Signals in Communication Engineering History
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Abstract
This paper is a study on various electric signals, which were employed over the History of Communication Engineering in its main landmarks: the telegraph and the telephone. The signals are presented in their time and frequency domain representations. The historical order has been followed in the presentation: wired systems; spark gap wireless; continuous wave (CW) and amplitude modulation (AM); detection by rectification; and frequency modulation (FM). The analysis of these signals is meant to lead into a better understanding on the evolution of communication technology. The material presented in this work could be used to illustrate "Signals and Systems" and "Communication Systems" courses, taking advantage of its technical as well as historical contents.

Index Terms
Communication signals, Telegraph, Telephone, Spectra, Engineering History, Signals and Systems.

I. INTRODUCTION

SINCE the electrical signals started to be used for conveying information in Wheatstone’s telegraphs (1837) till the upcoming of the high-fidelity communication era (1936) due to Armstrong’s ingenuity, many transformations occurred in signal waveforms and their corresponding spectra.

The easy-to-learn telegraph code proposed by Morse and Vail in the early 1840’s prevailed for over 150 years as the international standard for commercial and military communication. Composed by dots and dashes, represented by short and long electric pulses and implemented by ON and OFF states, the Morse code can be considered as an early form of a digital code.

By mid-1870s, as telegraph lines carrying individual messages were crossing the countries and visually polluting the city streets, great rewards were expected for an inventor who could send multiple messages over a single cable [1]. This was the motivation for the invention of the harmonic telegraph, almost concurrently by Elisha Gray and Graham Bell. By employing several vibrating reeds to produce different audible frequencies, the apparatus would multiplex several telegraph messages and fill the air near the lines with Morse broken singing tones [2]. Bell took a step forward, driven by his obsession to reproduce human speech. He developed a variable resistance device: the telephone, which could modulate the electric current along a wire, directly transmitting voice analog signals (1876).

These technological advancements, represented by the telephone and telegraph, were accomplished even before Maxwell’s theory on electromagnetic fields (1865) had been proven. That happened only in 1888, through Hertz’s diligent work. Between the terminals of his primitive but original dipole transmitter, he generated sparks, which were weakly reproduced in the open ends of a copper ring receiver, placed at a significant distance [3]. The electric signals he launched in the air through the inedited antenna resulted from energy exchange between inductive and capacitive elements, generating exponentially damped sinusoidal pulses. Hertz died without realizing all the extension and practical application for his achievements. However, various entrepreneurs, being Marconi the most famous, were soon (1895) profiting from the rising of wireless communications, sending hertzian spark gap pulses enveloped in telegraph Morse messages. Pollution was not visible any longer, but electromagnetic interference issues started to show their nails as simultaneous transmitters were spreading those wideband spectrum signals all over space. Yet, with new configurations for the transmitter, such as the so-called king-spark scheme, which incorporated Tesla’s coil, the damping factor could be at control, leading to narrower band signals [4].

Against all early radio pioneer’s beliefs that spark gap was essential for generating antenna radiation, Fessenden insisted that the only way to transmit voice (or music) over the air would be by using a high-frequency continuous wave (CW) carrier, with its amplitude modulated (AM) by the low- frequency audio variations (1906). Fessenden struggled all his life in trying to produce his AM signals and to detect them through his inventive heterodyne receivers, but technology had yet to advance before stable and tunable high-frequency generators could be realized for reliable communication and broadcasting [5].

With the replacement of spark gap systems by CW voice telephony and commercial broadcast radio, faster receivers became necessary: the old coherer/de-coherer scheme, useful for detecting slow-speed Morse code would not respond to continuously varying amplitude signals [4]. In fact, high-frequency null mean-value signals are not compatible with mechanically based detectors. They demand a rectifying process such as to create a measurable average value. Diodes were the answer for the problem, and Fleming, puzzled by the so-called Edison effect in lamps, succeeded in creating the thermionic valve (1904).
Subsequent technology of electronic valves provided power for the transmitters and improved the receiver’s sensitivity, increasing quality and extent of communications. In 1933, Armstrong demonstrated that the annoying static noise, ever present in AM broadcasting signals, could be greatly suppressed by modulating not the amplitude but the frequency of the carrier with the audio variation, thus introducing FM signals.

It is the objective of this work to present the electrical signals related to early times of Communication Engineering in their time and frequency domain representations, employing MATLAB® resources [6]. The historical order has been followed in the presentation: wired systems; spark gap wireless; continuous wave (CW) and amplitude modulation (AM); detection by rectification; and frequency (FM) modulation. The analysis of these signals is meant to lead into a better understanding on the evolution of communication technology. The material presented here could be used to illustrate “Signals and Systems” and “Communication Systems” courses, taking advantage of its technical as well as historical contents. For a better comprehension of the proposed analysis, basic knowledge on electrical circuits, communication systems, and signal processing is required.

II. Methodology

A. Spectra calculations

In order to obtain graphics of the communication signals in time and frequency domain, MATLAB® resources were employed1. Using this software for discrete-time signal processing, a proper choice of the sampling frequency $f_s$ is essential to ensure the correct signal representation. Thus, throughout the paper the sampling frequency was always chosen considering the Nyquist-Shannon sampling theorem, which establishes that $f_s$ should be at least twice the highest frequency contained in the signal spectrum $S(f)$ [7]–[10]. In other words, it was assumed that all the signals considered here had spectrum band limited to B Hz and if sampled uniformly at a rate $f_s > 2B$ samples per second could be exactly reconstructed [8], [9].

Using the function freqz.m from MATLAB® signal processing toolbox, the discrete Fourier transforms (DFT) of the sampled communication signals were calculated through an efficient algorithm known as the fast Fourier transform (FFT), originally developed by Cooley and Tukey in 1965 [8]. This type of algorithm can be more efficient if the number of points $N_{fft}$ is chosen to be a power of 2. Thus, assuming that the signal $s(t)$ is sampled at the rate $f_s$ resulting in a sequence of $N$ samples, the DFT is calculated by the FFT with a minimum of $N_{fft} = 2^\beta$ points, where $\beta = \lceil \log_2(N) \rceil$ and $\lceil \cdot \rceil$ represents the ceiling function, which maps a real number to its next larger integer. When $N_{fft} > N$, the FFT function automatically zero pads the sampled signal. With this method, one can obtain a good image of the spectrum of $s(t)$, denoted as $S(f)$. All the programs used to generate the signals and their corresponding spectra are available at [11].

B. The Morse Code Simulation

The short and long elements of Morse code are called dots and dashes, also colloquially known as ‘dits’ and ‘dahs’, so as to mimic the clicking sound of early armature receivers.

International Morse code is composed of five elements [12]:
- short mark, dot or ‘dit’ (•) – one unit long
- longer mark, dash or ‘dah’ (–) - three units long
- intra-character gap (between the dots and dashes within a character) - one unit long
- short gap (between letters) - three units long
- medium gap (between words) - seven units long

The Morse Code Alphabet is depicted in Table I, containing letters, numerals and signs. Originally, the shortest sequences were assigned to the most commonly used letters in English language. The speed of Morse code transmission is normally measured in “words per minute” (WPM) and usual values range from 5 WPM to 20 WPM (standard ability required from amateur radio licensees in sending and receiving Morse code at USA [13]). The word “PARIS” contains exactly 50 elements and is used as reference for calculating Morse code speed [14]. If it is sent 12 times within a minute (that is 12 WPM) one has 10 elements per second, meaning a unit duration of 0.1 s. Such value will be used along this work.

In order to generate the Morse code in MATLAB®, the function morse.m developed by Fahad Al Mahmood and available at [15] was modified to allow the use of different sampling frequencies $f_s$ and to fix the duration interval for each Morse unit to 0.1 s. Thus, the modified function, available at [11], converts text to playable Morse code considering the sampling frequency $f_s$.

1MATLAB® (Version 7.6.0.324 - R2008a) was chosen for being a well-known toll for engineering students. However, other numerical computation software could be used for the same purpose.
2In general, this theorem is demonstrated in almost all textbooks on signals and systems, assuming lowpass signals. A more general case of this theorem is shown in [7]
TABLE I
MORSE CODE ALPHABET.

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C. Speech signals

Since speech signals are generally nonstationary, it is more adequate to use the short-time Fourier transform (STFT) to show their characteristics in the frequency domain. However, a speech segment over a small time interval can be considered as a stationary signal, and, as a result, the DFT of the speech segment can provide a reasonable representation of the speech spectrum in this interval [16], [17]. The function `spectrogram.m` from MATLAB® signal processing toolbox was used, assuming $f_s = 44.1$ kHz combined to a Hamming window and an FFT with lengths equal to 256 and an overlapping of 50%.

With these parameters, wideband spectrograms of the speech signals were generated. For adequate comparison to the other signal spectra analyzed here, an average of the spectrum magnitude, denoted as $|S_{st}(f)|$, was also obtained. In this case, the DFT of each speech segment was calculated using a rectangular window with 256 samples and an overlapping of 50%.

III. SIGNALS AN THEIR SPECTRA

A. Morse Code wire telegraph

In 1844, Samuel Morse sent the famous message “What hath God wrought” through a wire linking Washington to Baltimore. The words had been taken straight from the Bible (Book of Numbers 23:23) to demonstrate that he could use electricity for the benefit of communications. Fig. 1 shows how this message would look like when encoded in Morse code (vertical bars indicate gap between words). When printed on a real telegraph paper tape, the words would appear in a serial fashion. It should be noticed that in Fig. 1 the message was broken into four segments in order to be accommodated within the column spacing.

In Fig. 2 we can appreciate the message converted into a pulsed electric signal in time and frequency domains. It is interesting to note that the resulting spectrum qualitatively approaches that of a periodical 5 Hz square wave, in the sense that odd harmonics are predominant (5 Hz, 15 Hz, 25 Hz, ...). This effect can be interpreted as a consequence of a resulting 0.2s (5 Hz) “average” ON/OFF waveform combining the short (0.1 s duration) and long (0.3 s duration) Morse code pulses, as they appear in a sequence of coded words. Therefore, in practical terms, one can infer that the spectrum of a Morse coded message may be considered as equivalent to that of a stationary pulsed wave.

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Fig. 1. Printed Morse coded telegraph message.
B. Harmonic telegraph

The harmonic telegraph can be considered the first multiplex communication system, being its objective to handle multiple telegraph messages along the same wire. Its invention was marked by a historical patent competition (in 1875) between Elisha Gray and Alexander Graham Bell, which was to follow dramatically with the invention of the telephone (in 1876)\(^3\) [1].

The operating principle behind the harmonic telegraph was that each message was modulated by an audible tone produced by the vibration of steel reeds operated by electromagnets. The current that drove one reed would pass over a line and set in motion, at the other side, a resonant reed that vibrated at the same frequency, while the other receiving reeds would remain unaffected, since they were tuned to other tones. The transmitted singing tone was interrupted by the dashes and dots of the Morse code. Therefore, various messages could be sent simultaneously through the system, each one corresponding to a pair of resonant reeds.

In Fig. 3 there is a representation of two Morse coded messages being transmitted simultaneously by modulating two different audible carriers: one at 500 Hz and another one at 1 kHz. The messages in this example are: “What hath God wrought” and “Mr. Watson, come here”, the latter being Graham Bell’s calling to his assistant, sent through his first telephone apparatus. The obtained spectrum can be interpreted as the convolution between the 500 Hz and 1 kHz tones with the 5 Hz square wave sinc-like spectrum of the Morse coded message shown in Fig. 2-b). As a result, the odd-harmonic spectrum of the Morse coded messages are spread around both sinusoidal carriers.

C. Wired Telephone

The strong interest of Graham Bell and his entire family on the education of deaf people drove him to gain expertise in human speech and associate such knowledge to the experience acquired on electricity when building the harmonic telegraph. His strategy was “to follow the analogy of nature” [18] and by understanding that sound and electricity could be visualized in terms of sinusoidal waves, he developed a variable resistance system based on the human ear, that modified an electric current according to speech, and not any longer to the telegraph make-or-break pattern. Such is the telephone.

In Fig. 4 one can visualize the rapid speech variations of the message “What hath God wrought”, when modulating an electric current, as transmitted in a wired telephone. The corresponding spectrum shows energy spreading over the audio frequency range. The corresponding spectrogram and average spectrum show how energy is distributed over the audio frequency range mainly concentrated around 1 kHz.

D. Hertz’s signals

Joseph Henry was the first scientist to report the oscillatory nature of the discharge of a Leyden jar in an inductive coupled circuit (1842) [3]. Later, in 1883, the British Maxwellian George Francis Fitzgerald, in his efforts to demonstrate Maxwell’s

\(^3\)It should be noted that in 2002 the American House of Representatives acknowledged Antonio Meucci for the first patent of the telephone (1871).
striking theory, suggested that resonant circuits could be used to generate electromagnetic waves [4,5]. It would be only in 1888 that Heinrich Rudolf Hertz’s persistence would lead to the anxiously pursued demonstration that the feeble electromagnetic signals he managed to produce in his laboratory possessed all the properties of visible light: radiation, reflection, refraction, diffraction and also identical velocity. He generated exponentially damped sinusoidal pulses using a Rühmkorff induction coil, whose secondary terminals were connected to his spark gap capacitively loaded dipole. The repetition of such pulses was caused by the mechanical abrupt interruptions of the current in the transformer primary, which induced a high voltage at the secondary, charging up the capacitance of the metallic spheres coupled to the dipole ends. As the electric field intensity was high enough to breakdown the air, short circuiting the gap, the antenna resonant RLC equivalent circuit (Fig. 5) would respond with its typical damped sinusoid. By using antennae and capacitive loads of various dimensions, Hertz was able to radiate oscillatory signals with approximate frequency from 50 to 500 MHz [19].

Fig. 6 shows a damped sinusoidal signal with oscillation frequency $f_2 = 5$ kHz and damping factor $\alpha$, together with the magnitude of its spectrum. It should be noticed that the sinusoid frequency has been scaled down from Hertz’s actual values, such as not to demand too many sampling points in MATLAB® calculations. No loss of generality affects the spectrum results. It can be observed that although mainly concentrated in frequency $f_2$, the energy in this spectrum spreads over a wider band when compared to a single sinusoidal tone, presenting also a DC component.

A signal that would look like the sparks generated by Hertz is reproduced in Fig. 7 with pulse repetition rate $f_1$, the oscillation frequency $f_2$, and damping factor $\alpha$. Fig. 8 shows the repeated spark signal and the magnitude of its spectrum, assuming $f_1 = 500$ Hz and $f_2 = 5$ kHz. This spectrum clearly shows the convolution occurring between the low frequency pulsed signal and the high frequency damped sinusoid.
Fig. 4. a) Waveform of the speech signal “What hath God wrought”, $f_s = 44.1$ kHz; b) Detail of $s(t)$ between 1.57 and 1.58 s; c) Wideband spectrogram, using a Hamming window of 256 samples with an overlapping of 128 samples, $N_{\text{fft}} = 2^{16}$; d) Average of the magnitude of the short-time spectrum, using a rectangular window of 256 samples with an overlapping of 128 samples, $N_{\text{fft}} = 2^{12}$.

E. Spark gap wireless telegraph

Marconi soon realized that “the artificially-formed Hertz oscillations could be used in practice for the transmission of telegraphic signals and their intelligible reception”, as he declared in his patent of 1897 [4]. Assembling various ideas and devices developed by others, he built his telegraph transmitter, including a Morse key that, when depressed for long or short intervals of time, would radiate into space the exponentially damped sinusoidal pulses, as depicted in Fig. 9. Fig 10 shows the wireless version of the Morse coded message signal “What hath God wrought”, assuming $f_1 = 500$ Hz, $f_2 = 5$ kHz, and $T = 0.1$ s. With such numbers, 50 sinusoidal pulses are fitted within each Morse unit (0.1 second) and 10 sinusoidal cycles are contained in each pulse. These values are realistic for typical spark gap Morse code transmitters [4]. The 500 Hz spark rate frequency would produce an audible tone in the headphones of the coherer or crystal sets receiving Morse code signals. The
The wideband spectrum of this composed signal, as can be observed in Fig. 10-b) and c), was the cause for many interference problems and early electromagnetic compatibility issues, which were observed as soon as wireless telegraphy started to become popular. With such a spectrum, there is no doubt why spark gap transmitters have been outlawed since 1923.

There was however a way to control the frequency spreading of energy, which characterized these transmitters: by varying the damping factor of the sinusoidal pulses. The more severe is the damping, the more pronounced is the power spreading [4]. When Karl Ferdinand Braun (Nobel prize recipient, together with Marconi, in 1909) used a Tesla’s coil structure in a telegraph transmitter in 1899 [4], he transferred the spark gap to a primary “tank” circuit that was inductively coupled to the aerial circuit (Fig. 11), both tuned at the same resonant frequency. The oscillation in the primary was induced to the secondary, but now the damping factor of the radiated signal would be dictated by the antenna circuit and the duration of oscillations could be much longer than that in the primary [5]. This effect is illustrated in Fig. 12, for a damping factor equals to $\alpha = 100 \text{ s}^{-1}$, as compared to Fig. 10, obtained with a damping factor of $\alpha = 2800 \text{ s}^{-1}$. A large damping factor means that the sinusoidal resonant frequencies of the antenna circuits in early spark transmitters varied from tens to hundreds of kHz. As an example, it can be mentioned that the international maritime distress frequency used in those times was 500 kHz. However, in order to accommodate for MATLAB® sampling restrictions, the sinusoid frequency has again been scaled down to 5 kHz, with no loss of generality in the spectral analysis. The result is a convolution in frequency-domain, of the three spectra of the signals involved in the time-domain product: the damped sinusoid, the 500 Hz repeated pulses and the “averaged” 5 Hz square wave Morse code. It is interesting to compare Figures 2 and 10, where the same Morse coded message signal has been reproduced in its wired and wireless spark gap versions, respectively.
F. CW carrier and audio signal; CW telegraph

The amplitude-damped spark gap radio waves were adequate for transmitting ON/OFF Morse coded-signals, but totally inappropriate for carrying voice or music information, since the receiver would not distinguish between the inherent spark amplitude variations and the audio signal continuous variations. Reginald Fessenden realized that in order to send voice wirelessly, he would need a source of constant amplitude oscillation, which he nominated “continuous wave” (CW). Eventually, in 1906, Fessenden managed to obtain such a carrier through mechanical alternators, operating at a frequency as high as 75 kHz, in order to be compatible with the antenna systems used at that time [5]. On Christmas evening that year, Fessenden presented the world’s first radio broadcast, transmitting speech and music modulating his sinusoidal carrier. Fig. 13 shows in the time and frequency domains the result of our standard message “What hath God wrought”, amplitude modulating a downscaled 5 kHz CW carrier, according to standard AM analytical expression [9, p. 90]. In time domain, it can be observed that the 5 kHz carrier amplitude varies according to the speech waveform of Figs. 4-a) and b). In the frequency domain, it can be observed that the spectrogram and average spectrum of Figs. 4-c) and d) have been translated and are now centered at 5 kHz in Figs. 13-c) and d), respectively.

Before this landmark, Fessenden had been working towards establishing a two-way transatlantic radiotelegraphy system, making a more CW-like spark transmitter, which led him to the development of the synchronous rotary-spark gap transmitter [5]. For the sake of comparison, it is shown in Fig. 14 a Morse coded message modulating a sinusoidal carrier with frequency $f_c$. Fig 15 shows our standard Morse coded message, assuming $T = 0.1 \text{ s}$ and $f_c = 5 \text{ kHz}$. The resulting spectrum should be compared to those of Figs. 2 and 10, outlining that the energy is now mostly concentrated near the carrier frequency, with much less dispersion than the spectra observed in spark gap systems. The spectrum of Fig. 15-b) looks much cleaner than the results shown in Figs. 10-b) and 12-b). This is mainly due to the fact that the convolution here occurs only between the single tone carrier and the Morse code equivalent square waveform, whereas spark gap spectra additionally involves the pulsed damped sinusoid, which causes a significant widening of the resulting bandwidth.

G. AM signal heterodyne detection

The use of CW signal frequencies beyond the audible range made Fessenden devise the methodology of combining two slightly different high frequencies to derive their sum and difference, the last one being within the audio range. The heterodyne reception system was proposed (1902) based on the “frequency beating” method well known to musicians by that time, who used it for tuning their instruments [5]. The external local oscillator that had to be used in this system should be tunable and stable to guarantee that the amplitude of the difference frequency component would follow the original modulating signal. Technology was not yet prepared to meet these requirements, and AM broadcasting had to wait for the invention of the triode vacuum tube by Lee De Forest (1906) [5]. Figs. 16 and 17 illustrate the steps for demodulating the AM signal through heterodyne detection. The audio message “What hath God wrought” AM modulated by the 5 kHz carrier, as depicted in Fig. 13 was beaten to a 6 kHz local oscillator. The resulting waveform is shown in Figs. 16-a) and b). The corresponding spectrogram and the average of the spectrum magnitude in Fig.16-c) and d) clearly show the transfer of audio information contents into the resulting trigonometric products of sum (11 kHz) and difference (1 kHz) between the carrier and local oscillator frequencies.
Fig. 8. a) Repeated spark signal as produced by Hertz with \(f_1 = 500\) Hz, \(f_2 = 5\) kHz, and \(\alpha = 2800\) s\(^{-1}\); b) Magnitude of the spectrum, \(f_s = 50\) kHz, \(N_{\text{ff}} = 2^{13}\); c) Detail of \(|S(f)|\) centered at 5 kHz.

Fig. 9. Wireless spark gap telegraph signal with pulse repetition rate \(f_1\), oscillation frequency \(f_2\), and \(T\) duration interval for each Morse unit.

A further step of passing this signal through a 2 kHz cut-off low-pass filter attenuates the high frequency product and results in signal \(y(t)\) consisting of the audible carrier of 1 kHz, with its amplitude varying accordingly to the message information (Fig. 17). As the filter does not completely eliminate the 11 kHz product, it is still possible to observe its attenuated presence in the spectrogram of Fig. 17-b) and also in the average of the spectrum magnitude at Fig. 17-c). It is interesting to compare Figs. 4-b), 13-b), 16-b) and 17-a), for they represent the same message processed by different procedures: audio message; amplitude modulated; AM signal beaten to local oscillator; and filtered (demodulated) message with 1 kHz carrier, respectively. It should be noticed that the audio message will be fully recovered only when the resulting waveform \(y(t)\), whose detail is shown in Fig. 17-a), is applied to an envelope detector.
Fig. 10. a) Wireless spark gap telegraph message with $f_1 = 500$ Hz, $f_2 = 5$ kHz, and damping factor $\alpha = 2800$ s$^{-1}$; b) Magnitude of the spectrum, $f_s = 50$ kHz, $N_{fft} = 2^{20}$; c) Detail of $|S(f)|$ near 5 kHz carrier.

Fig. 11. Braun/Tesla king spark transmitter equivalent circuit.

H. Rectifying the CW signal

Rectification of the continuous waves was initially achieved by John Ambrose Fleming, commissioned by Marconi to increase the sensitivity of radio receivers. The Fleming valve gave birth to the electronics age in communications, rectifying the alternate zeroed-mean-value CW signals and displacing the unreliable and slow Morse code coherer detector (1904) [5], [20].

The same AC to DC conversion effect was also performed by early crystals (like galena and carborundum [4]) and later, by semiconductor diodes. The spectrum of a half-wave rectified 1 kHz sinusoid, presented in Fig. 18, shows the presence of a 0 Hz component, which can be easily measured by a simple DC multimeter, illustrating thus the action of a diode detector over AC high frequency signals.
When Edwin Howard Armstrong came back from serving at the First World War, he started to study the problems affecting AM systems, particularly those related to static noise and interference, caused mainly by atmospheric discharges. In 1930 he established the concept of FM systems, where the carrier frequency, instead of its amplitude, would vary according to the audio signal variations. This would initiate the “high-fidelity” era of communications. Such modulation scheme had been tried before and discarded, for it was misused and did not solve the noise problem. In order to achieve noise immunity, Armstrong demonstrated that FM systems should make use of a high-frequency carrier, associated to a wideband receiver, against the standing belief that communication should be achieved with low frequency carrier (for reaching farther) and narrow band (for better selectivity and low interference) [21].

In Fig. 19 it is shown the appearance of a 10 kHz carrier being frequency modulated by the message “What hath God wrought”, according to standard FM analytical expression [9, p. 110]. Its corresponding wideband spectrum of Fig. 19-c) can be compared to its AM counterpart of Fig. 13-d). Carrier frequency was changed from 5 kHz (AM) to 10 kHz (FM) so that one could fully appreciate the energy spreading caused by frequency modulation. In the spectrogram of Fig. 19-b) such spreading in frequency clearly reproduces the original time domain message shaping presented in Fig. 4-a), nicely illustrating the concept of FM signals.

IV. CONCLUSION

Various electric signals widely employed along the History of Communication Engineering were presented and analyzed in this work. Their time and frequency domain representations were obtained through MATLAB® resources: sampling, FFT algorithm, signal processing toolbox and various functions. Careful study and analysis of these signals can provide a deeper comprehension on how technology gradually evolved from wired Morse code telegraphic communication to the high fidelity
frequency modulation scheme, passing through wired telephony, spark gap wireless telegraphy and audio systems, CW, AM and detection techniques. The signals and their corresponding spectra make clearer some interesting and practical aspects of communication technology, such as the heavy interference issues affecting early wireless spark gap transmitter systems.

The authors believe that this text, as well the developed MATLAB® accompanying programs [11] consist of a motivating material for teaching “Signals and Systems” and “Communication Systems” courses, through real and historical examples. The technical contents include topics on electrical circuits, communication systems and digital signal processing. Associated to that, engineering students can benefit from getting closer contact with some steps and personages in the history of communication technology, which can arise interest in searching for further information in this area.

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Fig. 14. CW modulated Morse coded message signal with carrier frequency \( f_c \) and a \( T \) duration interval for each Morse unit.

Fig. 15. a) CW modulated Morse coded message signal. Message: “What hath God wrought”; b) Magnitude of the spectrum, \( f_s = 50 \) kHz, \( N_{\text{FFT}} = 2^{20} \); c) Detail of \( |S(f)| \) centered at 5 kHz.

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REFERENCES

Fig. 16. a) AM modulated message “What hath God wrought” with $f_c = 5$ kHz carrier, beaten to $f_o = 6$ kHz local oscillator, $f_s = 44.1$ kHz, $N_{ft} = 2^8$; b) Detail of $s(t)$ between 1.57 and 1.58s; c) Wideband spectrogram, using a Hamming window of 256 samples with an overlapping of 128 samples, $N_{ft} = 2^{12}$; d) Average of the magnitude of the short-time spectrum, using a rectangular window of 256 samples with an overlapping of 128 samples, $N_{ft} = 2^{12}$.

Fig. 17. a) Detail of the demodulated signal after passing through a 2 kHz cut-off low-pass filter; b) Wideband spectrogram of the audio demodulated signal, using a Hamming window of 256 samples with an overlapping of 128 samples, \( N_{\text{fft}} = 256 \); c) Average of the magnitude of the short-time spectrum, using a rectangular window of 256 samples with an overlapping of 128 samples, \( N_{\text{fft}} = 2^{12} \).

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Fig. 18. a) Rectified CW signal, \( f_c = 1 \text{ kHz} \), \( f_s = 50 \text{ kHz} \), \( N_{\text{fft}} = 2^{13} \); b) Magnitude of the spectrum; c) Detail of \( |S(f)| \) between 0 and 2.5 kHz.
Fig. 19. a) Detail of the speech signal waveform “What hath God wrought”, modulating a CW carrier in frequency, $f_c = 10$ kHz, $f_c = 44.1$ kHz; b) Wideband spectrogram, using a Hamming window of 256 samples with an overlapping of 128 samples, $N_{\text{fft}} = 2^{8}$; c) Average of the magnitude of the short-time spectrum, using a rectangular window of 256 samples and an overlap of 128 samples, $N_{\text{fft}} = 2^{12}$. 