Digital Signal Processing for Communication Systems

- 1999. 7. 5.
- Prof. YONG HOON LEE
- DEPARTMENT OF ELECTRICAL ENGINEERING
- KAIST
1. DSP for TDMA (IS-136) Mobile Communication

2. DSP for CDMA (IS-95) Mobile Communication

3. Miscellaneous
   - PRML Receiver for DVD
   - Software Defined Radio
Access Method: TDMA/FDD

Frequency Band
- Mobile to Basestation: 824 - 849 MHz (25MHz Band)
- Basestation to Mobile: 869 - 894 MHz (25MHz Band)

Channel Bandwidth: 30 kHz

25MHz / 30kHz = 832 channels

Modulation: π/4 DQPSK

Bit rate: 48.6 kbps

Pulse Shaping Filter: Root Raised Cosine (roll off factor: 0.35)

One time slot have 14-symbol preamble and 148-symbol data
### Digital Traffic Channel Time Slots

#### Forward Time Slot

<table>
<thead>
<tr>
<th>28</th>
<th>12</th>
<th>130</th>
<th>12</th>
<th>130</th>
<th>1</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SYNC</strong></td>
<td><strong>SACCH</strong></td>
<td><strong>DATA</strong></td>
<td><strong>CDVCC</strong></td>
<td><strong>DATA</strong></td>
<td><strong>RSVD</strong>=1</td>
<td><strong>CDL</strong></td>
</tr>
</tbody>
</table>

*see section “Finding the DCCH”*

#### Reverse Time Slot

<table>
<thead>
<tr>
<th>6</th>
<th>6</th>
<th>16</th>
<th>28</th>
<th>122</th>
<th>12</th>
<th>12</th>
<th>122</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>G</strong></td>
<td><strong>R</strong></td>
<td><strong>DATA</strong></td>
<td><strong>SYNC</strong></td>
<td><strong>DATA</strong></td>
<td><strong>SACCH</strong></td>
<td><strong>CDVCC</strong></td>
<td><strong>DATA</strong></td>
</tr>
</tbody>
</table>

SACCH (slow associated control channel) : for power control & handoff
CDVCC (coded digital verification color code) : basestation ID number
SYNC (synchronization and training) : for synchronization & training
CDL (coded digital control channel locator) : control channel location information
RSVD (reserved) : for tolerating inter-slot overlapping
G (guard time) : for delay when power on
R (ramp up time) : for delay when power on
Mobile Station Block Diagram

FACCH (slow associated control channel): for power control & handoff
DVCC (digital verification color code): basestation ID number
Mobile Station H/W Block

- Modem Vocoder program
- Assembler
- Machine code
- ROM
- Instruction simulator
- DSP chip
- Voiceband Codec
- Micro Controller
  - Layer1 program
  - Layer2 program
  - Layer3 program
- MIC
- Speaker
- 80C196NU (Intel)

DC Lab.
Baseband Modem Block Diagram

Channel coded & Interleaved binary sequence → \( \pi/4 \) DQPSK modulator → \( \sqrt{\text{PSF}} \) → D/A → LPF

\( \pi/4 \) DQPSK demodulator

Equalizer

Timing recovery

A/D (oversampled by 8)

48.6kbps

24.3kbaud

24.3x4kbaud

24.3x8kbaud

Fading channel
Baseband Equivalent Channel Model

- Rayleigh fading channel with two ray delay spread model

\[ a_1(t)e^{j\phi_1(t)} \]
\[ a_2(t)e^{j\phi_2(t)} \]

\[ \text{transmitted signal} \]
\[ \text{delay} \quad ( < T ) \]
\[ \text{AWGN, } \eta(t) \]

\( a_1(t), a_2(t) \): Mutually independent and Rayleigh Distribution

\( \phi_1(t), \phi_2(t) \): Mutually independent and Uniform Distribution
Baseband equivalent channel \( \left( a_1(t) = 1, a_2(t) = 1, \phi_1(t) = 0 \text{ and } \phi_2(t) = 0 \right) \)

Digital channel

Transmitted symbol → 3-tap FIR filter → Channel output

Channel model for MLSE equalization
π/4 DQPSK MODEM

- **Differential PSK (DPSK)**
  
  Let the received signal $r(t)$ be:
  
  $$ r(t) = \text{Re} \left[ g(t) e^{j(w_0 t - \theta_k + \theta)} \right] $$
  
  where $\theta_k$ is the signal phase associated with the k-th symbol and $\theta$ is the phase offset.

  ![Diagram](image)

  (Differentially coherent receiver)

  At the modulator, we send $\theta_k = \theta_{k-1} + \tilde{\theta}(k)$ where $\tilde{\theta}(k)$ is determined depending on the symbol at $k$. 
e.g. Binary DPSK

<table>
<thead>
<tr>
<th>Symbol at K</th>
<th>( \tilde{\theta} (k) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( \pi )</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

e.g. DQPSK and \( \pi/4 \)-DQPSK (for IS-136) [1]-[2]

<table>
<thead>
<tr>
<th>Symbol at K</th>
<th>DQPSK</th>
<th>( \pi/4 )-DQPSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>0</td>
<td>( \pi/4 )</td>
</tr>
<tr>
<td>01</td>
<td>( \pi/2 )</td>
<td>3( \pi/4 )</td>
</tr>
<tr>
<td>10</td>
<td>-( \pi/2 )</td>
<td>-( \pi/4 )</td>
</tr>
<tr>
<td>11</td>
<td>( \pi )</td>
<td>-3( \pi/4 )</td>
</tr>
</tbody>
</table>

Binary input: 11 00 01 11

DQPSK \( \tilde{\theta} (k) \): \( \pi \) 0 \( \pi/2 \) \( \pi \)

DQPSK \( \theta (k) \): 0 \( \pi \) \( \pi \) 3\( \pi/2 \) \( \pi/2 \)

\( \pi/4 \) \( \tilde{\theta} (k) \): -3\( \pi/4 \) \( \pi/4 \) 3\( \pi/4 \) -3\( \pi/4 \)

\( \pi/4 \) \( \theta (k) \): 0 -3\( \pi/4 \) -2\( \pi/4 \) \( \pi/4 \) -2\( \pi/4 \)
Phase Ambiguity in PSK

- At the M-PSK receiver, the input given by

\[ r(t) = g(t) \cos(\omega_0 t - 2\pi i / M + \theta) = \text{Re}\left[g(t)e^{j(\omega_0 t - 2\pi i / M + \theta)}\right] \]

where \( g(t) \) is the signal pulse shape and \( \theta \) is the phase offset (noise-free case).

- Phase ambiguity occurs when \( \theta > \pi / M \). To avoid this, at least one reference symbol is required. Sometimes, DPSK with coherent demodulation is used. In fact, in IS-136 coherent demodulation of \( \pi / 4 \) DQPSK is employed to avoid phase ambiguity and to employ MLSE.

- Given a reference symbol, \( \theta \) can be estimated. This procedure is called carrier recovery.
Pulse shaping filter [3]

\[ h(t) \]

\[ h(t - T) \]
Raised Cosine Filters

Cascade of $T_x$ and $R_x$ filters having the following raised cosine spectrum.

- **Example**: Symbol (Baud) rate = 30ksymbol/sec
  
  $1/T = 30k$

  If the roll-off factor $r=0.5$ (50% excess BW) then the Tx BW is
  
  $3/4 \times 1/T = 3/4 \times 30k = 22.5 \text{ kHz}$
- Digital PSF

- Digital PSF: Interpolator
- The effect of ADC (ZOH) should be compensated.
- Often a digital PSF is a cascade of a raised cosine filter and an equalizer compensating for ADC.
(β = 0.2)
Synchronization

- **Symbol synchronization (Timing recovery)**
  - Nonlinear spectral line (NSL), Decision directed (DD)
    (In DD methods, frame sync. Is assumed)
- **Carrier synchronization (Phase and Frequency recovery)**
  - Decision directed is popular
- **Frame synchronization**
  - Matched filtering (In CDMA systems, code acquisition for symbol timing recovery is essentially the same as frame sync.)
- **Network synchronization**
- **Acquisition and tracking**
  - Known data sequence (preamble) is generally given during acquisition.
- **For the IS-136 system**
  
  - Timing recovery: NSL with oversampling by 8.
  - Carrier recovery:
    - Phase offset is compensated by the MLSE.
    - Frequency offset compensation is sometimes required.
- **Timing recovery**

  \[ d(nT) \xrightarrow{\sqrt{\text{PSF}}} \xrightarrow{\text{D/A}} \text{fading channel} \xrightarrow{\text{A/D (oversampled)}} \xrightarrow{\sqrt{\text{PSF}}} \xrightarrow{kT} r(nT) \]

- Nonlinear spectral line (NSL) method [4]

  \[ r(nT/k) \xrightarrow{\parallel} g(nT/k) \xrightarrow{\text{narrow BPF center freq. } = 1/T} f(nT/k) \xrightarrow{\text{Peak detector}} \]
- Baseband equivalent channel oversampled by 32 (k=32)

- NSL for BPSK in flat fading

- NSL for $\pi/4$ DPSK in flat fading channel (IS-136 preamble)
- Due to the fading, there are no ISI-free positions. Equalization for compensating ISI is essential.
Carrier frequency offset compensation (carrier recovery)

- Carrier frequency offset estimation with the help of preamble sequence.
- Principle of carrier offset estimation for AWGN [6]

\[
\begin{align*}
\gamma(nT) &= e^{j2\pi\Delta f nT} + \eta(nT) e^{j2\pi\Delta f nT} \\
\rho(nT) &= e^{j2\pi\Delta f T} + \text{noise related term}(\phi(nT))
\end{align*}
\]
Equalization and Demodulation

- Use of the differential decoder (detector) before equalization is not recommended, because the differential decoder introduces nonlinearities to the channel.

- MLSE (maximum likelihood sequence estimation) outperforms the linear and decision-feedback equalizers which are associated with symbol-by-symbol detectors.
MLSE via Viterbi Algorithm (VA) [5]

- For M-ary symbol and L-tap channel, the number of states for VA is $M^L$. In $\pi/4$ DQPSK, signal constellation at even and odd time instants are different, but at a given time $M=4$. Therefore, we define 16 states assuming $L=3$. In this case, however, the state vectors at even and odd time instants should be different.

- The channel is estimated from the SYNC Preamble by using the RLS algorithm.
e.g. An MLSE equalizer with 4 states (M=2, L=3)

\[ d(j, k) : \text{Hypothesized input vector when the transition from the state } j \text{ to the state } k \text{ occurs.} \]

e.g. \[ d(0, 0) = [-1, -1, -1]^T, \quad d(0, 1) = [-1, -1, 1]^T, \quad d(3, 2) = [1, 1, -1]^T \]
- **State vectors for π/4 DQPSK (M=4, L=3)**

<table>
<thead>
<tr>
<th>Time</th>
<th>n=0</th>
<th>n=1</th>
<th>n=2</th>
<th>n=3</th>
<th>n=4</th>
<th>n=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 1/4</td>
<td>0 3/4</td>
<td>0 7/4</td>
<td>1/2 1/4</td>
<td>1/2 7/4</td>
<td>1/4 0</td>
</tr>
<tr>
<td></td>
<td>0 3/4</td>
<td>1/4 1/2</td>
<td>1/4 3/2</td>
<td>1/2 1/4</td>
<td>1/2 7/4</td>
<td>1/4 0</td>
</tr>
<tr>
<td></td>
<td>0 5/4</td>
<td>1 5/4</td>
<td>1 7/4</td>
<td>1/2 5/4</td>
<td>1/2 7/4</td>
<td>1/4 1</td>
</tr>
<tr>
<td></td>
<td>1/2 7/4</td>
<td>3/4 3/2</td>
<td>1/2 7/4</td>
<td>3/4 3/2</td>
<td>3/4 5/4</td>
<td>1/2 7/4</td>
</tr>
<tr>
<td></td>
<td>3/2 1/4</td>
<td>7/4 0</td>
<td>3/2 1/4</td>
<td>7/4 0</td>
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