Lab 2. Quadrature Amplitude Modulation

Purpose: To simulate quadrature amplitude modulation (QAM) communication system, to obtain practical skills in its development, and to verify main properties of QAM scheme.

1. Home task

1. The following expression is usually used to describe the QAM modulation process:

   $$s_{\text{mod}}(t) = I(t)\cos 2\pi f_0 t - Q(t)\sin 2\pi f_0 t. \tag{1}$$

   It is well known that the phase difference between carrier waves for the in-phase and quadrature components is $\pi/2$. Therefore there are eight possible QAM expressions:

   $$\begin{aligned}
   s_{\text{mod}}(t) &= +I(t)\cos 2\pi f_0 t - Q(t)\sin 2\pi f_0 t;\\
   s_{\text{mod}}(t) &= +I(t)\cos 2\pi f_0 t + Q(t)\sin 2\pi f_0 t;\\
   s_{\text{mod}}(t) &= +I(t)\sin 2\pi f_0 t - Q(t)\cos 2\pi f_0 t;\\
   s_{\text{mod}}(t) &= +I(t)\sin 2\pi f_0 t + Q(t)\cos 2\pi f_0 t;\\
   s_{\text{mod}}(t) &= -I(t)\cos 2\pi f_0 t - Q(t)\sin 2\pi f_0 t;\\
   s_{\text{mod}}(t) &= -I(t)\cos 2\pi f_0 t + Q(t)\sin 2\pi f_0 t;\\
   s_{\text{mod}}(t) &= -I(t)\sin 2\pi f_0 t - Q(t)\cos 2\pi f_0 t;\\
   s_{\text{mod}}(t) &= -I(t)\sin 2\pi f_0 t + Q(t)\cos 2\pi f_0 t.
   \end{aligned}$$

   Split this set of expressions into two groups, in which all expressions describe the same up to the initial phase. Draw a conclusion about spectral inversion for these two groups.

   Hint 1: Use the approach from slide 13 of lecture 3.

   Hint 2: Recall that $\mathrm{e}^0 = 1$, $\mathrm{e}^{j\pi/2} = j$, $\mathrm{e}^{j\pi} = -1$, and $\mathrm{e}^{-j\pi/2} = -j$.

2. Find out necessary expressions for the in-phase $I(t)$ and quadrature $Q(t)$ component to obtain a dual-tone signal at the output of the QAM modulator. Show the correctness of your choice, using the approach from lecture 3.

3. Try to demodulate QAM components if the receiver's local oscillator generates sine and cosine waves of the frequency $f_1 \neq f_0$. Write expressions for the signals that are obtained after demodulation. Assume $\Delta f = f_0 - f_1$.

4. **OPTIONAL**. Calculate the impulse response of the raised cosine filter. Use inverse Fourier transform and frequency response expression from lecture 4. Plot this impulse response in MATLAB and compare it with the one calculated by the built-in MATLAB function *firrcos()*.

2. MATLAB simulations

For the simulation use the following parameters:

- Baseband sampling frequency $f_s = 100\,\text{MHz}$.
- An in-phase and quadrature components, if not stated differently, are 4-PAM signals, i.e., symbols are from the set $\{-3; -1; 1; 3\}$. Take the symbol rate equal to 20Mbaud, calculate the number of samples per symbol on your own.
- Intermediate frequency, if applicable, is equal to $f_{IF} = 140\,\text{MHz}$.
- For the simulation of the modulation process, if needed, resample baseband signal to the sampling frequency $f_d = 4\,\text{GHz}$.

Perform the following experiments:

1. Single-tone and dual-tone signal generation

1. Create a QAM communication system model in MATLAB. It should consist of the following blocks: quadrature components generation block (with the necessary number of samples per symbol), pulse-shaping filter, upsampling block, quadrature modulator, quadrature demodulator, low-pass filter, and downsampling block.
2. Choose the in-phase $I(t)$ and quadrature $Q(t)$ component values to obtain two harmonic waves ($f_1 = 145\,\text{MHz}$ and $f_2 = 135\,\text{MHz}$) at the output of the QAM modulator.
3. Choose the in-phase $I(t)$ and quadrature $Q(t)$ component values to obtain two harmonic waves ($f_1 = 150\,\text{MHz}$ and $f_2 = 133\,\text{MHz}$) at the output of the QAM modulator. The first harmonic wave power should be 3 dB greater.

2. Spectral asymmetry and inversion

1. Rewrite the QAM communication system model, if necessary, to ensure the following requirement fulfillment:
   - Each channel signal is 4-PAM modulation. Establish zero insertion between symbols accordingly to the number of samples per symbol.
   - As a pulse-shaping filter, a raised cosine filter with a roll-off factor $\beta = 0.25$ is chosen.
2. In the baseband, add to the in-phase $I(t)$ and quadrature $Q(t)$ components signals to obtain a harmonic wave at frequency $f_1 = 145\,\text{MHz}$ in the signal spectrum. **Note:** a harmonic wave should be seen over the other spectral components at the spectral plot.
3. Show the asymmetry of the QAM signal spectrum.
4. Perform necessary operations to invert the spectrum of the generated signal. Use three approaches: in-phase component sign inversion, complex conjugation, and component swap. Add to the report spectra of the initial and processed signal, as well as their timing diagrams.

3. Pulse-shaping and matched filter

1. Perform simulation with the raised cosine filter at the transmitter side (exclude matched filter from the receiver). Pay attention to the filter bandwidth. Add constellation to the report.
2. After the QAM modulator, add a transmission channel emulating block. It should be able to add noise to the signal. The signal-to-noise ratio (SNR) is assumed to be analog-like, i.e., signal and noise power ratio. Ensure SNR=20 dB.
3. Perform simulation with the raised cosine filter at the transmitter side (exclude matched filter from the receiver). Add constellation to the report.
4. Split the raised cosine filter into two root-raised-cosine filters. The transmitter part of this filter should comply with the spectral mask. It is defined with the set of frequency response samples given frequencies: $f_m = \{0, 0.2, 0.25, 0.4, 0.7, 1\}$, $H_m = \{0, 0, -30, -40, -50, -50\}\,\text{dB}$. Adjust filter's roll-off factor β and the number of coefficients to match this requirement.

Hint: use MATLAB function *freqz()* to built frequency response of the filer. Note that this function outputs cyclic frequency, i.e., Nyquist is equal to π. Add spectral mask plots to rhe report.

5. Perform simulation with the developed pair of filters. Add constellation to the report.

4. Non-coherent receiving

1. Set SNR=120 dB.

2. In the QAM demodulator, change an initial phase of the local oscillator generated waves, i.e., $\sin 2\pi f_0 t$ becomes $\sin(2\pi f_0 t - \varphi_0)$, and $\cos 2\pi f_0 t$ becomes $\cos(2\pi f_0 t - \varphi_0)$. Choose $\varphi_0 = \pi/3$. Construct constellation of the received signal.

3. In the QAM demodulator, use harmonic waves of the frequency $f_1 = f_0 \pm \Delta f$, where f_0 is the carrier frequency, and Δf is the difference of these frequencies. Choose $\Delta f = 100$ kHz. Construct constellation of the received signal.

4. Rewrite the model concerning the complex baseband concept. Perform the last two paragraphs with complex numbers.

3. Task of increased complexity[1]

Formulation: Build a QAM communication system in which the number of constellation points is equal to the number of letters in the English alphabet. On the constellation, points are positioned in such a way to form your initials—first letters of your name and surname. A message to be transmitted consists of English lowercase letters without spaces. In the beginning, transmit 500 random letters; then transmit a phrase 'Feci quod potui, faciant meliora potentesa' and end the message with 500 random letters. On the receiving side, you should te recover the message and find the phrase. Some notes that could be useful:

- To convert a phrase to integers in MATLAB, a command *double(...)-96* can be used. Do not forget to delete spaces, commas and convert letters to lowercase.

- The integer-to-character conversion can be done by *char(...+96)*.

[1]Necessary to get mark higher than 8 (eight)

- A pair of root-raised-cosine filters changes the amplitude of the signal; therefore, received constellation points do not match the transmitter constellation. It can be fixed by dividing the output signal by the maximal coefficient of the merged (convolved) filter.
- To detect a symbol, you should find the nearest point it is located to. Possibly, something like *min(abs(ALPH-x))==abs(ALPH-x)* can be useful. You can also use *find()* function.

4. Report structure

1. Home task.
2. Constellations, timing diagrams, and spectra of the signals to demonstrate the essence of the experiment.
3. Listings.
4. Conclusions.