Comparing Technologies:
DMT vs. QAM

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Agenda

• Brief Intro
• Technical Merits
• Market Merits
• Summary
Defining the selection before us…

• VDSL line code choice should be based on:
  – Technical Merits
    • Various parameters compared including Application/protocol stack integration, Power consumption, and Density
  – Market Merits
• Additionally, we must remember we are defining an Ethernet PHY, not a DSL
Brief Intro

- **DMT**
  - Discrete Multi-Tone
  - subset of Multi-Carrier Modulation - MCM
  - Found in ADSL
    - About 7.5M lines installed (Cahners In-Stat, OECD)
    - 8 years to get interoperability

- **QAM**
  - Quadrature Amplitude Modulation
  - subset of Single Carrier Modulation - SCM
  - Found in Cable modems
    - About 8.5M installed (Cahners In-Stat, OECD)
    - 2 years to get interoperability
  - Found in 100BT2/1000BT
    - Many 10s of millions installed
QAM and DMT
Modulation Techniques

- QAM and DMT are 2 classes of modulation techniques that have both found application in DSL.
- QAM is a generalization of PAM techniques, a subset of single carrier modulation (SCM). Five level PAM used in 100BaseT2,1000BaseT (802.3 2000 30.3.2.1.2).
- QAM - in VB modems, HDSL, SDSL, SHDSL, IDSL, RADSL, Ethernet, cable modems, direct satellites, etc.
- DMT - in ADSL, certain wireless applications.
QAM for VDSL

- 4 independent QAM bands, 2 for upstream, 2 for down, plus Band 0
- Standards bodies conclusion: 4 bands optimal for mixture of VDSL service types and loop lengths
- Specification enables bandwidth optimization within each band (current QAM technology in use)
DMT for VDSL

- Each band divided into hundreds of 4 kHz sub-bands
- Each sub-band carries a narrow QAM signal
- Bandwidth optimization and frequency division duplexing occur by zeroing many (half) sub-bands
Version data and installed base

- **DMT**
  - No version data available on DMT
  - No installed base

- **QAM**
  - Third and or fourth generation now coming available
  - Across whole VDSL family
    - Shipments of over 1M chipsets in 2001
Technical Merits Comparison

- QAM versus DMT performance: stationary noise
- QAM versus DMT performance: bursty noise
- Field Experience
- Implementation and Practical Effects
- Standards Support
- Performance Summary
QAM vs. DMT Performance: Stationary Wideband Noise Case

- QAM / DMT performance virtually identical, when using worldwide band plans
- Reason: QAM DFE averages input SNR while DMT averages bits per sub-channel - very similar
- Fully accepted in peer-reviewed academic context:

- Notched channel comparison: See “Practical Effects”
QAM vs. DMT Performance: Stationary Narrowband Noise Case

- QAM DFE nulls narrowband ingress, automatically and almost immediately, with no loss beyond that dictated by Shannon theory limit
- DMT reduces constellation in effected channels
  - Requires use of windowed FFT for effective performance; VDSL specific (not used in ADSL), requires more overhead
  - Requires handshaking and negotiation to adapt to new continuous interferer
  - Slower and less robust than automatic QAM DFE approach
- QAM has advantage for this case
QAM vs. DMT Performance: Bursty Noise Cases

- 6 burst noise cases: (High, Moderate, Low) levels with x (Narrowband, Impulse) noise types
- Comparative performance varies with case
- Results highlight the time/frequency domain duality of QAM/DMT: When one line code excels for a particular case, the other line code excels for the dual case
High, Moderate, and Low Noise Levels

- By definition, in the following performance comparison table, for the given channel:
  - *Low level narrowband* is the *max* ingress level which does *not* cause QAM symbol errors
  - *High level narrowband* is the *min* ingress level which saturates the ADC
  - *Moderate level narrowband* refers to levels in between
  - *Low level impulse* is the *max* impulse level which does *not* cause DMT sub-channel errors
  - *High level impulse* is the *min* ingress level which saturates the ADC
  - Moderate level impulse refers to levels in between

- Narrowband ingress and impulse noise are duals
## Burst Noise Field Experience

(Not all bursty noise scenarios are likely in the real world)

<table>
<thead>
<tr>
<th>Noise Case</th>
<th>QAM Result</th>
<th>DMT Result</th>
<th>Advantage</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Level Narrowband</td>
<td>No pre-FEC errors</td>
<td>Correctable errors made</td>
<td>QAM</td>
<td>Common</td>
</tr>
<tr>
<td>Moderate Level Narrowband</td>
<td>Errors extended by DFE tracking time, deeper impulse required to correct</td>
<td>Correctable errors made, same as low level NB case</td>
<td>DMT</td>
<td>Uncommon</td>
</tr>
<tr>
<td>High Level Narrowband</td>
<td>Analog common-to-differential canceler required</td>
<td>Analog common-to-differential canceler required</td>
<td>Tie</td>
<td>Very Uncommon</td>
</tr>
<tr>
<td>Low Level Impulse</td>
<td>Correctable errors made</td>
<td>No pre-FEC errors</td>
<td>DMT</td>
<td>Very Common</td>
</tr>
<tr>
<td>Moderate Level Impulse</td>
<td>Correctable errors made, same as low level impulse case</td>
<td>Impulse errors extended by DMT spreading, deeper impulse required to correct</td>
<td>QAM</td>
<td>Very Common</td>
</tr>
<tr>
<td>High Level Impulse</td>
<td>Same as moderate level</td>
<td>Same as moderate level</td>
<td>QAM</td>
<td>Uncommon</td>
</tr>
</tbody>
</table>

**Burst noise field conditions favor QAM**
Practical Effects -
SNR Averaging

- DMT requires constellation dense enough for highest SNR region, while QAM gets to average SNR variations, thereby requiring smaller constellations
  - QAM requires less analog and digital precision = lower power
  - QAM less sensitive to timing jitter, EQ imperfections
- DMT 11 bit limit = high SNR performance penalty
- QAM averaging penalty for low SNR amateur notches < 0.5 dB
- Duality again: High SNR vs. Low SNR
Practical Effects - Digital Duplexing

• Frequency Division Duplexing w/o use of analog filters
• Both QAM & DMT can use, but severe analog requirements
  – Without analog filters local echo 30 dB stronger than received signal
    – Effects Range, noise sensitivity, etc.
  – 5 extra ADC bits required; or accept very high quantization noise floor
  – Current cost/performance tradeoff strongly favors passive LC filters
Practical Effects - Digital Duplexing

- Claims that QAM cannot inherently do digital duplexing are disingenuous and misleading.
- In fact, DMT cannot take advantage of analog splitting filters without suffering from out of band filter distortion. No such problem for QAM.
Standards Support

- Worldwide, Telcos committed to not repeating the DMT ADSL time-to-market/interoperability issues

- Standards bodies:
  - Want both QAM and DMT vendors developing standards-compliant systems
  - Market determining ultimate winner, or there will be spectrally peaceful coexistence
Blind Acquisition/Handshake

• DMT cannot do blind acquisition, QAM can
• DMT requires handshake to start up, needs a longer time to start
  – Handshake defined with HDLC and additional processing requirements
• QAM does not require handshake to start, faster start up
Power Consumption

- Standards call for max. 1.5W per VDSL port
- DMT suppliers do not have commercially available products on the market to compare
- QAM vendors now supplying singles at <1.5W/port and multi-port at <1W/port for all components needed in a design
Performance Summary - “Is it a Wash?”

• All things considered, for properly designed systems QAM and DMT performance are technically equal

• 10 years of QAM vs. DMT fighting boil down to:
  – Small (< 0.5 dB) differences in various continuous noise conditions
  – Bursty noise frequency/time domain duality trade-offs that cancel out

• QAM VDSL is the right choice

• Technical Reference: IEEE Communications article by Saltzberg from 1998 comparing the technologies
Comparison of Single-Carrier and Multitone Digital Modulation for ADSL Applications

Burton R. Saltzberg

<table>
<thead>
<tr>
<th>Issue</th>
<th>Single-carrier</th>
<th>Multitone</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance in Gaussian noise</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Sensitivity to impulse noise</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>(uncoded)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to narrowband noise</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(uncoded)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to clipping</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to timing jitter</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency (delay)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Need for echo cancellation</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computations per unit time</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Complexity of algorithms</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost and power consumption in analog</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sections</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adaptability of bit rate</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 1. Relative advantages of single-carrier and multitone modulation for ADSL. X denotes the system with better performance or lower cost.
Densities

- **DMT**
  - No commercially available VDSL data
  - Per various web sites, single port ES only available, some rumors of Quads due out for later ES

- **QAM**
  - For commercially available chips:
    - 2-Band (EoVDSL)
      - Single and Octal
    - 3/4-Band
      - Singles
      - Multi-port (quad and octal)
Regarding Intellectual Property

- **DMT**
  - Requires IP licensing
  - Does this need to be addressed to the IEEE?

- **QAM**
  - Public Domain
  - No hidden costs
  - More in line with IEEE
Market Merits -
Market availability, Interoperability

- **DMT**
  - No commercially available systems (TI has a chipset announced, no data on if single manufacturer has delivered systems, however the system vendor has dropped the product)
  - No interoperability

- **QAM**
  - 3 years commercial availability
  - Multiple system vendors have products
  - Interoperability targeted by end of 2002
Market Merits - Installed base

DMT
No established market data on commercially available DMT VDSL, extrapolate ADSL data?

QAM
- Could extrapolate from cable modems or 100BaseT and/or 1000BaseT, however there is data on QAM VDSL, including Ethernet over VDSL
- Immediate availability, commercially available
- Multiple sources drive costs down
- Interoperability efforts
- >1M QAM VDSL ports shipped in 2001, with >700K EoVDSL ports shipped
# Market Merits - Relative Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>DMT</th>
<th>QAM</th>
<th>Advantage/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters/Magnetics</td>
<td>Lower complexity so lower cost</td>
<td></td>
<td>DMT</td>
</tr>
<tr>
<td>Line Drivers</td>
<td>Higher complexity</td>
<td>Lower complexity so lower costs</td>
<td>QAM</td>
</tr>
<tr>
<td>AFE</td>
<td>Higher complexity and AD/DA</td>
<td>Lower complexity so lower costs</td>
<td>QAM</td>
</tr>
<tr>
<td>Digital</td>
<td>Same</td>
<td>Same</td>
<td>No advantage</td>
</tr>
<tr>
<td>Rest of circuit design</td>
<td>Higher power requirements</td>
<td>Lower power, less heat dissipation</td>
<td>QAM</td>
</tr>
</tbody>
</table>
Summary Findings

- Technical Merits almost balanced, QAM ahead
- Market Merits (as VDSL)
  - QAM is
    - In the market, commercially available
    - Has been tested
    - Defined interoperability effort