LIGHTING UP COPPER

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ABSTRACT

This invited "History of Communications" paper provides a perspective on the many contributions and achievements to the science of high-speed transmission on telephone-line copper twisted-pair. This perspective relies largely on the author's 30-year academic and industrial DSL working experience, but nevertheless attempts to include key events and mention key individuals in the steady march from the kilobits/second of voiceband modems to the Gigabits/second of today's copper connections over those three-plus decades. Digital Subscriber Lines (DSL) and its ancestors are emphasized, while some Ethernet contributions to DSL are also cited.

INTRODUCTION

There are today more than 1.3 billion copper phone-line connections upon which the modern world of telecommunications inexorably relies, a growing 1/3 of them now using DSL. These DSL numbers still steadily increase each year by far larger amounts than does use of optical fiber, as Fig. 1 illustrates for broadband connections on three media. (Indeed about 3/4 of the lower FTTx (fiber to the x = node/cabinet/building) numbers are actually hybrid fiber and DSL connections, but are counted inexplicably by the source only as "fiber.") Most modern wireless communication relies on cell base stations that connect to the remainder of the network via copper cables, and indeed that wireless dependency upon copper[1] is projected to explode as wireless "smartphone" data usage stresses spectrum resources and increasingly leads to smaller (WiFi and/or femto) cells that "backhaul" on residential DSL services that today are already a growing 70 percent of all broadband connections. With such essential copper dependency, perhaps an attempt to document historical DSL contributions is in order and attempted here.

The history of copper advance is one of incremental steps not unlike silicon-based semiconductors' famous "Moore's Law" where steady evolution of telecommunications networks has consistently prevailed over revolutionary and costly replacement with new, near infinite-bandwidth media, with said steady increase evident the last few years in Fig. 1. Figure 2 provides some key steps in steady bandwidth advance for use of telephony copper twisted pairs. Many technologists' portended death of copper has been always answered by unexpected technical advances that squeeze yet more bandwidth from copper than many ever believed possible. Those advances initially came from large telephone company research labs, but over the last two decades have instead come from small startup companies and academic institutions. Those few correctly recognized that the cost of replacement of billions of connections would eventually yield to simple increase of speed on the existing copper facilities. They were "lighting up copper" instead.

This history will not attempt to include further the legacy of voiceband modems, whose significant contribution to early data communication is well documented elsewhere[2] (see for instance the upcoming paper in this magazine [1]). Rather, this history begins with the first serious efforts to circumvent the analog voiceband. The next section, "Going Digital," recalls some first efforts to expand beyond voiceband modems to an all-digital telecommunications network. While none of these early all-digital-network approaches were commercially successful, they laid a foundation for the DSL successes to come. The subsequent "Data Com" section also cites early "10base-T" and "100base-T" in data communication, which were indeed commercially successful and also contributed to a foundation of copper transmission methodology. The "Modern Copper Age" section continues to the specific Asymmetric Digital Subscriber Line (ADSL) technology that today dominates worldwide broadband connectivity. The next section then progresses to the emergence of fiber to shorten, but rarely replace completely, copper customer connections, leading to what is known as "VDSL," which is the telecommunications service providers' commercially viable alternative to satisfy the growing data bandwidth needs of an increasingly connected digital world. No history ever should terminate, and indeed DSL-based copper-transmission growth today is at unprecedented levels and continues to expand, so the last full section then prognosticates briefly on recent "DSM" (Dynamic Spectrum Management) advances shown on the right in Fig. 2, as copper-fed customers learn to enjoy Gb/s connections to their abodes over the next decade.

EARLY TWISTED-PAIR DIGITAL TRANSMISSION

Since Bell's 1881 invention of the twisted pair [2], the number of twisted-pair telephone connections has steadily grown to roughly 1.3 billion worldwide. This copper infrastructure is an enormous asset to the telecommunications industry. While history often contends others also invented the analog telephone, no one else claims Bell's more long-lasting copper twisted-pair invention.

GOING DIGITAL

Harry Nyquist's seminal 1928 work [3] motivated conversion from analog to digitized voice transmission. Decades later, an analog hierarchy of crossbar switches consequently transcended to digital switching, leveraging the simultaneously evolving semiconductor technology that more efficiently processed digital bits than analog signals. A voice signal can be well represented by 64 kb/s and reliably regenerated and transmitted over long distances with almost no degradation. Thus, if the telecommunications network core switches much more effectively handled digital traffic, and analog signals became too distorted on long paths between these older analog switches, then why use analog signals between those switches?

The reader is also referred to a survey by Lechleider written roughly 20 years ago that outlines contributions to that time [3].

T1 Carrier — Bell Laboratories' Robert Aaron [JH1] recognized such digital-switch-connect simplification with the 1962 introduction of "T1" transmission technology [4].[3] T1 allowed twisted-pair

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[1] *It is often said that "there is no wireless without wires, but the converse is not true."*

[2] *Good histories of voiceband modems appeared in the September 1984 IEEE JSACs (p. 632) by G.D. Forney, R. Gallager et. al., as well as the January 1998 IEEE Communications Magazine article (p. 16) by K. Pahlavan and J. Holsinger.*

[3] *See also the Bell Telephone Laboratories "Blue Book" (Transmission Systems for Communications), 4th Edition, 1971, Western Electric Publications.*

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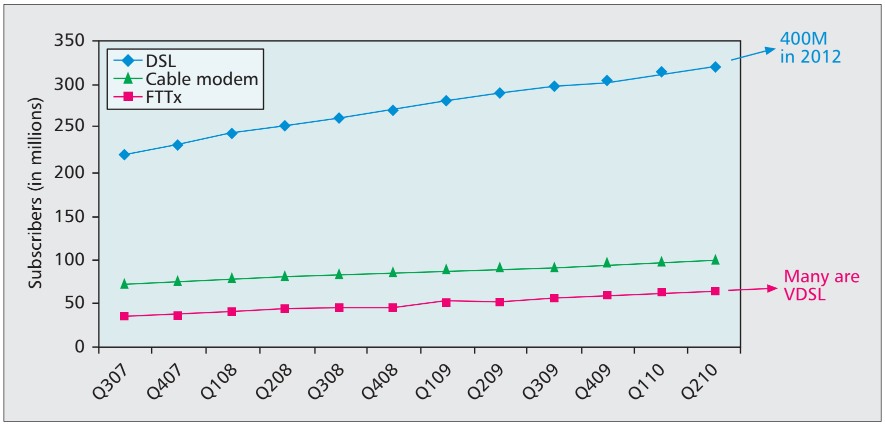

Figure 1. *Worldwide broadband growth (source: Point Topic). Q= 3-month quarter of year shown.*

transmission lines between switches to carry 1.544 Mb/s digitally over roughly one mile. While simple to implement in the 1960s, T1 used a low-cost early transmission line code called "alternate mark inversion" (AMI). AMI achieved less than a few percent of the famous (Claude) Shannon capacity, well known to Aaron and others of the times, but was simple to implement and sufficient for the intended use. T1 repeaters were used to reinvigorate digital signals every mile between switches, and higher performance (longer distance) was not needed. T1 carried 24 sixty-four kilobit/second voice channels, and an extra 8 kb/s of signaling/control information.[4] Two copper pairs were necessary, one for each direction of transmission. T1 enabled a digital telecommunications network. T1 might perhaps be considered the "first DSL," and was the initial step toward lighting copper. A history of T1 transmission can be found in a separate *Communications Magazine* history paper by F. T. Andrews that should be published before this DSL history, but exact publication date to create a reference was not available at time of writing.

All Digital — PSDC/Integrated Services Digital Network (ISDN) — The consequent digital core network and proliferation of digital switches left analog transmission only in the last few miles of copper closest to the customer. However, these last few miles represented over 99 percent of the wired connections, and the cost of replacing such wired connections could not be shared over many customers. Then, as now, it made no economic sense to entireley replace such "last-mile" wires.[5] Thus, telecommunications engineers around the world began to think how they might better digitize this last segment to create an end-to-end digital system. Digital voice transmission in the last few miles did not really help voice quality, nor did it then have any other economic value or driver, but it was too much of an elegant challenge for these many researchers to ignore.

Circa 1980, Ralph Wyndrum, Barry Bossick, Joe Lechleider and many others at Bell Telephone Laboratories in Whippany, New Jersey were trying to complete a plan for an all-digital network. They investigated simple transmission technologies slightly more advanced than T1, and determined that up to 160 kb/s of bi-directional transmission could be achieved over the last four to five miles of twisted-pair transmission, enough for two 64 kb/s voice channels, some overhead (16 kb/s), and 16 kb/s of data (much more than the 4.8 kb/s voiceband modems achieved in those days). Peter Adams in Britain, Kazuo Murano in Japan, and others also developed similar methods. Originally, this was called "Public Switched Digital Capacity (PSDC)" but later yielded to the name "ISDN" (Integrated Services Digital Network). The data rates contemplated did not yet anticipate a need for higher-speed services and instead focused on ubiquitous digital extension of the voice network.

Their biggest challenge was simultaneous bi-directional digital transmission on a single twisted pair, which exhibits echo of digital signals from a local transmitter to a co-located opposite-direction receiver. Analog voice also had echoes that were simply addressed.[6] Digital transmission could not so simply handle echo. Digital transmission required either that time-division multiplexing (ping-pong), frequency division multiplexing, or digital echo cancellation be used to separate the two directions of transmission. A dispute arose as to which multiplexing method was best. Echo cancellation had been successful in analog voice networks for small intervals of overlapping speech, but successful digital transmission now continuously required 100 times greater precision, but echo cancellation effectively doubles the data bandwidth. So researchers began to investigate data-driven echo cancellation for this subscriber line application, which continuous data-driven echo cancellation had only months earlier been demonstrated at that 100 times greater precision for voiceband modems by a young 23-year-old engineer working in the voiceband modem area at Holmdel Bell Telephone Laboratories (BTL). The Whippany investigators (coincidentally, sans Lechleider) invited the very young designer to a meeting that would compare echo cancellation versus ping-pong (frequency division had been eliminated) for ISDN. They preferred ping-pong, so the meeting was contentious. Worse yet, after explaining the echo cancellation to a hostile audience and how it could be done, the same young engineer then had the audacity to suggest that 160 kb/s was too slow, and they really ought to consider a much higher speed, enough for video at perhaps 1.5 Mb/s, much closer to Shannon capacity for a four-mile twisted-pair telephone connection, at least in the toward-customer direction. The laughter was thunderous, and the kid was embarrassed beyond belief

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[4] *Outside the USA, the equivalent of T1 was called E1 and used a very similar technology to carry 2.048 Mb/s (or 32, a nice power of 2, voice signals). There was no doubt that E1 used a more elegant packet layer than T1's prime-number 193 bits every 125 microseconds (8 kHz network clock), but E1 came later and introduced nothing more to digital transmission on copper than did T1.*

[5] *A 2010 FCC Report lists the average cost of installing fiber (PON, shared connections - point-to-point fiber is yet more expensive) as $2500/customer. DSL costs is under $100/customer. VDSL systems that mix some fiber and copper (and allow a higher DSL speed) cost roughly $500/customer.*

[6] *Although use of echo suppression and even some cancellation was well-known for voice signals over very long distances (delays) at the time, but did not require the same levels of echo reduction as were required in simultaneous bi-directional data transmission.*

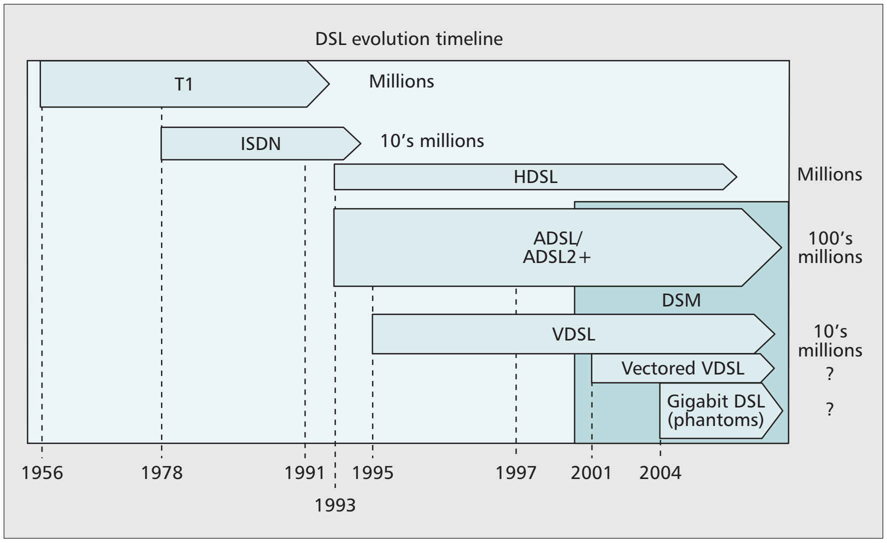

Figure 2. *Estimates of DSL and copper predecessor introductions and volumes of deployment.*

(particularly when even his own boss told him to "shut up and sit down"). But that was modern DSL's birth. I know well — that kid was me.

ISDN activities migrated to the American National Standards Institute's "T1D1.3" committee. Standards became very necessary with the 1984 ATT divestiture, which allowed for equipment other than that of Western Electric to be connected to the network. Lechleider, absent from that first echo/ping-pong-debate meeting, independently championed echo cancellation. The debates on the 160 kb/s ISDN transmission method raged in that standards committee, monitored by a fairly young man in his early 30's from Ameritech (one of the seven just-divested operating companies) who just happened to be on his way to becoming one of the most productive standards chairmen in telecommunications history, Mr. Thomas Starr.[7] Under his guidance, a compromise proposal for 2B1Q (suggested by Peter Adams of BT) transmission (two bits as one of four levels, 80 thousand times per second) with echo cancellation was driven through standards by Starr. ISDN became reality. Nonetheless, the Japanese did their own ping-pong standard for Japan, while Germany did a wider bandwidth ISDN standard using three levels instead of four — while the American standard was adopted internationally. The Japanese and German independence forced each country on to a special standard in each subsequent generation of DSL to follow, rather than each profiting from the volume of the worldwide standard, a decision that still today costs each country's operators a premium in DSL equipment. The time frame for this activity was the mid-to late-1980s.

While T1 might have been the first DSL, ISDN might more realistically be considered first because it really did connect the subscriber digitally while T1 basically did not (usually). As such, ISDN formed a foundation for future DSLs. Many of the same people involved in ISDN, including in particular Starr, became DSL advocates and experts. However, ISDN was a commercial failure almost everywhere in the world[8] — basically, ISDN was too slow to offer anything much more than analog phone service (voiceband modems eventually passed ISDN's 16 kb/s data channel, and voice is, well, voice — digital or analog). ISDN earned itself the well-known substitute acronym "ISDN = innovation subscribers didn't need." It was going to take at least a Mb/s to light up the average consumer with excitement; ISDN was too slow and satisfied no customer need, but it did initiate DSL expertise.

DATA COM

Contributions from the "Ethernet" community should not be ignored in a history of telecommunications copper and DSL, particularly as data and telecommunication networks have increasingly converged together in recent years. Ethernet originally started via reproduction of wireless ALOHA[9] networks' carrier-sense and collision avoidance on shared coaxial cables, as conceived by Bob Metcalfe in 1973 while at Xerox.[10] Ethernet's evolution to 10base-T and its offspring have proliferated to be used on an estimated two billion wired Ethernet connections.[11] They also provided practical motivating proof that higher speeds on copper were possible.

Early Ethernet transmission "Manchester Encoding" was essentially a positive or negative (±1 or one bit) single square-wave cycle sent on the link roughly 10 million times/second. Manchester Encoding is as inefficient as the early T1 transmission's AMI code, but enabled cheap 1980s manufacture of Ethernet transceivers. More sophisticated Ethernet line codes increased user bit rate to 100 Mb/s by 1995.[12] This was an important precedent to note for future DSL.

MODERN COPPER AGE

Repeated T1 connections extended the digital network closer to business customer's locations, facilitating multi-

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[7] *While Starr did not assume the chairmanship from a legacy AT&T colleague until 1989, he was clearly the leader of this American group and later internationally in the DSL area. He has been listed recently as one of the 100 most influential people in telecommunications, largely because of his unusual highly respected standards-compromising-crafting skills.*

[8] *At one point, ISDN connections appear to have peaked at about 25M, but they have largely yielded to faster ADSL connections (in both directions, down and up) everywhere, so there are only an estimated millions of them still in service as in Fig. 2.*

[9] *ALOHA protocols were introduced in the late 1960's by N. Abramson of the University of Hawaii, as in "The ALOHA System - Another Alternative for Computer Communications',' Proc. 1970 Fall Joint Computer Conference AFIPS Press, see also IEEE Communications Magazine, August 2009, for Abramson's history "The Aloha Net: Surfing for Wireless Data."*

[10] *The best Metcalfe reference is his 1973 Harvard dissertation, reproduced in "Packet Communication", MIT Project MAC Technical Report MAC TR-114, December, 1973 , but the work was done at Xerox Parc.*

[11] *This estimate comes from Jag Bolaria of Linley Marketing Group.*

[12] *A good reference on this is the IEEE 802.3-1995 Ethernet standard.*

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ple digital phone connections. However, T1's one-mile inter-repeater spacing was too short. Following ISDN standardization success, Lechleider (then at Bellcore) proposed [3] that each of T1's two twisted pairs instead use ISDN's improved echo-cancelled 2B1Q line code to double T1 repeater spacing to two miles. The proposed 2B1Q system basically transmitted bi-directionally two bits 400,000 times a second (as one of four levels each time) for 800 kb/s on each pair, yielding a 1.6 Mb/s total. Lechleider called this "High-Speed Digital Subscriber Line" (HDSL). By 1991, HDSL's 2B1Q was essentially standardized in the USA after a competition with other proposals (see the section on "Line Code Wars" below). Tom Starr again skillfully guided a consensus HDSL standard/report in the American DSL standards group, then operating under the revised name ANSI T1E1.4. Europe's "E1" T1-equivalents use 2.048 Mb/s at roughly 20 percent higher sampling rates, but also re-used the 2B1Q line code.[13] Unlike ISDN, HDSL's higher speeds increase the (imperfectly) twisted pair's radiation. These HDSLs thus also sense radiated energy from one another, a phenomenon known as "crosstalk." Crosstalk noise thus limited HDSL's signal-to-noise ratio and consequently HDSL's data rates, but at least 1.6 Mb/s (800 kb/s on each line) could reliably traverse two miles. The largest crosstalk occurs between signals traveling in opposite directions, where the near-end large transmit signal crosstalks at a high level into the attenuated signal coming from the far-end. This is called NEXT[14] in copper transmission.

A significant fraction of telephone lines, however, have lengths greater than two miles. Something more was needed for digital connectivity to the residential customer (above ISDN's too slow 160 kb/s). Lechleider proposed asymmetric transmission rates in non-overlapping upstream/downstream frequency bands to avoid NEXT. Lechleider's asymmetry then avoided NEXT. Thus was born a basic concept of ADSL (where A = asymmetric).

At this point, after getting a Ph.D. and working on disk drives at IBM for a while, I returned to Stanford as faculty in 1986, heard of ADSL and was elated, and found a way to meet Joe Lechleider, recalling my earlier "1980 laughed-out" meeting (at which he was coincidentally not present). While we differed in age by more than three decades, our early conversations and meetings were very exciting. Lechleider explained that digital applications (video to customer or information to customer) were likely to be asymmetric, thus more frequencies should be allocated to the downstream (to customer) direction than the upstream (from customer). If the upstream frequencies were limited, then the NEXT would also be limited, and all the rest of the frequency band was then NEXT-free. My earlier 1.6 Mb/s at four miles calculation had a legitimate supporter in "Uncle Joe." Lechleider introduced me to Belcore's Dave Waring, who successfully managed Bellcore's DSL efforts thereafter for decades (and still does today) as well as re-acquainted me with Ken Kerpez, who made numerous contributions in modeling and fair testing of DSL over the years, despite having a limited budget with which to work for years.

There was a hand-off at this point. Joe was nearing retirement age, and knew he would stay only to finish the HDSL work. He found Bellcore money to finance the first years of Stanford research in ADSL, which the National Science Foundation also matched. There was just barely enough to develop a design and to prototype. Some interesting findings emerged from this effort — basically, only a multicarrier transmission approach could achieve the data rates, and indeed if fiber were used in part of the network (say within two miles of the customer, or even several HDSLs to the two-mile point), the last two miles could sustain 6 Mb/s in ADSL. This was big — 6 Mb/s is a lot of data (even today) and certainly enough for good video (and perhaps a few simultaneous videos). ADSL had legs. Uncle Joe sent one last check as Bellcore also reduced funding overall of the area, told me it was up to me, and retired. Little did I know that there was a gauntlet to run of unpredictably epic proportion before DSL could really light up.[15]

LINE CODE WARS

While it would seem HDSL was a logical simple extension of ISDN in terms of transmission, even such a simple extension did not go unchallenged. The remnants of that challenge plagued DSL advance for years. AT&T Information Systems[16] proposed carrier-less amplitude/phase modulation[17] (CAP) for HDSL. CAP is QAM with a minor simplification that causes the carrier frequency and symbol clocks to be exactly synchronized. CAP demonstrated a slight improvement in recorded independent laboratory tests in a 1991 T1E1.4 investigation. Nonetheless, HDSL stayed with ISDN's known 2B1Q transmission line code. The CAP proponents were disappointed about this HDSL decision, and believed CAP then deserved the next standard (ADSL).

CAP was proposed for ADSL, but its use there would have been fatally flawed (as would have been also 2B1Q). The billion telephone lines exhibit wide variation (varying linear transfer characteristics and highly variable and time-variant noise spectra), which when stretched close to Shannon limits, forcing a highly variable best transmission bandwidth. The optimum Shannon spectrum often has a different on/off/on/off/.... /off nature for realistic DSL channels. On/off/on/off means the optimum transmitted spectrum places energy in separated spectrum segments, Basic transmission theory shows that a single carrier can never achieve the performance of the on/off/..../off spectrum (at least one carrier for each "on" band is necessary [5]). This effect is amplified in practice because of realistic code implementation and a 6 dB margin required for unforeseen line impulse noise changes. The Stanford work had studied this problem for years and the conclusion was irrefutable: multiple carriers were necessary, or the industry could forget 1.6 Mb/s at four miles and 6 Mb/s at two miles, or essentially DSL would have failed.[18]

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[13] *In some cases 3 American-speed lines operating each at 800kb/s were used for a total of 2.4Mb/s with an extra 352kb/s of overhead.*

[14] *Near-End Crosstalk. X =Cross. FEXT or Far-End CrossTalk is between signals traveling in the same direction on adjacent twisted pairs.*

[15] *I still wonder today if Joe knew well of that gauntlet before handing off with a smile on his face.*

[16] *This group later became Lucent, and a DSL modem portion of ATT then was spun off as ATT Paradyne.*

[17] *This is a slight simplification of basic quadrature-phase modulation that exploits the symbol clock and carrier frequency can be synchronized in DSL transmission since there is no intermediate independent carrier adjustment in a twisted-pair transmission channel. Most prefer to simply call both CAP and QAM as "QAM" since the difference is trivial.*

[18] *Some examples further illustrate the theory simply in the textbook reference at website http://www.stanford.edu/group/cioffi/ee379c/ , which extends reference [5].*

A DIGRESSION INTO BASIC DSL TRANSMISSION THEORY

This papers' reviewers encouraged inclusion of some transmission theory here to expound upon this point. There are those who confuse a result that applies only to voiceband modems with application of its conclusion to DSL. Figure 3 will help illustrate this "multi-bowl" point. Reference [5] first made it general, expounding on some earlier results of Price, Kalet, Zervos, Salz and others that appear19 in the references of [5]. Simply stated for the purposes of this historical article, many authors make an infinite signal-to-noise-ratio ($SNR(f)$) approximation $1+SNR(f) \approx SNR(f)$ in transmission analysis, and this approximation holds well over the entire used bandwidth of a voiceband modem. However, in DSL, $SNR(f)$ is often zero in Shannon's famous water-filling spectra shown in Fig. 3. The assumption $1+0 \approx 0$ is not accurate in all the unused bands (and near their edges). If one follows the assumption in these earlier works, it is equivalent to assuming that there is infinite energy (water) available to be poured from above, causing all of the Shannon bowls to overflow into one another, and thus into one very large single carrier (for which a DFE would be optimum with QAM or CAP). It is also important to note that assumptions equivalent to "generalized Nyquist bands" made by these same authors are described as DFEs in those articles but a review of filter-realization theory and Paley-Wiener criteria will reveal that discontiguous bands in that theory MUST be implemented with multiple carriers. So the authors call it single carrier, but it is really a number of carriers equal to the number of bands. However, the amount of water (energy) needed to force a single carrier and thus single band on most DSL channels greatly exceeds that available, and thus the equivalence of multi-carrier and single-carrier does not hold. Reference [5] also shows that if codes less than capacity achieving are used with any gap (or margin) above 0 dB (DSL uses a 9.8 dB gap to capacity with 6 dB of it left for time-varying noise effects), that the difference between single-carrier and multicarrier rapidly magnifies. This effect was in plain evidence in the so-called DSL Olympics test results that are mentioned later in this history.

Further, it is not possible to design a single DFE that corresponds to the same three spectra, as the fundamental assumptions behind DFE realization then no longer apply (essentially the filters blow up). Correct DFE theory interpretation is that three separate DFEs are necessary for the situation in Fig. 3 (see Reference [5]).

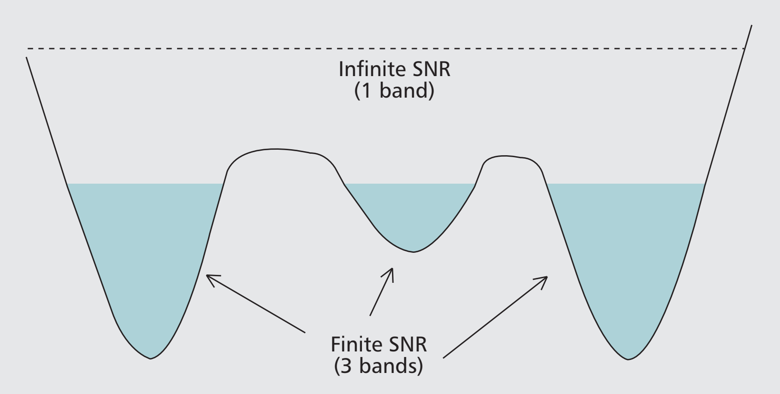

Figure 3. *Plot of Shannon's water-filling. The curve is NSR(f), the inverse of SNR(f), and energy/water is poured into the curve to lie at a constant level, with three "bowls" illustrated. This is the optimum spectra for best performance, and a single-carrier cannot achieve optimum performance unless the SNR is infinite. Use of the same three disjoint spectra in a single decision feedback equalizer causes a violation of basic filter design (causes an unrealizable filtering effect) and the assumptions underlying decision-feedback theory no longer apply and the decision-feedback system cannot be realized (instead three are needed, one for each band). The difference between a single-carrier system and multicarrier system is magnified, when as in DSL, the capacity gap is nonzero (minimum of 6 dB in DSL to account for time-varying noises).*

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But the CAP supporters wanted their standard. I made a considerable effort to talk to the various interests to explain CAP's fundamental-flaw for ADSL. However, I was not successful. Broadcom was formed as a spin-out of HDSL supplier Pairgain, where UCLA Professor Henry Samueli was CTO and had done a very good job implementing the first HDSL 2B1Q transmission chips that were used in the above-mentioned HDSL laboratory tests. He was joined in the Broadcom spin-out by Pairgain's VP of Engineering Henry Nicholas. It was more expedient for them to adjust their HDSL design to CAP's close cousin QAM (thus avoiding AT&T patents on CAP) and rapidly market a QAM ADSL chip. They thus proposed a "compromise" of doing QAM (close enough to CAP), argued similarly to AT&T Information Systems/Paradyne. This placated somewhat the CAP supporters (although they really wanted CAP) and they formed something of an anti-DMT alliance. The Broadcom founders were astute businessmen, and they knew full well they (Broadcom) could get a chip to market faster than AT&T-Microelectronics (the chip partner of Paradyne and AT&T-IS, now known as Agere) and thus uniquely capitalize on ADSL's potentially enormous market of one billion customers worldwide. All efforts to convince them to use multiple carriers aborted because Broadcom would lose a time-to-market advantage, and that economic incentive blurred the ability to see the technical argument that a single QAM carrier would fail from a transmission standpoint. I had failed to convince anyone that the right transmission strategy was multicarrier (Uncle Joe understood, but he had retired), except for some exceptionally talented Stanford students, Jacky Chow, Jim Aslanis, and Peter Chow, and some very experienced friends from multicarrier-voiceband-modem manufacturer Telebit (a consulting job for me) CTO John Bingham and Mark Flowers.

Together, that latter group became Amati Communications Corporation, which was founded in June 1991 to design and manufacturer a multicarrer ADSL modem. With less than 10 employees, and funding from Nortel's American marketing group[19] (Nortel's

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[19] *A special thanks is still due today to Northern Telecom Marketing VP Stephen Fleming, now at Georgia Tech, for his faith and funding of that early effort.*

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