# Chapter 7

# *Breakout: The 1990s*

## What was Happening in the 1990s

***movies people were watching:***
*Forrest Gump*
*Jurassic Park*
*Lion King*
*Pulp Fiction*

***TV shows people were watching:***
"The Oprah Winfrey Show"
"Seinfeld"
"The X Files"

***music people were listening to:***
(and dancing to) the Macarena
Spice Girls

***books people were reading:***
Robert James Waller's *Bridges of Madison County*
Stephen Covey's *The 7 Habits of Highly Effective People*

The 1990s began a new era in international relations. The Cold War had dominated the years from 1945 to 1990, as that struggle between the superpowers was often superimposed on regional and local conflicts. In the 1990s it was economic relations—in an increasingly globalized marketplace—that took center stage.[1] World trade had increased 10-fold from 1950 to the early 1990s, and in the mid 1990s there were some 37,000 multinational enterprises with some 200,000 foreign affiliates worldwide. One of the essential factors leading to this growth of international trade and multinational enterprise was the modern system of global communications that facilitated transnational operation.[2]

The 1990s may be remembered as the decade the human race made its greatest strides toward interconnection. The worldwide telephone network continued to grow in extent, especially in the less industrially developed parts of the world, but rather unexpectedly it grew spectacularly in density, as it connected modems, pagers, cellular phones, fax machines, and the second and third telephones that many families found they wanted. To traditional broadcasting- and cable-television was added, for millions of people, television broadcast from satellites. Even more so than in previous decades, much of the

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[1]J.A.S. Grenville, *A History of the World in the Twentieth Century* (Cambridge, MA: Harvard University Press, 1994), pp. 925–926. In the 1990s the states of central and eastern Europe faced huge problems in converting from a Communist command-economy to a free-market economy.

[2]Richard Overy, ed., *Hammond Atlas of the 20th Century* (London: Times Books, 1996), pp. 172–173.

world experienced through television the same events at the same time, such as the Persian Gulf War in 1991 and the funeral of Princess Diana in 1997. Added to this was the effect of the Internet, as personal computers, in addition to being stand-alone devices, became tools of access to this network, and millions of people all around the world viewed the same Web sites and joined in virtual communities concerned with almost any conceivable subject.[3]

Signal processing played an important part in all of these changes. So it is not surprising that, after decades of steady growth and the cultivation of niche markets, signal processing achieved something of a breakout in the 1990s. In 1985 there were only three large commercial markets for DSP chips—speech coding, video compression, and modems—which, together, were a $50-million business. The growth of these three applications and the appearance of many new ones, such as cellular phones, sound boards, hard-disk drives, scientific instruments, and robotics resulted in a DSP business totaling $2.2 billion in 1995, as programmable and function-specific DSP achieved large markets.[4]

The breakout for signal processing came with continuing growth of the consumer electronics market. Some of the products that have become popular in the 1990s, besides those already mentioned, are multimedia PCs, laptop computers, scanners, projection TVs, widescreen TVs, broadcast satellite antennas, camcorders, digital cameras, fax machines, cordless telephones, and tapeless answering machines. Most of these products contained DSP chips, and signal processing thus provided a significant push to consumer electronics.

The advance of integrated circuit technology continued in the 1990s, as the density of components on chips continued to follow Moore's law, doubling every 18 months.[5] An important benchmark was the Pentium

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[3]The number of Web servers increased from about 10 in 1991 to 100,000 in 1994 [*Scientific American*, vol. 277 (1997), no. 6, p. 36]. The number of hosts attached to the Internet increased from fewer than 1 million in 1992 to almost 20 million in July 1997 [*IEEE Spectrum*, vol. 35 (1998), no. 1, p. 37].

[4]Gene Frantz and Panos Papamichalis, "Introduction to DSP solutions" (*Texas Instruments Technical Journal*, vol. 13 (1996), no. 2, pp. 5–16).

[5]The course of development of most new technologies describes an S curve when some measure of performance is graphed against time. There is, roughly speaking, exponential growth in the first half of this S curve, followed by a decreasing growth rate. What is remarkable for microelectronics—and perhaps without precedent in the history of technology—is the length of this period of exponential growth (measured in number of consecutive doublings of performance). The exponential growth in component density (Moore's law) has been, not surprisingly, reflected in exponential growth in many other aspects of the computing. For example, the software company Microsoft has doubled in size every two years, and judging by value of shares, Microsoft is worth more than the three large U.S. carmakers put together [*Economist* 31 January 1998, p. 65].

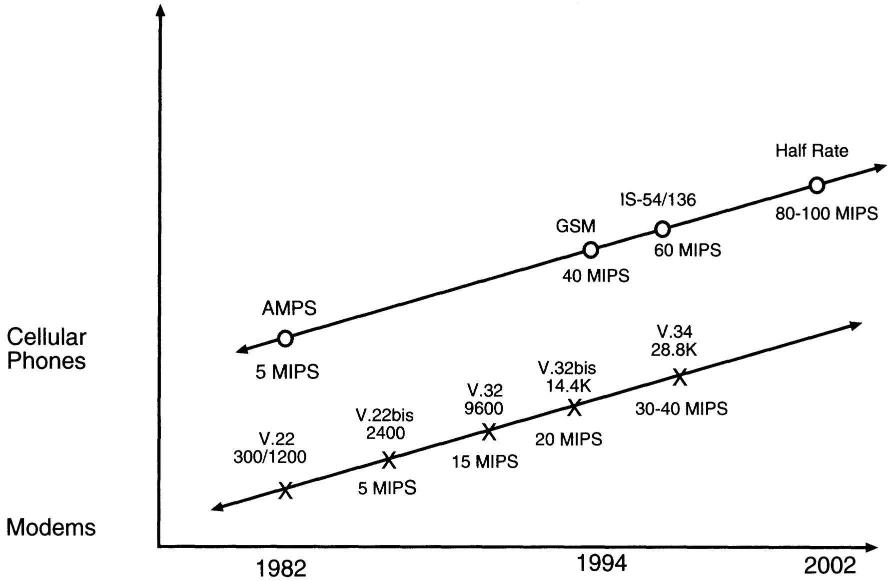


**FIGURE 1.** This graph shows the increase since 1982 in DSP speeds, measured in millions of instructions per second (MIPS), for two applications, cellular phones and modems. (Redrawn after Figure 11 of Gene Frantz and Panos Papamichalis, "Introduction to DSP solutions" (*Texas Instruments Technical Journal*, vol. 13 (1996), no. 2, pp. 5–16).)

chip, introduced in 1994, which contained five million transistors.[6] DSP chips, too, attained greater component density, and the Texas Instruments DSP chip TMS320C805, introduced the same year as the Pentium, also contained five million transistors. There were also reductions in IC power dissipation, and it became common to include analog functions on a DSP chip.[7]

Such advances, combined with mass production, brought down the cost of digital signal processing. In the 1990s it could be less than $1 per MIPS (millions of instructions per second), while in the 1960s the machines capable of digital signal processing cost perhaps $1000 per MIPS.[8] (See Figure 1.) This fact alone goes far in explaining the explosive growth of DSP applications. With IC technology, as with the consumer electronics

[6]Frantz and Papamichalis *op. cit.*

[7]Frantz and Papamichalis *op. cit.*

[8]Frantz and Papamichalis *op. cit.* According to James Kaiser [personal communication 12 February 1998] the cost per MIPS in the 1960s was considerably higher than $1000.

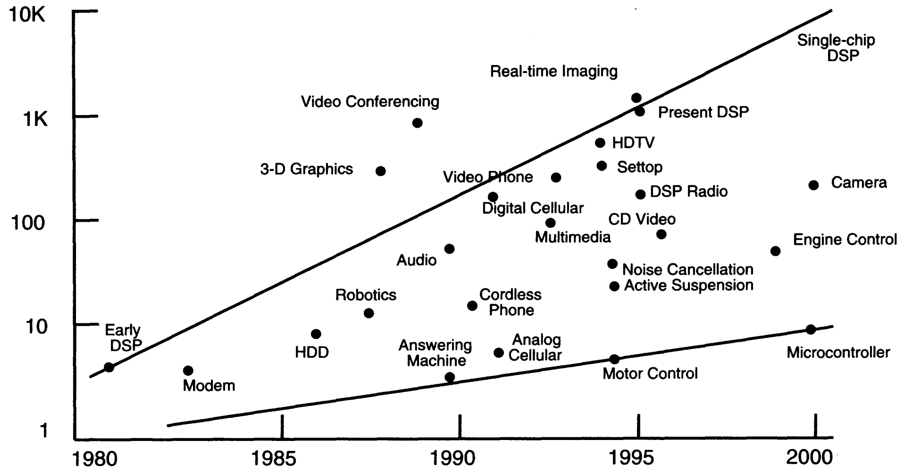


**FIGURE 2.** The chart shows the increase in speed (measured in millions of operations per second) for single-chip DSPs and microcontrollers respectively. New application areas are placed according to date and processing speed. (Redrawn after Figure 14 of Gene Frantz and Panos Papamichalis, "Introduction to DSP solutions" (*Texas Instruments Technical Journal*, vol. 13 (1996), no. 2, pp. 5–16).)

market, signal processing gave as well as received: DSP applications are today as important as the computer industry in driving the technology of high-speed, low-power integrated circuits.[9]

The lowered cost of calculation certainly opened new areas of application. So too did increased speed, especially with real-time signal processing. This resulted from faster ICs and, more importantly, better algorithms. Figure 2 relates DSP performance and new applications. The proliferation of applications led to a greater variety of DSP chips: in the late 1990s Motorola offered a compatible line of 16-, 24-, and 32-bit DSPs; Texas Instruments offered more than 150 DSPs, most notably those in its TMS320 family; and Analog Devices, IBM, Lucent, NEC, and many other manufacturers offered a great many more DSP chips.

Extremely important in the growth of DSP applications has been the availability of software support. Filter-design programs go back several decades, such as the Parks-McClellan program from the early 1970s, which has been perhaps the most widely used.[10] More recently, two classes of soft-

[9]Paul G. Flikkema, "Spread-spectrum techniques for wireless communications" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 3, pp. 26–36).

[10]Bede Liu personal communication 27 January 1998.

ware have been of great importance: code-generation tools and tools for system integration and debugging. The former allow a programmer to use a higher-level language. For example, the optimizing C-compiler produces assembly-language code that is nearly as efficient as the hand-assembled programs. The system integration and debugging tools, such as software simulators, hardware emulators, and system evaluation tools, have streamlined the development process.[11]

Among the many advances in communications in the 1990s were the rapid development of mobile communications, as cellular phones became commonplace. The transmission capacity of optical fiber continued to follow its own law of exponential increase: 10-fold every four years since 1975.[12] By 1990 virtually all of the 140 largest metropolitan areas in the United States were connected by optical fiber.[13] Videoconferencing did become easier, but is still not very much used.[14]

There was also a continuing movement toward the digitization of communications and information storage. Digital cellular phones and PCS (Personal Communication Services), also digital, became popular. Digital standard television was introduced. Image scanners became common. They allowed the digitization of documents of all sorts, especially those with graphs, charts, diagrams, and pictures, and they were made more useful by the use of software for optical character recognition.

Until the 1990s telephone answering machines incorporated an analog tape recorder. In the mid 1990s digital telephone answering devices (DTADs) began to claim a large share of the market. DTADs offer many advantages, such as message manipulation capability (skip, save, selective delete, and so on), increased reliability (not having the tape recording and reading mechanism), and the ability to add value-enhancing features (such as caller-ID, full-duplex speakerphone, and speech recognition) with small addition to the unit cost. DTADs are, needless to say, highly dependent upon DSP technology.[15]

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[11]Rose Marie Piedra and Andy Fritsch, "Digital signal processing comes of age" (*IEEE Spectrum*, vol. 33 (1996), no. 5, pp. 70–74).

[12]Emmanuel Desurvire, "Lightwave communications: the fifth generation" (*Scientific American*, vol. 266 (1992), no. 1, pp. 114–121).

[13]*Britannica Yearbook of Science and the Future 1990* (Chicago: Encyclopaedia Britannica, 1989), p. 323.

[14]W. Wayt Gibbs, "Taking computers to task" (*Scientific American*, vol. 277 (1997), no. 1, pp. 82–89).

[15]Tandhoni S. Rao, "DSP software technology for digital telephone answering devices" (*Texas Instruments Technical Journal*, vol. 13, no. 2 (March-April 1996), pp. 57–64).

**MAURICE BELLANGER:** Yes. One important aspect for the acceptance of more sophisticated, intelligent terminals and appliances is that they must be friendly, easy to manipulate. That's certainly one area where signal processing has a lot more potential. We need more flexible terminals, and in computer science we can see the agent technology being developed. I believe that the concept of agent might apply to signal processing as well. By agent, I mean an autonomous subset which can find its own way of operating and just report to the user. If we take again the mobile radio receiver, one can imagine a receiver which would help the user—it would select the best available channel, best modulation, do all that by itself, and just report its decisions to the user. Some kind of internal intelligence. Definitely the man-machine interface is really critical for the near future.[1]

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**MAURICE BELLANGER:** We feel indeed that in Europe we have always had some excellent laboratories, certainly at the same level. We had, for example, excellent background in mathematics and in the basics, which prepared the young people to develop these techniques. The advantage of being in the U.S. is certainly the availability of the technology, which undoubtedly came at that time from U.S. companies, particularly California companies. Another difference is that in Europe the students and engineers are not forced to publish. It's perfectly feasible to present a thesis without having published internationally. Local publication and local appreciation may be enough. There is also the language issue, so there are a number of reasons why the signal processing field might appear more developed in the U.S. than in Europe, but I don't think that's the case. We could draw a history of European contributions to signal processing quite easily.[2]

[1]Maurice Bellanger oral-history interview 22 April 1997, p. 26.

[2]Maurice Bellanger oral-history interview 22 April 1997, pp. 21–22.

There has been progress in speech recognition. An important text by Larry Rabiner and Biing-Hwang Juang, *Fundamentals of Speech Recognition* (1993), covered both theory and practical aspects.[16] Some systems now have error rates below five percent for most speakers.[17] Apple Computer of-

[16]Lawrence R. Rabiner and Biing-Hwang Juang, *Fundamentals of Speech Recognition* (Englewood Cliffs, NJ: Prentice-Hall, 1993).

[17]Steve Young, "A review of large-vocabulary continuous-speech recognition" (*IEEE Signal Processing Magazine*, vol. 13 (1996), no. 5, pp. 45–57).

fers software for voice dictation of Mandarin Chinese.[18] In 1992 AT&T introduced an automated operator service called VRCP (Voice Recognition Call Processing), which can handle call processing without operator assistance; VRCP currently handles more than a billion voice-recognitions per year.[19] MIT researchers have built a system (GALAXY) that can understand and answer spoken questions about weather, airline flights, and the city of Boston; the system, however, often makes mistakes. There is also a speech-recognition system that takes dictation from radiologists with 97 percent accuracy, yet a study found that radiologists completed their reports faster without the dictation system. Widespread use of speech recognition remains an elusive goal, as does the even more challenging goal of building reliable language-understanding systems.[20]

As we have seen in the preceding two chapters, digital means have gradually displaced analog means for recording, processing, transmission, and reproduction of audio. In the 1990s two new standards, MPEG1 and MPEG2 (discussed further below) made efficient coding of audio widely used, as they allowed CD-like quality with six-to-one or twelve-to-one compression ratios.[21] In the early and mid 1990s the film industry switched from analog to digital formats.[22] In the 1990s there has been much work on microphone arrays, especially for teleconferencing, such as self-steering arrays (that electronically aim at the person speaking at that moment) and adaptive beamforming (in which the beamforming program adjusts its parameters on the basis of received data). Also notable has been work on recording and reproducing a 3-dimensional sound-field,[23] and on DSP-assisted loudspeakers (which have built-in digital filters to correct for the shortcomings of speaker performance).[24]

Since the 1930s engineers have worked on active noise control (ANC), the intentional generation of sound to interfere destructively with unwanted sound. But it was not until the 1990s that signal processing tech-

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[18]Lin-Shan Lee, "Voice dictation of Mandarin Chinese" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 4, pp. 63–101).

[19]Lawrence Rabiner personal communication 30 January 1998.

[20]Gibbs *op. cit.*

[21]Marina Bosi, "Perceptual audio coding" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 5, pp. 43–49).

[22]Bosi *op. cit.*

[23]Gary Elko, "Electroacoustic transducers" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 5, pp. 31–36).

[24]Ken Kantor, "DSP in audio" (*Audio*, December 1996, pp. 27–32).

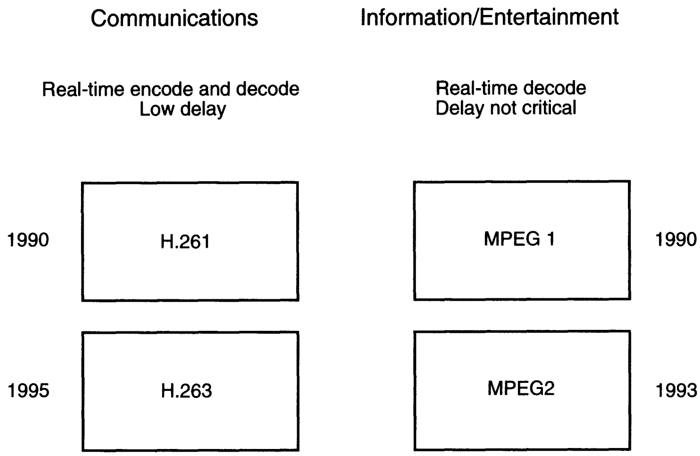


**FIGURE 3.** Four important standards for video compression. (Redrawn after Figure 2, with dates of adoption added, of Karen Oehler, Raj Talluri, Yuji Itoh, and Fritz Whittington, "Digital video compression" (*Texas Instruments Technical Journal*, vol. 13, no. 2 (March-April 1996), pp. 27–40).)

niques were advanced enough to build commercially viable systems. This work is related to, but distinct from, adaptive noise-cancellation, where the cancellation takes place in the electrical system, as with the echo-cancelers used in telephony. ANC systems have been commercialized for the control of propeller noise in aircraft and for the control of noise in ventilation ducts.[25]

In the 1990s image processing became an even more prominent branch of signal processing. Since video in uncompressed form requires great bandwidth, effective means of image compression are required for many transmission and storage technologies to be practical. Here, as with many other areas of DSP, international standards have been vital to rapid technological and commercial development. Figure 3 depicts the relationships among four important compression standards: H.261 and H.263 designed for real-time encoding and decoding with very low delay, as for videophone communication; and MPEG1 and MPEG2 for multimedia PC and television where some delay is acceptable.[26]

[25]Stephen J. Elliot, "Active noise control" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 5, pp. 36–39).

[26]Karen Oehler, Raj Talluri, Yuji Itoh, and Fritz Whittington, "Digital video compression" (*Texas Instruments Technical Journal*, vol. 13, no. 2 (March-April 1996), pp. 27–40).

**Thomas Huang:** In the good-old-days it was more fun, but now things have changed. We are more application-driven now, even if our main interest is still in basic research. At that time I was more romantic—I did things just for fun and didn't worry too much about the application.[1]

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**Thomas Huang:** First, there was differential PCM, next was transform coding, and then came fractal coding, a really novel idea in image coding. After transform coding, nothing really new happened in image coding, people just tried to improve it, at least until Barnsley's idea of fractal coding. Michael Barnsley was a mathematician at Georgia Tech, then he left to form his own company. The wavelet method is still a traditional signal processing approach, but it's not that different from transform coding. Fractal coding is completely new.

The idea is, you have an image and you try to find a mathematical function—a system—for which this image is an attractor, what in mathematics they call a fixed point. You have a system for the input. If you can find an input which, when fed into the system, looks exactly the same when it is output, then this input is called a fixed-point of the system.

... The interesting thing is that for most systems, if the input is not a fixed point, and you repeatedly feed its output back into the system, it will approach a fixed point. With any real, positive number, if you take the square root, and the square root of that, again and again, it will approach one. So, the idea of fractal coding is to take an image and find a system for which this image becomes a fixed point. The description of the system is your compressed data. Once you have this system, you can take any image, feed it in iteratively, and eventually you will get the original image back. You try to make this system simple, like linear transformation. Fractal coding is a completely radical idea.[2]

[1]Thomas S. Huang oral-history interview 20 March 1997, p. 4.

[2]Thomas S. Huang oral-history interview 20 March 1997, pp. 15–16.

As a standard for videophones the International Telecommunications Union developed H.261; approved in 1990, it was intended for use on ISDN lines at 64 kbps or a multiple of that rate. (See Figure 4.) For lower bit-rates, H.263 was defined in 1995. The Moving Pictures Expert Group (MPEG) reached agreement in 1990 on a standard for CD video and audio, known as MPEG1, then went on to define a more general syntax that could be used for broadcast video. MPEG2, adopted in 1993, can apply to digital standard television, digital high-definition television, and the DVD (digital

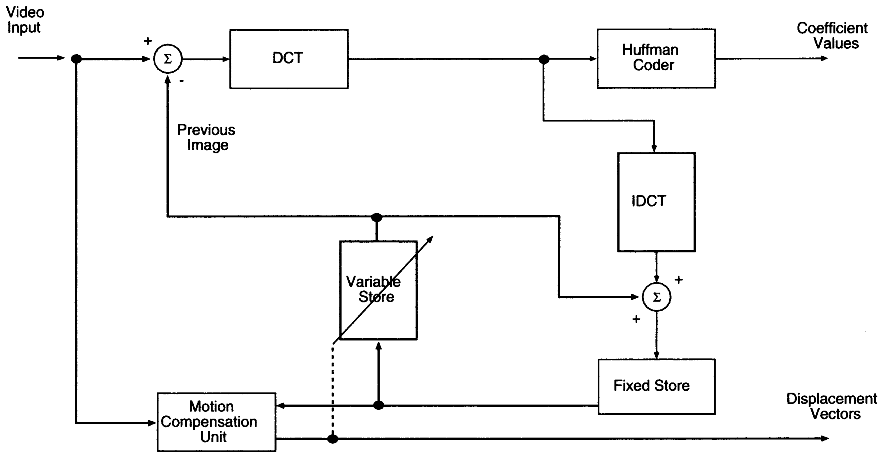


**FIGURE 4.** The encoding scheme of H.261 is shown. (Redrawn after Figure 6.35 of Craig Marven and Gillian Ewers, *A Simple Approach to Digital Signal Processing* (New York: John Wiley & Sons, 1996).)

versatile disk).[27] MPEG4, still under development, will apply to video coding at low bit-rates, such as are typical for Internet connections.[28]

MPEG2 has been a great achievement from several points of view. At its meetings, which began in 1990, hundreds of experts from around the world contributed their knowledge and opinions. It became a very broad standard: it includes MPEG1 as a subset, and its original goal of defining coding for standard digital television expanded to include HDTV, thus obviating the planned MPEG3. The standard was reached swiftly, as MPEG was meant to be an anticipatory standard. And it has been of enormous commercial importance: it has been adopted for direct-broadcast and cable television, and it is the core of the so-called Grand Alliance standard for HDTV. The driving force behind MPEG has been Leonardo Chiariglione of the Centro Studi e Laboratori Telecomunicazioni SpA (CSELT) in Turin, Italy. In 1996 the U.S. broadcasting industry awarded MPEG, along with JPEG, an Emmy.[29]

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[27]Oehler *et al. op. cit.*

[28]William Sweet, "Chiariglione and the birth of MPEG" (*IEEE Spectrum*, vol. 34 (1997), no. 9, pp. 70–77).

[29]Sweet *op. cit.*

**Thomas Huang:** I guess one way of looking at this is to look at the different goals: compression, enhancement, restoration, and analysis. In compression, the milestones are fairly clear: differential PCM, transform coding, then wavelets, fractals and now perhaps model-based compression. In the enhancement area, a major milestone of image reconstruction that we have completely ignored in this discussion is computer tomography. That's really one of the major achievements in image enhancement and reconstruction.

... More recently of course we have magnetic resonance imaging. For analysis, the milestones are harder to say, there are so many different facets. Object recognition in images has been going on for a long time, but it's hard to pinpoint milestones. Object recognition is maybe too vague—we have to be more specific. I would think OCR, fingerprints, and more recently, many people are getting into face recognition.[1]

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**Thomas Huang:** The Fourier Transform spreads things all over. If you have a small object in the image, its Fourier transform is spread over the whole frequency domain. So, it has advantages and disadvantages. If you want to search for the object, you cannot do it in frequency domain because it's spread all over. Also, if you make mistakes or have errors in the frequency domain, they are spread all over the image. On the other hand, the wavelet transform is concentrated in both frequency and in the spatial domain. The transform domain has several different layers with different frequencies in the components. In each layer, the original object remains concentrated, not spread out.

One application for image representation is in retrieval. You want to retrieve images, but in the meantime you want to represent the image in your database in an efficient way. So, you want to compress, but still be able to retrieve different objects. If you use the Fourier Transform you have to decompress before you can search for your object, but if you're in the wavelet representation, you can search for objects directly (although this is not completely done yet).[2]

[1]Thomas S. Huang oral-history interview 20 March 1997, pp. 28–29.

[2]Thomas S. Huang oral-history interview 20 March 1997, pp. 11–12.

The 1990s have been years of rapid change for television. On 3 June 1989 Japan initiated broadcasting of HDTV programs; although the source signal is defined in a digital format, the transmission is analog. It now appears that Japan, like the rest of the world, will adopt fully digital HDTV.[30]

[30]*Britannica Yearbook of Science and the Future 1991* (Chicago: Encyclopaedia Britannica, 1990), p. 231, and Hiroshi Watanabe and Hiroshi Yasuda, "Obtaining higher resolution in Asia" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 4, pp. 52–62).

Digital satellite systems, broadcasting television directly to homes, have rapidly become a large business; in 1996 more than three million direct-to-home systems were sold in the United States.[31] Digital cable television began to be available in some areas. In the United States since 1993 new television sets with 13-inch or larger screens have contained captioning decoders.[32] And though 4-channel sound had failed to gain consumer acceptance when it was introduced under the name 'quadraphonic sound' in 1969, multichannel audio did succeed in the 1990s in the form of "surround sound" or "home-theater" systems.[33]

Another area of application of DSP has been digital photography. By 1997 almost every major camera manufacturer was offering digital cameras, which allow editing and enhancement of images in the cameras themselves and easy transfer of images to business and home computers.[34] Techniques of digital image enhancement include contrast enhancement, edge sharpening, pseudo-color enhancement (because the human eye discriminates many more colors than it does shades of gray), and removal of the effects of degrading phenomena (such as lens aberration), and such techniques have been of great importance in science, being used by archeologists, astronomers, ecologists, geologists, meteorologists, oceanographers, and others. Work on multispectral image compression has been important for satellite sensing systems, since such systems are constrained by downlink communications bandwidth.[35]

The 1990s have seen the widespread application of signal processing in medical imaging, such as x-ray computed tomography, positron-emission tomography, electrical impedance tomography, optical imaging, cardiac

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[31] *U.S. Consumer Electronics Industry Today* (Arlington, VA: Consumer Electronics Manufacturers Association, 1997), p. 27.

[32] *U.S. Consumer Electronics Industry Today op. cit.*, p. 21.

[33] *The U.S. Consumer Electronics Industry in Review: 94 Edition* (Washington, DC: Electronic Industries Association, 1994), pp. 19–20. Dolby Pro Logic is a 4–channel system: a center channel, left and right front-channels, and a rear-channel (usually conveyed to two speakers, one to the left and one to the right, at the rear of the room).

[34] *U.S. Consumer Electronics Industry Today op. cit.*, p. 59. There are also many companies manufacturing digital cameras that did not make film-based cameras. Digital cameras have been used for some years in the news gathering business; what is new is their widespread marketing.

[35] Val D. Vaughn and Timothy S. Wilkinson, "Systems considerations for multispectral image compression designs" (*IEEE Signal Processing Magazine*, vol. 12 (1995), no. 1, pp. 19–31).

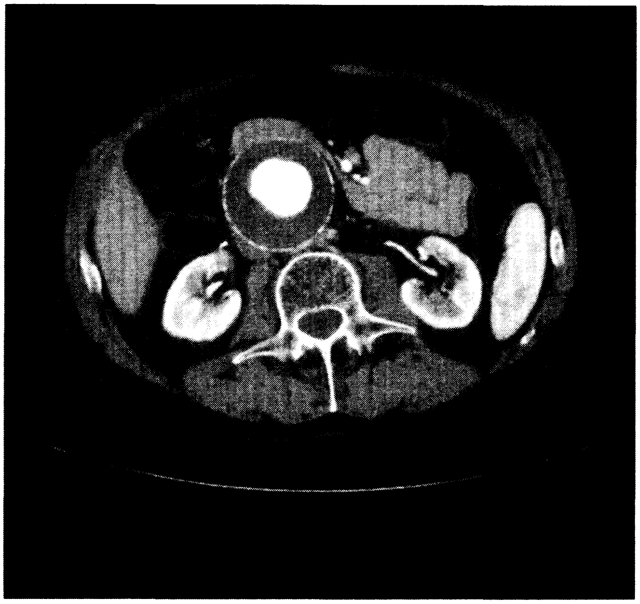

**FIGURE 5.** This example of computed tomography is an abdominal section produced by CT fan-beam reconstruction. (Reproduced by permission from *IEEE Signal Processing Magazine*, March 1997, p. 56.)

electrical imaging, magnetic resonance imaging, ultrasound imaging.[36] (See Figure 5.) Image restoration techniques were important in processing images from the Hubble Space Telescope.

Signal processing has contributed to a variety of techniques for extracting information from signals. In swept frequency acoustic interferometry, for example, an acoustic signal is used to look inside metal objects, such as artillery shells.[37] Building on earlier work, Didier Massonnet and his colleagues at the French space agency (CNES) have shown that ground motions of a few millimeters may be detected by the interference fringes created when two images, taken from the same position at different times, are superimposed. This technique, called satellite radar interferometry, has already proven valuable in mapping geologic faults and volcanic mountains.[38]

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[36]See, for example, four articles in the January 1997 issue of *IEEE Signal Processing Magazine* on, respectively, electrical imaging of the heart, positron-emission tomography, magnetic resonance imaging, and ultrasound imaging.

[37]*Scientific American*, vol. 277 (1997), no. 6, p. 42.

[38]Didier Massonnet, "Satellite radar interferometry" (*Scientific American*, vol. 276 (1997), no. 2, pp. 46–53).

**THOMAS KAILATH:** Here is an example of signal processing in our semiconductor work. We heat a wafer to 1,000 degrees very fast in a chamber with hot halogen lamps. How do you measure the temperature? You can't touch the wafer with a probe, because it pollutes the wafer. You've got to be indirect. So what you say is there's radiation coming off the wafer. If you can count the number of photons, then that's related to the temperature by Planck's law, which says how many photons are emitted at a given temperature. However, the number of photons is random, so you get a count that's random. You're interested in something else, which is the temperature of that wafer as it changes in form. You've got to infer knowledge about one signal, which is not observable, from another signal, which is observable. Both of these are random (in the latter case, because of the errors in measurement), but there's some dependence between them, some statistical dependence. That's signal processing in its fundamental or generic form. It's extracting information from signals for other purposes.[1]

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**INTERVIEWER:** Can you tell us about particularly important advances in the last ten years or so?

**JAMES KAISER:** Two words. Chaos theory, and wavelets. There are a lot of books out on wavelets now, 30 or 40 at least. Wavelets is a wonderful technique, but it's an analytic technique. It's a very efficient way to represent quite a broad range of signals, but it hasn't to my knowledge increased our physical understanding of those signals. It's another tool, but the danger is expecting that tool to increase your physical understanding of what's going on.[2]

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**JAMES KAISER:** I also want to stress again this is an engineering agenda versus science agenda issue. It has become so easy to do so much computation using computers that people will press keys on the keyboard without thinking what they are doing. I think that there has got to be a resurgence of work on the scientific end of things. It's so easy to generate a tremendous amount of garbage that you've got to understand what it is you're doing. So it is very important that we get back to basic understanding, get a much better grounding of what science underlies the phenomenon we are looking at. We have got to be able to do that. I mean, this world is not an ideal world. It's time-varying and nonlinear. That's the first message.

The next message is that the young people—or anybody, really—who are using these tools have got to thoroughly understand what assumptions underlie the tool that they are using. That will tell them what they can expect to get out. You want to know what the guts of the filter are so you can know what you have filtered out and what will pass through that filter. You've got to know that—issues such as quantization, and, even more so, linearity versus nonlinearity.[3]

[1]Thomas Kailath oral-history interview 13 March 1997, p. 22.

[2]James Kaiser oral-history interview 11 February 1997, pp. 57–58.

[3]James Kaiser oral-history interview 11 February 1997, p. 54.

The field of signal processing has continued to make heavy use of computers, and in the 1990s it became common for computers to assist with analytical, as well as numerical problems, through symbolic processing and object-oriented programming.[39] In the 1990s the debt was more than repaid in the way DSP enhanced the performance of personal computers and workstations. Indeed, Leonardo Chiariglione has argued that the signal processing field and the data processing field are converging, as programmable signal-processors have become common and as computers use complex signal processing for input, output, and storage.[40]

For example, in the 1990s DSP chips became a standard part of hard-disk drives and CD-ROM drives, being used to control the disk and the reading head.[41] At first it took a dozen DSP chips to run a disk drive. The number was reduced by half in the late 1990s, and manufacturers now aim at being able to run a disk drive with a single chip.

This is one of many instances of the use of DSP in control systems. Much more prominent have been the enhancements to computer interfaces, notably in the multimedia computers of the 1990s, where DSP chips handle audio and visual information quickly, taking over this task from the main microprocessor.[42] People have begun using voice-recognition software for computer control. And signal processing has played a central part in the growth of the Internet and the World Wide Web, as high-speed modems and data-compression techniques vastly expand the possibilities of interconnected computers.

In the 1990s there has been increased interest in neural networks for signal processing. As it has proved very difficult for a program to detect eyes, noses, and mouths accurately, Takeo Kanade and colleagues at Carnegie Mellon University have trained a neural network program (using a large collection of face and nonface images) to recognize these features together in an appropriate configuration, that is, to recognize faces.[43] The ca-

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[39]Benjamin Monderer, "Computer aided signal processing tools for research" (*IEEE ASSP Magazine*, vol. 7 (1990), no. 2, p. 4.

[40]Leonardo Chiariglione, "Signal processing and standardization (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 4, pp. 33–34).

[41]Frantz and Papamichalis *op. cit.*

[42]William Gates, "Personal computers in the Information Age", in *Britannica Yearbook of Science and the Future 1992* (Chicago: Encyclopaedia Britannica, 1991), pp. 144–153.

[43]David Forsythe, Jitendra Malik, and Robert Wilensky, "Searching for digital pictures" (*Scientific American*, vol. 276 (1997), no. 6, pp. 88–93).

**Charles Rader:** Back somewhere before the '80s, I was thinking in the terms of leaving the laboratory and becoming a professor somewhere, and when you do that, they like you to give a talk. I put together a talk on the field of digital signal processing. And I was able to put on one sheet of paper a set of topics and connect them all together with lines, showing what had led to what and what was related to what. I don't think anybody can do that anymore. First of all, if you tried to put it all on one piece of paper, no matter how big, there would be so many lines crossing one another that you couldn't follow it.[1]

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**Enders Robinson:** Much of the signal processing today is geared towards image processing. People don't want to see just text, they want to see a picture. It might be cosmetic because you're essentially using the old signal processing algorithms but in much greater detail. But in some ways anything that gives you a better picture is not cosmetic. It's sort of like when the magnifying glass or the microscope or the telescope came in. You could see the moon before, but when Galileo saw it it was a different moon. And that's sort of what's going on today. You could see pictures of the underground, but now you can see them almost like looking through a telescope. So it's a different ball game.[2]

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**Hans Schuessler:** Well, for me the theoretical core was and still is the essential point. As an engineer, I am lucky that all of this can be applied. And the influence is to be seen not only in industrial regions, but for the public as well. The first application was a compact disc for music. It was done already 15 years ago, somewhat more. As an engineer I am glad about that. But the main reason for me to be interested and to still work on signal processing is just the intellectual core in it.[3]

[1]Charles Rader oral-history interview 27 February 1997, pp. 48–49.

[2]Enders Robinson oral-history interview 6 March 1997, p. 64.

[3]Hans Wilhelm Schuessler oral-history interview 21 April 1997, pp. 34–35.

pability of training by example, so that a neural network can recognize an object not readily definable or identify an unknown function based on a set of training data, is valuable in many contexts.[44]

[44]Neural Networks for Signal Processing Committee, "The past, present, and future of neural networks for signal processing" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 6, pp. 28–48).

Neural networks have proved useful for interference rejection in wireless communications.[45] Neural networks for aircraft control and for automobile-engine control are being developed.[46] Simon Haykin has demonstrated several ways neural networks can improve the processing of radar images.[47] Neural network techniques have helped in image restoration and, because of their highly parallel nature, led to efficient VLSI architectures for image restoration.[48] The VLSI implementation of neural networks is exemplified also by the work of Carver Mead and others in building models of biological signal-processors, such as the retina and the cochlea; a silicon retina built by Misha Mahowald and Carver Mead displayed behavior quite similar to that of the human retina, including susceptibility to certain optical illusions.[49]

Among the most exciting developments of the past decade have been the application by SP engineers of the concepts of fractals, chaos, and wavelets. Fractals are objects in geometry that have non-integral dimension. Fractal coding has been extensively applied in image compression.[50] (See Figure 6.)

In physics, a chaotic system is a mathematically defined system that evolves in a seemingly random way, neither approaching a steady state nor cycling through a sequence of states.[51] First recognized in meteorology in the 1960s,[52] chaotic systems have since been discerned in astronomy, biol-

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[45]Jeff D. Laster and Jeffrey H. Reed, "Interference rejection in digital wireless communications" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 3, pp. 37–62).

[46]Neural Networks for Signal Processing Committee *op. cit.*

[47]Simon Haykin, "Neural networks expand SP's horizons" (*IEEE Signal Processing Magazine*, vol. 13 (1996), no. 2, pp. 24–49).

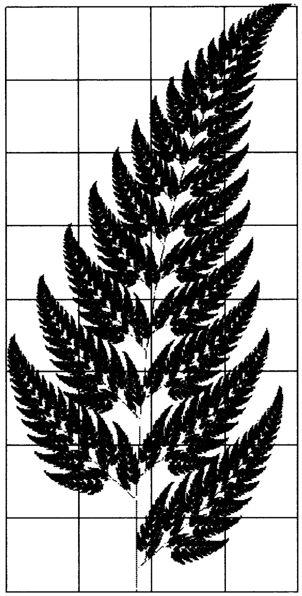
[48]Mark R. Banham and Aggelos K. Katsaggelos, "Digital image restoration" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 2, pp. 24–41).

[49]Misha Mahowald and Carver Mead, "The silicon retina" (*Scientific American*, vol. 264 (1991), no. 5, pp. 76–82).

[50]See, for example, Arnaud E. Jacquin, "Image coding based on a fractal theory of iterated contractive image transformations" (*IEEE Transactions on Image Processing*, vol. 1 (1992), pp. 18–30), and Tim Bedford, F. Michel Dekking, Marcel Breeuwer, Michael S. Keane, and Daan van Schooneveld, "Fractal coding of monochrome images" (*Signal Processing: Image Communication*, vol. 6 (1994), pp. 405–419).

[51]Fractals and chaos are related. The behavior of a dynamical system may be described by a trajectory in state space, and that trajectory delimits a mathematical form called an attractor. A system is chaotic exactly when its attractor is a fractal, in which case it is called a "strange attractor".

[52]Frederik Nebeker, *Calculating the Weather: Meteorology in the 20th Century* (New York: Academic Press, 1995), pp. 188–194.



$r = 128$, $N = 27$

**FIGURE 6.** A fractal that has found application in signal processing is Barnsley's fern.

ogy, chemistry, and other sciences. Recently, chaotic models have been employed in signal processing. For example, Simon Haykin modeled sea clutter (that is, the radar backscattering from an ocean surface) as a chaotic process in order to build a neural network for use in canceling sea clutter.[53]

Wavelets are a mathematical decomposition technique, which may be viewed as an extension of Fourier analysis. The theory underwent considerable development in the mid 1980s, and it was soon applied to digital signal processing by Ingrid Daubechies and Stefan Mallat.[54] Besides stimulating some new approaches to signal processing, wavelet theory provides a unified framework for techniques already developed for particular SP applica-

[53]Simon Haykin *op. cit.*

[54]Ingrid Daubechies, "Orthonormal bases of compactly supported wavelets" (*Communications in Pure and Applied Mathematics*, vol. 41 (1988), pp. 909–996), Stefan Mallat, "A theory for multiresolution signal decomposition: the wavelet representation" (*IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 11 (1989), pp. 674–693), and Stefan Mallat, "Multifrequency channel decomposition of images and wavelet models" (*IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 37 (1989), pp. 2091–2110).

tions.[55] Among the areas where wavelets have been successfully applied are image processing, speech processing, data compression, subband coding, multiresolution analysis, and wideband correlation processing.[56]

There have been other new departures for signal processing in the 1990s. One example is work, which has led to commercial application, on so-called fuzzy algorithms, which use fuzzy logic. This type of logic, invented by Lotfi Zadeh in the 1960s, is based on the concept of a fuzzy set, for which membership is expressed in varying degrees.[57] Another example is work on so-called genetic algorithms, which use a searching process modeled on the laws of genetics and natural selection. Genetic algorithms have been applied as an optimization tool in many areas of signal processing.[58] The widespread use of object-oriented programming for DSP might also be mentioned.[59]

One sign of the fecundity of signal processing is its growth into other areas of engineering, such as control systems, imaging systems, and instrumentation. Indeed, the wide applicability of its concepts and techniques is eroding boundaries between disciplines.[60] Information theory, coding theory, communication theory, and neural network theory are all closely related to signal processing theory.

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[55]Olivier Rioul and Martin Vetterli, "Wavelets and signal processing" (*IEEE Signal Processing Magazine*, vol. 8 (1991), no. 4, pp. 14–38).

[56]Lora G. Weiss, "Wavelets and wideband correlation processing" (*IEEE Signal Processing Magazine*, vol. 11 (1994), no. 1, pp. 13–32).

[57]Craig Marven and Gillian Ewers, *A Simple Approach to Digital Signal Processing* (New York: John Wiley & Sons, 1996), p. 7.

[58]Kit S. Tang, Kim F. Man, Sam T. Kwong, and Q. He, "Genetic algorithms and their applications" (*IEEE Signal Processing Magazine*, vol. 13 (1996), no. 6, pp. 22–37). In 1996 the IEEE established a journal, *IEEE Transactions on Evolutionary Computation*, in this area.

[59]Matti Karjalainen, "DSP software integration by object-oriented programming: a case study of QuickSig" (*IEEE Signal Processing Magazine*, vol. 7 (1990), no. 2, pp. 21–31).

[60]See, for example, Arogyaswami Paulraj, Vwani Roychowdhury, and Charles D. Schaper, eds., *Communications, Computation, Control and Signal Processing: A Tribute to Thomas Kailath* (Boston: Kluwer Academic Publishers, 1997). One example is the use of the minimax formulation introduced in control theory a decade ago, which has recently been used to show the optimality of the widely used—but generally regarded as suboptimal—least-mean-squares adaptive filtering algorithm of Widrow and Hoff [Babak Hassibi, Ali H. Sayed, and Thomas Kailath, "H-infinity optimality of the LMS algorithm" (*IEEE Transactions on Signal Processing*, vol. 44 (1996), pp. 267–280)]. Another example is the use of a stochastic Kalman filtering formulation to unify the rapidly growing field of deterministic adaptive filtering; see Ali H. Sayed and Thomas Kailath, "A state-space approach to adaptive RLS filtering" (*IEEE Signal Processing Magazine*, vol. 13 (1996), no. 1, pp. 18–60).

Another sign of the vitality of signal processing is the recent proliferation of acronyms. Authors of signal-processing texts have felt the need to provide a listing of acronyms, as have even article-writers on occasion. (See Figure 7.) There are even second-order acronyms, such as FAM for "FFT Accumulation Method" or AAL for "ATM Adaptation Layer" (ATM being Asynchronous Transfer Mode). (Acronyms are a 20th-century phenomenon, called forth by the multiplication of human agencies, either social, as the many commissions and boards of Franklin Roosevelt's New Deal, or technological, as devices or procedures.)[61]

On 1 January 1990 the Acoustics, Speech, and Signal Processing Society officially changed its name to the Signal Processing Society.[62] Its growth continued, in number of members, in publication, and in activities. Its main publication, *Transactions*, split into three: *Transactions on Signal Processing*, *Transactions on Image Processing*, and *Transactions on Speech and Audio Processing*. This resulted in an increase in the number of pages published and a reduction in the backlog of articles awaiting publication.[63] The Society acquired a full-time professional staff, and Mercy Kowalczyk was hired as Executive Officer. The Society became increasingly international, with many more members and many more conferences and workshops in Europe and Asia.

In the 1990s the Society has undertaken many new ventures. A second major international conference series, the International Conference on Image Processing (ICIP), began in 1994. That same year the Society initiated *Signal Processing Letters* for fast publication of important results. A new

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[61]The New Deal brought acronyms to the public attention—the NRA (National Recovery Administration), the CCC (Civilian Conservation Corps), the TVA (Tennessee Valley Authority), the REA (Rural Electrification Administration), the WPA (Works Progress Administration), and many others—and was called the alphabet-soup government. It is worth noting that scientists handled the plenitude of the biological and geological worlds with names of the traditional sort. One might argue that, unlike naturally occurring objects and materials, instrumentalities invented by humans are quite unlimited in number, hence the need for acronyms to avoid inconveniently long names.

[62]Image processing had become a large field within the Society—and it was still growing rapidly—but adding 'image processing' to an already long name did not seem wise. So the Society decided to simplify the name, using 'signal processing' as an all-inclusive term. [David Munson personal communication 5 February 1988.]

[63]Tariq Durrani, "President's message" (*IEEE Signal Processing Magazine*, vol. 11 (1994), no. 4, pp. 8–10). Initially, circulation declined because previously *Transactions* had come automatically with Society membership; with the splitting of the journal, subscription to the different *Transactions* became optional.

**Table 1. Abbreviations Used Throughout This Article**

| | |
|---|---|
| A/D | Analog-to-Digital |
| ACI | Adjacent-Channel Interference |
| ADC | Analog-to-Digital Converter |
| ADF | Adaptive Digital Filter |
| AEQ | Adaptive Linear Equalizer |
| AGC | Automatic gain control |
| AIC | Adaptive Interference Canceler |
| ALE | Adaptive Line Enhancer |
| AM | Amplitude Modulation |
| AMPS | Advanced Mobile Phone System |
| ANC | Adaptive Nonlinear Converter |
| ANLE | Adaptive Nonlinear Equalizer |
| AR | Autoregressive |
| ATF | Adaptive Time-Frequency |
| AWGN | Additive White Gaussian Noise |
| B-CDMA | Broadband CDMA |
| BER | Bit Error Rate |
| BPF | Bandpass Filter |
| CCI | Co-Channel Interference |
| CDMA | Code Division Multiple Access |
| CMA | Constant Modulus Algorithm |
| CNNDFF | Complex Neural-Network-Based Adapive DF Filter |
| COF | Code-Orthogonalizing Filter |
| CPM | Continuous Phase Modulation |
| CW | Continuous Wave |
| DEDS | Discrete Event Dynamic System |
| DF | Decision Feedback |
| DFE | Decision Feedback Equalizer |
| DPSK | Differential Phase-Shift Keying |
| DS | Direct Sequence |
| DSSS | DS Spread Spectrum |
| FDM | Frequency-Division Multiplexing |
| FDMA | Frequency-Division Multiple Access |
| FER | Frame Error Rate |
| FFH | Fast Frequency Hopping |
| FH | Frequency Hopping |
| FIMM | Fast Interacting Multiple Model |
| FIR | Finite Impulse Response |
| FLA | Fast Learning Algorithm |
| FM | Frequency Modulation |
| FRESH | FREquency SHift |
| FSBLP | Fractionally Spaced Bilinear Perceptron |
| FSDFMLP | Fractionally Spaced DF Multilayer Perceptron |
| FSE | Fractionally-Spaced Equalizer |
| FSRPP | Fractionally Spaced Recursive Polynomial Perceptron |
| FSK | Frequency Shift Keying |
| GFC | Gradient-Search Fast Converging |
| GLRT | Generalized Likelihood-Ratio Test |
| GMSK | Gaussian Minimum Shift Keying |
| GPS | Global Positioning System |
| HDTV | High-Definition Television |
| HOS | Higher-Order Statistics |
| ICE | Interference-Canceling Equalizer |
| IMM | Interacting Multiple Model |
| IPA | Infinitesimal Perturbation Analysis |
| IS-54 | Intermediate Standard - 54 |
| ISI | Intersymbol Interference |
| J/S | Jammer-to-Signal Ratio |
| LCCM | Linearly Constrained Constant Modulus |
| LEO | Low-Earth Orbiting |
| LFSE | Linear Fractionally Spaced Equalizer |
| LMS | Least-Mean-Square |
| LO | Locally Optimal |
| LPP | Lattice Polynomial Perceptron |
| LPF | Lowpass Filter |
| LS | Least Squares |
| LTE | Linear Transversal Equalizer |
| MA | Multiple Access |
| MAI | Multiple Access Interference |
| MF | Misadjustment Filter |
| ML | Maximum Likelihood |
| MLSE | Maximum Likelihood Sequence Estimation |
| MMSE | Minimum Mean Squared Error |
| M-QAM | Multilevel QAM |
| NBI | Narrowband Interference |
| NED | Normalized Envelope Detection |
| NTSC | National Television System Committee |
| OS | Order Statistics |
| OTDR | Optimal Time-Dependent Receiver |
| PCS | Personal Communications Systems |
| PSK | Phase Shift Keying |
| PN | Pseudo-Noise |
| PP | Polynomial Perceptron |
| QAM | Quadrature AM |
| QPRS | Quadrature Partial Response Signaling |
| QPSK | Quadrature PSK |
| RBF | Radial Basis Function |
| RLS | Recursive Least Squares |
| SDR | Symmetric Dimension Reduction |
| SIR | Signal-to-Interference Ratio |
| SINR | Signal-to-Interference Noise Ratio |
| SNR | Signal-to-Noise Ratio |
| SOI | Signal-of-Interest |
| SNOI | Signal-Not-of-Interest |
| SOM | Self-Organizing Feature Map |
| SPREIS | Spectral Redundancy Exploiting Interference Suppressor |
| SSMA | Spread Spectrum Multiple Access |
| SSMF | Spread Spectrum Matched Filter |
| SS | Spread Spectrum |
| TDAF | Time-Dependent Adaptive FilterTDL Tapped-Delay Line |
| TDMA | Time-Division Multiple Access |
| TFD | Time-Frequency Distributions |
| THE | Threshold Excision |
| VSIE | Vector-Space Interference Excision |
| WF | Wiener Filter |
| WHT | Walsh-Hadamard Transform |

**FIGURE 7.** Jeff D. Laster and Jeffrey H. Reed provided this listing of acronyms for their article on "Interference rejection in digital wireless communications".[64] It may be regarded as an example of discipline-specific speech coding.

[64] Laster and Reed *op. cit.*

technical committee, on Multimedia Signal Processing, was established in 1996. And the Society has embarked on electronic publication, both online and on CD-ROM.

Ours is an information age. Much of the economy and a large part of an individual's experience depend upon electronically-mediated information flows. Even more broadly, the rapid pace and global scope of all of modern life—economy, politics, entertainment, science—depend on electronic communications. And virtually all of these information flows involve the work of signal-processing engineers. What's more, no longer is signal processing an obscure technical specialty. In the 1990s, Stephen Hawking (a physicist who, because of a neuromotor disease, is able to talk only through a voice synthesizer) and tapeless answering machines call attention to speech synthesis. Advertisers tout the number of pixels in images from digital cameras. People using the Internet discuss modem rates and data compression. And widely available computer software allows anyone to manipulate music or enhance images. In short, after 50 years of development, signal processing has taken on a large and prominent role in modern life.