Digital Communication Systems Engineering with Software-Defined Radio

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Lecture 16

Extending Single Carrier to Multicarrier

- Multicarrier modulation can be viewed as the simultaneous transmission of several low data rate single carrier signals summed together
  - These signals, referred to as *subcarriers* are kept separate in the frequency domain
- In this lecture, we begin with the development of an *orthogonal quadrature amplitude modulation* (OQAM) multicarrier framework
  - Multiple QAM signals modulated to different carrier frequencies and summed toegther
- We then extend this result in the subsequent lecture to show it can be implemented using a *discrete Fourier transform* (DFT) and its inverse (IDFT)
  - This is referred to as *orthogonal frequency division multiplexing* (OFDM)

Rectangular M-ary QAM Revisited

- D bits are taken from the input bit stream $d[m]$
- Used to select one of 2^D combinations of amplitudes for the two carriers, $a[\ell]$ and $b[\ell]$
- Resulting M-ary QAM signal is equal to:

$$s[n] = a'[n]\cos(\omega_k n) + b'[n]\sin(\omega_k n) \tag{1}$$

where

  - $a'[n]$ and $b'[n]$ piecewise constant signals
  - $\omega_k = 2\pi k/2N$ is the carrier frequency
  - $2N$ is the period of the symbol

Rectangular *M*-ary QAM Revisited

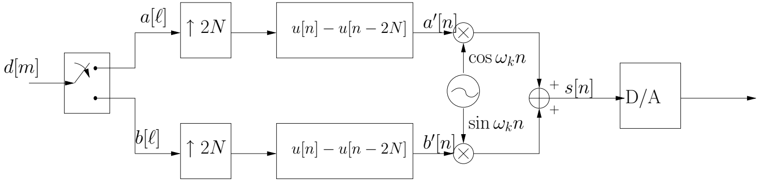


Figure : Rectangular *M*-ary QAM Transmitter.

Rectangular M-ary QAM Revisited

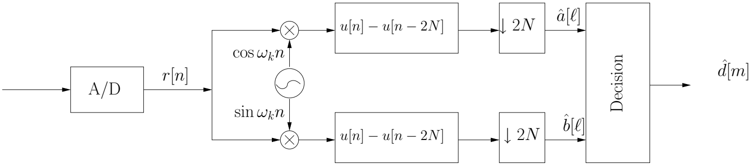


Figure : Rectangular M-ary QAM Receiver.

Sample *M*-ary QAM Signal Constellations

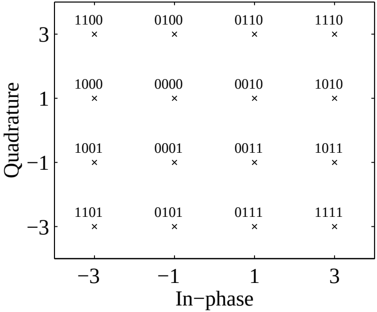


Figure : Rectangular 16-QAM Signal Constellation with Gray Coding.

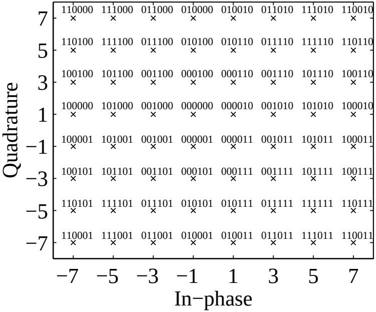


Figure : Rectangular 64-QAM Signal Constellation with Gray Coding.

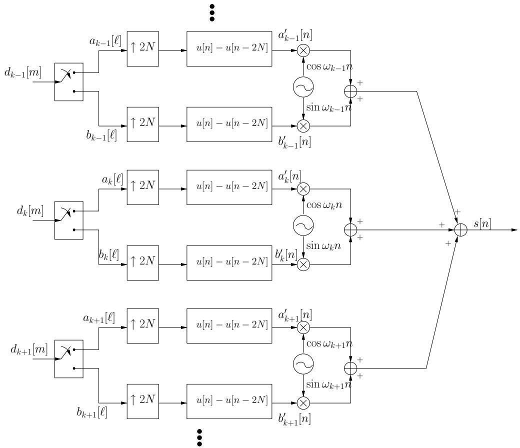
Rectangular M-ary QAM Demodulation

$$
\begin{aligned}
\hat{a}[\ell] &= \sum_{n=2\ell N}^{2\ell N+2N-1} r[n]\cos(\omega_k n) \\
&= \sum_{n=2\ell N}^{2\ell N+2N-1} a'[n]\cos(\omega_k n)\cos(\omega_k n) + b'[n]\sin(\omega_k n)\cos(\omega_k n) \\
&= \sum_{n=2\ell N}^{2\ell N+2N-1} a'[n]\cos\left(\frac{2\pi kn}{2N}\right)\cos\left(\frac{2\pi kn}{2N}\right) \\
&\qquad + b'[n]\sin\left(\frac{2\pi kn}{2N}\right)\cos\left(\frac{2\pi kn}{2N}\right) \\
&= \sum_{n=2\ell N}^{2\ell N+2N-1} \frac{a'[n]}{2}
\end{aligned}
$$

Rectangular M-ary QAM Demodulation

$$
\begin{aligned}
\hat{b}[\ell] &= \sum_{n=2\ell N}^{2\ell N+2N-1} r[n]\sin(\omega_k n) \\
&= \sum_{n=2\ell N}^{2\ell N+2N-1} a'[n]\cos(\omega_k n)\sin(\omega_k n) + b'[n]\sin(\omega_k n)\sin(\omega_k n) \\
&= \sum_{n=2\ell N}^{2\ell N+2N-1} a'[n]\cos\left(\frac{2\pi kn}{2N}\right)\sin\left(\frac{2\pi kn}{2N}\right) \\
&\quad + b'[n]\sin\left(\frac{2\pi kn}{2N}\right)\sin\left(\frac{2\pi kn}{2N}\right) \\
&= \sum_{n=2\ell N}^{2\ell N+2N-1} \frac{b'[n]}{2}
\end{aligned}
$$

Orthogonally Multiplexed Quadrature Amplitude Modulation



Equivalence Between OQAM and OFDM

- *Orthogonal frequency division multiplexing* (OFDM) is an efficient type of multicarrier modulation
  - Employs discrete Fourier transform (DFT) and inverse DFT (IDFT) to modulate and demodulate data streams
- Carriers used in OQAM transmission are sinusoidal function of $2\pi kn/2N$
  - A $2N$-point DFT or IDFT can carry out the same modulation
  - It contains also summations of terms of the form $e^{\pm 2\pi kn/2N}$