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History

Introduction

UWB – ultra-wideband – is an unconventional type of radio, but to understand a variation on the convention, we must grasp the basics of traditional radio. When most people hear the word “radio” they think of the small device that brings music and news into their homes and automobiles. That is true, but radio has many forms. In fact, many common devices that perform some function in a wireless mode are a variety of radio, such as wireless baby monitors, wireless Internet connections, garage door openers, and mobile or cell phones.

In this chapter, we introduce the basics of traditional radio. We follow the history of the development of wireless – to be dubbed radio at the start of the broadcast era – from its inception as crude wideband spark signals, through its relentless march towards narrowband-channelized solutions. Finally, we see its resurgence as the modern “wireless.” History reveals that the march towards narrowband admits several instances in which wideband signaling has significant advantages over narrowband techniques. The present evolution to UWB is but an inevitable step in the evolution of wireless and radio.

1.1 The Basics of Radio

Radio is the art of sending and receiving electromagnetic signals between transmitters and receivers wirelessly, as depicted in Figure 1.1. Radio requires transmitters for generating signals, and receivers to translate the received information. Both use antennas for sending the signals as
electromagnetic energy and for collecting that energy at the receiver. Information, such as voice into a microphone, is supplied to transmitters, which then encode, or *modulate*, the information in some fashion on the signal. This information could be someone’s voice, music, data, or other information. Receivers recover that information by decoding, or *demodulating*, the received signal and presenting it as received information.

Signals, electromagnetic energy-bearing information, inundate our surroundings. They usually originate from commercial broadcasting such as our familiar AM- and FM-band radio stations, television stations or consumer devices such as mobile phones, and garage door openers. There is a plethora of services that carry voice, music, video, telephony, and control instructions. There are also signals that originate from beyond the earth’s immediate vicinity. They are natural stellar sources, pulsars, and such. Their “information” is carefully deciphered by radio astronomers to glean knowledge about our universe.

All signals, regardless of origin, simultaneously share the same “transmission medium” – the near vacuum of space, the air enveloping the earth and the many materials surrounding us. Yet we can selectively choose the signal we want, such as the radio station to which we wish to listen, the television program we want to watch, or the call intended for our mobile telephone. Radio signals in the electromagnetic spectrum (see Figure 1.2) keep us informed, entertained, and safe.

Conventional radio signals can be discerned one from the other because they occupy unique locations in the radio spectrum (see Figure 1.3), for

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**Figure 1.1** A basic radio link includes a transmitter, waves propagating and filling space, and a receiver [McKeown 2003].
Figure 1.2 Radio services occupy unique locations in the electromagnetic spectrum.

Figure 1.3 Sines and cosines of different wavelengths occupy unique spots in the spectrum.
instance, unique audio tones or discrete colors in the rainbow spectrum. They are distinct, narrowband places on a radio dial, indicated by channel numbers. They are all crafted that way because of a century-old historical interplay between the technological development of radio and the regulations that brought order to the radio spectrum. Radio signals share the limited spectrum by occupying slivers of spectrum that are as narrow as possible. A signal without information has zero bandwidth. Modulating information on that signal spreads its bandwidth in proportion to the information bandwidth. For example, a music signal with tonal content up to 15 kHz requires at least 15 kHz of information bandwidth. The “ideal” in radio spectrum usage has been to use the smallest bandwidth compared to the bandwidth of the signal information. Narrowband signals are often represented by their zero bandwidth ideals, the sine and cosine functions, also known as circular functions or harmonic waves. They are the narrowest possible representation of signals in the spectrum at distinct frequencies. Tuning radios to a particular frequency allows us to select the desired narrow band signal. So, the dogma of the circular functions, sines and cosines, [Harmuth 1968] began to dominate radio development.

Separation of signals by bands, by channels, and by frequencies is not the only way to share the radio spectrum. Information-bearing signals can also be separated in time, especially in tiny slivers of time. These

![Diagram](image)

**Figure 1.4** A finite length signal in time occupies a definite spectrum width in frequency, for that finite time.
signals occupy wide bandwidths, ultrawide bandwidths – but short – and ultrashort slivers of time (see Figure 1.4). The tinier the sliver of time, the wider is the bandwidth of the signal in the radio spectrum as seen in Figure 1.5. When confined to just four cycles of a sine wave, the signal occupies significant bandwidth, on the order of 50%.

Clever coding, modulating, and packing of short signals in time, rather than in frequency, allows us to separate these desired short signals to distinguish one user from another. This variety of radio signaling is called UWB.

Finally, in Figure 1.6 we see that the entire frequency spectrum can be occupied by multiple users. The users in this case are separated in time rather than in frequency. This is the direct analog of the separation in frequency depicted in Figure 1.3. UWB radio tends to the extreme of separating users in time, while simultaneously occupying large segments of the electromagnetic spectrum.

We see now that there are two ways of sharing the electromagnetic spectrum among many users. The spectrum can be divided in frequency and each user can be assigned a small sliver of the spectrum – a channel. Alternatively, the many users can each occupy the whole spectrum, but for a short sliver of time each. There is, of course, a wide range of intermediate possibilities of separating signals by combinations of time and frequency.
1.2 The History of Radio

Radio, called wireless at its inception, started out as “ultra-wideband.” This could have been entirely by accident or as a consequence of the first transmitters being electromechanical contraptions that generated signals using sparks flying between gaps. From UWB’s point of view, the early history of wireless is the story of invention, engineering, and legislation in a relentless march towards narrowband-channelized usage of the radio spectrum.

In 1864, James Clerk Maxwell, while chair at the University of Edinburgh, formulated the concept of electricity and magnetism using the language of mathematics in his equations of electromagnetism. His theory predicted that energy can be transported through materials and through space at a finite velocity by the action of electric and magnetic waves moving through time and space. That finite velocity was, astounding at the time, the velocity of light. The surprise was that this velocity linked light and electromagnetic waves as being the same phenomenon. Maxwell never validated his theory by experiment, and his results were opposed at the time.

Heinrich Rudolf Hertz, starting 22 years later, put into practice what Maxwell proposed with mathematics in a remarkable set of historical experiments [Bryant 1988] spanning the years 1886 to 1891. Hertz calculated that an electric current oscillating in a conducting wire would
radiate electromagnetic waves into the surrounding space. In 1886, using a spark-gap apparatus to generate radio energy, he created and detected such oscillations over a distance of several meters in his lab. The radiated waves were dubbed *Hertzian Waves* at the time, and today the basic unit of measuring oscillations per second is the Hertz, abbreviated to Hz. Through these experiments, wireless became a harmonic oscillation game – sine waves. The era of “wireless” had begun.

At the turn of the century, the radio arts were developed to practical usability by pioneer inventors and scientists like Alexander S. Popov (also spelled ‘Popoff’) and Nikola Tesla with their grasp of tuned resonant transmitter and receiver circuits. Popov stated on 7 May 1895 in a lecture before the Russian Physicist Society of St. Petersburg that he had transmitted and received signals across a distance of 600 m. In that same year, Guglielmo Marconi, using a Hertz oscillator, antenna, and receiver very similar to Popov’s, successfully transmitted and received signals within the limits of his father’s estate at Bologna, Italy. Popov’s radio receiving and transmitting system would eventually earn him a Grand Gold Medal for research at the Paris International Exposition of 1900 [Howeth 1963]. On the other hand, the entrepreneur Marconi took his wireless hardware to Britain. In 1896, for his efforts, Marconi was awarded British Patent number 12039 on 2 June in the same year. In 1897, he formed his first company, Wireless Telegraph and Signal Company, in Britain, and began manufacturing wireless sets in 1898. By 1901, Marconi, putting to use his innovations with those of his predecessors, had bridged the 3,000-km distance [Desoto 1936] between St. John’s Newfoundland and Cornwall, on the southwest tip of England, using Morse code transmissions of the letter “S.” With this achievement, Marconi introduced long-distance communication.

Marconi brought his technology to the United States in 1899 with the Marconi Company. Soon, he controlled patents for the tuner, patented by British inventor Oliver J. Lodge in 1898 [Lodge 1898], and for the John A. Fleming valve (vacuum tube) of 1904 that acted as a diode tube to efficiently detect wireless signals. The Lodge patent is particularly interesting in that it offers advantages in transmitting and receiving “tuning” circuits so that multiple stations may operate side by side in the radio spectrum without mutual interference. The movement was primarily away from wideband signals because at that time there was no way to effectively recover the wideband energy emitted by a spark-gap transmitter. There was also no way to discriminate among many such wideband signals in a receiver. Wideband signals simply caused too much interference with one another to be useful.
1826: Mahlon Loomis was born in New York

1831: Electromagnetic induction discovered by Michael Faraday

1831: James Clerk Maxwell was born in Edinburgh, Scotland

1837: Morse and the team of Cook and Wheatstone both develop a telegraph system

1846: Faraday says that light and electricity could be the same force

1847: Boolean Algebra invented by George Boole

1849: John Ambrose Fleming was born in Lancaster, England
History

1850s–1860s

\[ \nabla \times E = -\frac{\partial B}{\partial t} \]
\[ \nabla \cdot D = \rho \]
\[ \nabla \times H = \frac{\partial D}{\partial t} + J \]
\[ \nabla \cdot B = 0 \]

1856: Nikola Tesla was born in Croatia

1857: Heinrich Hertz born in Hamburg, Germany

1864: Maxwell explains the behavior of electromagnetic waves with “Maxwell’s Equations”

1865: Mahlon Loomis transmits a message between two mountains in Virginia using a wireless telegraph

1866: Reginald Fessenden was born in Quebec, Canada

1870s

1872: Mahlon Loomis is granted Patent #129, 971 by the US Government for a type of wireless communication

1872: Fessenden sends voice approximately one mile using a spark generator

1874: Guglielmo Marconi was born in Bologna, Italy
1880s

UWB overview:
— Hertzian experiments were UWB
— Apparatus was spark gap
— Large RF bandwidths

1886–1889: Hertz conducted a series of experiments that proved Maxwell’s theory that light was a form of electromagnetic radiation

1895: Alexander S. Popov demonstrates radio transmission using tuned circuits

1900s

UWB overview:
— Wireless is “tuned”

1901: Marconi receives the Morse code letter “S” in Newfoundland transmitted by Fleming from England

1901: Fleming invents the first tube known as the “Fleming Valve”

1901: Heterodyne Reception is invented by Fessenden

1909: Karl Braun and Marconi are jointly awarded the Nobel Prize in physics for their contribution to developing wireless telegraphy
UWB overview:
— Analog processing
— Long process of innovation

1910s–1920s

1910: Wireless station installed in the Eiffel Tower by the French Army Signal Corps

1912: Armstrong invents regeneration

1912: *US Congress* passes Radio Act of 1912

1920s

1920: Using a shortwave radio, Marconi establishes a link between London and Birmingham, England

1920: Armstrong announces the first superheterodyne circuit

1930s

1934: US Congress creates the *Federal Communications Commission (FCC)* through the Communications Act

1934: Armstrong applies his theory to FM
UWB overview:
—Shannon’s papers refer to the “down in the noise” as most efficient communication

1940s

1942: US Patent #2,292,387 issued to H.K. Markey and George Antheil for a frequency-hopping technique in communications

1943: US Supreme Court overturned Marconi invention of “modern radio” in favor of Tesla

1948: Claude Shannon's *A Mathematical Theory of Communication* is published

1950s–1970s

UWB overview:
—1950s UWB & impulse technology heavily investigated for communications, radar & other applications
—1960s Patents begin appearing using UWB-like techniques
—1970s Digital techniques applied to UWB impulse radios

1958: Jack Kilby produces the first integrated circuit

1971: Intel develops the first microprocessor

1979: First cellular phone network begins in Japan
1980s—2000s

UWB overview:
—1980s Publications on UWB start to appear
—1990s Attempts to make UWB legal again
—2000s UWB is made legal in the United States
—International entities are “on the verge”

1983: The United States starts cellular phone network

1988: Time Domain Corporation introduces the FCC to UWB

1993: First UWB chip set created by Aether Wire & Location, Inc.

1998: FCC notice of inquiry on UWB

1999: FCC waivers for UWB-imaging systems

2000: Notice of proposed rulemaking by FCC

2002: FCC approves UWB for commercialized use
1.3 About the Technology of the Time

Early wireless communications relied on Morse code signaling, which was generated by hand and copied by ear. Morse signaling consists of keying a carrier signal on and off in combinations of dots (“dits”) and dashes (“dahs”) that represent alphabetic characters. A moderate messaging rate was about 25 words per minute – which, in today’s measure, is equivalent to 20 bps. So the information bandwidth of the early wireless signals was relatively small, 10s of Hertz, yet the crude transmitting apparatus emitted very wideband signals, often 100s of kilohertz wide. The consequences were as follows:

1. Signals occupied significantly more spectrum than necessary for communications. Hence, there was significant interference among stations.

2. Receivers were likewise wideband and relatively “deaf” (inefficient). Thus, they collected excess background noise compared to the information bandwidth and could “hear” only the strongest signals. Consequently, the signal-to-noise ratio (SNR) was poor.

With the combination of spectral inefficiency and receiver inefficiency, interference among wireless communicators was a serious issue. Wireless needed to become narrowband for survival.

1.4 Wireless Becomes Radio: The Era of Broadcasting and Regulations

By 1905, Reginald Fessenden of Canada invented a continuous-wave voice transmitter using a high-frequency mechanical alternator that was developed by Charles Steinmetz at General Electric in 1903 to generate the radio signal carrier. Fessenden had found a way to change the amplitude of the wireless signal in step with audio amplitude variations: amplitude modulation or AM was born. Information no longer needed to be broken down into the on/off carrier interruptions according to the Morse
Code; AM allowed audio to be sent directly on the carrier. He made voice broadcasts from Brant Rock, Massachusetts, on Christmas Eve, 1906, and astonished ship radio operators hundreds of miles out in the Atlantic who heard the audio program amid their Morse code dits and dahs. It would be another 10 years before voice broadcasting became commonplace. It needed inventions and developments like Harold D. Arnold’s amplifying vacuum tube in 1913 that made possible coast-to-coast telephony and the first transatlantic radio transmission in 1915.

Prior to 1912, radio was largely the domain of amateur experimenters and ship-to-shore communications for both naval and commercial operations. Interference was a serious problem. Obsolete spark transmitters emitted wideband signals. In the United States, the Radio Act of 23 July 1912 stepped in to mitigate the interference issues but was largely unsuccessful. The Radio Act of 1927 established the Federal Radio Commission (FRC), and the Communications Act of 1934 established the Federal Communications Commission (FCC) giving regulatory powers in both wire-line and radio-based communications. Stations were to be licensed and separated by wavelength, or frequency, and stations were to use a “pure wave” and a “sharp wave” (sine wave carriers) in the words of the FRC. Sine wave communications and narrowband signals were now mandated. Unfiltered spark emissions, dubbed “class B damped sine wave emissions,” were prohibited. Radio signals were destined to become “channelized” (see Figure 1.3). These rules required that radio signals be narrowband. By organizing the spectrum and controlling interference, the regulations smoothed the way for commercial AM broadcasting to grow.

1.5 Advantages in Wider Bandwidths

The information in AM is encoded by amplitude variations in a carrier. Any other natural amplitude variations, such as amplitude noise, static, and lightning crashes, would add to the desired amplitude modulated information and be perceived as noise and distortion. Edwin Armstrong set himself to the task of finding a way to make broadcast radio insensitive to these amplitude distortions. In 1933, he discovered the advantages of wideband frequency modulation (FM) [Armstrong 1933]. In FM modulation, the frequency rather than the amplitude of the transmitter carrier was varied in proportion to the amplitude of the voice signal. Most importantly, Armstrong realized that an FM signal did not need to have a narrow bandwidth. It could vary over a wide range, several times as wide as an AM signal, and as a result have a far better SNR than AM. This meant that
programs broadcasted using wideband FM could be made higher fidelity and less distorted than AM broadcasts.

Armstrong’s discovery laid the foundations for information theory, which quantifies how signal bandwidth can be exchanged for noise immunity, that is, for a reduction in amplitude noise distortion. Voice and music transmissions could now be static free. The intentional and controlled bandwidth spreading of a signal beyond its information bandwidth was shown to have significant desirable benefits – this was a small but very important challenge to the narrowband mantra.

Commercial broadcast interests developed along channelized services in the AM broadcast band, and, later, in wider channel bandwidths in the FM broadcast band. Specific allocations in the frequency spectrum were established for radio amateurs, for broadcasting, and, later on, for television and personal communications. Wireless, now radio, communications were becoming a practical reality. The radio frequencies of interest to personal communications were steadily evolving into voice communications using analog modulations: AM and FM, both narrow and wideband. By the mid-1930s, the era of two-way radio communications in the low VHF range (30 to 40 MHz) became a reality. FM, developed by Edwin Armstrong and championed by Dan Noble for two-way land-mobile communications, effectively opened up the VHF bands for economical communications systems. By the mid-1940s, radio frequencies for land-mobile communications were allocated in the 150-MHz range. This was followed by the allocation of frequencies in the 450-MHz range during the decade of the 1960s. As the pressure increased for more and more radio signaling and radio services, higher and higher frequencies in the radio spectrum were being assigned, channelized, and developed.

1.6 Radio Takes Another Wider-band Step

Traditionally, the FCC had favored narrowband radios, which concentrate all of their power in fairly narrow channels within the radio frequency spectrum. However, as the number of users sharing the spectrum was increased, the number of available channels became limited. Claude Shannon, in 1948, offered a new paradigm, redefining the relationship among power density, noise, and information capacity [Shannon 1948].

Shannon said that under certain specific conditions, the more an information signal is spread in bandwidth in a way that makes the signal resemble background noise, the more information it is capable of holding. Because one signal spread in this way resembles noise to another signal
that is similarly spread, both can coexist because, under some specific conditions, signal energy can be detected more efficiently than noise energy. Thus, with wider bandwidth, more such sharing can occur and more total information can be conveyed. Hence, an alternative to transmitting a signal with a high power density and low bandwidth would be to use a low power density and a wide bandwidth [Malik 2001].

Shannon’s observations led to “spread-spectrum” modulation in which the signals are intentionally spread using a special family of digital codes to many times their information bandwidth. Special digital codes are used to distinguish multiple users that are simultaneously sharing the same band. Spread-spectrum technology applied to cellular telephone system resulted in a change in spectrum-regulation policy. It was the second time in the history of radio that the advantages of wideband signaling was recognized as important enough to result in changes in the regulations away from the narrowband mantra. This time, the FCC had allocated a block of spectrum within which multiple users shared the entire block of spectrum by overlapping signals across the entire band, rather than by allocating narrow slivers of bandwidth per user. Spread-spectrum users would be separated by coding rather than by frequency channels. Because of the increased efficiency in the use of precious (and expensive) spectrum, this led to improvements in the capacity of cellular systems that in turn reduced the cost of spread-spectrum cellular services.

Today, a significant growth in personal communications is taking place using spread-spectrum techniques in blocks of spectrum that have been set aside for unlicensed operations shared by other users. These signals appear covert and coexist well with other signals transmitted in the same frequency bands. This method makes much more efficient use of the congested spectra and allows greatly expanded utilization. The modern era of “digital wireless” has begun.

1.7 Still Wider has More Advantages

Through the years, a small cadre of scientists has worked to develop various techniques of sending and receiving short-impulse signals between antennas. Impulses are short time signals – the shorter the impulse, the wider its bandwidth. The experiments led to “impulse radio,” later dubbed UWB radio. By the late 1960s and 1970s ([Harmuth 1968] and [Harmuth 1978]), the virtues of wideband nonsinusoidal communications were being investigated for nongovernment uses. Prior to that, the primary focus was on impulse radar techniques and government sponsored projects. In the
late 1970s and 1980s, the practicality of modern low-power impulse radio techniques for communications and positioning/location was demonstrated using a time-coded time-modulated approach by Fullerton [Fullerton 1989], and later by others [Fleming 1998] using UWB spread-spectrum impulse techniques. Digital impulse radio, the modern echo of the Hertz and Marconi century-old spark transmissions, now reemerges as ultra-wideband radio. On 14 February 2002 [FCC15 2002], the FCC adopted the formal rule changes officially permitting ultra-wideband operations. The ruling defines access to a 7,500-MHz-wide swath of unlicensed spectrum between 3.1 and 10.6 GHz that is made available for commercial communications development in the United States.

1.8 Summary

Wireless began as wideband signaling – UWB by today’s measure and definition – because the transmitters of the time were spark-gap devices that emitted wideband, noisy signals. The receivers in use at the time were simple amplitude detectors that could not efficiently gather the wideband energy. This resulted in an inferior SNR performance, hence requiring large transmitter powers to achieve desired ranges. High-transmitter powers and excessively wide signal bandwidths meant significant spectrum sharing problems and plenty of interference. The receiver efficiency and interference issues drove wireless to narrower and narrower bandwidths per signal. The ideal was a signal as narrow as the information bandwidth. Regulations in 1912 mandated the narrowest bandwidths possible, and codified the separation of wireless services by wavelength (frequency).

In 1933, the advantages of intentional and controlled signal widening to many times the information bandwidth were discovered in the form of wideband FM radio. In this approach, bandwidth could be exchanged for noise immunity – to the delight of the FM broadcast industry. Since 1912, all spectra were allocated on a per channel basis per user to the exclusion of other users, and emissions were to be kept to the narrowest practical bandwidth. Then came spread-spectrum technology. By 1985, the FCC began allowing spectrum technology in which multiple users would be separated by direct-sequence codes rather than by discrete frequency channels. Commercial deployment of Code Division Multiple Access (CDMA) spread-spectrum cellular telephony followed in 1995. In 1999, the International Telecommunication Union adopted an industry standard for third-generation (3G) wireless systems that can deliver high-speed data and other new features. The 3G standard includes three operating modes based on CDMA technology. Thus, spectrum policy shifted away
from “separation by wavelength.” However, those multiple users were in a block of spectrum allocated for that purpose. Throughout the last half of the twentieth century, much experimentation and development took place in wideband impulse radar transmissions – the forerunner of modern UWB. Independently, commercial experiments, inventions and petitions before the FCC in the 1980s and 1990s led to the landmark FCC regulations of 2002 to permit low-power UWB for commercial development. This was a major shift in spectrum policy. Under the new regulations, multiple unlicensed users could share spectrum previously allocated to other users, including licensed users, on a noninterference basis. Thus, UWB is as much about an exciting new technology as it is about the unprecedented, unlicensed access to a huge amount of spectrum. Standards are being developed, and the UWB industry is on the verge of market deployment.

References


Further Reading


