UCLA — Electrical and Computer Engineering Dept.
ECE132A: Introduction to Communication Systems
Project
Due: Friday March 15, 2024

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1. Please form groups of **one to two** people. Make sure that at least one person in the group is reasonably familiar with MATLAB.

2. Submit MATLAB code and all the figures. Please, **comment your code**! (Remember that in MATLAB anything that follows a % sign is considered a comment.)

3. Each group should generate one set of charts (one per group) describing the work you've done, the results (plots, block diagrams, if any, etc.), and any comments you may have. Preferably, use Powerpoint or Keynote. **Alternatively** submit a very well commented Matlab live script. Please indicate clearly the names of the team members in the front page of your charts or at the start of your code.

4. Please submit your projects to Gradescope. Also submit your code, because I will want to run it and verify your results.

5. Please work ethically. **Every team should work independently. If two or more projects raise suspicions of communication among teams, the evidence will be submitted to the Dean of Students.**

Project Description

In this project, you will simulate communication systems that employ multiple antennas at the transmitter and/or at the receiver. A system that employs one antenna on each end is called *single-input single-output* or SISO. In contrast, a system that employs multiple antennas is known as *multiple-input multiple-output* or MIMO. The following is the definition of MIMO in Wikipedia:

> In radio, multiple-input and multiple-output (MIMO) is a method for multiplying the capacity of a radio link using multiple transmission and receiving antennas to exploit multipath propagation. MIMO has become an essential element of wireless communication standards including IEEE 802.11n (Wi-Fi 4), IEEE 802.11ac (Wi-Fi 5), HSPA+ (3G), WiMAX, and Long Term Evolution (LTE). More recently, MIMO has been applied to power-line communication for three-wire installations as part of the ITU G.hn standard and of the HomePlug AV2 specification.

1 Assignment

1. We will start by simulating a SISO communication system that uses QPSK modulation with square-root raised cosine pulse shaping in an AWGN channel and a slow flat fading channel. We'll assume perfect channel state information.
   (a) Generate a sufficiently long vector of bits.
   (b) From the bits, generate a Gray-coded QPSK vector of complex symbols.

(c) Generate the complex baseband sampled waveform by applying SRRC pulse shaping. Upsample by at least a factor 2. Let the symbols be unit energy.

(d) AWGN channel.

   i. In the case of AWGN, add noise to the modulated waveform in order to match a desired signal to noise ratio (SNR). You may simulate different SNRs, anywhere from -3 dB to 20 dB.

   ii. Pass the received waveform through a matched filter and sample at one sample per symbol.

   iii. Demodulate.

   iv. Compute the bit error rate, plot against $\mathcal{E}_{\mathrm{b}}/N_0$, compare and describe with theory.

(e) Slow flat fading channel.

   i. Assume that the entire transmission is affected by the same fading. Multiply the entire waveform by a complex Gaussian random variable with zero mean and a given variance. You will have to simulate many times to compute an average bit error rate.

   ii. From here apply all the steps you followed in the AWGN case (add noise, matched-filter, demodulate, compute the bit error rate), but before demodulation, apply a phase correction to the received waveform (or matched filter outputs).

(f) Verify that you would have obtained the same results by simulating at *symbol level*, i.e., without upsampling, pulse shaping and matched-filtering, with the important difference that the noise you add to the symbols now has variance equal to N_0.

2. Now that you are comfortable with symbol-level simulations, consider a 2×2 MIMO system, i.e., a system with $N_{\mathrm{t}} = 2$ antennas at the transmitter and $N_{\mathrm{r}} = 2$ antennas at the receiver.

   (a) Generate a sufficiently long vector of bits and the corresponding vector of Gray-coded complex QPSK symbols.

   (b) Generate a 2×2 MIMO channel matrix, H, with complex Gaussian coefficients with zero mean and a given variance. You will have to simulate many times to compute the average bit error rate.

   (c) Assume perfect channel state information at the receiver. Compute the received symbols as in:

$$y = Hx + n$$

   where y, x, and n are 2×1 complex vectors, x being a vector containing the 2 QPSK symbols sent simultaneously. Compute the zero-forcing (ZF) and linear minimum mean-squared error (LMMSE) estimated symbols for each transmission:

$$\hat{x}_{\mathrm{ZF}} = (H^{\mathsf{H}} H)^{-1} H^{\mathsf{H}} y, \quad \hat{x}_{\mathrm{LMMSE}} = \left(H^{\mathsf{H}} H + \frac{1}{\mathrm{SNR}} \mathrm{I} \right)^{-1} H^{\mathsf{H}} y.$$

   Compute the bit error rate.

(d) Assume perfect channel state information at the transmitter and receiver. Let x be the 2×1 vector of QPSK symbols. Precode x using the right singular matrix if the SVD of $H = U\Sigma V^{\mathsf{H}}$, namely, compute $\tilde{x} = Vx$. The received vector is $\tilde{y} = H\tilde{x} + n$. Premultiply $\tilde{y}$ by U^{H}. Demodulate and compute the bit error rate.

(e) Assume no channel state information at transmitter or receiver. The channel needs to be estimated at the receiver. The transmitter sends a set of pilot symbols known to the receiver. A number $N_{\mathrm{p}} \geq 2$ of 2×1 pilot vectors, p_i, $i = 0, \ldots, N_{\mathrm{p}} - 1$, are sent out by the transmitter: Rewrite $y_i = Hp_i + n$ as $y_i = P_i h + n$. Where P_i is a 2×4 matrix obtained from p_i, and h is 4×1 (unknown, for now). Stack together all the P_i matrices to generate a $2N_{\mathrm{p}} \times 4$ P matrix, and stack all the y_i vectors to generate a $2N_{\mathrm{p}} \times 1$ vector y. Estimate h by using a ZF or an LMMSE estimation method. Now send the QPSK symbols as you did in part (c). Use the estimated channel matrix to estimate the symbols. Compare the results.

(f) Assume perfect channel state information at the receiver. Use the Alamouti code. In this case $N_{\mathrm{t}} = 2$. Suppose $N_{\mathrm{r}} = 1$. At time 0 the transmitter sends symbols s_0 and s_1 on the two antennas, and at time 1 it sends $-s_1^\star$ and $s_0^\star$. The channel matrix is $H = [h_0, h_1]$. Let $y(n)$ be the output of the received antenna at time n, $n = 0, 1$. In absence of noise:

$$\begin{aligned} y(0) &= h_0 s_0 + h_1 s_1 + n(0), \\ y(1) &= -h_0 s_1^\star + h_1 s_0^\star, \end{aligned}$$

which can be rewritten as

$$y := \begin{bmatrix} y(0) \\ y(1)^\star \end{bmatrix} \begin{bmatrix} h_0 & h_1 \\ h_1^\star & -h_0^\star \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix}.$$

Let

$$H_{\mathrm{ala}} := \begin{bmatrix} h_0 & h_1 \\ h_1^\star & -h_0^\star \end{bmatrix}.$$

Then

$$H_{\mathrm{ala}}^{\mathsf{H}} \begin{bmatrix} y(0) \\ y(1)^\star \end{bmatrix} = \left(|h_0|^2 + |h_1|^2\right) \begin{bmatrix} s_0 \\ s_1 \end{bmatrix}.$$

If $N_{\mathrm{r}} = 2$, then the channel matrix is given by:

$$H = \begin{bmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \end{bmatrix}.$$

Define

$$H_{\mathrm{ala},0} := \begin{bmatrix} h_{00} & h_{01} \\ h_{01}^\star & -h_{01}^\star \end{bmatrix}, \quad H_{\mathrm{ala},1} := \begin{bmatrix} h_{10} & h_{11} \\ h_{11}^\star & -h_{11}^\star \end{bmatrix}, \quad H_{\mathrm{ala}} := \begin{bmatrix} H_{\mathrm{ala},0} \\ H_{\mathrm{ala},1} \end{bmatrix},$$

then, in absence of noise,

$$H_{\mathrm{ala}} \begin{bmatrix} y_0(0) \\ y_0(1)^\star \\ y_1(0) \\ y_1(1)^\star \end{bmatrix} = 2\ \left(|h_0|^2 + |h_1|^2\right) \begin{bmatrix} s_0 \\ s_1 \end{bmatrix}.$$

Note that running the code provided without change is **not** sufficient. The more you do (if done properly), the more bonus points you'll get, up to a maximum of **10 points**. *I encourage you to discuss with me at any time. Do not hesitate to email me.* In summary:

Task #1	simulate SISO comm system: SRRC, AWGN, MF Rx **sample level**	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare to theory	1 pt.
Task #2	simulate SISO comm system: **symbol level**	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare and describe	1 pt.
Task #3	simulate SISO comm system: SRRC, fading, MF Rx average over fading for each SNR point **sample level**	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare and describe	1 pt.
Task #4	simulate SISO comm system: fading average over fading for each SNR point **symbol level**	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare and describe	1 pt.
Task #5	simulate MIMO comm system: fading $N_\mathrm{t} = 2$, $N_\mathrm{r} = 2$ throughput CSIR, CSIT	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare and describe	1 pt.
Task #6	simulate MIMO comm system: fading $N_\mathrm{t} = 2$, $N_\mathrm{r} = 2$ diversity CSIR, CSIT	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare and describe	1 pt.
Task #7	simulate MIMO comm system: fading $N_\mathrm{t} = 2$, $N_\mathrm{r} = 2$ throughput CSIR, ZF, LMMSE	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare and describe	2 pts.
Task #8	simulate MIMO comm system: fading $N_\mathrm{t} = 2$, $N_\mathrm{r} = 2$ diversity CSIR, ZF, LMMSE	Plot BER vs. $\mathcal{E}_\mathrm{b}/N_0$ compare and describe	2 pts.
Extras	different N_t, N_r		≤ 2 pts.
	channel estimation with pilots		≤ 4 pts.
	Alamouti with $N_\mathrm{t} = 2$ and various N_r		≤ 2 pts.
	different modulations		≤ 4 pts.