Wireless Communications Lab

Lecture #28

Professor Robert Heath

The University of Texas at Austin
Announcements

1) Graduate students: Please do not forget to turn in your project. Upload is through blackboard.

2) Final exam will be Monday December 16 from 9am to noon. The final is the duration of two midterm exams (150 minutes of exam in 180 minutes). You may have 3 pages of handwritten notes front / back.
Review of Class Syllabus
<table>
<thead>
<tr>
<th>Lecture</th>
<th>Date</th>
<th>Topic</th>
<th>Lab</th>
<th>Out</th>
<th>Due</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8/28</td>
<td>Introduction to the wireless communications lab, wireless communication past and present</td>
<td></td>
<td>HW #1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9/4</td>
<td>Digital communication overview</td>
<td>No lab but go to session</td>
<td>HW #2</td>
<td>HW #1</td>
</tr>
<tr>
<td>3</td>
<td>9/9</td>
<td>Types of signals, stochastic processes</td>
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<td>Prelab 1.1</td>
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<tr>
<td>4</td>
<td>9/11</td>
<td>Review of transforms, sampling theorem, discrete-time processing of continuous-time signals (Prof. Heath on travel)</td>
<td>Lab 1 Part 1</td>
<td>HW #3</td>
<td>HW #2,</td>
</tr>
<tr>
<td>5</td>
<td>9/16</td>
<td>Frequency response of random signals, power spectrum, bandwidth, complex envelope notation (Prof. Heath on travel)</td>
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<td>Prelab 1.2</td>
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<tr>
<td>6</td>
<td>9/18</td>
<td>Up conversion, down conversion, complex baseband representation, complex baseband equivalent channel</td>
<td>Lab 1 Part 2</td>
<td>HW #4</td>
<td>HW #3</td>
</tr>
<tr>
<td>7</td>
<td>9/23</td>
<td>Quadrature pulse amplitude modulation, PAM, QAM, transmit energy, transmit bandwidth, additive white Gaussian noise channels</td>
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<td>Prelab 2.1</td>
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<tr>
<td>8</td>
<td>9/25</td>
<td>Optimal pulse shapes for AWGN, Nyquist pulse shapes, implementing optimal pulse shapes using multi-rate identities</td>
<td>Lab 2 Part 1</td>
<td></td>
<td>HW #4, Report Lab 1</td>
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<tr>
<td>9</td>
<td>9/30</td>
<td>Maximum likelihood detection in additive white noise, probability of error analysis, dB</td>
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<tr>
<td>10</td>
<td>10/2</td>
<td>Midterm #1</td>
<td></td>
<td>HW 5</td>
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<tr>
<td>11</td>
<td>10/7</td>
<td>Sample timing offset, algorithms for sample timing</td>
<td>Sample timing offset, algorithms for sample timing</td>
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<tr>
<td>12</td>
<td>10/9</td>
<td>Narrowband frame synchronization, channel estimation, linear least squares estimation problems, introduction to frequency selective channels</td>
<td>Lab 2 Part 2</td>
<td>HW #6</td>
<td>HW #5</td>
</tr>
<tr>
<td>13</td>
<td>10/14</td>
<td>Least squares channel estimation, least squares equalizer, introduction to frequency domain equalization, the DFT</td>
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<td>Prelab 3</td>
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<tr>
<td>14</td>
<td>10/16</td>
<td>Single carrier frequency domain equalization (SC-FDE), OFDM, the cyclic prefix</td>
<td>Lab 3</td>
<td></td>
<td>HW #7, Report Lab 2</td>
</tr>
<tr>
<td>Week</td>
<td>Date</td>
<td>Topic</td>
<td>Lab</td>
<td>HW Assignment</td>
<td>Notes</td>
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<tr>
<td>15</td>
<td>10/21</td>
<td>Comparison between SC-FDE and OFDM, channel estimation in OFDM, introduction to frequency offset</td>
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<td>Lab 3</td>
<td>Prelab 4</td>
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<tr>
<td></td>
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<td>Carrier frequency offset estimation and correction, the Moose algorithm</td>
<td></td>
<td>HW #5</td>
<td>HW #7, Report Lab 3, Project proposals (grad)</td>
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<tr>
<td></td>
<td>10/28</td>
<td>Demystifying the IEEE 802.11a standard</td>
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<td>Prelab 5</td>
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<tr>
<td>18</td>
<td>10/30</td>
<td>Demystifying the original GSM standard</td>
<td>Lab 5</td>
<td>HW #8</td>
<td>HW #8, Report Lab 4</td>
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<tr>
<td></td>
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<td>Introduction to propagation, large-scale fading, link budgets, path loss (Prof. Heath on travel)</td>
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<tr>
<td>20</td>
<td>11/6</td>
<td>midterm #2</td>
<td>No lab</td>
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<tr>
<td>21</td>
<td>11/11</td>
<td>Small-scale fading, coherence time, coherence bandwidth, regions of selectivity, Rayleigh fading</td>
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<td>HW #8</td>
<td>Prelab 6</td>
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<tr>
<td>22</td>
<td>11/13</td>
<td>Probability of error in fading channels, receive diversity, selection diversity and maximum ratio combining, probability of error with diversity</td>
<td>Lab 6</td>
<td>HW #9</td>
<td>HW #8, Report Lab 5</td>
</tr>
<tr>
<td>23</td>
<td>11/18</td>
<td>Sources of diversity, Alamouti space-time code, transmit beamforming</td>
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<td>Prelab 7</td>
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<tr>
<td>24</td>
<td>11/20</td>
<td>Introduction to MIMO wireless communication, spatial multiplexing</td>
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<td>HW #10</td>
<td>HW #9</td>
</tr>
<tr>
<td>25</td>
<td>11/25</td>
<td>Receivers for spatial multiplexing, performance analysis</td>
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<td>Prelab 8</td>
</tr>
<tr>
<td>26</td>
<td>11/27</td>
<td>Dealing with practical impairments in MIMO communication systems, channel estimation and synchronization</td>
<td>Lab 7</td>
<td>HW #11</td>
<td>HW #10, Report Lab 6, 7</td>
</tr>
<tr>
<td>27</td>
<td>12/2</td>
<td>Introduction to MIMO-OFDM, highlights of the IEEE 802.11n standard</td>
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<tr>
<td>28</td>
<td>12/4</td>
<td>Course Review</td>
<td>No lab (end of semester)</td>
<td></td>
<td>HW #11, Final projects due Friday (grad)</td>
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<tr>
<td>29</td>
<td>12/16</td>
<td>Final Exam – Tentative</td>
<td>9am-noon</td>
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</table>
\[ x(t) \xrightarrow{\text{filter}} y(t) \]
\[ x(t) \xrightarrow{T} y(t) \]
\[ h(t) = T \left( L(\omega) \ast h(\omega) \right) \]
\[ \text{T, s.t. N. satisfied} \]

\[ \text{Sample } h(t) \]

\[ x(t) = \sqrt{3} \sum_n s[n] g(t - nT) \]

\[ y(t) = x(t) + \epsilon(t) \]

\[ y(h) = s[h] + \epsilon(h) \]

\[ \text{argmin } \| y(h) - s[h] \| ^2 \]

\[ y(t) \xrightarrow{\text{matched filter, zero ISI}} T \]

\[ P_s \{ s \text{ BLA} \rightarrow s' \} = Q \left( \sqrt{ \frac{E_x + E_s - s'^2}{2n} } \right) \]

\[ P_c \{ \text{excess} \} \leq (M - 1) Q \left( \sqrt{ \frac{E_x}{2n^2} } \right) \]
\[ Pr \{ s \to s' \mid s \text{ source} \} = Pr \{ |y - s'| > |y - s| \} \]

\[ y = s + v \]

\[ Q(t) = \int_{-\infty}^{\infty} \omega e^{-\frac{1}{2} \omega^2} d\omega \]
\[ y = h \frac{t}{t^T} + \frac{1}{t} \]

\[
h = \min_{h} \frac{1}{h} ||y - h t||^2
\]

\[
h = \frac{t^*y}{t^*t}
\]

\[ y = Ax \Rightarrow x_S = (A^*A)^{-1}A^*y \]
\[ y[n] = \sum_{e=0}^{L-1} h[e] s[e-n] + u[n] \]

\[ \Rightarrow y = Sh + u \]

\[ \hat{h} = (S^T S)^{-1} S^T y \]

\[ S = \begin{bmatrix} \theta[1] & \theta[2] & \cdots & \theta[L] \\ \vdots & \vdots & \ddots & \vdots \\ \theta[N_e-1] & \cdots & \theta[N_e+L-1] \\ (N_e-L-1) \times (L+1) \end{bmatrix} \]

\[ \begin{bmatrix} h[0] \\ \vdots \\ h[L] \end{bmatrix} \]
DFT

- Time shift \( t[(n-k)N] \leftrightarrow e^{-j\frac{2\pi kn}{N}} T[m] \)
- \( \sum_{m=0}^{N-1} t[(n-m)N] q[m] \leftrightarrow T[k] Q[k] \)

Circular Convolution

\( h \ast w \equiv \{ \text{shift } n \in \mathbb{Z} \} \text{ circular convolution } t \in \{0, \ldots, N-1\} \)

Cyclic prefix

\( \rightarrow \text{OFDM, SC-POF} \)
\[ y[n] = e^{j\omega} e_n \]

\[ \sum_{n=0}^{\infty} y[n] = e! \]

\[ e_j\omega \sum_{n=0}^{\infty} y[n] = e! \]
\[ y(n) = e^{j2\pi fn} e^{j\theta} \sum_{k=-\infty}^{\infty} h(k)(e^{j\phi} + e^{j\phi + \pi N}) + v(n) \quad n = 0, \ldots, N-1 \]

\[ y(n+N) = e^{j2\pi fn} e^{j\theta} \sum_{k=-\infty}^{\infty} h(k)e^{j\phi} + v(n+N) \]

\[ e^{j2\pi fn} y(n) \]
Small scale

large scale

Pr

\( y \)
\[ y(n) = b \delta(n) + vn \]

\[ P_e(\varepsilon_{\text{th}} h) \leq (M-1) C \sqrt{\frac{\varepsilon_{\text{th}} h^2 d^2_m}{n_0 \sigma^2}} \]

\[ E_h P_e(\varepsilon_{\text{th}} h) \leq (M-1) C \varepsilon_{\text{th}} \alpha \sqrt{\frac{\varepsilon_{\text{th}} h^2 d^2_m}{n_0 \sigma^2}} \]

\[ \leq (M-1) \frac{1}{\left( \frac{\varepsilon_{\text{th}} h^2 d^2_m + 1}{n_0 \sigma^2} \right)^{\frac{1}{2}}} \]

Rayleigh

Solute mg/L
Review of Schmidl-Cox Algorithm

Learning Objectives:

Explain the key ideas of frequency offset correction using Schmidl-Cox
1. OOFM

\[ W[n] = \sum_{m=0}^{N-1} s[m] e^{j \frac{2\pi (n-2m)}{N}} \quad n = 0, \ldots, N-1 \]

2. Turn off odd subcarriers

\[ W[n] = W[n+N/2] \quad n = Lc + b, \ldots, N/2 - 1 \]

3. Exploit periodicity

\[ y[n] = \sum_{e=0}^{L-1} h[e] s[n - e] + v[n] \]
\[ y[n+N/2] = e^{j \frac{2\pi n}{N}} \sum_{e=0}^{L-1} h[e] s[n + N/2 - e] + v[n+N/2] \]
\[ = e^{j \frac{2\pi n}{N}} y[n] \quad n = Lc, \ldots, Lc+N/2-1 \]

4. Moore phase

\[ \phi = \text{phase} \left\{ \sum_{n=Lc}^{Lc+N/2-1} y[n+N/2] y[n] \right\} \]

5. Integer offset

\[ W[n] = \sum_{m=0}^{N/2-1} s[2m] e^{j \frac{2\pi (n-2m)l}{N/2}} \quad \text{QPSK} \]
\[ g[n] = \sum_{m=0}^{N/2-1} s[2m] e^{j \frac{2\pi (n-2m)l}{N/2}} \quad \text{Differential} \]
\[ t_3[n] = s[n] b_2[n] \]
\[ s_3[n] = t_3[n] \]
After correction

\[ y_1[k] = e^{j \frac{2\pi d m}{N}} \left[ h[k-2mN] \delta[k-4mN] \right] + n_1[k] \]

\[ y_2[k] = e^{j \frac{2\pi d m}{N}} \left[ h[k-2mN] \beta[k-4mN] \right] + n_2[k] \]

\[ y_3[k] = e^{j \frac{2\pi d m}{N}} \left| H[k-2mN] \right|^2 T_3 \delta[k-4mN] + \text{other terms} \]

\[ T_2 \left[ (k-2mN) \right] \]