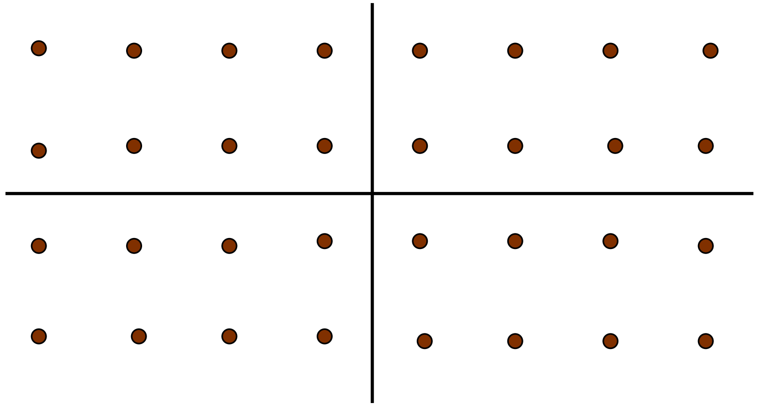
$$G^{-}_{+2} = R_{p+2} - R_p,\; G^{-}_{+3} = R_{p+3} - R_p$$
$$G^{-}_{-2} = R_{p-2} - R_p,\; G^{-}_{-3} = R_{p-3} - R_p$$
$$G^{-}_{+23} = R_{p+3} - R_{p+2}$$
$$G^{-}_{-23} = R_{p-3} - R_{p-2}$$

  – $R_{p\pm 1}$ are not used: due to the nature of pulse shaping, they are similar to R_p

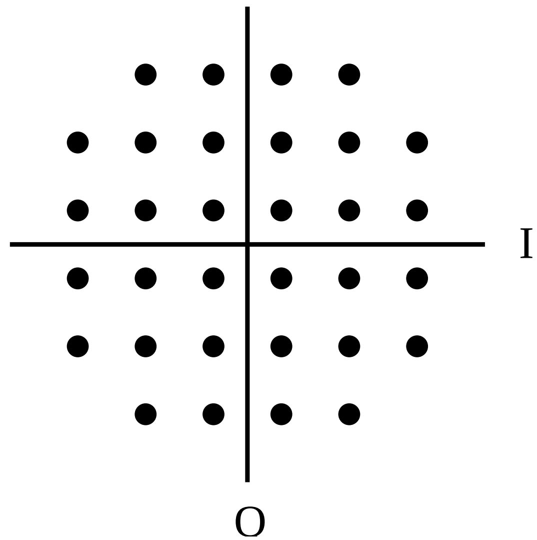
- If only a positive or negative peak, it is dominant; if both peaks exist, which is dominant is determined by calculating P_{score} and N_{score} and comparing them
- The difference between the current sampling time and the dominant peak is used to drive PLL

Odd-Bit QAM

- Square QAM constellation requires even number of bits per symbol
  - Throughput requirement may need scheme with odd number of bits per symbol
- To transmit odd number of bits per symbol, "rectangular" scheme could be used
  - An example of 5-bit rectangular QAM may looks like
  - Bad as I and Q signals would be treated differently

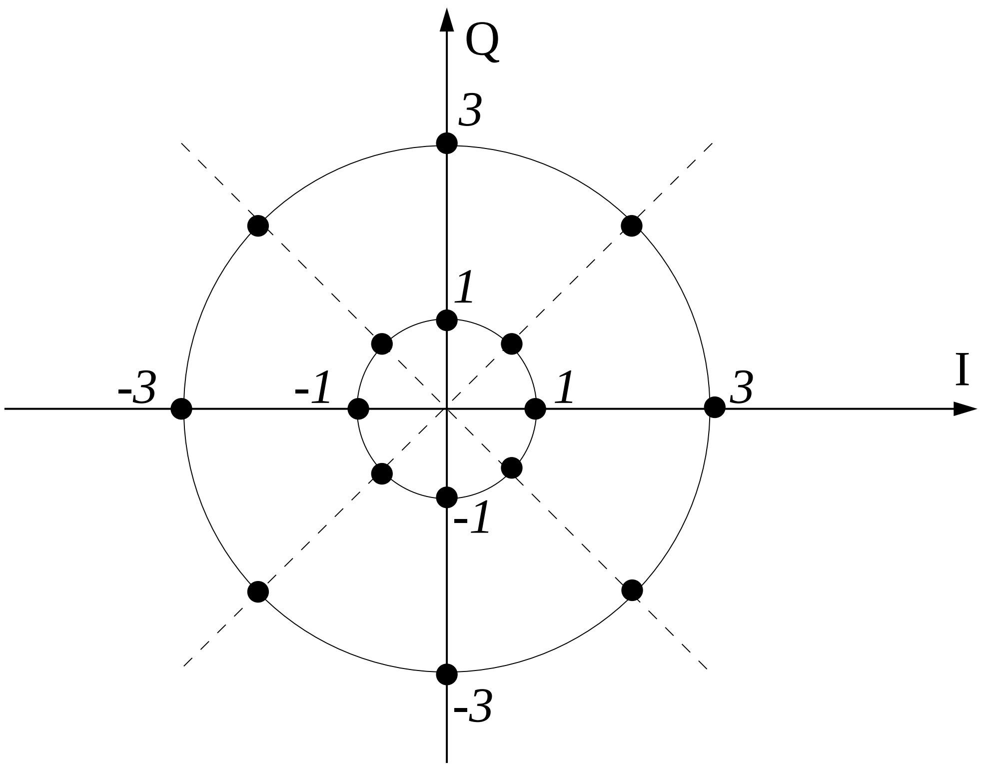


- "Symmetric" constellation is better
  - 5-bit QAM example:
  - Inphase and quadrature components are symmetric
  - Constellation points most affected by nonlinear distortion of RF amplifier and/or channel are omitted
- This principle widely adopted in very high-order QAM, such as microwave trunk link



Star QAM

- In Lecture 7, we learn square QAM is optimal for AWGN, but star QAM or product-APSK is better for fading channels
  - Recall slide 95, square 16QAM has 20% higher minimum distance at same average energy than star 16QAM, but latter has larger minimum phase separation
- Star 16QAM example
  - Four bits $b_1 b_2 b_3 b_4$ per symbol for star 16QAM, as for square 16QAM
  - I and Q amplitudes for star 16QAM: $0, \pm 0.707, \pm 1, \pm 2.12, \pm 3$ (d dropped for convenience)
  - Compare this with $\pm 3, \pm 1$ for square 16QAM



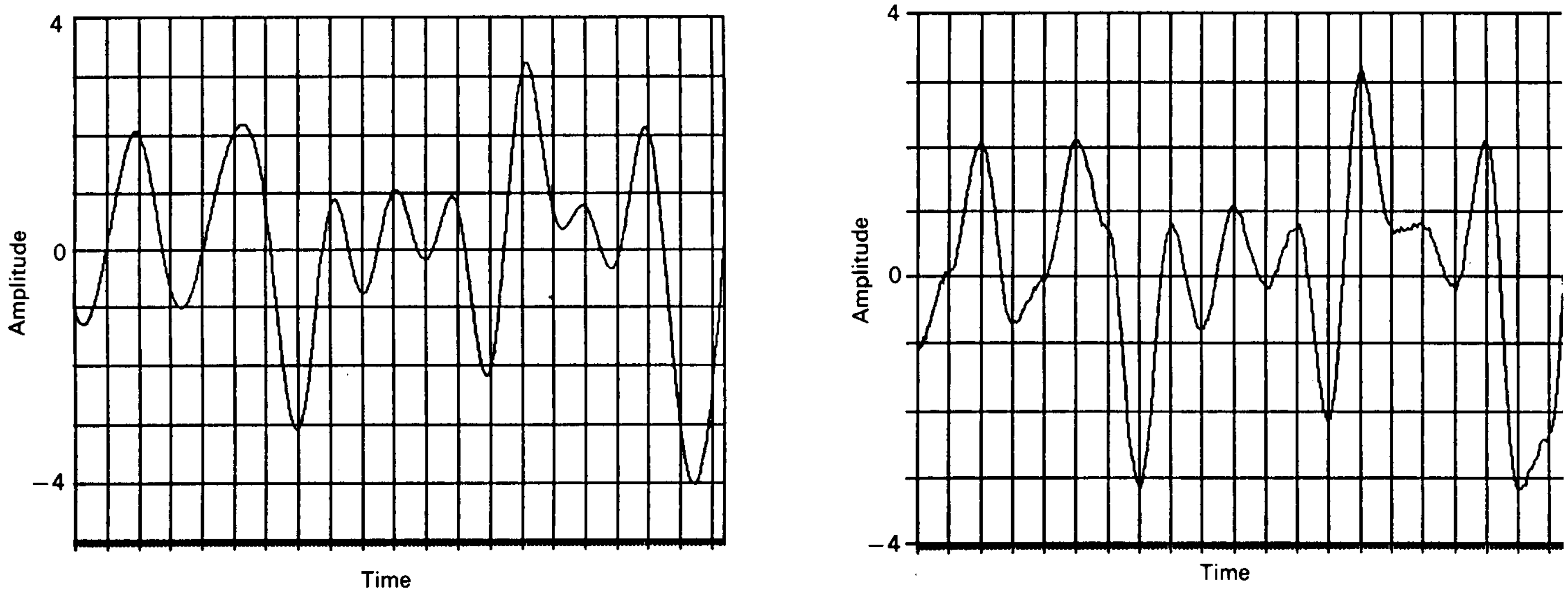
- There are **unexpected** consequences

Star QAM: Clock Recovery

- Raised cosine pulse shaped I or Q channel: peaks are not always coincide with equispaced sampling points, see figure (a), which will cause serious problem for clock recovery
  - Timing recovery often relies on peaks occurring at equispaced sampling points
- Using nonlinear filtering to make peaks at symbol-spaced, at the cost of small extra bandwidth, the PSD of this NLF:

$$S(f) = T_s \left(\frac{\sin(2\pi f T_s)}{2\pi f T_s} \frac{1}{1 - 4(f T_s)^2} \right)^2$$

- I or Q channel before (a) and after (b) NLF



(a) (b)

Differential Coding for Star 16QAM

- For star 16QAM, we can have coherent detection, which requires expensive carrier recovery
  - Star 16QAM has advantage in **non-coherent** detection with **differential** coding, particularly for **fading** environment
- There are two phasor amplitudes for star 16QAM, and first bit b_1 differentially encoded onto QAM phasor amplitude, i.e. deciding which phasor ring
  - $b_1 = 1$: current symbol changes to amplitude ring not used in previous symbol
  - $b_1 = 0$: current symbol remains at amplitude ring used in previous symbol
- There are 8 different phases, and remaining three bits $b_2 b_3 b_4$ are differentially **Gray** encoded onto phase, i.e. deciding which phase
- An example of this differentially Gray encoded phase
  - 000: current symbol transmitted with same phase as previous one
  - 001: current symbol transmitted with 45 degree phase shift relative to previous one
  - 011: current symbol transmitted with 90 degree phase shift relative to previous one
  - 010: current symbol transmitted with 135 degree phase shift relative to previous one
  - 110: current symbol transmitted with 180 degree phase shift relative to previous one
  - 111: current symbol transmitted with 225 degree phase shift relative to previous one
  - 101: current symbol transmitted with 270 degree phase shift relative to previous one
  - 100: current symbol transmitted with 315 degree phase shift relative to previous one
- Initial condition, i.e. amplitude and phase of initial symbol s_0 is fixed, and known to receiver

Differential Decoding for Star 16QAM

- Let two amplitude levels of star 16QAM be A_1 and A_2; received amplitudes at k and $k-1$ be Z_k and Z_{k-1}; received phases at k and $k-1$ be θ_k and θ_{k-1}

- Decision rule for first bit b_1: If $Z_k \geq \frac{A_1+A_2}{2} Z_{k-1}$ or $Z_k < \frac{2}{A_1+A_2} Z_{k-1}$ $b_1 = 1$; otherwise $b_1 = 0$

- Decision rule for remaining bits $b_2 b_3 b_4$: Let

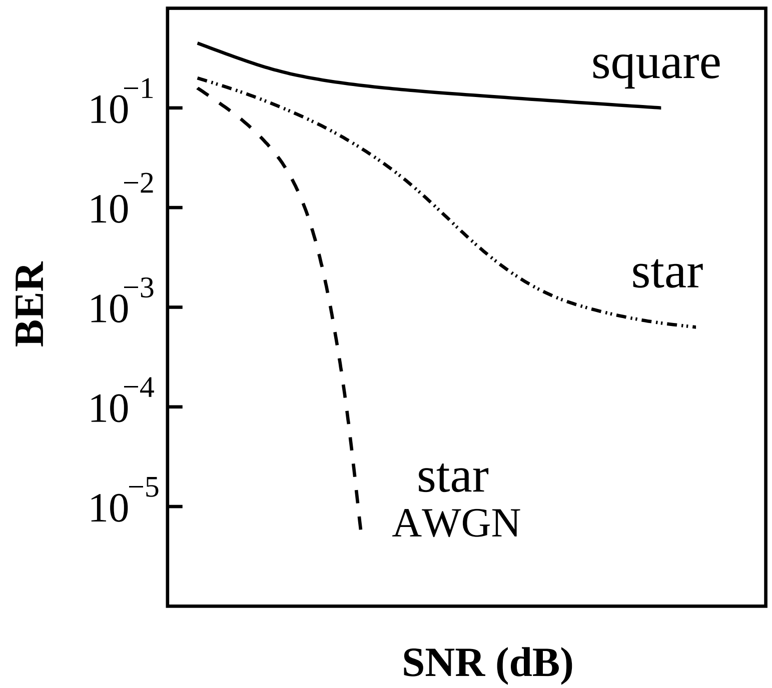
$$\theta_{\text{dem}} = (\theta_k - \theta_{k-1}) \bmod 2\pi$$

  θ_{dem} is quantised to nearest 0°, 45°, 95°, 135°, 180°, 225° or 270°, 315°

  Quantised θ_{dem} is used to output $b_2 b_3 b_4$ according to Gray encoding rule look up table

- Star 16QAM has better BER (order 2 improvement) than square one in fading

Simulated 16QAM in Rayleigh channel



Summary

- Carrier recovery for QAM: Why time-2 carrier recovery does not work for QAM, Time-4 carrier recovery for QAM
- Clock recovery methods for binary modulation have problems for 16QAM or higher except synchroniser
  - Why early-late clock recovery does not work satisfactorily for 16QAM or higher
  - How modified early-late clock recovery works
- Non-square old-bit QAM constellations
- Non-square star QAM:
  - Raised cosine pulse shaped I and Q: peaks are not always at symbol-spaced points, and this time recovery difficulty can be overcome by nonlinear filtering
  - Differential encoding and decoding for star 16QAM, BER performance comparison with square 16QAM