

Line Code Debates

The line code (modulation method) for ADSL has been a topic of heated discussion among engineers, with people taking steadfastly rigid sides on the subject. In January 1993, Bellcore (with BT and NYNEX) organized the "ADSL Olympics" as a test, to compare the three main candidates: DMT (discrete multitone), CAP (carrierless amplitude/phase), and QAM (quadrature amplitude modulation).

While they were perhaps not completely authoritative (there are continued complaints it was not a fair test), the results of the trial indicated DMT had better performance, and the ANSI committee made its choice on that basis. Had the stakes not been as high as they are, that might have been the end of it, but that was not to be...

QAM is a very well understood and widely-used modulation technique. In essence, it is a single carrier signal, where the data rate is split in two and modulated onto two orthogonal carriers (I and Q) using sine/cosine mixers, before being combined and transmitted. CAP is very closely related to QAM—indeed, the two can be considered identical and compatible; the difference is primarily in the implementation.

Instead of the two signals being generated by a sine/cosine mixer, the modulation of the orthogonal signals is performed digitally using two digital transversal band-pass filters with the same amplitude characteristics and a $\pi/2$ difference in phase response (Hilbert pair), before being combined, fed to a digital-to-audio converter (DAC), and transmitted. The advantage over QAM is that the digital implementation can be realized very elegantly in silicon, and there is great scope for flexibility or efficiency in the implementation.

Being a multicarrier modulation system, DMT is a very different animal. DMT (essentially the same as OFDM—orthogonal frequency division multiplexing) divides the frequency range up onto a large number of discrete bands, or sub-channels. Each of these is independently modulated—with a carrier frequency corresponding to the center frequency of the bin—and the system uses them all in parallel, all at the same time.

The multi-carrier modulation technique requires orthogonality between all the subcarriers. A very elegant way to achieve this is by using fast Fourier transforms (FFTs). In ANSI standard DMT, there are 256 subcarriers, each with 4-kHz bandwidth, that can be independently modulated from zero to a maximum of 15 bits/Hz. This allows up to 60 kbits/s per tone. At low frequencies where the copper's attenuation is low and there is a good signal-to-noise ratio (SNR), it is easy to use a very dense constellation—10 bits/Hz is typical. Where the line is in worse condition, the modulation can be relaxed to allow for the lower SNR—perhaps to 4 bits/Hz or less, to give the necessary noise immunity. Furthermore, as the modem measures the line, it can avoid or compensate for crosstalk or interference. For example, an adaptive sys-

tem can reduce the modulation in the band where an AM station is causing RFI.

The two techniques can be considered as duals: QAM/CAP techniques are frequency domain-based, as they have fast symbols, each lasting a short time, with a big bandwidth (*see the figure*). For example, in a 6-Mbit/s DSL scheme, the symbol rate is 1088 baud—roughly about a symbol per microsecond—modulated to 256 points, with a bandwidth of 1.4 MHz. The short symbol time increases CAP's susceptibility to time-domain noise interference.

DMT is a time-domain approach, with symbols lasting a long time but only occupying a narrow frequency band (*see the figure, again*). With a leisurely 250-ms symbol time, a 256-tone DMT system (4 kHz per tone, 1.1 MHz total bandwidth) needs only a 4-kbaud symbol rate to deliver 6 Mbits/s! This long symbol time makes it less susceptible to time-domain noise.

As duals, the two should, in principle, achieve the same throughput on a channel (Shannon's law does not specify line code). In practice, they will have implementation differences and will be affected differently by noise in the time domain or frequency domain—so real performance and complexity will differ. A single RF tone will be averaged across the wide band of a single carrier system—effectively rendering these systems highly resistant to narrow-band interference.

In contrast, a narrow-band signal will directly hit a subcarrier on a DMT system. This effect is clearly seen in VDSL, where the higher frequency range overlaps with the amateur radio ("Ham") operator's bands and a system must cope with strong pulses of narrow-band RFI. The reverse is true for a wideband noise signal—for example impulse noise burst from lightning, a hair-dryer or an electric light dimmer—which will be averaged across a short time on many DMT symbols, but will seriously clobber a single carrier symbol.

Both use error correction and interleaving to deal with these problems, and both are very effective. DMT claims an advantage in that time-domain noise is hard to predict, while RFI tends to be more stable and can be measured and adjusted for during training or operation.

There are many discussions on the relative advantages/disadvantages of CAP & DMT. A reasonably impartial summary of these is:

- DMT can direct information to subcarriers and modulate them independently, while CAP has a single carrier which has to be treated as a whole, even though the channel characteristics vary widely. As a result, DMT may deliver better performance or be more spectrally efficient. DMT has more complex initialization and needs more start-up time than CAP.

- DMT is inherently and straightforwardly rate-adaptive, delivering the maximum data for any given line. This

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method offers the flexibility to support higher rates over shorter loops (e.g., 8 Mbits/s), or sub-rate connections at very long reach.

- While CAP can support rate adaptation (by varying the constellation and the bandwidth), it is less obvious and requires more careful design of the analog circuitry. In addition, the rates have much lower granularity
- DMT steps in 32-kbit/s steps from 64 kbits/s to 8 Mbits/s, versus CAP's 320 kbit/s steps from 320 kbits/s to 7 Mbits/s. "DMT can be compared to a first-rate mountain bike—it has more gears to cope with the more different terrains it will encounter"
- DMT has much greater latency. This may actually be in violation of some specifications for particular services (e.g., ISDN).
- CAP is more resistant to RFI, although it is possible that DMT is more adept at coping with multiple or varying RFI sources. CAP has a lower peak-to-average ratio, simplifying the design of the analog stage and reducing its power needs.
- It is simple for DMT to meet an arbitrary or variable power mask spectrum for spectral compatibility.
- Echo cancellation in DMT is more difficult.
- DMT has greater immunity to impulse noise than CAP

(as the symbols are longer).

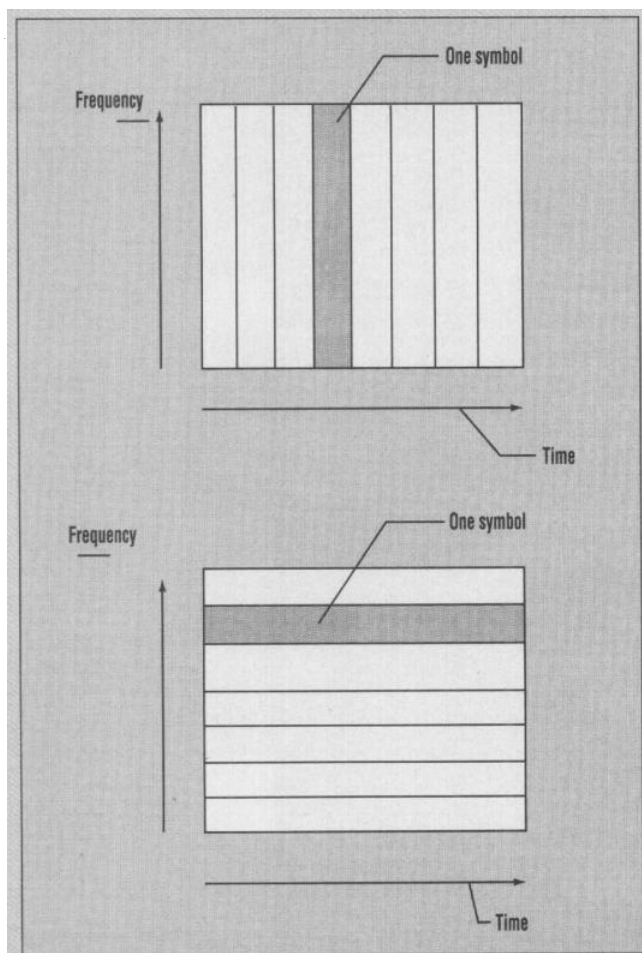
- CAP can be simpler or optimized to a specific application. DMT is more complex, but this supports more versatility and flexibility (important in ADSL with many applications and a wide range of environments).
- DMT's analysis and measurement functions can be used as diagnostics and testing (e.g., to detect out-of-spec systems, or for preventive maintenance of the copper lines.)
- Engineers have more experience with CAP (QAM) and more specialized equipment exists—this may accelerate design and test of systems.
- Both are patented techniques, and intellectual property situation is comparable.

To give readers an idea of how these advantages and disadvantages translate into real-world implementations: CAP chip sets and DMT chip sets are approximately the same price, and will draw similar power. However, DMT is almost 50% more efficient than CAP, requiring 1.1 MHz for 6 Mbit/s throughputs, rather than 1.5 MHz. It is hard to compare performance as few results have been made public at the present time. The only independent public tests I know of were conducted by GTE Labs and the magazine *tele.com* on a number of ADSL systems. Interestingly, not a single CAP supplier was willing to submit modems for such impartial testing, but we can assume they'll be similar.

In summary, there is no single answer. This is an engineering decision, and the best technology depends on the needs of the application, and the tools to implement it. In general, while CAP can be simpler and is easy to optimize (in cost and power) for a particular situation DMT is more complex and more versatile. Given the wide variety of applications and environments ADSL faces, this can deliver several benefits in real implementations (obviously CAP can be designed to incorporate similar flexibility, but then it ends up with additional complexity!). However, for the more defined constraints of HDSL and VDSL, single-carrier approaches look more suitable.

To a large degree, it doesn't matter. Both technologies could work reasonably well, and will deliver roughly similar performance at roughly similar costs. It is fair to say that to date, most systems have been based on CAP, simply because as a single-source proprietary product, it had a significant time-to-market benefit (no need to wait for painfully slowly standards to thrash out a consensus) and hence was available sooner.

On the other hand, DMT is defined as ADSL—it is the only method that has been selected as the international standard (for good reasons), defined, and documented by non-proprietary groups, supported by multiple manufacturers and interoperability. In an industry as international, as standards focused, and with the need for interoperability that characterizes the telecommunications industry, that may be all that is necessary to carry the day. In any case, the public will most likely be the biggest winner as DSL and CAP begin to give more and more citizens high-speed access to the information networks shaping our future.



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by simply varying the duty cycle of send/receive. Secondly, the complexity is lower: little effort is needed to separate signals (i.e., no filters are required), and hardware can be shared at each end—swapped between transmitting and receiving as required.

On the other hand, DMT is perhaps more power-hungry than is desirable in the power-limited environment of an ONU. Secondly, the ping-pong system must be very tightly controlled between all systems (if there is any difference or jitter, a transmitter will swamp a receiver)—this might be difficult in a deregulated environment with competitive access. Finally, there is some concern that the proposed ping-pong frame rate (2 kHz) might be demodulated into an annoying audio-frequency signal (perhaps in an adjacent pair, which might not have a VDSL-splitter or filter). This has been claimed to occur with TDMA digital cellphones, where the burst frequency is detected in hearing aids.

A number of manufacturers are supporting a frequency division duplex system, with CAP for the downstream. This has the advantage that it is a low-power solution, and can be optimized to give a simple transmitter. Being a high-capacity broadband signal, it also is resistant to RFI and can be placed in a region where there is less concern with impulse noise.

Manufacturers including Analog Devices, Aware, Orckit, BBT, Globespan, Broadcomm and others all are developing a common draft standard based on this technology. (Importantly, the first three have all developed DMT solutions for ADSL, showing that line-code choices can be decided by technical criteria and are not unchanging). However, the consensus breaks down for the upstream. Some manufacturers are proposing single carrier techniques (CAP or QPSK) which have the attractions of low power and simplicity. On the other hand, in the home (where the upstream signal starts), low power is not as critical as it is in the ONU, so this is of less use.

Coping With Noise

Then there is the problem of noise, and how to deal with it. The low-frequency bands can be very noisy, with

a lot of impulse noise and ingress from sources like electric light dimmers, vacuum cleaners, and the like. This can inflict a lot of grief on a system, in the form of noise that is very hard to filter out or work around. To get around this, some systems (for example, DAVIC 1.0's FTTC) place the up stream signal high in frequency—above the downstream. Here the system avoids the low-frequency wideband noise, and the filtering can be easier (reducing the waste from a large guard band).

Unfortunately, this region has lots of attenuation in the copper, reducing the useful capacity of the system; the DAVIC system only has 1.6 Mbits/s upstream and it is doubtful if the same arguments would work for higher rates of say 3 Mbits/s. In addition, the (narrow) high-frequency upstream link is now very vulnerable to notches in the channel caused by bridge taps.

Recognizing the very different characteristics of downstream (power constraints, high-speed/high-band-width) and upstream (lots of impulse noise, concern on frequency plan), Analog Devices, Aware, and BBT have proposed a hybrid solution, that uses very different techniques for each direction—hopefully getting the best of both worlds.

By adopting a CAP single carrier for the down-stream channel, the benefits listed above are achieved. The upstream is located at low frequencies, and uses a new multi-carrier technique—discrete wavelet multitone (DWMT). This copes extremely well with impulse noise, so the frequency plan can use the "good" low-frequency copper without worrying about noise. In addition, the technique easily lends itself to support multi-drop in-home wiring (multi-point to point/passive network architectures).

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