Land Forces Academy Review
Vol. XXIX, No. 4(116), 2024

WAVEFORM ANALYSIS IN INTEGRATED TACTICAL RADIO SYSTEMS

Andreea MUREȘAN
"Nicolae Bălcescu" Land Forces Academy, Sibiu, Romania
deea_16m88@yahoo.com

Paul BECHET
"Nicolae Bălcescu" Land Forces Academy, Sibiu, Romania
bechet.paul@armyacademy.ro

ABSTRACT

This article investigates the evolving requirements and challenges of modern tactical communications systems, with a particular focus on military-specific waveforms. It is imperative that these systems integrate IP technology, provide sufficient bandwidth, and maintain reliable operation in harsh environments. In designing waveforms, the key criteria include data transmission rate, coverage area, robustness and protection against jamming and detection. However, the implementation of high data transmission rates can lead to reduced coverage area, thus necessitating the use of multiple waveforms that are tailored to different operational requirements. This paper examines a part of the characteristics of narrowband and wideband waveforms operating in the frequency range from 3 MHz to 5 GHz, with channel bandwidths from 3kHz to 50 MHz and supporting data rates of up to 300 Mbps. The analysis focuses on some critical parameters, including signal-to-noise ratio, bit error rate and modulation schemes, with the objective of optimizing long-distance communications and data rate between fixed and mobile points in tactical environments.

KEYWORDS: Tactical communications systems, Signal-to-noise ratio, Channel bandwidth, Data transmission rate, Coverage area

1. Introduction and Objectives

The demands placed on tactical communication systems have become increasingly diverse and complex in terms of performance. Modern tactical communication systems are required to integrate seamlessly with IP-based information systems, provide sufficient bandwidth to support a diverse range of services, and ensure uninterrupted operation even in challenging environmental and operational conditions typical of tactical scenarios (Wang, Chuang, Davidson & Liu, 2018). To achieve rapid and dependable communication, military forces across the globe are adopting high-capacity, multiband radios and radio relay systems (Fostea, Barbu, Arseni & Boiangiu, 2015).

The user profile for tactical communication systems encompasses both secure and non-secure capabilities for transmitting data, voice, and video (Pawgasame & Wipusitwarakun, 2015). This is achieved through the utilization of both wideband and narrowband waveforms. In the context of radio technology, the term "waveform" is used to describe the complete set of radio functions, encompassing both the user input and the radio frequency (RF) output, as well as the

DOI: 10.2478/raft-2024-0060

transmission and reception of data (Lussier, 2006). This encompasses fundamental signal characteristics, including modulation techniques, data transmission rates, and the codes utilized for frequency hopping or to secure transmitted information (Șorecău, Șorecău, Cîrstea & Bechet, 2024). A waveform is defined by four critical requirements: data transmission rate, coverage area, resilience, and protection against jamming or detection/recognition efforts (Șorecău, Șorecău, Vasile & Bechet, 2023). These criteria ensure that the waveform is capable of delivering data at the requisite rate, covering the necessary geographical area, maintaining operational reliability in challenging conditions, and protecting against electronic warfare tactics. Furthermore, waveform design frequently considers additional factors, such as power efficiency, latency, interoperability with other communication systems, and compliance with regulatory standards, with the objective of optimizing performance and reliability in diverse operational settings.

The necessity for higher data transmission rates requires the use of a wider bandwidth, which, in turn, results in a reduction of the coverage area if the transmission power remains constant. The optimal solution is the adoption of multiple waveforms, each optimized for a specific set of requirements. To illustrate this, the JTRS (Joint Tactical Radio System) program, initiated by the U.S. Army, provides a range of waveforms tailored to different operational categories (Feickert, 2005; Lussier, 2006).

The data transmission rate represents a critical element in the functionality of any communication system. It is typically influenced by the available bandwidth. Wideband waveforms (WBWFs) are a fundamental component of tactical communication systems (Liedtke et al, 2012), as they facilitate high data transmission rates. These waveforms are designed to operate in frequencies ranging from 200 MHz to 5GHz, typically utilizing channel widths of 5 MHz to 100 MHz. This configuration allows for data transmission speeds of approximately 2 Mbps to 50 Mbps, which are crucial for supporting bandwidth-intensive applications such as video streaming and real-time data exchange in tactical environments (Șorecău, Șorecău, Vasile & Bechet, 2023).

This paper presents a theoretical examination of military-specific radio links, based on simulations that assess the performance of the waveforms in both line-of-sight (VHF, UHF) and non-line-of-sight (HF) scenarios. These scenarios underscore the practical significance of parameters, including data transfer rate, transmission power, channel bandwidth, signal-to-noise ratio (SNR), bit error rate (BER), and modulation schemes. These elements are vital for the establishment of dependable communication links. Furthermore, the study employs VOACAP software to assess high frequency (HF) waveforms for long-distance communication, considering variables such as transmission frequency, time of day, signal strength, and ionospheric conditions. The aim is to establish the optimal configuration for effective coverage between a fixed point in Bistrița city (Romania) and the designated receiving locations in Romania.

2. Materials and Methods

This section outlines the principal methodologies and materials employed to assess the efficacy of diverse modulation techniques used in military communications, with a particular emphasis on amplitude modulation (AM), frequency modulation (FM), digital modulation, and their deployment in very high frequency (VHF) and HF links. Moreover, simulation tools, such as Radio Mobile and VOACAP, are utilized to quantify essential parameters, including bandwidth, SNR, and BER. Furthermore, manual calculations were performed for parameters not included in the simulators, such as the channel capacity.

The following modulation techniques are examined in order to ascertain their efficacy in a variety of communication contexts. AM is utilized due to its simplicity and capacity to facilitate long-distance ground-to-air communication, particularly in challenging environments. The modulation index in AM, which controls the degree of carrier amplitude variation, is meticulously monitored. If not properly monitored, high modulation indexes can result in overmodulation and signal distortion, which can impair communication quality.

FM is investigated with regard to its prevalent deployment in VHF bands, especially those above 30 MHz, where it offers superior audio quality and resilience to interference. In military applications, where maintaining communication clarity in environments with high interference is of paramount importance, FM is especially advantageous. The relationship between the carrier wave frequency and the modulating signal is a central area of investigation, with frequency deviations reflecting data transmission.

The efficiency of various digital modulation techniques, including Quadrature Amplitude Modulation (QAM), Phase Shift Keying (PSK), and Frequency Shift Keying (FSK), is being examined with regard to their capacity to transmit data in an efficient manner over radio frequency (RF) channels. These digital techniques offer enhanced resilience to noise, higher data rates, and are of high importance for the secure, high-capacity transmission of military communications.

In order to accurately assess the data transmission performance in various digital modulated communication scenarios, it is necessary to consider a number of key factors, including bandwidth and channel capacity. The aforementioned parameters are vital for evaluating the efficacy and dependability of disparate modulation schemes in military communication systems.

Bandwidth is defined as the range of frequencies available for data transmission and is measured in hertz (Hz). In addition to bandwidth, the channel capacity is of substantial significance in determining the maximum amount of information that can be transmitted successfully through a communication channel within a specified time interval. The channel capacity (C) is a function of both the transmitted power and the available bandwidth. In order to quantify the performance of a communication system, the following parameters are considered here, similar to (Dănăilă & Șorecău, 2023):

− Bit Rate (R_b): The number of bits transmitted per unit of time.

− Symbol Rate (R_s): The number of symbols transmitted per unit of time, where each symbol may represent multiple bits depending on the modulation scheme employed.

The Nyquist limit sets the maximum permissible transmission rate for an ideal, noiseless channel, thus assuring accurate data recovery.

$$C = 2 * B * \log_2 M \qquad (1)$$

where:

C = capacity;

B = bandwidth;

M = bits packing factor;

In contrast, the Shannon limit establishes the theoretical upper limit for the channel capacity that can be supported by a noisy channel. These concepts are fundamental to the optimization of data transmission, as they determine the efficiency with which bandwidth and power are utilized.

$$C = B * \log_2(1 + \mathrm{SNR}) \qquad (2)$$

SNR quantifies the ratio of the useful signal power to the background noise power present in the channel. The quality of data transmission is contingent upon the SNR, which is usually expressed logarithmically in decibels (dB). A higher SNR indicates a clearer signal with fewer transmission errors, which is essential for maximizing channel capacity and ensuring reliable communications.

$$\text{SNR} = 10 * \log 10 \left(\frac{\text{Channel power}}{\text{Noise power}}\right) \quad (3)$$

* when noise and channel power are not expressed in decibels;

In order to evaluate the efficiency of these modulation techniques, two primary software tools were utilized.

Radio Mobile is a simulation tool that enables the assessment of radio link performance in a variety of terrains and environmental conditions (Figure no. 1). It supports the design and analysis of communication systems while providing insights regarding the performance of various modulation techniques with respect to signal quality, range, and interference. Radio Mobile facilitates the testing of parameters including signal power, interference levels, and terrain obstructions (Dănăilă & Şorecău, 2023).

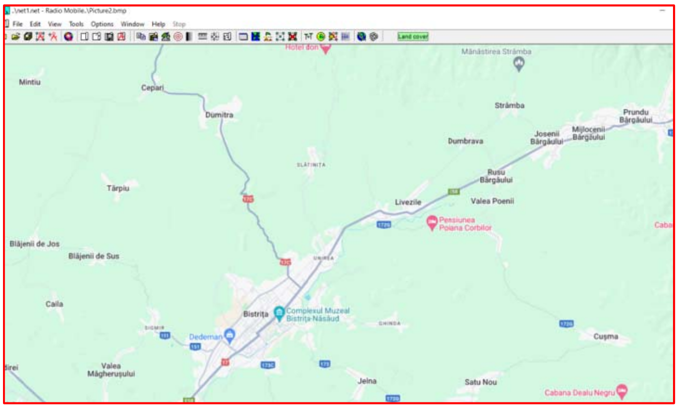

Figure no. 1: *A viewing window of Radio Mobile software for VHF/UHF radio simulation*

The software calculates the propagation of radio waves based on the underlying physical environment, enabling the prediction of potential coverage areas, signal strength, and interference scenarios. Such capabilities facilitate the comprehension of the efficacy of modulation techniques within realistic military contexts.

VOACAP simulates the propagation of HF signals, taking into account ionospheric conditions, solar activity, and other factors that affect HF propagation (Figure no. 2). It helps in determining the best frequencies for long-distance communication and predicting signal strength over various distances and times of day. This is essential for evaluating AM and other HF modulation techniques in military applications.

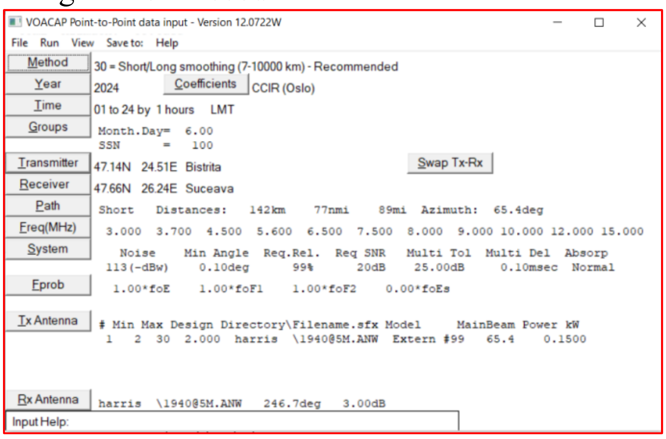

Figure no. 2: *A viewing window of HF communications simulation software − VOACAP*

In order to test the station's capability, the Radio Mobile simulation environment will be used, and the specifications provided by the manufacturer, both for the station and for the antenna type used, will be implemented in the application. The evaluation scenario will be accomplished in Bistrița-Năsăud county.

This initial scenario aims to use the two types of modulation according to the manufacturer's specifications.

3. Results and Discussions

3.1. Efficient Waveform Analysis for VHF/UHF Coverage Area Using Radio Mobile

Scenario 1: AM versus FM modulation

The first scenario under test proposes the evaluation of analog modulations used by military radios stations. Consequently, since it is intended to test both types of signals, the capability of a multi-band radio station providing both AM and FM voice services was analyzed. The chosen transmit power in this case was 10 W (40 dBm). In the first stage the parameters for verifying the radio link using AM were configured, and as can be seen in the planned conditions according to all technical specifications the link is not functional (Figure no. 3). It can therefore be concluded that the use of AM modulation under these conditions is totally not recommended.

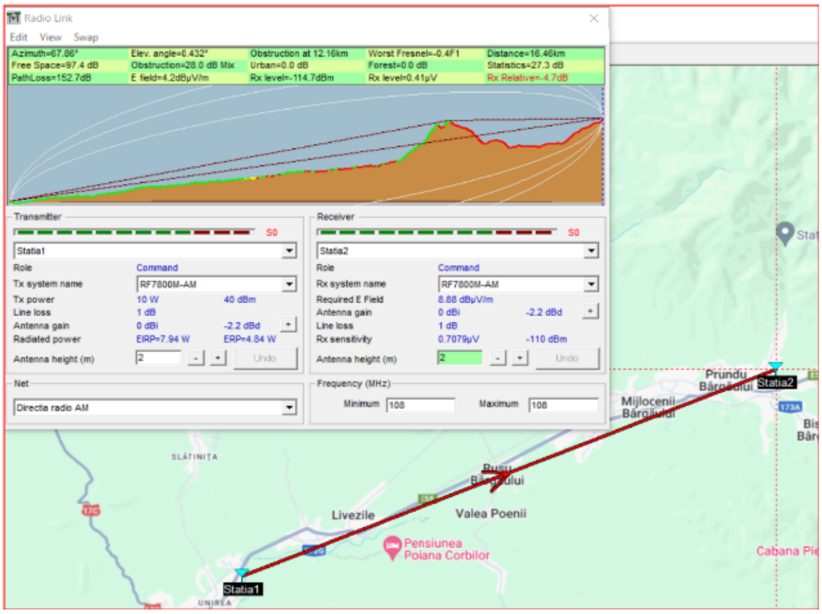

Figure no. 3: *Radio link using AM modulation: Results of running first scenario*

For the FM radio link, the same types of equipment were implemented in the computational software as in the AM case, and they were placed at the same geographical coordinates as before, in order to have a comparison capability. Thus, after running the application, the FM radio link is functional, with a reception level of -109.7 dBm, 5dB better than -114.7 in AM case, as can be seen in Figures no. 3 and 4.

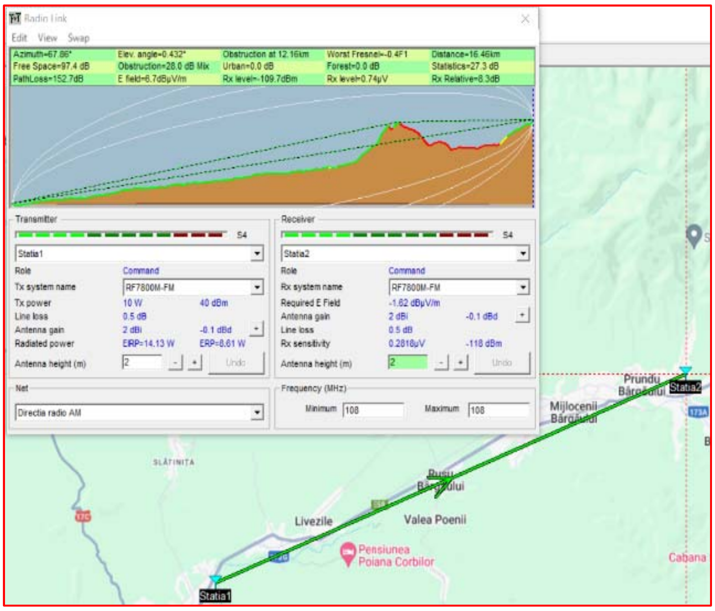

Figure no. 4: *Radio link using FM modulation: Results of running first scenario*

To validate the stated receiver sensitivity parameters, the noise figure associated with each modulation type was calculated for the specified bandwidths. The objective was to ascertain whether these figures align with the manufacturer's specifications. To maximize the precision of the calculated values, a consistent bandwidth of 25 kHz was selected for both AM and FM transmissions.

For both FM and AM modulations with a bandwidth (B) of 25 kHz, the channel noise power is -130 dBm.

$$N[dBm] = -174 + 10\lg(25 * 10^3) = \mathbf{-130\ dBm} \quad (4)$$

The addition of a SNR of 10 dB for both modulations results in a receiver sensitivity of -120 dBm. In the case of FM, the receiver sensitivity, as indicated in the specifications (L3Harris, 2021a), is -118 dBm. This value implies that the internal noise of the equipment is 2 dB. Therefore, the calculated sensitivity for FM is in accordance with the specifications provided by the manufacturer. In the case of AM, while the channel noise is also -130 dBm for the same bandwidth, the specifications indicate a difference of 8 dB in comparison to FM. Thus, by adding 10 dB SNR and the 8 dB difference to the noise power, we obtain -112 dBm. In consideration of the 2 dB internal noise, the receiver sensitivity for AM is determined to be -110 dBm, which aligns with the specified value.

Scenario 2: digital modulation

In order to guarantee the optimal data transfer rate, the 20 MHz equipment bandwidth was selected as the initial scenario. The radio-relay equipment is equipped with the capability of spectral flexibility, as indicated by the manufacturer, which allows for the support of four distinct channel sizes (5, 10, 20, and 50 MHz) in Point-to-Point (PTP) mode (L3Harris, 2021b).

As the Radio Mobile simulation application lacks the capacity to plan a line-of-sight (LOS) radio link that considers channel bandwidth, signal-to-noise ratio (SNR), modulation type, and bit error rate (BER), these parameters will be calculated and integrated into the simulation to ensure the planning process closely resembles the actual scenario.

Test 1. The data from which we started to calculate the reception sensitivity (the value required to be set in the simulation) are as follows:

− Bandwidth: 20MHz;
− Modulation: 32PSK;
− BER: 10^{-6};
− Transmit Power: 37dBm.

To find the transfer rate, the Nyquist formula (1) for the channel capacity will be used.

$$C = 2 * 20 * \log_2 32 = 200 \text{ Mbps} \qquad (5)$$

The channel noise power in the 20 MHz bandwidth is calculated in the same way as in the previous subsection using formula (3).

$$N = -174 + 10 \log_{10} 20 * 10^6 = -101 \text{ dBm} \qquad (6)$$

The value of E_b/N_0 ratio for 32PSK modulation is found in the MATLAB numerical computing environment functions, using the application - Bit Error Rate Analysis. For the desired BER of 10^{-6}, $E_b/N_0 = 23$ dB.

$$SNR = E_b/N_0 \times R_b/B = 200 \cdot 200/20 = 2000 = 33\text{dB} \qquad (7)$$

This results in a receive sensitivity of -68 dBm (-101+33).

To set the antenna parameters, an antenna type supplied by the manufacturer with a gain of 21 dBi was used, the antenna being placed on a 21m height telescopic mast, which is found in the equipment set.

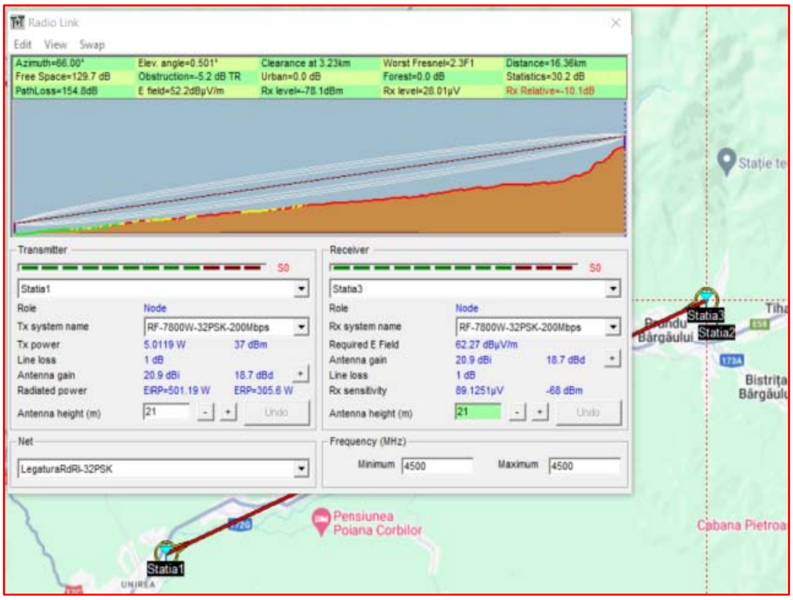

Figure no. 5: *Result of the radio-relay link for 32PSK modulation*

The result of the radio link from running the simulation over a distance of 16.36 km for the chosen modulation type is not a solution in this context. The result shows that the received signal level is -78 dBm, and what was desired for a BER of 10^{-6} was -68 dBm, the Relative Rx being -10 dB (Figure no. 5).

Test 2. In the second case we want to analyze for the same radio-relay link, except that the parameters were changed: the bandwidth was increased and the bit packing factor was decreased (a weaker modulation was chosen):

− Bandwidth: 50MHz;
− Modulation: 8PSK;
− BER: 10^{-6};
− Transmit Power: 37dBm.

The result of the radio link after running the simulation and compute the calculation of capacity and SNR, over the same distance, for the chosen modulation type, show a data transfer rate increased to 300Mbps, but indicates that the data link is functional (Figure no. 6). The result shows that the received signal level is 5.2dB (Relative Rx) better than that calculated for a BER of 10^{-6} of -83.24 dBm.

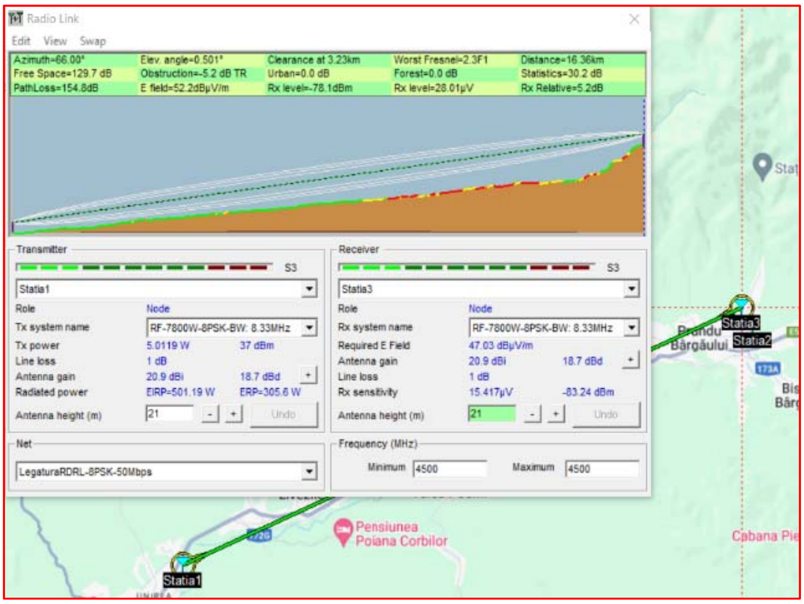

Figure no. 6: *Result of the radio-relay link for 8PSK modulation*

While higher order modulations can offer higher data transfer rates, they also require better channel conditions, especially in terms of signal-to-noise ratio. This makes them less effective for longer distances or in environments with higher levels of noise and interference. Therefore, it is essential to consider the modulation scheme in relation to the desired channel conditions and BER to optimize the performance of a radio link, balancing the trade-offs between data rate, bandwidths, digital modulation and power requirements.

3.2. Efficient Waveform Analysis for HF Coverage Area Using VOACAP

This study will analyze the most efficient waveform for radio coverage between a transmitting point located in Bistrița city and receiving points located in Suceava, Timișoara and Constanța cities. The analysis will be performed using the VOACAP software, which is a standard tool in the field of radio communications for predicting the propagation of short-wave radio waves.

For the coverage analysis, the following main parameters were considered:

-Transmitting point: Bistrița

-Receiving points: Suceava, Timișoara, Constanța

-Transmission frequencies: 3, 3.7, 4.5, 5.6, 6.5, 7.5, 8, 9, 10, 12, 15 MHz

-Transmission power: 150 W

-Broadcasting time: 24h

-Calendar month: January (winter) vs August (summer)

-Wave type: Shortwave (HF)

Simulations were performed for different combinations of the above-mentioned parameters to determine the most efficient waveform and configuration for each destination.

Scenario 1: Bistrița - Suceava (142 km distance)

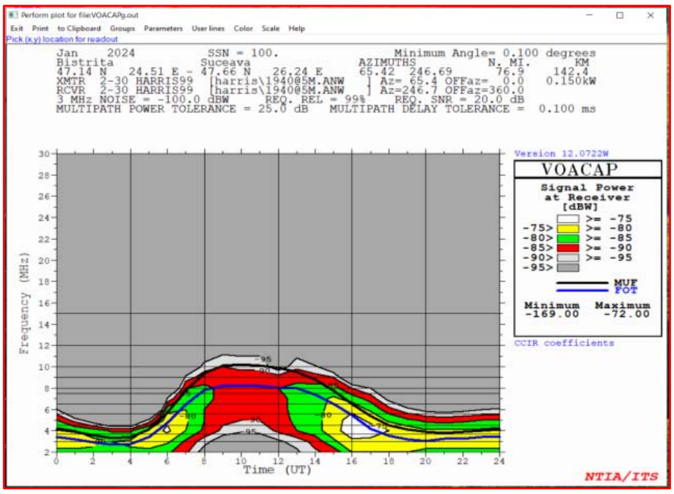

Figure no. 7: *Received signal power vs frequency vs time − Suceava*

In graph of Figure no. 7, the Maximum useable frequency (MUF) decreases significantly during the night and reaches a minimum around 3:00 AM, then increases again during the day, reaching maximum values around 09:00-12:00. This indicates that in winter, ionospheric conditions are more favorable for high frequencies during the day, but much less effective at night.

The lower blue line indicates the Frequency of Optimum Transmission (FOT), which is the optimum frequency for stable communication with the best SNR. FOT follows a similar pattern to MUF, but at lower values.

Scenario 2: Bistrița – Timișoara (295 km away)

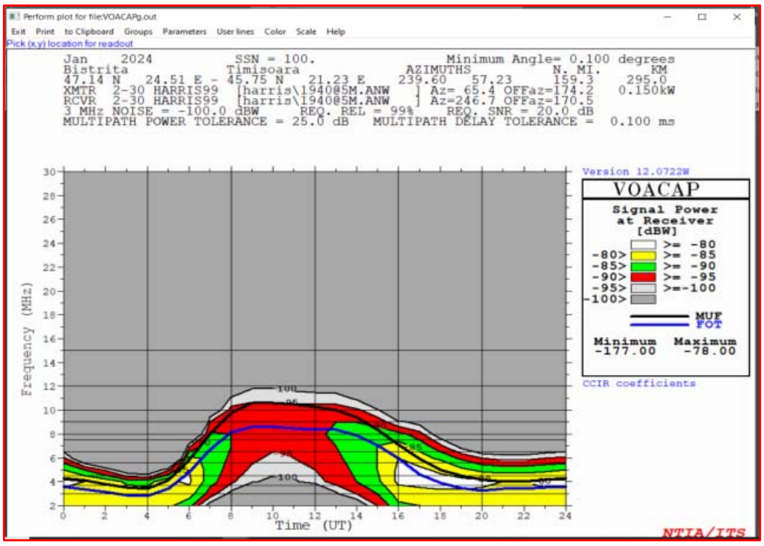

Figure no. 8: *Received signal power vs frequency vs time – Timișoara*

MUF and FOT, in Figure no. 8, maintain in large proportions the same values as in the case of the link between Bistrita and Suceava. Therefore, the frequencies used for the first link can be efficiently used also in this case where the link distance has been increased.

Scenario 3: Bistrița − Constanța (460 km away)

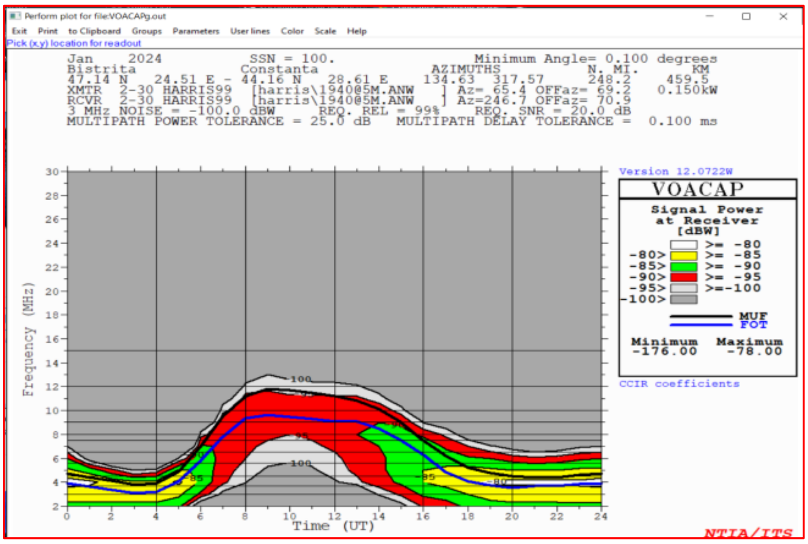

Figure no. 9: *Received signal strength vs frequency vs time – Constanța*

In another experiment, a similar behavior was observed when the link distance was extended to 460 km, corresponding to a link between Bistrița and Constanța. Although the extension of the distance led, as in the previous case, to a decrease in signal strength, an improvement was observed during the daytime (Figure no. 9).

The holding constant of FOT and MUF suggests that, although the distance has increased, the frequencies remain optimal for the communication link, probably due to the ionosphere's ability to sustain these frequencies under varying conditions.

These observations highlight that under summer conditions, on an extended HF link between Bistrița and Constanța, operators can expect an improved SNR performance during daytime, which may partially compensate for the overall SNR decrease due to the increased distance. This is important for optimizing long distance communications, especially in tactical/operational scenarios, where every SNR decibel counts.

4. Conclusions

This paper presents examples of examination of the performance characteristics of various waveforms employed in military contexts. These waveforms play a pivotal role in ensuring the reliability and security of communication links in diverse and often challenging operational environments. The practical scenarios realized in the simulation environment provided by the Radio Mobile and VOACAP applications, offer valuable insights into the tactical radio communication planning process, ensuring that the installed equipment will provide the planned radio link performance at the time of installation. Accordingly, the initial scenario was designed to assess the functionality of voice communication assurance in Bistrița-Năsăud County between two locations established according to the mission/exercise parameters using analog modulation.

The subsequent tests concentrated on the analysis of the waveform, this time in the context of digital modulation for data communications. As in the preceding case, the operational parameters of military radio stations were employed in the simulation, in this instance, the high-capacity radio relay systems.

Given that the paper addresses VHF, UHF, and HF waveforms, the final study focused on the most efficient parameters for radio links that extend beyond line-of-sight, specifically HF waveforms. The scenarios were created in the VOACAP simulation environment and involved three situations between a fixed transmitting point in Bistrița and three receiving points in different locations at various distances.

The results of the simulations, demonstrate that in order to establish functional and reliable links in the field, comprehensive and precise analyses are essential, taking into account all the technical aspects of a planned radio link in terms of modulation, desired bit error rate, transmit power, distance, frequency, time of day, desired minimum transfer rate, signal-to-noise ratio, and so forth. However, this must be done in close correlation with the actual capabilities of the system or equipment in question.

The tests have demonstrated the VHF conditions of using of a certain modulation to the detriment of another in order to ensure voice communications. In UHF, the conditions for an efficient data link must be taken into account, as well as the minimum transfer rate to be ensured. Finally, in HF, the conditions for an efficient link must take into account a set of frequencies that are consistently chosen for different distances. In addition, the time of day, season, and ionospheric conditions must be taken into account.

REFERENCES

Dănăilă, N., & Şorecău, M. (2023). Web Application for Estimating Radio Link Budget Based on Channel Capacity And Bit Error Rate. *Land Forces Academy Review, Vol. 28*, 222-232.

Fostea, D., Barbu, A., Arseni, S., & Boiangiu, L. (2015). Testing state of the art radio communications equipments with regard to the legacy systems used in tactical environment. *“Mircea cel Batran” Naval Academy Scientific Bulletin*.

L3Harris. (2021a). *L3HARRIS FALCON III®. RF-7800M-MP. Wideband Networking Manpack Radio.* Available at: https://www.l3harris.com/sites/default/files/2021-01/cs-tcom-falcon-iii-rf-7800m-mp-multiband-networking-manpack-radio-datasheet.pdf, accessed on August 05, 2024.

L3Harris. (2021b). *FALCON III RF-7800W. High Capacity LOS radios with up to 430 Mbps of throughput.* Available at: https://www.l3harris.com/sites/default/files/2021-01/cs-tcom-rf-7800w-high-capacity-los-radio-datasheet_0.pdf, Available online, last accessed 06.08.2024.

Liedtke, F., Tschauner, M., Singh, S., Adrat, M., & Antweiler, M. (2012). Selection and investigation of a civil Wideband Waveform for potential military use. *2012 Military Communications and Information Systems Conference (MCC)*, 1-8.

Lussier F.M. (2006). *The army’s future combat systems program and alternatives*. A CBO study, The Library of Congress. Available at: https://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/74xx/doc7461/08-02-army.pdf.

Pawgasame, W., & Wipusitwarakun, K. (2015). Tactical wireless networks: A survey for issues and challenges. *2015 Asian Conference on Defence Technology (ACDT)*, 97-102.

Şorecău, E., Şorecău, M., Vasile, A., & Bechet, P. (2023). Advanced Military Radio Channels Monitoring System Based on Software Defined Radio Platform: Preliminary Analysis. *International conference KNOWLEDGE-BASED ORGANIZATION*, Vol. 29, 107-112.

Şorecău, M., Şorecău, E., Cîrstea, R., & Bechet, P. (2024). Enhanced Spectrum Monitoring Capabilities Based on Software-Defined Radio Systems: Validation of a Real Time Frequency Hopping Signal Detection. *International Conference KNOWLEDGE-BASED ORGANIZATION*, *Vol. 30*, 1-10.

Wang, M., Chuang, Y.S., Davidson, S.A., & Liu, B. (2018). In the design of tactical communication systems. *2018 Annual IEEE International Systems Conference (SysCon)*, 1-6.