mobile communications series

SOFTWARE-DEFINED RADIO for ENGINEERS

TRAVIS F. COLLINS
ROBIN GETZ
DI PU
ALEXANDER M. WYGLINSKI

Software-Defined Radio for Engineers

For a listing of recent titles in the *Artech House Mobile Communications*, turn to the back of this book.

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Dedication

To my wife Lauren
—Travis Collins

To my wonderful children, Matthew, Lauren, and Isaac, and my patient wife, Michelle—sorry I have been hiding in the basement working on this book. To all my fantastic colleagues at Analog Devices: Dave, Michael, Lars-Peter, Andrei, Mihai, Travis, Wyatt and many more, without whom Pluto SDR and IIO would not exist.
—Robin Getz

To my lovely son Aidi, my husband Di, and my parents Lingzhen and Xuexun
—Di Pu

To my wife Jen
—Alexander Wyglinski

Contents

APPENDIX A

A Longer History of Communications

A.1 History Overview

This section is included not to encourage mindless memorization of names or dates, or to overwhelm the reader, but to help understand how communications systems have changed, how adoption of new concepts can be lengthy, and how the technology we use every day in our modern communications infrastructure came to be. Some may wonder if this section is necessary at all; however, as Carl Sagan famously said, "If you wish to make an apple pie from scratch, you must first invent the universe" [1]. The more the history of communications is understood, the more of a modern marvel the current communications are. It was only 260 short years ago that an an anonymous letter in a magazine was published theorizing instantaneous communication by routing 26 wires (one for each letter of the alphabet; coding schemes were not commonplace), sending static electric pulses down the wire, and watching pith balls move at the other end (Volta had not developed the battery yet). This was an early trigger for the multicentury communications revolution.

It goes without saying that communications systems are limited to the transmission media that are available at the time. Aboriginal Australians in the Western Desert, indigenous peoples of North America, ancient Chinese soldiers stationed along the Great Wall, and the ancient Greeks all devised complex systems of how to transmit messages based on fire or smoke signals. Polybius, a Greek historian, developed a an early coding system of alphabetical smoke signals around 150 BCE that converted Greek alphabetic characters into numeric characters [2]. Each of these approaches possesses the same sort of engineering trade-offs that modern communication systems struggle with today, including *transmission distance* and *data rate*.

Some of these communication schemes are still used today; for example the semaphores shown in Figure A.1 that are used when stealth outside of the line of sight is required (flags don't emit RF, which could give away location).

It wasn't until the early 1990s when everything was beginning to come together. It was the unique combination of RF capability, software, algorithms, and computer hardware that are necessary to actually implement things. In fact it was only in 1993 that the term software-defined radio was mentioned.

This brief history will ignore the improvements of Johannes Gutenberg's movable type printing press, developed in around 1440, which spawned an entire printing and publishing economy. By 1700, the number of various books and scholarly journals published in Europe was an estimated 150 to 200 million copies [3]. This ability to share ideas and concepts with contemporary scientists,

Figure A.1 Persian Gulf (Novmber 29, 2005) Quartermaster Seaman Ryan Ruona signals with semaphore flags during a replenishment at sea aboard the Nimitz-class aircraft carrier USS Theodore Roosevelt (CVN 71). Roosevelt and embarked Carrier Air Wing Eight (CVW-8) are currently underway on a regularly scheduled deployment conducting maritime security operations. (U.S. Navy photo by Photographer's Mate Airman Javier Capella (RELEASED).)

inventors, and engineers of the day and of future helped to usher in the continuing scientific revolution.

People like Leonardo da Vinci are not noted in this list. While he made substantial discoveries in anatomy, civil engineering, geology, optics, and hydrodynamics, he did not publish his findings. Future generations of inventors, scientists, and engineers had no formal documentation to study or expand upon [4].

A.2 1750–1850: Industrial Revolution

By many accounts, 1750 kicks off the Industrial Revolution, which occurred from approximately 1750 to 1850. This transition created change for many:

- Hand production giving way to to mechanization;
- New processes for chemical and iron production;
- The increased adoption of steam power;
- The rise of the factory system;
- People moving from cottage-based industries to factory jobs.

Innovations developed late in the period, such as adoption of locomotives, steamboats and steamships, hot blast iron smelting and other new technologies, such as the electrical telegraph, continued to change daily life for many [5].

1748: Leonhard Euler publishes *Introductio in Analysin Infinitorum* ("Introduction to the analysis of the infinite") [6]. Euler was not only one of the most important and influential mathematicians, but also the most prolific. He wrote more than 500 books and papers during his lifetime [7].

1752: Benjamin Franklin shows that lightning is caused by electricity during his well-known kite experiment in Philadelphia [8].

1753: An anonymous writer in the *Scots Magazine* suggests an electrostatic telegraph. Using multiple wires, a message would be transmitted by observing the deflection of pith balls [9].

1769: James Watt develops a reciprocating steam engine, capable of powering a fly wheel [10].

1792: Claude Chappe constructs a semaphore network across France during the French Revolution to provide a swift and reliable communication system. It brought news over a distance of 230 kilometers in under one hour, faster than any other communications method at the time [11].

1800: Alessandro Volta develops the voltaic pile (now known as a battery). With a constant source of DC voltage, more practical experiments could be made and new apparatus invented [12].

1804: Improving on James Watt's steam engine, Richard Trevithicks build the first full-scale working railway steam locomotive [13].

1820: Johann Schweigger builds the first sensitive galvanometer, an electro-mechanical instrument for detecting and indicating electric current [14].

1827: Georg Ohm publishes the book *Die galvanische Kette, mathematisch bearbeitet* [15] ("The Galvanic Circuit Investigated Mathematically"), where the fundamental law of electric circuits, $V = I \times R$—what becomes known as Ohm's law—is shared. At the time, Ohm's employor, the Dreikönigsgymnasium in Cologne, did not appreciate his work and Ohm resigned from his teaching position [16].

1827: André-Marie Ampère publishes the book *Mémoire sur la théorie mathématique des phénomènes électrodynamiques uniquement déduite de lexperience* ("Memoir on the Mathematical Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience") [17]. This is the text that created electrodynamics as a field of study.

1831: Michael Faraday produces current from a moving magnet, called a disc dynamo, later to be known as an electrical generator [18].

1833: Carl Friedrich Gauss installs a 1,200m long wire above Göttingen's roofs to experiment with the telegraph [19].

1837: Charles Babbage designs the mechanical analytical engine, the first a general-purpose computer [20].

1837: Samuel Morse patents a recording electric telegraph. In order to sell his new equipment, an alphabet encoding scheme referred to as *Morse code* was used in order to communicate strings of characters [21]. Simple to use, electric telegraphs were extensively employed during most of the 1800s, with data rates dependent on the skill of the telegraph operator and the capabilities of the equipment.

A.3 1850–1945: Technological Revolution

The Technological Revolution, or what many call the Second Industrial Revolution, was punctuated by advancements in manufacturing that enabled the widespread adoption of preexisting technological systems such as telegraph and railroad networks, gas and water supply, and sewage systems. The enormous expansion of rail and telegraph lines after 1870 allowed unprecedented movement of people and ideas. In the same time period, new technological systems were introduced, most significantly electrical power and telephones.

1860: Giovanni Caselli demonstrates his pantelegraph, an early form of facsimile machine, which transmitted a likeness of a signature over 140 km over normal telegraph lines [22].

1864: James Maxwell publishes a paper, *A Dynamical Theory of the Electromagnetic Field*, which tells the world about his findings about electromagnetic waves and the math behind them. A collection of 20 equations become known as *Maxwell's equations* [23].

1865: At the International Telegraph Convention in Paris, the *Union Tèlègraphique Internationale (International Telegraph Union or ITU)* was formed to codify and ensure interoperability within the growing international telegraphic traffic within Europe [24].

1869: The First Transcontinental Railroad is completed. It was a 3,077 km continuous railroad line that connected the eastern U.S. rail network with the Pacific coast in San Francisco Bay [25]

1873: Maxwell publishes his text *A Treatise on Electricity and Magnetism* [26]. This would be read by many, including Hermann von Helmholtz, a faculty member at the University of Berlin.

1874: Karl Braun develops the cat's-whisker detector, later known as a point-contact rectifier. Consisting of a thin wire that lightly touches a crystal of semiconducting mineral (usually galena), this device was used as the detector in early crystal radios, from the early twentieth century through 1945 [27].

1876: Alexander Graham Bell successfully implementes the world's first telephone, ushering in a new age of voice-based electronic communications [28]. It was now possible for any individual to communicate with any other individual anywhere on the planet, constrained only by the wired medium connecting the two of them to each other.

1879: Thomas Edison files for a U.S. patent for an electric lamp using "a carbon filament or strip coiled and connected ... to platina contact wires" [29].

1879: Heinrich Hertz, a Ph.D. student, is given the challenge by his faculty advisor, Hermann von Helmholtz, to prove the practical uses of Maxwell's equations, which were published only a few years before. Although Hertz did some analysis, he thought this suggestion was too difficult and worked on electromagnetic induction instead [30].

1885: Karl Benz builds the first practical motorized automobile [31].

1886: Heinrich Hertz receives his professorship at the Karlsruhe Institute of Technology and is finally able to fulfill his advisor's challenge and builts an apparatus for generating and detecting radio waves [30]. This eliminated the needed wired medium for communications (no more cables), since radio waves would be generated by a transmitter and propagate throughout an area until they are intercepted by a receiver.

1894: Jagadish Bose uses a cat's-whisker detector to detect radio waves in his pioneering experiments with microwaves [32], finally applying for a patent on a galena detector in 1901 [33].

1897: Karl Braun builds the first cathode-ray tube (CRT) and cathode ray tube oscilloscope [34].

1901: Guglielmo Marconi demonstrates the very first trans-Atlantic wireless transmission between Poldhu, Cornwall, in England and Signal Hill, St. John's, in Newfoundland in 1901 [35], using messages encoded using Morse code [36]. The viability of wirelessly transmitting information over very large distances was proven. With the success of this experiment, wireless data transmission became an option for connecting people around the world without the need for any wired communication infrastructure.

1904: John Fleming develops the oscillation valve, later to be called the two-electrode vacuum-tube rectifier (now known as a diode) [37]. Fleming's diode was used in radio receivers and radars for many decades afterward as part of the ring mixer, as shown in Figure A.2.

1905: While accepting his 1909 Nobel Prize for physics, Karl Braun describes how he carefully arranged three antennas to transmit a directional signal [38]. This invention led to the development of radar, smart antennas, and MIMO.

1905: Reginald Fessenden describes a proposed method of producing an audible signal from the new Morse code continuous wave transmitters he calls the *heterodyne* principle [39]. It was not a practical device at the time, since the oscillating vacuum-tube had not been developed yet.

1906: The International Radiotelegraph Union was unofficially established at first International Radiotelegraph Convention in Berlin [40].

1907: Lee De Forest develops grid audions, the first vacuum tube based amplifier, the precursor to the triode [41].

1912: Henry Ford develops and manufactures the first affordable automobile, turning the automobile into a practical conveyance [42].

1913: While an undergraduate student at Columbia, Edwin Armstrong prepares a series of comprehensive demonstrations and papers that carefully document his research on De Forest's grid audions, employing regeneration (later known as positive feedback) producing amplification hundreds of times greater than previously thought possible [43].

1915: Alexander Graham Bell and Thomas A. Watson talk to each other over a 3,400-km wire between New York and San Francisco [44].

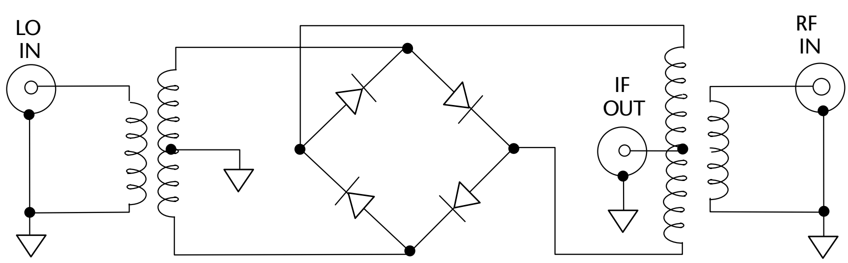

Figure A.2 Diode ring mixer based on Fleming's oscillation valve [45].

1917: Eric Tigerstedt files a patent for a pocket-size folding telephone with a very thin carbon microphone, a suggestion of the mobile phones we know today [46].

1917: The superheterodyne is patented. With three different patent applications being filed by three different people, Lucien Lèvy, Edwin Armstrong, and Walter Schottky, it is unknown who actually was first. Eventually, the U.S. patent office recognizes both Armstrong and Lèvy as the inventors [47]. The superheterodyne is the design used in almost all modern radio receivers. Figure A.3 shows a block diagram of a single-conversion superheterodyne radio receiver used as the fundamental architecture for many modern radios.

1924: Harry Nyquist, an engineer in AT&T's Department of Development and Research (later to be known as Bell Telephone Laboratories) studies telegraph signaling with the objective of finding the maximum signaling rate that could be used over a channel with a given bandwidth, and publishes "Certain Factors Affecting Telegraph Speed" [48].

1927: Charles Ducas patents a method of electroplating circuit patterns, the fundamental technology used in the manufacturing of printed circuit boards [49].

1928: Harold Black of Bell Labs patents negative feedback in amplifiers, where he defines negative feedback as a type of coupling that reduces the gain of the amplifier, in the process greatly increasing its stability and bandwidth [50].

1928: Nyquist also publishes futher findings in his article, "Certain Topics in Telegraph Transmission Theory" [51]. Both his papers provide fundamental contributions to a quantitative understanding of data transmission.

1932: The International Telegraph Convention and International Radiotelegraph Convention merge into the International Telecommunication Union (ITU) in Madrid. This new convention covers the three fields of communication: telegraphy, telephony, and radio [40].

1932: Since superheterodyne architecture was normally implemented in multiple stages, and required large components, a team of British scientists develop what they call the homodyne, later renamed as synchrodyne, what we now

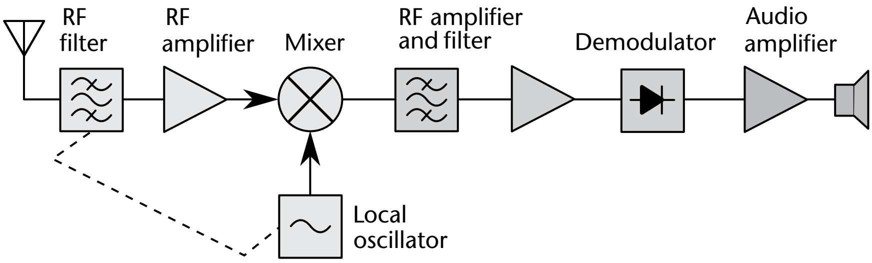

Figure A.3 Single-conversion superheterodyne radio receiver. The incoming radio signal from the antenna (left) is passed through an RF filter to attenuate some undesired signals, amplified in a radio frequency (RF) amplifier, and mixed with an unmodulated sine wave from a local oscillator. The result is a beat frequency or heterodyne at the difference between the input signal and local oscillator frequencies, a lower frequency called the IF. The IF signal is selected and strengthened by several IF stages that bandpass filter and amplify the signal. The IF signal is then applied to a demodulator that extracts the modulated audio signal. An audio amplifier further amplifies the signal, and the speaker makes it audible.

call the zero-IF radio architecture [52]. While the homodyne had shown performance improvements from the superheterodyne, it was difficult to implement due to component tolerances at the time, which must be of small variation for this type of circuit to function successfully and the requirement of a PLL (the superhet only requires a oscillator).

1940: The term RADAR was used by the United States Navy as an acronym for radio detection and ranging [53].

1945: Arthur C. Clarke, science fiction writer, pens a letter to the editor of *Wireless World* describing how geostationary satellites would be ideal telecommunications relays [54].

A.4 1946–1960: Jet Age and Space Age

While research was being done and patents filed about jet engines since the 1920s, it was not until Hans von Ohain and Max Hahn designed and built what would be the first gasoline-fueled jet engine, known as HeS 3. Providing 5 kN of force, it was fitted to simple and compact He 178 airframe and in 1939, the Jet Age began [55]. Commercial aviation introduced jets with the first scheduled flight of the de Havilland Comet, the world's first commercial jetliner, in 1952 [56, 57].

With people hurling through the sky at hundreds of kilometers per hour, the need for sophisticated communications grew, and knowing your location, and where other people are (collision avoidance), becomes more critical.

1946: Electronic Numerical Integrator and Computer (ENIAC) is formally dedicated at the University of Pennsylvania, becoming one of the earliest electronic general-purpose computers made [58].

1947: Engineers at Bell Labs observe that when two gold contacts are applied to a crystal of germanium, a signal is produced with the output power greater than the input, and this device is soon to be known as the transistor. Group leader William Shockley sees the potential in this, and over the next few months works to greatly expand the knowledge of semiconductors [59].

1948: Claude Shannon publishes "A Mathematical Theory of Communication" [60] in the *Bell System Technical Journal*. Shannon shows that all communication (voice, radio, data, etc.) is fundamentally the same, and furthermore, that any source can be represented by digital data. He was able to quantify that communication channels had a speed limit, measured in binary digits per second, something that was revolutionary for its time. Shannon gave a mathematical proof that there had to exist codes that would approach the limit without losing any information at all, and this proof still holds to this day [61].

The concepts of digital communication took off in the late 1950s, since Shannon showed *perfect information transfer* is possible no matter the noise, distortion, or signal amplitude. The concept of *relay stations* became important, as data could be transfered from the source at A, to B (the relay) to C (the destination) without the loss of information.

1950: The *Auto-Sembly* process is patented by the United States Army [62]. This was the solder dipped circuit process of assembling electrical circuits and was widely adopted by both military and industrial designers [63].

1950: William Shockley publishes *Electrons and Holes in Semiconductors* [64], becoming the reference text for other scientists working to develop and improve new variants of the transistor.

1954: Epsco, a company founded by former UNIVAC engineer Bernie Gordon, releases the first commercially offered analog-to-digital (ADC) to utilize the shift-programmable successive approximation architecture and include sample-and-hold function. It was called the 11-bit, 50-kSPS, 150 lbs, Datrac converter. Implemented with vacuum tubes, it dissipated 500 watts, was designed for rack mounting (19" × 15" × 26"), and sold for $8,000 to $9,000. It was the first commercial ADC suitable for digitizing AC waveforms, such as speech [65]. Because of vacuum tube technology, the converters were very expensive, bulky, and dissipated lots of power. There was practically no volume commercial usage of these devices.

1956: William Shockley moves to Mountain View, California, to start Shockley Semiconductor Laboratory, starting the silicon valley revolution [66].

1957: Because of Shockley's management style, a eight unhappy employees leave Shockley Semiconductor Laboratory and form Fairchild Semiconductor [66]. This is the start of a trend in silicon valley that continues to this day.

1957: The Soviet Union launches Elementary Satellite 1, or Sputnik 1, into elliptical low earth orbit [67].

1958: Jack Kilby, a junior engineer at Texas Instruments (TI), comes to the conclusion that the manufacturing of circuit components could be done on a single piece of semiconductor material. He then files for the first integrated circuit patent, *miniaturized electronic circuits*, the next year [68].

1962: The first communications satellite, *Telstar 1* is launched [69]. Telstar 1 relayed data, a single television channel, or multiplexed telephone circuits between Andover, Maine, Goonhilly Downs in southwestern England, and at Pleumeur-Bodou, in northwestern France. Its use for transatlantic signals was limited to 20 minutes in each 2.5 hour when the non geosynchronous orbit passed the satellite over the Atlantic Ocean [70].

1965: Ray Stata and Matthew Lorber, two MIT graduates, found Analog Devices Inc. [71]. The same year, the company releases its first product, the model 101 op-amp, which was a hockey-puck-sized module used in test and measurement equipment [72].

1965: Gordon Moore, director of research and development at Fairchild Semiconductor, observes that the number of components (transistors, resistors, diodes, or capacitors) in a dense integrated circuit had doubled approximately every year, and speculated that it would continue to do so for at least the next ten years. He later revised the forecast rate to approximately every two years [73]. This has become known as Moore's law.

1966: Analog-to-digital converters (ADC) are now not enjoying the same amount of scaling that their pure digital counterparts were. Computer Labs (acquired by Analog Devices in 1978) were selling an 8-bit, 10-MSPS converter that was rack mounted, contained its own linear power supply, dissipating nearly 150 watts, and selling for approximately $10,000 [65].

1967: Barrie Gilbert develops a ring mixer based on transistors, which becomes known as the *Gilbert cell* or the four quadrant multiplier [74]. Building on the diode based ring mixer shown in Figure A.2, the diodes were replaced by four transistors, performing the same switching function. This formed the basis of the now-classical bipolar circuit shown in Figure A.4, which is a minimal configuration for the fully balanced version. Millions of such mixers have been made, now including variants in CMOS, BiCMOS, and GaAs.

The Gilbert cell is attractive as an active mixer for the following reasons:

- It can be monolithically integrated with other signal processing circuitry.
- It can provide conversion gain, whereas a diode-ring mixer always has an insertion loss.
- It requires much less power to drive the LO port.
- It provides improved isolation between the signal ports.
- Is far less sensitive to load-matching, requiring neither diplexer nor broadband termination.

1967: Andrew Viterbi, a faculty of electrical engineering at UCLA and UCSD, publishes an algorithm to decode convolutionally encoded data [75], known as the *Viterbi algorithm*. It is still used widely in cellular phones for error correcting codes, as well as many other applications. Viterbi did not patent the algorithm, a decision he does not regret [76].

1969: The first successful message on the ARPANET, which laid the foundations of the internet is sent by a UCLA student programmer [77].

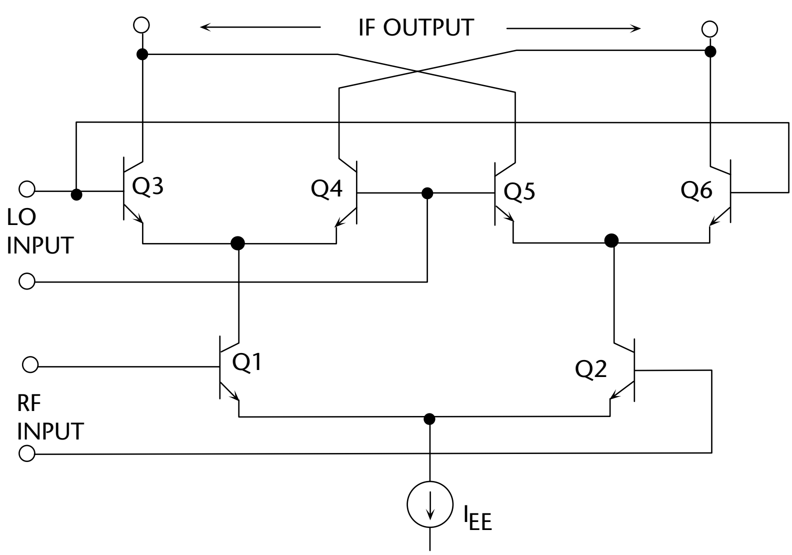

Figure A.4 Classic integrated active mixer [45].

A.5 1970–1979: Information Age

The Information Age is characterized by the shift from traditional industry that the Industrial Revolution, to an economy based on information computerization. The 1970s were driven by a large number of emerging applications, including high-volume calculators, high-resolution digital voltmeters, industrial process control, digital video, military phased array radar, medical imaging, vector scan displays, and raster scan displays. These systems had formerly utilized conventional (at the time) analog signal processing techniques, or ASICs, but the increased availability of low-cost computing technology generated a desire to take advantage of the increased performance and flexibility offered by digital signal processing, as well as the need for compatible data converters. Central to this age is the mass production and widespread use of digital logic circuits and their derived technologies, including the computer and cellular phones.

1970: The term digital receiver is coined by a researcher at a United States Department of Defense laboratory, where a software baseband analysis tool called Midas (multiuser interactive digital analysis system) was created, which had its operation defined in software running on a mainframe of the time [78].

1971: The Intel Corporation releases, the Intel 4004, the first commercially available 4-bit central processing unit (CPU) [79].

1971: Texas Instruments invents and releases the first microcontroller (MCU), the TMS1802NC [80].

1971: ALOHAnet connects the Hawaiian islands with a UHF wireless packet network. The goal was to use low-cost commercial radio equipment to connect users on Oahu and the other Hawaiian islands with a central time-sharing computer on the main University of Hawaii, Oahu campus [81].

1972: Signetics (later acquired by Philips Semiconductors, and now NXP, and, at the time of this writing is being acquired by Qualcomm) introduces the NE555V timer. As of 2003, it was estimated that 1 billion units were manufactured every year [82].

1972: Pulse code modulation (PCM) of voice frequencies, the ITU-T standard for audio companding known as G.711 is released. It is a narrowband (300–3400 Hz) audio codec that provides voice quality similar to analog signal transmission over copper lines, known as plain old telephone service (POTS) [83].

1973: Martin Cooper of Motorola makes the first publicized handheld mobile phone call on a prototype DynaTAC, a 4.4-lb (2-kg) phone.

1973: The U.S. Department of Defense kicks off planning for the Defense Navigation Satellite System (DNSS), soon to be renamed Navigation System Using Timing and Ranging (Navstar), and eventually Global Positioning System (GPS). Ten prototype satellites are launched between 1978 and 1985.

1975: Paul Allen and Bill Gates officially establish Microsoft and license Altair BASIC [84].

1975: Analog Devices releases the AD7570, a 10-bit, 50-kHz CMOS SAR ADC on a monolithic device. Due to the difficulty of designing good comparartors, amplifiers, and references on the early CMOS processes, the AD7570 required an external comparator as well as an external voltage reference [65].

1975: Barrie Gilbert joins Analog Devices and releases the AD534 [85] Precision IC Multiplier. This is the first device to utilize laser trimming and the Gilbert cell, to provide less than ±0.25 % 4-quadrant error [86].

1975: Steven Sasson develops the first digital camera [87]. At 3.6 kg, using a 100,100-pixel (0.01 megapixels) sensor, the resulting black-and-white digital image is recorded onto a cassette tape, taking 23 seconds [88].

1976: Steve Jobs, Steve Wozniak, and Ronald Wayne found Apple Computer [89]. The company's first product is the Apple I, a computer designed and hand-built by Wozniak [90].

1977: What *Byte magazine* later refers to the 1977 Trinity of personal computing [91]:

- Apple releases the Apple, based on 6502 running at 1.023 MHz
- Commodore releases the Commodore Personal Electronic Transactor (PET), based on 6502 running at 1 MHz
- Tandy releases the TRS-80 based on a Zilog Z80 at 1.77 MHz

1978: The EEPROM (electrically erasable programmable read-only memory) is developed by Hughes Microelectronics Division, which offers a huge improvement from EPROM in that it is now not necessary to shine UV light on the memory to erase it [92].

1978: Texas Instrument produces the first Speak & Spell, with the technological centerpiece being the TMS5100, the industry's first digital signal processor (DSP). It also sets other milestones, being the first chip to use linear predictive coding to perform speech synthesis [93].

1978: The AD574 is released by Analog Devices, the most significant SAR ADC ever produced [94]. It is the first device representing a complete solution, including Zener reference, timing circuits, and three-state output buffers for direct interfacing to an 8-, 12- or 16-bit microcontroller or microprocessor bus [65]. This becomes the industry standard 12-bit ADC for its time, but is based on two die in the same package.

1978: Fred Harris, professor of electrical engineering, San Diego State University, publishes his most cited paper, "On the use of windows for harmonic analysis with the Discrete Fourier Transform" [95], receiving over 10,000 peer citations for the papers he has published and information he has shared [96]. Dr Harris started publishing papers in 1962, and continues to this day.

A.6 1980–1989: Digital Revolution

The Digital Revolution is the continued change from mechanical and analog electronic technology to digital electronics which began, depending on the market segment, anywhere from the late 1950s to the late 1970s with the adoption of digital signal processing and desktop computing that continues to the present day.

1981: IBM Personal Computer is introduced, based on a 4.77 MHz Intel 8088 16 KB RAM, color graphics adapter, and no disk drives [97].

1982: The Internet Protocol Suite (TCP/IP) is standardized by the U.S. Department of Defense, which permits worldwide proliferation of interconnected networks [98].

1983: The Motorola DynaTAC 8000X commercial portable cellular phone is released. A full charge takes roughly 10 hours and offers 30 minutes of talk time. It was priced at $3,995 in 1984, and used an analog modulation scheme, known as advanced mobile phone system, or AMPS.

1983: John G. Proakis [99] publishes his first of ten books on digital communications and signal processing, including *Digital Communications* (McGraw Hill) [100]. He goes on write many books on the subject: *Digital Signal Processing* [101], *Digital Signal Processing Laboratory* [102], *Advanced Digital Signal Processing* [101], *Digital Processing of Speech Signals* [103], and *Communication Systems Engineering* [104]. His books have educated a generation of students and engineers about the fundamentals and theory associated with SDR.

1983: Altera is founded and delivers the industry's first reprogrammable logic device in 1984, the EP300, which features a quartz window in the package that requires users to shine an ultraviolet lamp on the die to erase the EPROM cells that hold the device configuration [105].

1983: President Ronald Reagan issues a directive making GPS freely available for civilian use, once it is sufficiently developed, as a common good. The first production satellite was launched on February 14, 1989, and the 24th satellite was launched in 1994.

1983: Work begins to develop a European standard for digital cellular voice telecommunications, which eventually becomes GSM.

1984: Apple Computer introduces the first Macintosh computer. It is the first commercially successful personal computer to use a graphical user interface (GUI) and mouse, which become standard features in computers [106]. It features a 7.83 MHz 32-bit Motorola 68000 CPU, built-in 9-inch monochrome screen, 512×342 graphics, 400 kB 3.5-inch Sony floppy disk drive, mouse, 128 kB RAM. Weight is 20 pounds, size is $9.7 \times 10.9 \times 13.5$ inches, and price ranges from $1,995 to $2,495.

1984: The term software radio is coined by a team at the Garland, Texas Division of E-Systems Inc. (now Raytheon) to refer to a digital baseband receiver and the team publishes in their E-Team company newsletter [107].

1984: MathWorks is founded, and MATLAB made its public debut at the IEEE Conference on Decision and Control in Las Vegas, Nevada [108]. Used in industry and education, in particular the teaching of linear algebra, numerical analysis, it is popular with scientists involved in signal processing.

1984: The ITU releases the V.32 recommendation for a dial-up modem, allowing bidirectional data transfer at either 9.6 kbit/s at a symbol rate of 2,400 baud using QAM modulation [109].

1985: Analog Devices rereleases AD574 in single-chip monolithic form, as shown in Figure A.5. For the first time a low-cost commercial plastic converter is available in mass volume.

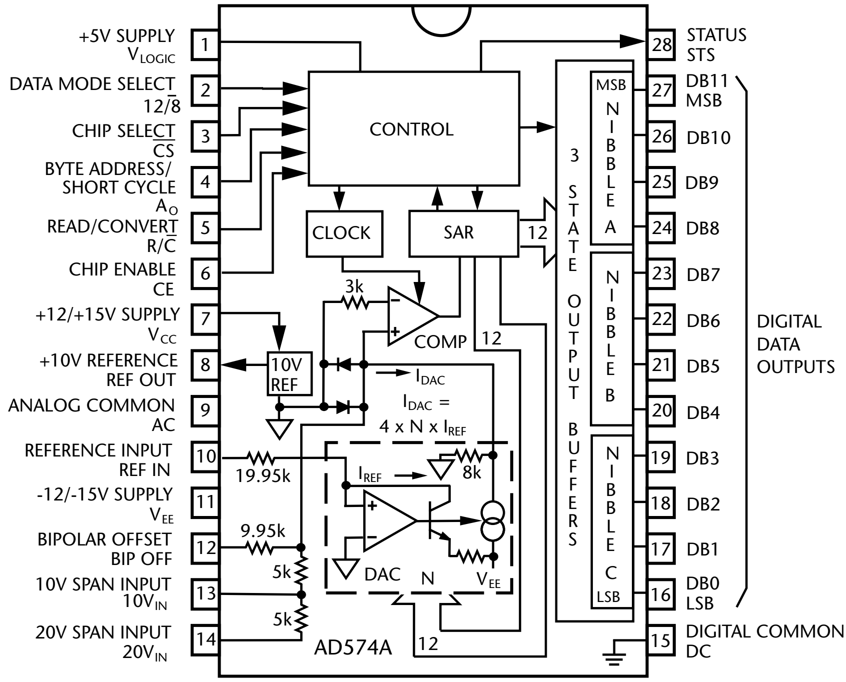

Figure A.5 The industry standard AD574 12 bit 28.5 kSPS ADC.

1985: A ruling by the U.S. Federal Communications Commission releases 902 to 928, 2400 to 2483.5 and 5725 to 5850 MHz bands for unlicensed use [110]. This creates the industrial, scientific, and medical (ISM) radio bands.

1987: Fifteen representatives from 13 European countries sign a memorandum of understanding in Copenhagen to develop and deploy a common cellular telephone system across Europe, and EU rules are passed to make GSM a mandatory standard.

1987: Flash memory (both NOR and NAND types) is developed by Toshiba and presented at the IEEE 1984 International Electron Devices Meeting (IEDM) held in San Francisco [111].

1987: Over 15 billion USD from venture capital is invested in semiconductor startups from 1980 through 1987 [112]. The semiconductor industry continues to grow, with startups such as Linear Technologies (founded 1987, acquired by Analog Devices 2016), Hittite Microwave (founded acquired by Analog Devices), Wolfson Microeltronics (founded acquired by Cirrus Logic), Atmel (founded 1984, acquired by Microchip 2016), Xilinx (founded 1984), Altera (founded 1983, acquired by Intel 2015), Maxim (1983), and Micron (1978).

1988: The ITU-T approves G.722, an wideband (507000 Hz) audio codec operating at 48, 56 and 64 kbit/s. Technology of the codec is based on subband ADPCM (SB-ADPCM). G722 provides improved speech quality due to a the wider bandwidth of G.711 released 16 years earlier [113].

1988: Crystal Semiconductor (later purchased by Cirrus Logic) releases the monolithic CSZ5316, the first commercial Σ-Δ ADC. With 16-bit resolution, and an effective throughput rate of 20 kSPS is suitable for voiceband digitization [65].

1989: Nils Rydbeck, CTO at Ericsson Mobile, proposes a short-link radio technology to connect wireless headsets to mobile phones, which eventually becomes known as Bluetooth.

1989: public commercial use of the internet begins with the connection of MCI Mail and Compuserve's email capabilities [114].

A.7 1990–1999: Age of the Public Internet (Web 1.0)

Digital signal processing and computing technology continue to revolutionize the 1990s. Between 1990 and 1997, individual PC ownership in the United States rose from 15% to 35%. Cell phones of the early 1990s and earlier were very large, lacked extra features, and were used by only a few percent of the population. Only a few million people used online services in 1990, and the World Wide Web had only just been invented. The first Web browser went online in 1993 and by 2001, more than 50% of some Western countries had internet access, and more than 25% had cell phone access. Advancements in computer modems, ISDN, cable modems, and DSL lead to faster connections to the internet.

Wireless transmission technology has gradually evolved over time; the superheterodyne architecture developed in 1917, shown in Figure A.3, is still the go-to radio architecture of the time. It has taken advantage of the current integrated circuits and morphed into multistage receiver architectures typically consisting of one or two mixing stages, which are fed into single-chip ADCs and DACs. A multistage superheterodyne transceiver architecture can be seen in Figure A.6.

The first conversion stage converters (up or down) the RF frequencies to a lower intermediate frequency (IF_1). The first IF_1 is then translated down to a lower frequency (IF_2) baseband frequency that the ADC or DAC can digitize. In addition to the mixers, there are filters, amplifiers, and step attenuators at each stage. The filtering is used to reject unwanted out-of-band (OOB) signals. If unchecked, these OOB signals can create spurious signals (spurs) that falls on top of a desired signal, making it difficult or impossible to demodulate. The actual IF_1 or IF_2 frequencies depends on the frequency and spur planning, as well as mixer performance and available filters for the RF front-end. These radios are mostly fixed frequency (not very tunable), as the desire for performance (sensitivity) has been traded off for flexibility.

1990: Advanced RISC Machines Ltd (ARM) is founded as a joint venture between Acorn Computers, Apple Computer (now Apple Inc.) and VLSI Technology. The company develops the Acorn RISC Machine (ARM) processor, which is now used in 98% of the more than 1 billion mobile phones sold each year [115].

1991: Algorithms for MPEG-1 Audio Layer I, II and III, which become known as international standard ISO/IEC 11172-3 [116] (MPEG-1 Audio or MPEG-1 Part 3), or mp3, are approved in 1991 and finalized in 1992 [117].

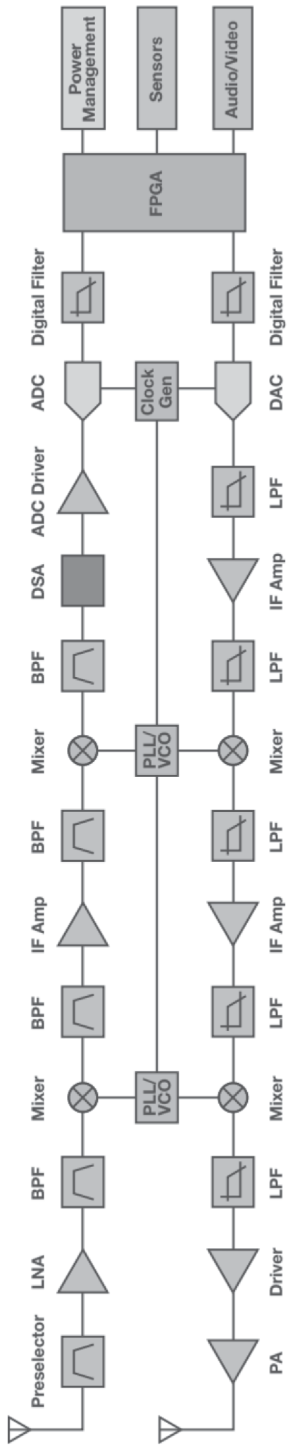

Figure A.6 Multistage superheterodyne receive and transmit signal chains [118].

1991: The ITU releases the V.32bis recommendation for a dial-up modem, allowing bidirectional data transfer at 14.4 kbit/s using trellis-modulated data using the Viterbi algorithm [109].

1991: Linus Torvalds, a computer science student, starts working on some simple ideas for an operating system, and 10,239 lines of code, version 0.01 of the Linux kernel, is released on the FTP server [119].

1991: Former Finnish prime minister Harri Holkeri makes the world's first GSM call, calling Kaarina Suonio (mayor of the city of Tampere, where Nokia was founded) [120].

1991: SpeakEasy I, a software-defined radio project, is kicked off by the U.S. military [121] Although different parts of SDR technology were available since the 1970s and the first demonstration as a SDR prototype (with a fixed RF implementation) was presented in 1988 [122], SpeakEasy was the first large-scale software radio.

When a communication device is designed for one unique unique purpose, only using one unique waveform, at one unique frequency, different devices made by different people are not interoperable with one another. The U.S. military had this exact problem—they had many different types of radios and waveforms for each branch and group of the armed services, and in times of conflict, they could not talk to each other in real time. This was not an academic exercise—lives were being lost due to the inability to communicate. They needed a single system that could communicate with over 10 other different types of military radios.

This was the key milestone for the advancement of SDR technology. The developers wanted to test the feasibility of a multiband (different RF frequencies), multimode (different waveforms) radio in practical settings.

1991: CERN, a European organization for particle research, publicizes the new World Wide Web project.

1992: The first short messaging service (SMS or text message) message is sent over the GSM network.

1993: Joseph Mitola coins the term software-defined radio [123].

1994: The SpeakEasy project is successfully demonstrated. It was not only a success, but a significant leap forward in SDR technology. It used four Texas Instruments TMS320C40 processor, which ran at 40 MHz and a SUN Sparc 10 workstation as the man-machine interface, implementing more than ten military communication standards, with transmission carrier frequencies ranging from 2 to 2000 MHz, which at that time was a major advancement in communication systems engineering. The SpeakEasy implementation allowed for software upgrades of new functional blocks, such as modulation schemes and coding schemes. Note that given the microprocessor technology at the time, the physical size of the SpeakEasy prototypes were large enough to fit in the back of a truck and required a significant amount of power.

Since the SpeakEasy program had taken 3 years to complete, (two cycles of Moore's law), many thought it would be easy to scale down to a faster, lower-power processor. However, since everything was hand-coded in assembly (to maximize performance), this was not possible. Development was stuck. The observation was that it had taken 3 years to write software for a platform that Moore's law made obsolete in 18 months.

1994: Linus Torvalds releases the Linux kernel 1.0, with 176,250 lines of code [124].

1995: Sony releases the Playstation worldwide. It is the first computer entertainment platform to ship 100 million units, which it reached 9 years and 6 months after its initial launch [125]

1996: John O'Sullivan takes a technique he developed in 1977 for sharpening and improving picture clarity in radio astronomy images using Fourier, and reapplies the technique for reducing multipath interference of radio signals as part of a research project to detect exploding mini black holes the size of an atomic particles. While his main experiment failed, his signal processing techniques were patented and applied to future 802.11 standards.

1996: Linus Torvalds releases the Linux kernel 2.0, with 632,062 lines of code [126].

1997: The first version of the 802.11 protocol is released and provides up to 2 Mbit/s link speeds.

1998: The Bluetooth Special Interest Group (SIG) is formed, and the first specification is released.

1998: The ITU releases the V.90 recommendation for a dial-up modem, allowing 56 kbit/s digital download and 33.6 kbit/s analog upload. using digital modulation [127].

1999: The IEEE ratifies an upgrade to the 802.11 specification with 802.11b to permit 11 Mbit/s link speeds.

2000: Bluetooth products begin to ship, including mice, PC cards, headsets, and phones [128].

2001: Jimmy Wales and Larry Sanger launch Wikipedia [129].

A.8 Post-2000: Everything comes together

Since 2000, the amount of research and development activities has exploded. New, faster-, or lower-power communications schemes are almost being announced on a yearly basis. In 2008, worldwide GSM subscribers exceeded three billion people; however in 2016, operators are decommissioning networks to make ready for LTE and other standards. The rate of change has increased substantially.

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