Lecture 15 QAM Transmitters

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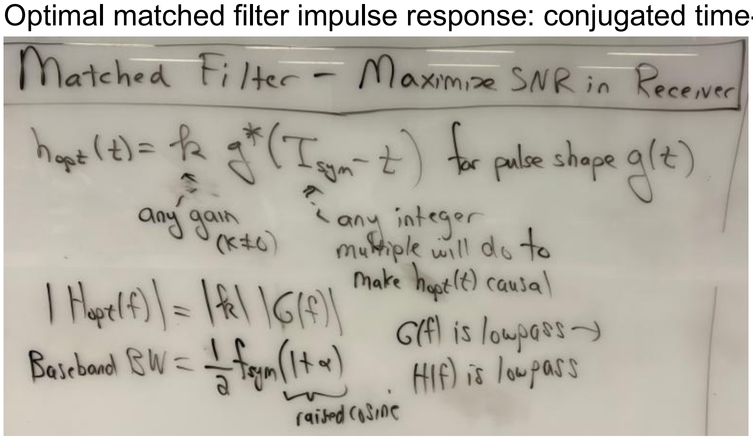
Analog/RF Front Ends

- Announcement
- What does that transmission actually look like on a laptop?
  - Computational platform in the base of the laptop under the keyboard
    - CPUs running at a clock speed of 1.6 to 5 GHz
    - PCI Express data lines – each serial line transmits 10 bits at a time with an 8-bit data and 2-bit embedded clock for timing synchronization operating at a clock speeds of 1.25, 2.5, 4, 8, or 16 GHz for 1-5 generations, respectively. Each "lane" has a serial line in one direction and a second serial line in the other direction for bi-directional communication. Sixth-generation PCI Express uses 4-PAM signaling.
    - Memory – memory locations are written into using an error correcting code so when the data is read, any bit flips can be detected and corrected
    - Pixel clock driving the display – from 100 MHz to 1 GHz. High-power clock with high-power harmonics that leak and interfere with wireless transmissions
  - Antennas for Wi-Fi and Bluetooth transmission
    - Placed in the laptop lid to maximize distance from the RF emissions of the computational platform including memory I/O and pixel clock and its harmonics
    - This antenna placement reduces the interference of the Wi-Fi and Bluetooth transmissions on the operation of the computational platform under the keyboard and vice-versa

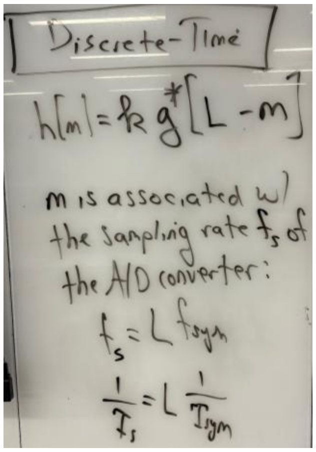
Review of Previous Lecture

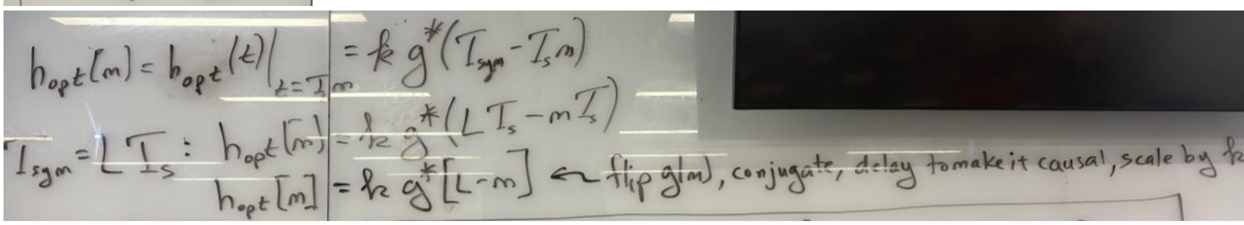
- Matched filter
  - Compensates for additive thermal noise in RF front end
  - Placed in the baseband signal processing in the receiver after demodulation
  - Optimal matched filter impulse response: conjugated time-reversed pulse shape



  - Can be delayed any integer multiple of T_{sym}
  - Can have any gain k but k≠0 in practice (k=0 means nothing gets through)
  - Baseband bandwidth for raised cosine is between ½ f_{sym} to f_{sym}

- Discrete time
    - L samples per symbol, so delay by L samples rather than T_{sym} in continuous time

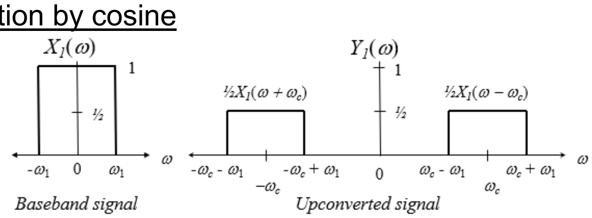




<u>QAM</u>

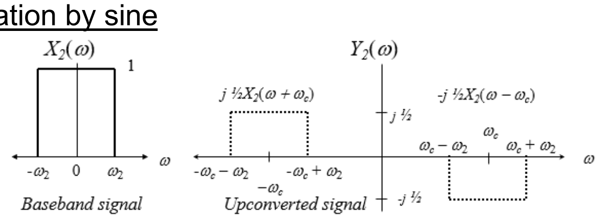
- 2D PAM
- Increase bit rate while using same transmission bandwidth as upconverted PAM
- Essentially 2 M-PAM signals, one modulated with a cosine and the other modulated by a sine and placed in the same transmission band for spectral efficiency
- Because the bit information is transmitted in the amplitude and phase, the QAM receiver more sensitive to phase error than a PAM receiver
- Need to scale by 2 somewhere in the receiver to compensate for loss in modulation

<u>Modulation by cosine</u>



- Modulated signal is real-valued in the frequency domain
- Demodulate using modulation by the cosine and lowpass filtering

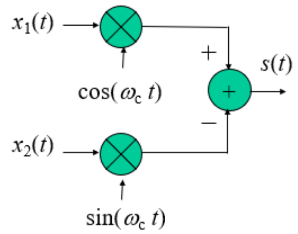
<u>Modulation by sine</u>



- Modulated signal is imaginary-valued in the frequency domain

- Demodulate using modulation by the sine and lowpass filtering

QAM bandwidth efficiency

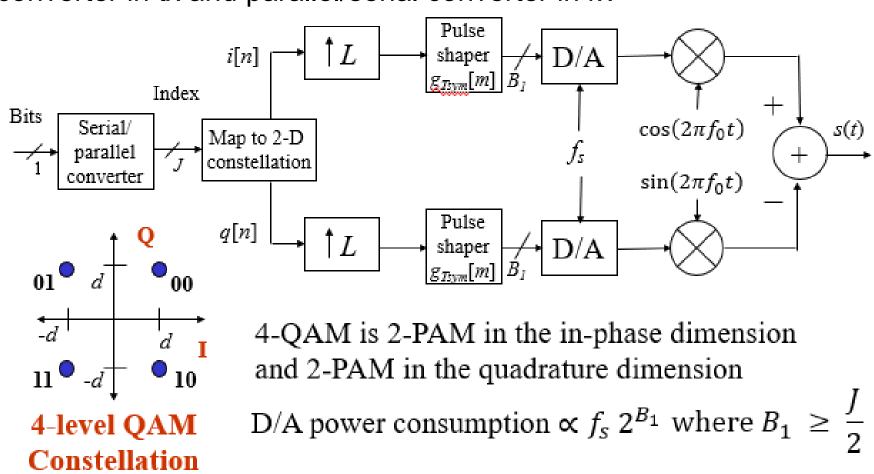


$$S(\omega)=\frac{1}{2}\left(X_1(\omega+\omega_c)+X_1(\omega-\omega_c)\right)-j\frac{1}{2}\left(X_2(\omega+\omega_c)-X_2(\omega-\omega_c)\right)$$

- Cosine modulated signal is orthogonal to sine modulated signal, so can separate through demodulation with cosine and sine, respectively

QAM Architecture 1

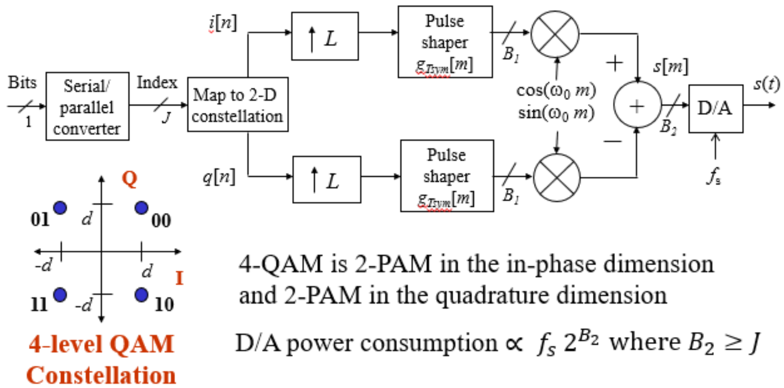
- Each component will have a corresponding component in receiver, ie serial/parallel converter in tx and parallel/serial converter in rx



- 4-QAM constellation will include 2-PAM in the in-phase dimension (horizontal dimension) and 2-PAM in quadrature dimension (vertical dimension)
- Upsample, pulse shape, and D/A converter is the same for I and Q component
- This architecture upconverts analog signal
  - Lower power than placing modulation in software b/c D/A converter power is exponential in the number of bits
- Each D/A converter must handle >= J/2 bits
  - At least as many bits in the I or Q dimension

QAM Architecture 2

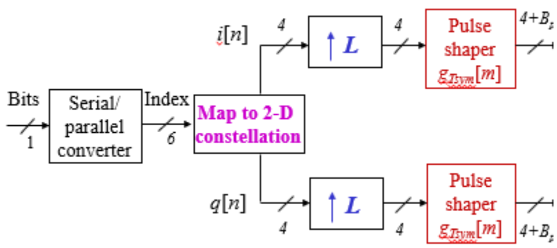
- Done in lab
- Only 1 D/A converter



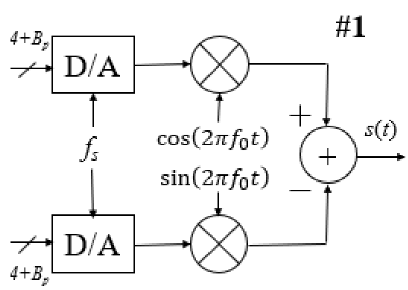
- Need many more bits in D/A converter to accurately represent sine and cosine, so much more power hungry
  - For 4-QAM: 1 bit for I, 1 bit for Q, ~8 bits for sin and cosine

<u>Comparison for 64-QAM</u>

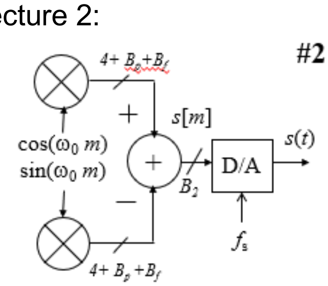
- Same for both architectures:



- i[n] and q[n] are 8-PAM, which need 4 bits each
- Pulse shaper will introduce B_p bits to represent pulse
- Architecture 1:



  - 4+B_p bits sent to D/A
- Architecture 2:



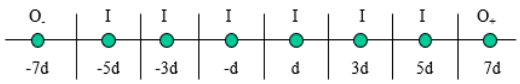
  - 4+B_p+B_f bits sent to D/A

<u>PAM Performance Analysis</u>

- If we sampled matched filter output at correct time instances without any ISI, received signal only contains tx signal + noise

  $$x(nT_{sym}) = s(nT_{sym}) + v(nT_{sym}) \qquad \mathbf{v(nT) \sim N(0;\ \sigma^2/T_{sym})}$$

- For 8-PAM :



- Decision error for an inner constellation point – a symbol error can occur in one of two directions. Consider transmitting a symbol amplitude of -5d and receiving a symbol amplitude of -5d plus a random variable following a Gaussian distribution with zero mean and variance sigma^2 / sqrt(Tsym). An error occurs if the received symbol is less than -6d or greater than -4d. The probability of error is calculated by integrating two tails of a normalized Gaussian PDF.

  $$P_I(e) = P(|v(nT_{sym})| > d) = 2\,Q\left(\frac{d}{\sigma}\sqrt{T_{sym}}\right)$$

- Decision error for outer points – a symbol error can occur in only one direction. Consider transmitting a symbol amplitude of -7d and receiving a symbol amplitude of -7d plus a random variable following a Gaussian distribution with zero mean and variance sigma^2 / sqrt(Tsym). An error occurs if the received symbol is greater than -6d. This is similar to the case for 2-PAM– the probability of error is calculated by integrating one tail of a normalized Gaussian PDF.

  $$P_{O_-}(e) = P(v(nT_{sym}) > d) = Q\left(\frac{d}{\sigma}\sqrt{T_{sym}}\right)$$

  $$P_{O_+}(e) = P(v(nT_{sym}) < -d) = P(v(nT_{sym}) > d) = Q\left(\frac{d}{\sigma}\sqrt{T_{sym}}\right)$$

- Symbol error probability
  - (fraction of inner points) * (decision error for inner points) + (fraction of outer points) * (decision error for outer points)

    $$P(e) = \frac{M-2}{M}P_I(e) + \frac{1}{M}P_{O_+}(e) + \frac{1}{M}P_{O_-}(e) = \frac{2(M-1)}{M}Q\left(\frac{d}{\sigma}\sqrt{T_{sym}}\right)$$