Multi-channel Modulation

Multi-channel transmission

- Multi-channel modulation methods are generally the best for data transmission channels with moderate or severe inter-symbol interference.
- Basic concept of adaptive multi-channel (“multi-tone”) transmission:
  - Use each tone as a basis function
  - Each tone transmits narrow QAM signal and satisfies Nyquist criterion – i.e. no ISI per tone
  - Put less energy where channel is bad or where there is more noise

Basic multi-tone transmission

- Multi-tone transmission uses two or more coordinated passband (QAM or QAM-like) signals to carry a single bit stream over a communication channel.
- The passband signals are independently demodulated in the receiver and then re-multiplexed into the original bit stream.
- The heuristic motivation for multi-tone modulation is that if the bandwidth of each of the “tones” is sufficiently narrow, then no ISI occurs on any sub-channel.

History

- 1948 Shannon constructs capacity bounds
  - AWGN channel with linear ISI – effectively uses multi-tone modulation
- Analog multi-tone
  - 1958 Collins Kineplex modem (first voiceband modem) – analog multitone
  - 1964 Holsinger’s MIT thesis – modem that approximates Shannon’s “water-filling”
  - 1967 Saltzberg, 1973 Bell Labs, 1980 IBM ...
- Digital multi-tone ~ 1990s
  - DMT for DSL - Major push by prof. Cioffi’s group at Stanford
  - Use DSP power to improve the robustness and algorithms for discrete multi-tone modulation
Basic multi-tone transmission

The effect of the channel

Channel Partitioning

- Channel Partitioning methods divide a transmission channel into a set of parallel and ideally independent channels.
- Multi-tone transmission (MT) is an example of channel partitioning where each sub-channel has a frequency index and all sub-channels are independent.
- The MT basis functions \( \{\varphi_n(t)\} \) form an orthonormal basis while also exhibiting the desirable property that the set of channel-output functions \( \{h(t)\ast\varphi_n(t)\} \) remains orthogonal for any \( h(t) \).

Channel Partitioning
 Modal modulation

\[ x(t) = h(t) * h^*(t) \] (\(T_H / 2, T_H / 2\))

\[ p_n \cdot \phi_n(t) = \int_{-T/2}^{T/2} r(t - \tau) \phi_n(\tau) d\tau, \quad n = 1, \ldots, \infty, \quad \forall \Omega \in [-T - T_H / 2, T + T_H / 2]\]

\[ \begin{array}{c}
X_{1,k} \\
X_{2,k} \\
\vdots \\
X_{N,k}
\end{array} \hspace{1cm} \begin{array}{c}
\phi_0(t) \\
\phi_2(t) \\
\vdots \\
\phi_N(t)
\end{array} \hspace{1cm} \begin{array}{c}
x_0(t) \\
x_2(t) \\
\vdots \\
x_N(t)
\end{array} \]

\[ \begin{aligned}
x(t) &= \sum_{n=1}^{N} x_n \phi_n(t) \\
y(t) &= \sum_{n=1}^{N} (p_n \phi_n) \cdot \phi_n(t)
\end{aligned} \]

Discrete-time channel partitioning

\[ \begin{bmatrix}
Y_{N-1} \\
Y_{N-2} \\
\vdots \\
Y_0
\end{bmatrix} = \begin{bmatrix}
p_0 & p_1 & \cdots & p_{N-1} & 0 & \cdots & 0 \\
0 & p_0 & \cdots & \vdots & \cdots & \cdots & 0 \\
0 & 0 & \cdots & 0 & p_0 & p_1 & \cdots & p_{N-1} \\
0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots
\end{bmatrix} \begin{bmatrix}
X_{N-1} \\
X_{N-2} \\
\vdots \\
X_0
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

DMT and OFDM

- Discrete MultiTone (DMT) and Orthogonal Frequency Division Multiplexing (OFDM)
- DMT is used on slowly time-varying two-way channels, like telephone lines.
- OFDM is used in wireless time-varying channels with codes that allow recovery of lost sub-channels caused by time-varying notches in multi-path inter-symbol interference.

Motivation:
- High-data-rate wireless communications -> Large bandwidth
- Limitations caused by the radio environment - multipath propagation
- OFDM can overcome and take advantage of multipath fading and thus eliminate inherent data rate limitations
- OFDM is good for high-data-rate systems

DMT/OFDM implementation

\[ X_0 \xrightarrow{IDFT} x_0(t) \]

\[ \begin{aligned}
&X_1 \\
&\vdots \\
&X_{N-2} \\
&X_{N-1} \\
&X_0 = X^* \text{ if } x(t) \text{ is real}
\end{aligned} \]

\[ \begin{aligned}
&x_0(t) \xrightarrow{DFT} X_0 \\
&x_1(t) \xrightarrow{DFT} X_1 \\
&\vdots \\
&x_{N-2}(t) \xrightarrow{DFT} X_{N-2} \\
&x_{N-1}(t) \xrightarrow{DFT} X_{N-1}
\end{aligned} \]

\[ \begin{aligned}
&Y_0 \\
&Y_1 \\
&\vdots \\
&Y_{N-2} \\
&Y_{N-1}
\end{aligned} \]

\[ \begin{aligned}
&Y_0 \xrightarrow{parallel to serial & cyclic prefix insert} n(t) \xrightarrow{IDFT} x(t) \xrightarrow{parallel to cyclic prefix remover} \}
\end{aligned} \]
High-level system view

Transmitter architecture detail

Scrambling
- Need to randomize incoming data
- Enables a number of tracking algorithms in the receiver
- Provides flat spectrum in the given band

Convolutional Encoder
- Puncture code
- Provides a number of tracking algorithms in the receiver
- Enables a number of tracking algorithms in the receiver
- Provides flat spectrum in the given band

pseudo-random bit sequence (prbs) generator
Signal mapper

- BPSK, QPSK, 16-QAM, 64-QAM
  - Data divided into groups of (1,2,4,6) bits and mapped to a constellation point (i.e. a complex number)
  - Gray-coded constellation mappings

\[ d = (I + jQ) \times K_{\text{MOD}} \]

<table>
<thead>
<tr>
<th>Modulation</th>
<th>( K_{\text{MOD}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
</tr>
<tr>
<td>64-QAM</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Receiver architecture

1. I and Q from analog front-end
2. Remove DC offset
3. Rotate
4. FFT
5. Channel correction
6. Deinterleave
7. Viterbi
8. Rx data to MAC

OFDM packet structure

Channel correction
References


