Voiceband Modems:
A Signal Processing Success Story

August 1999

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Introduction

This paper focuses on a particularly important representative of signal processing's technological evolution as it has been applied to communications systems, namely modulators and demodulators used to convey data over telephone networks. Nine different voiceband modems with ever-increasing capability are illustrated, demonstrating the trend of inexorable improvement brought about with signal processing innovation, and the incredible improvement in semiconductor technology.

The voiceband modem shown in Figure 2 could carry a full-duplex 1200 b/s data link over two conditioned voice channels. The modem shown in Figure 12 operates more than 40 times faster, using only a single pair of wires. Further, it costs and weighs less by a similar factor. While many elements contributed to this stunning improvement, a very important one was the application of digital signal processing. In this paper, we discuss the history of voiceband modems—including both market forces that made their development possible.

The Market Driver for Voiceband Modems

Before the availability of electronic computers in the mid-1950s, most data communication was conducted at rate of 50 or 75 b/s. Electromechanical terminals called teletypewriters were employed, and most of the traffic was short messages between human users called *telegrams*. As soon as electronic computers began to appear in the marketplace in some volume, it became clear that "networking" them in some fashion would "add value" for their owners. Important early examples of such networking were airline reservation services and the transfer of accounting data between a central computation facility and remote enterprises. A typical arrangement of equipment for one of these early computer networks is shown in Figure 1. Central to the network concept is the ability of the various computers in the network to communicate with one another. Further, it is generally true that the faster the computers in a network can communicate with one another, the better the performance is to its users. The low-speed transmission techniques suitable for electromechanical terminals would no longer suffice. Therefore, the push began in the late 1950s to increase the rate at which data could be sent between distant mainframe computers.

The transmission medium of choice in this era (and now) was the telephone network, principally because of its ubiquity in developed countries and its common, well-engineered interfaces. This telephone network, however, was totally analog in its implementation. Thus, to carry data instead of analog voice waveforms, it was necessary to build modulators and demodulators to place data from a computer onto a telephone *voice grade channel* and to recover data from the analog signal at the other end. This paper chronicles more than forty years of evolution in the design of such modems.

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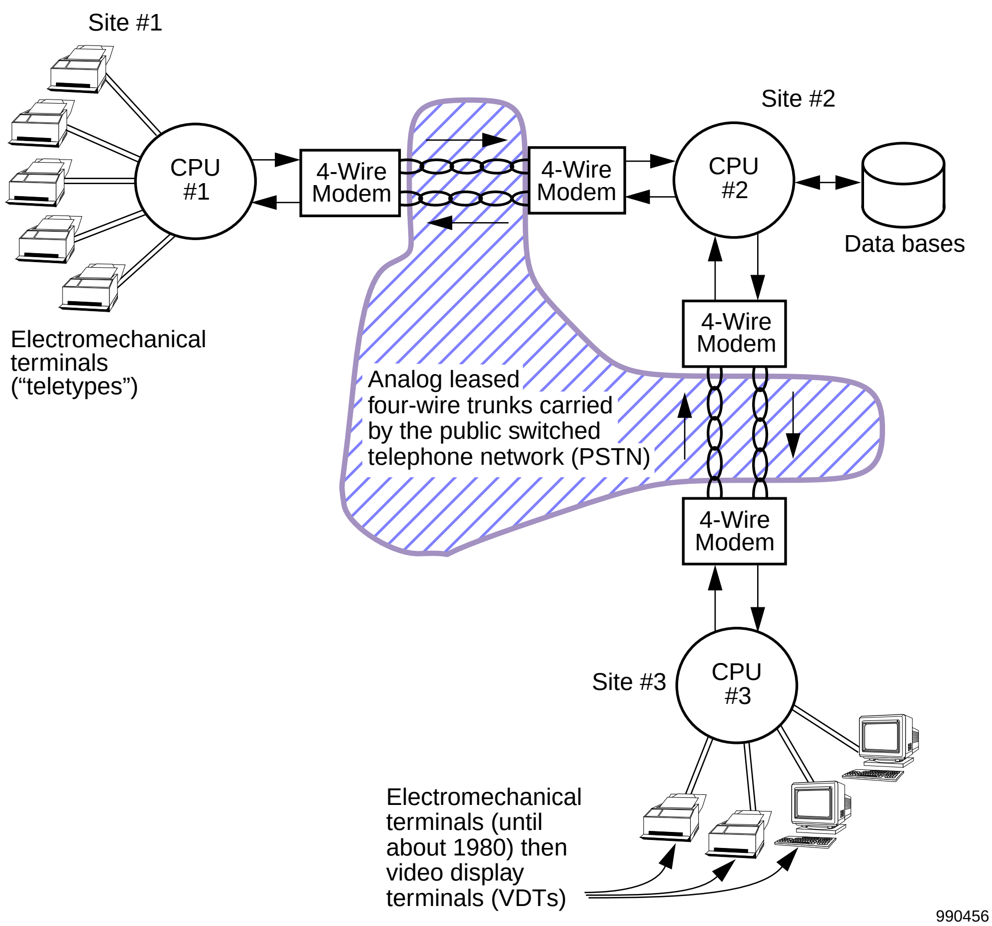

Figure 1. Initial Use for High-speed Modems—Connecting computers into a network via the analog telephone system

Not only does the voiceband modem illustrate the rapid evolution of signal processing technology, but the quest for its improvement led to many innovations in signal processing theory and implementation. In fact, these improvements set the stage for the use of digital signal processing in another very important commercial communications marketplace—cellular telephony.

The First Step: Analog Implementations

Figure 2 shows the first voiceband modem commonly used to interconnect computers. Called the Bell 202, it was manufactured by Western Electric Co. for use in AT&T's national network in the U.S. It was a four-wire modem—it required two separate voice channels to carry the two paths needed for a full-duplex connection. It employed two-level frequency-shift keying (FSK) to attain a transmission rate of 1200 b/s in each direction, and was implemented virtually entirely with analog components. The key technical problem in the development of this modem was the frequency-selective dispersion of a telephone channel and the distortion this produced in a wideband FSK signal. Frequency-shift keying was already widely used at this time on telephone circuits, but rarely with bandwidths greater than 100 Hz. The principal technical achievement in the design of this modem was the introduction of an equalizer, shown with an arrow in Figure 2 It was implemented with analog components, and was designed as a compromise, that is, one fixed design was expected to adequately handle a variety of actual transmission channel characteristics. Though the Bell 202 was developed in the U.S., the International Telecommunications Union later designated a variant of it as Recommendation V.23. (Of all of the modems discussed in this paper, the modulation format used by Bell 202 is probably currently the most common. The reason for this remarkable fact is that it is the standard used to convey Caller ID to the called subscriber in modern telephones.)

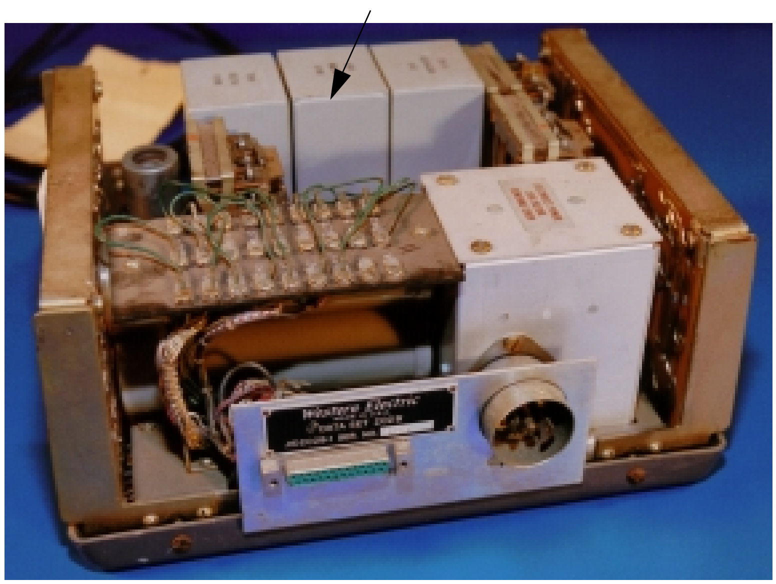

Figure 2. The Bell 202 FSK, 1200 b/s, Four-wire Leased-line Modem

Figure 3 shows the next step, introduced in the early 1960s. Called the Bell 201, it was also manufactured by Western Electric and deployed within the AT&T network. It used quadrature phase-shift keying (QPSK) to improve the transmission rate to 2400 b/s while occupying roughly the same signal bandwidth as the Bell 202. Also implemented with analog components, it introduced the use of a carrier-tracking loop to compensate for frequency offsets often encountered in analog telephone transmission systems. Just as with the Bell 202, the ability to equalize the telephone channel's dispersion was a fundamental limit to the modem's attainable transmission rate. The arrow in Figure 3 indicates the circuit card filled with capacitors and toroidal inductors which constitutes the compromise equalizer for the Bell 201. It also had the ability to *fall back*, that is, to be operated at the slower rate of 2000 b/s if the compromise equalizer proved inadequate for the channel.

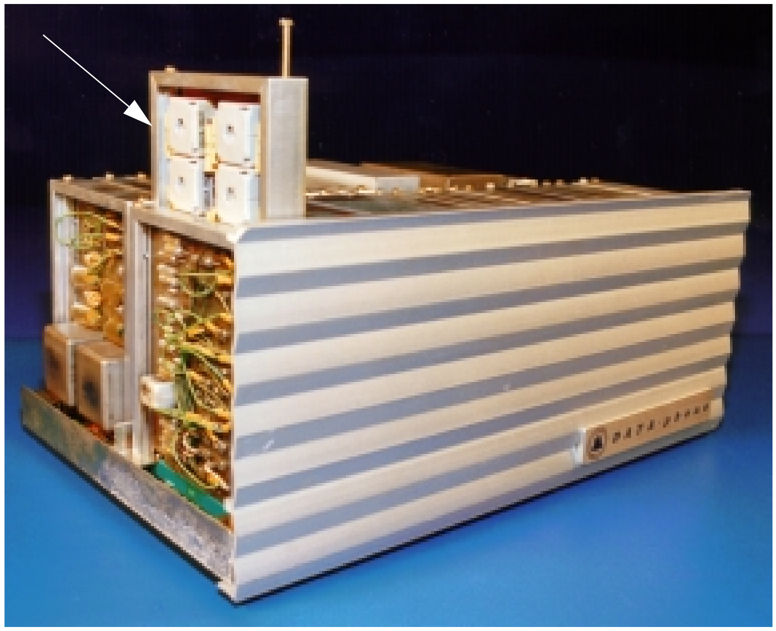

Figure 3. The Bell 201 QPSK, 2400 b/s, Four-wire Leased-line Modem

The Big Breakthroughs in the Late 1960s: Technology and Market

While the Bell 201 and its international equivalent, the V.26 modem, were widely deployed, computers were also improving, as were the expectations of what computers could do for the business community when networked properly. This demand for higher data transmission speed was aided significantly in the late 1960s by two diverse factors. The first was the growing practicality of digital signal processing (DSP). The theoretical underpinnings of DSP had been under development for more than a decade, but the semiconductor industry was just beginning to produce the types of devices and integration technology (e.g., TTL MSI, the 7400 series) that would make it practical to implement something like a voiceband modem with digital components. The second important factor was the Carterphone Decision, a legal ruling in the U.S. that AT&T could no longer prevent equipment not manufactured or otherwise approved by them from being connected to the telephone network. This new freedom allowed competition and attracted a number of companies into the marketplace. Armed with a market demand (for higher speed), a new technology (DSP), and an open marketplace, the performance of voiceband modems has increased enormously (from 2400 to 56000 b/s) in the timeframe between 1968 and 1998, and the marketplace has grown to billions of dollars per year.

Figure 4 shows the first economically viable example of this confluence. A non-Bell company, Codex Corporation, revolutionized the marketplace in the early 1970s with a 9600 b/s four-wire modem that employed digital signal processing throughout its modulator and demodulator. It used 16-level quadrature amplitude modulation (16-QAM) and a symbol rate of 2400 Hz to achieve a peak transmission rate of 9600 b/s. It is virtually impossible to use a symbol rate this high when employing a compromise equalizer.

As a result, the Codex design incorporated a digitally-implemented adaptive equalizer, a concept first introduced only five years earlier by Bob Lucky of the Bell Telephone Laboratories[4].

Figure 4. One Model of the Codex 9600 Series of Four-wire Leased Line Modems

Successive Improvement in Four-wire Modems

The success of the Codex 9600 b/s modem (which became the ITU Recommendation V.29 modem), coupled with rapid improvements in semiconductor technology, fueled substantial research into ways to make four-wire modems even faster. Figure 5, 6, and 7 illustrate examples of these improvements. (Just as the Bell 202 modem has proved long-lived due to a new application, so has the V.29, being a key part of virtually all Group 3 fax machines. To support the dial-up facsimile application, however, it is used in a two-wire, simplex mode rather that its original four-wire, full-duplex mode of operation.)

These particular modems were manufactured by Codex Corporation, but in fact, many companies introduced similar products. Figure 5 is a photograph of the Codex 2660, a four-wire modem that used 256-QAM and a new concept called *trellis coding* to achieve the unheard-of transmission rate of 16800 b/s in each direction. Trellis coding, first suggested by Ungerbock at IBM's European research facility, allowed the signal coding work that had been underway in the communications community to be used in the bandwidth-limited environment of a telephone voice grade channel. Scoffed at initially, trellis coding has become an integral part of all advanced voiceband modems. A slightly slower variation of the Codex 2660 was approved by the ITU as Recommendation V.33, the highest speed, internationally recognized four-wire modem.

Figure 5. A Codex 2660 Four-wire, Leased-line Modem that Employed Trellis Coding and 256-QAM to Attain a Transmission Rate of 16800 b/s

Figure 6 illustrates the Codex 2680, a modem which achieves a maximum transmission rate of 19200 b / s. To attain this higher rate, the modem uses a higher symbol rate (2743 Hz) and more advanced trellis coding—an eight-dimensional, 64-state design.

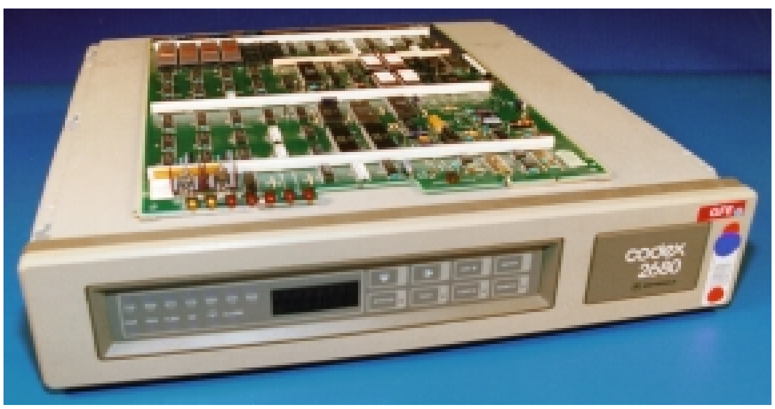

Figure 6. The Codex 2680 19.2 kb/s Four-wire, Leased-line Modem

Figure 7 shows the last of this line—the Codex 3600, which was introduced in 1990. It reaches 24000 b / s, using a combination of an even higher symbol rate (3200 Hz) and a technique called *trellis precoding*. All three of the modems shown in Figure 5, 6, and 7 implemented their digital signal processing algorithms with specially designed large- and very-large scale integrated (LSI / VLSI) circuits. The potential market volume for these modems justified the large financial investment required to develop them. Rather than use custom devices, however, some competing companies began to employ programmable DSP chips, arguing that their flexibility permitted the easy introduction of new features, and that their performance had evolved to the point that it was comparable to custom designs.

Figure 7. A Codex 3600 Modem that Used a Higher Symbol Rate and Trellis Precoding to Attain Transmission Rates of 24000 b/s

Shifting Attention to Two-wire Dial-up Modems

There are still many four-wire modems in use in the world—some because analog transmission facilities are still in use, thereby requiring the use of a modem, and some because no investment argument can be made to replace them. In locations with modern digital telephone transmission systems, however, the telephone system can haul the data between computers directly without requiring conversion to and from analog form by a modem. As a result, the use of four-wire modems in these advanced telephone networks is declining. More than compensating for this, however, is a trend that began in earnest with the introduction of the personal computer in the early 1980s. Four-wire modems were initially developed to provide communications pathways between large mainframe computers. In order to attain the highest data transfer rate, four-wire transmission over leased and conditioned circuits was used.

The advent of the personal computer, however, changed the communications requirement considerably. A single personal computer might need to communicate with any of a number of bigger computers and possibly from different locations, as is shown in Figure 8. This implied the need to operate over classical two-wire dial-up telephone lines that were not conditioned to minimize their noise and dispersion characteristics. Due to these considerations, modems intended for dial-up use, which we will term here *two-wire modems*, had only achieved transfer rates of up to 2400 b/s by the mid-1980s. The next phase of voiceband modem development, therefore, was to move all of the four-wire modem technology to the dial-up problem, attempting to attain full-duplex transfer rates of 9600 and even 14400 b/s with two-wire modems. This goal was greatly exceeded.

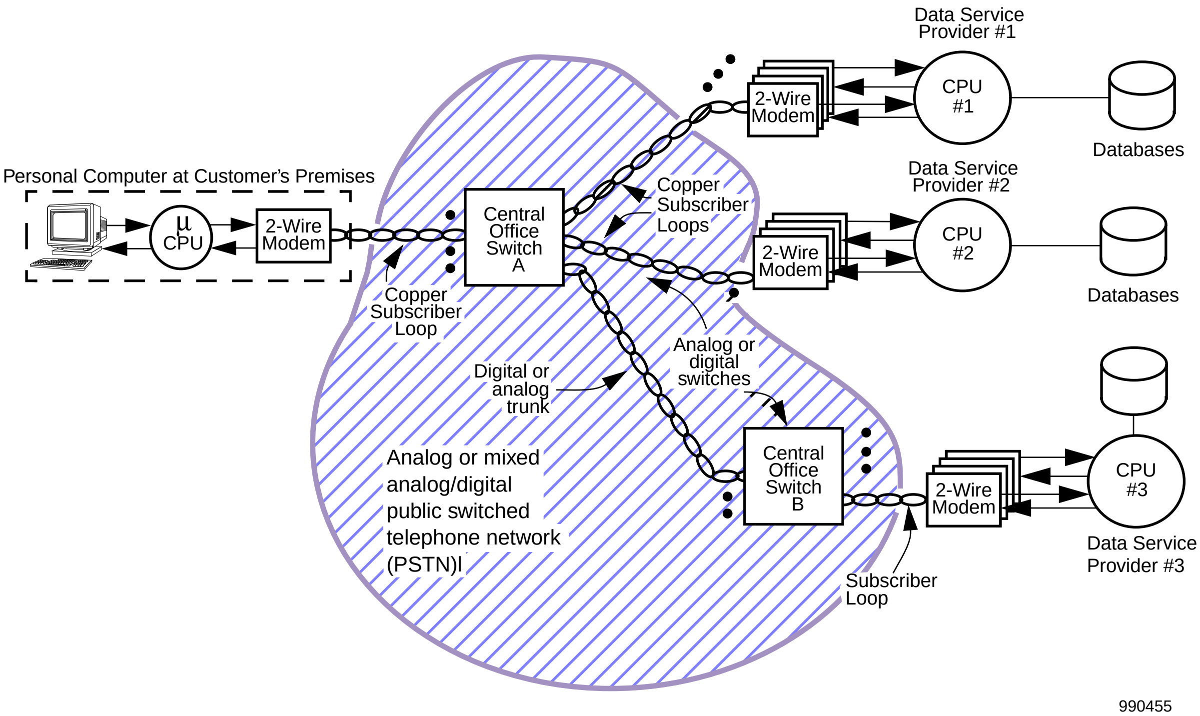

Figure 8. The Impact of the Personal Computer–The users can use the switched telephone network to gain access to any of many data service providers

Figure 9 shows a commercially available V.32 modem. First approved as an ITU recommendation in 1984, the concept of the V.32 modem was to combine the modulation (32-QAM) and trellis-coding (2-D, 8-state) of the V.33 four-wire modem with the advanced digital signal processing techniques developed for telephone echo cancellation to produce a modem capable of attaining transmission rates of 9600 b/s over an unconditioned dial-up telephone line. This proved more difficult than expected, but by 1988 these modems were generally available, and improvements were already being made to extend their speed to 14400 b/s and even 19200 b/s. Even so, work was underway to reach the next levels of speed and performance. This modem, ultimately designated by the ITU as V.34, combined virtually every signal processing and coding technique ever developed, with symbol rates even higher than the nominal bandwidth of telephone voice channel (3429 versus 3100 Hz) to attain peak rates of 28800 and then 33600 b/s. An example of such a modem, this one manufactured by AT&T's Paradyne division, is shown in Figure 10. It should be noted as this point that the V.34 modem achieved higher transmission rates than the Codex 3600, even though the two-wire dial-up channel is generally considerably more problematic than a four-wire leased, conditioned circuit. A part of this differential is, of course, due to algorithmic improvements. Part of it, however, was a benefit of the ever-improving telephone transmission system (e.g., better SNR and less impulsive noise). Yet another part was the fact that the availability of higher speed, lower cost semiconductors made it possible to economically apply even more computational resources to the signal processing problems at hand.

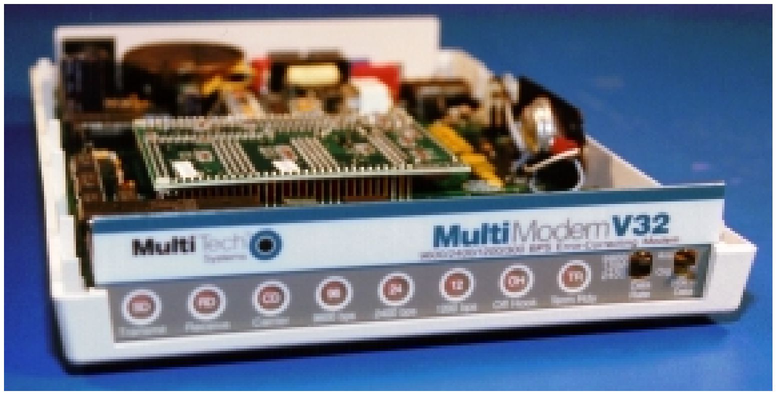

Figure 9. A V.32 Two-wire Dial-up Modem

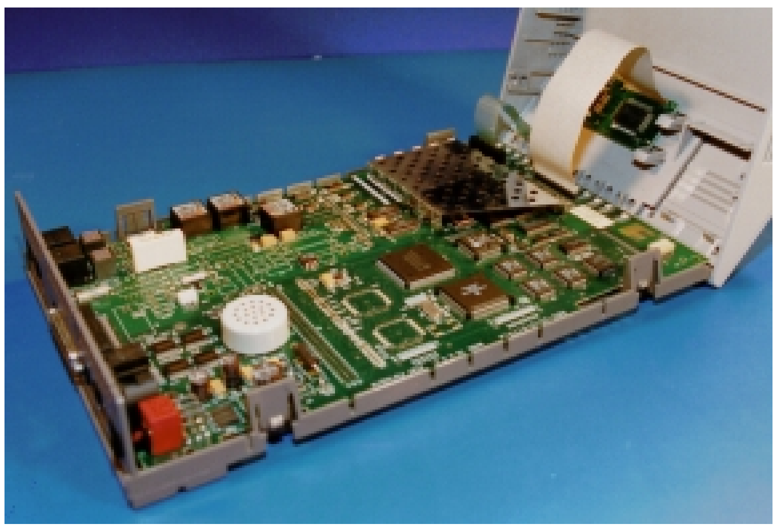

Figure 10. An AT&T/Paradyne V.34 Two-wire Modem for Dial-up Circuits

A visual inspection of modern V.34 modems shows that most are built with digital signal microprocessors rather than employing application-specific semiconductor designs.

The PCM Modem and the Focus on the Local Loop

Figure 12 shows a V.90 modem, one designed specifically for operation in a telephone environment shown in Figure 11, one consisting of twisted-pair local loops and PCM/TDM transmission from the telephone central office to points beyond. By abandoning the classical, bandlimited, low-30s SNR telephone transmission model, the designers of the V.90 modem achieved data rates of up to 56000 b/s in the downstream direction. This was made possible by yet another change in the computer-to-computer paradigm.

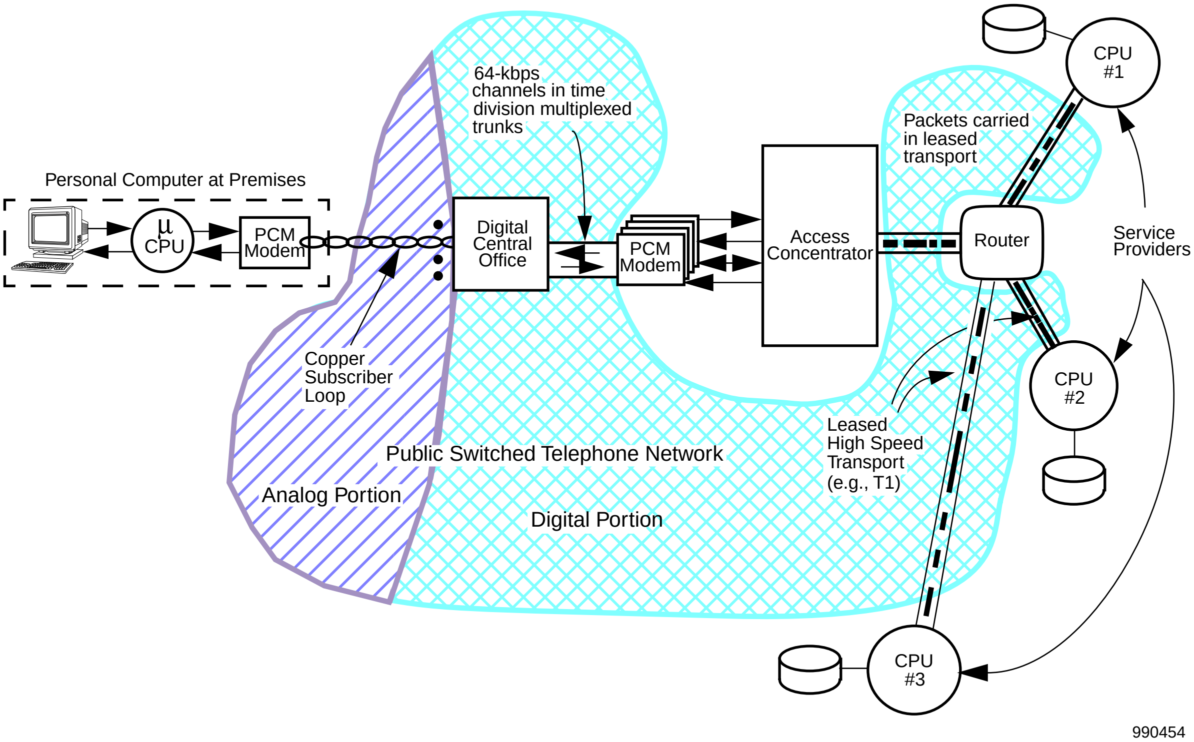

Figure 11. The PCM Modem—It is used to convey data over the only remaining analog portion of the PSTN, the local subscriber's copper loop

Specifically, it is assumed for the V.90 modem that the user's computer need not have a telephone connection directly to the desired host computer. Instead it is assumed that the user wants a connection to a nearby access server. This server concentrates traffic from many users into a high-speed (e.g., T1 or T3) data link extending back to the computer or server of ultimate interest. By optimizing operation on the twisted pair portion of the telephone connection (rather than the complete end-to-end connection) it is possible to attain the 56000 b/s rate and even to extend it well beyond that rate.

This is, in fact, the basis for the current theoretical and commercial work in what are termed digital subscriber loop (DSL) modems. It is interesting to note the historical contrast. The first voiceband modems were designed to transmit data from one computer to another over a path stretching from one end of a totally analog telephone system to the other. The newest modems operate over only the twisted-pair subscriber loop—the only remaining analog portion of most end-to-end telephone connections.

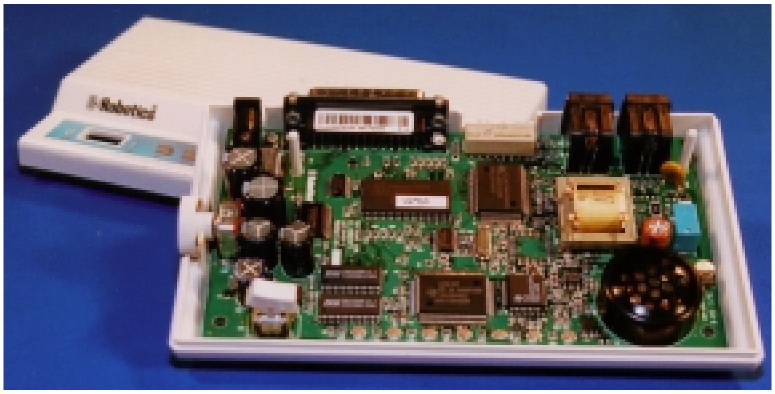

Figure 12. A US Robotics V.90 “PCM Modem” For Short Dial-up Circuits

The Big Picture

The modem illustrated in Figure 2 could carry a full-duplex 1200 b/s data link over two, conditioned voice channels. The V.90 modem, shown in Figure 12, operates more than 40 times faster, using only a single pair of wires. Further, it weighs less than the Bell 202 by a similar factor. It is tempting to attribute all of this improvement to one source, but in fact there are four:

- Transition from analog to digital implementations
- Improved algorithms for demodulation, equalization, coding, and echo cancellation
- Improved semiconductor technology
- Improved quality of the telephone network itself

The digital signal processing community has been a key contributor to the first, second, and even fourth items. It is clear that much of this factor of 40 and the resulting billions of dollars of economic impact accrue directly from the creative energies of the members of the IEEE Signal Processing Society.

To learn more about the early technical history of two-wire and four-wire voiceband modems, the reader is referred to [1], [3], and [5]. A more general coverage of the design of voiceband modems appears in [2].

[extracted from “Highlights of Signal Processing for Communications,” *IEEE Signal Processing Magazine*, March 1999, edited by G.B. Giannakis]

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