QAM Demodulation

- Application area
- What is QAM?
- What are QAM Demodulation Functions?
- General block diagram of QAM demodulator
- Explanation of the main function
  - (Nyquist shaping, Clock & Carrier Recovery, AGC, Adaptive Equaliser)
- Performance
- Conclusion
Example Application Area

“Wireless Cable” Digital TV using Microwave Transmission

- Compression = bit rate reduction
- Multiplexing = assembly of multiple programs
- Modulation = conversion to transmission format

- Set-top Box = Integrated Receiver Decoder (IRD), provides a subscriber access to a wide range of programs
What is QAM?

- Amplitude Modulation of
- Two Orthogonal Carriers

\[ x_i(t) = \sqrt{2E_o/T_s} a_i \cos(\omega_c t) + \sqrt{2E_o/T_s} b_i \sin(\omega_c t) \]

64QAM in time domain

64QAM Constellation diagram
M-ary QAM

- Satellite: $S/N > 3$ dB for $M=4$
- Cable: $S/N > 21$ dB for $M=64$
- $S/N > 27$ dB for $M=256$

Wireless Communications
What to do to recover the information?

<table>
<thead>
<tr>
<th>Functions</th>
<th>Result</th>
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</thead>
<tbody>
<tr>
<td>Automatic Gain Control</td>
<td>Optimal position of constellation diagram in reception window</td>
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<tr>
<td>Quadrature down conversion</td>
<td>I &amp; Q base band signals</td>
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<tr>
<td>(Half) Nyquist Filtering</td>
<td>Pulse shaping</td>
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<td>Clock Recovery</td>
<td>Sampling reference for A/D Converter</td>
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<td>Carrier Recovery</td>
<td>Carrier frequency reference</td>
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<tr>
<td>Adaptive Equaliser</td>
<td>Compensate for channel distortion</td>
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<tr>
<td>Demapping</td>
<td>Representation of received data in bits</td>
</tr>
</tbody>
</table>
System Block Diagram

Wireless Communications
Automatic Gain Control

- 2 loops AGC
- Coarse AGC to prevent ADC from overloading
- After Nyquist filtering and Equalisation ‘small’ QAM remains.
- Fine AGC to position constellation diagram to decision window

Wireless Communications
(Half) Nyquist Filtering

* Pulse Shaping required to realise ISI=0 in limited BW

* ISI=0 when zero crossings occur at multiples of $T_s=1/f_s$

* Achieved with Nyquist Criterion
  (DVB: $\alpha = 15\%$)

* Cascade of Transmitter & Receiver fulfil Nyquist Criterion
  (Half Nyquist each)

* Digital implementation
  ($T_{delay} = 9 T_{symbol}$)

* This delay is in the loops and thus influences the demodulator architecture

Wireless Communications
Clock Recovery

- Recovery with 2\textsuperscript{nd} order PLL

- Clock Detector
  - Energy Maximization algorithm
  - After Half Nyquist Filter to achieve ISI=0 at detector input

- Half Nyquist Filter in loop is allowed
  - Received clock has crystal accuracy (100 ppm at 7 Msym/s))
  - Loop BW may be small
  - Delay in loop is allowed (no instability)

- Quadarture Demodulation
  - $f_{\text{clock}} = 4 f_{\text{symbol}}$
  - Simple with $j^n$ ($n=0,1,2,3,...$)

Wireless Communications
**Carrier Recovery**

- Recovery with 2\textsuperscript{nd} order PLL
- **Carrier Detector**
  - Decision directed
  - After equaliser
  - PD (lock) and PFD (unlock)
    * PFD for large acquisition range (100 kHz)
    * PD for stable behaviour once in lock
- **Half Nyquist & Equaliser in loop**
  - Large delay causes problems for disturbances like:
    * phase noise
    * microphonics (mechanical vibrations)
- **Alternative solution required**

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**Wireless Communications**
Carrier Phase Disturbances (I)

- **Additive White Gaussian Noise**
  - Random distribution
  - Mainly inserted in the cable channel

- **Result**
  - Enlarged constellation points

- ** PLL Properties**
  - Average the noise
  - Loop BW small
  - Low IL

**Implementation Loss**

**Diagram:**
- **Cable** → **Tuner** → **QAM demod** → **s(t)** → **+** → **r(t)** → **n(t)** → **BW**
Carrier Phase Disturbances (2)

* Phase Noise & Microphonics
  - No random distribution
  - Mainly inserted in the tuner by LC oscillators which are sensitive for mechanical vibrations (Microphonics)

* Result
  - Rotation of constellation diagram.

* PLL Properties
  - Follow the phase disturbance
  - Loop BW large
  - Low IL

* PLL properties for AWGN and phase noise are in contradiction

Wireless Communications
Phase noise versus AWGN

* Loop BW trade of between:
  a. Ability to follow phase noise
  b. Ability to average AWGN

* Rule of thumb:
  \[ BW = \frac{1}{1000f_{symbol}} \]

* Simulations show this is approximately correct

* Optimum depends on S/N and amount of phase noise

* Problem: Optimum loop BW instable due to large delay in the loop (Half Nyquist + Equaliser).
Double Loop Carrier Recovery

* Introduction of second loop with (relatively) small delay

* Outer loop
  - Adjust (static) frequency offset
  - Small loop BW due to large delay
  - PD/PFD

* Inner Loop
  - Optimum loop BW as trade off between phase noise & AWGN
  - Large Loop BW due to small delay
  - PD only

* Conclusion: optimum loop BW can be selected and causes no instability
Equalisation

* Nyquist Criterion specifies a frequency domain condition on the received pulses to achieve ISI=0

* Generally this is NOT satisfied unless the channel is equalised

* Equalise the channel = compensate for channel distortion

* Unfortunately, any equalisation enhances noise from the channel

* Tradeoff between:

  * Accurately minimising ISI
  * Minimising the noise

* Different types of Equaliser
Multipath Distortion

* Multipath distortion causes ISI
* Each original point consists of \( M \) new points in the shape of constellation diagram
* Amplitude, delay and phase of the echo determine shape/size of the small constellation diagrams
* Varying channel requires *Adaptive Equaliser*
Equaliser Structure

**Linear Equaliser (LE)**

Symbol Decision → Coefficients → Complex FIR filter → I_{out} Q_{out} → I_{in} Q_{in}

**Decision Feedback Equaliser (DFE)**

Symbol Decision → I_{out} Q_{out} → I_{in} Q_{in}

FFE + DFE

Wireless Communications
Equaliser Structure

Linear Equaliser (LE)

\[ H(z) = 1 + A z^{-\tau} \]
\[ G(z) = 1 - A z^{-\tau} \]
\[ H(z) G(z) = 1 - A^2 z^{-2\tau} \]

(-) Residual ISI (\(A^2,2\tau\))

(+) ‘Fast’ acquisition

(-) ‘High’ noise amplification

Decision Feedback Equaliser (DFE)

\[ G(z) = \frac{1}{1 + A z^{-\tau}} \]
\[ H(z) G(z) = 1 \]

(+) No residual ISI

(-) ‘Slow’ acquisition

(+) ‘Low’ noise amplification

Wireless Communications
## Equaliser Adaptation Algorithm

<table>
<thead>
<tr>
<th><strong>Zero Forcing (ZF)</strong></th>
<th><strong>Mean Square Error (MSE)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>(+) Complete elimination of ISI</td>
<td>(+) Minimize sum of ISI and noise</td>
</tr>
<tr>
<td>(-) Penalty = Noise amplification</td>
<td>(+) Less noise amplification by</td>
</tr>
<tr>
<td></td>
<td>(-) Allowing residual ISI</td>
</tr>
</tbody>
</table>
### Adaptive Equaliser

<table>
<thead>
<tr>
<th></th>
<th>ZF (Zero Forcing)</th>
<th>MSE (Mean Square Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE</td>
<td>Suited for QAM with M ≤ 64</td>
<td>Suited for QAM with M ≤ 64</td>
</tr>
<tr>
<td></td>
<td>(-) residual ISI does not allow higher M</td>
<td>(-) residual ISI does not allow higher M</td>
</tr>
<tr>
<td></td>
<td>(+) Fast acquisition</td>
<td>(+) Fast acquisition</td>
</tr>
<tr>
<td></td>
<td>(+) High stability</td>
<td>(+) High stability</td>
</tr>
<tr>
<td>DFE</td>
<td>No suitable solution</td>
<td>Required for QAM with M &gt; 64</td>
</tr>
<tr>
<td></td>
<td>(-) Because of complete elimination of ISI system is instable when zero in spectrum</td>
<td>(+) Stability guaranteed when zero in spectrum</td>
</tr>
<tr>
<td></td>
<td><img src="chart.png" alt="Equaliser" /></td>
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</tr>
<tr>
<td></td>
<td>channel</td>
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</tr>
</tbody>
</table>

(-) ‘Slow’ acquisition

**Wireless Communications**
Measurement Results

- Theory
- AWGN (single car loop)
- AWGN (double car loop)
- 1 ray echo
- 2 ray echo
- 3 ray echo

Implementation Loss:
- 0.6 dB
- 1.1 dB
- 1.6 dB
- 1.9 dB
- 2.0 dB

BER vs. $S/N$ graph with different scenarios labeled.
Conclusion

Single Chip QAM Demodulator with low Implementation Loss
- Double Loop AGC for optimum usage of A/D Converter
- Delay in half Nyquist filter and equaliser require double carrier recovery loop structure to achieve high performance on phase noise & microphonics
- Adaptive equaliser
  * LE/ZF or LE/MSE preferred for QAM with $M \leq 64$
  * DFE/MSE required for QAM with $M > 64$