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Domain Electrical Engineering

DOCTORAL THESIS

- SUMMARY -

"Analysis of noise present in ionospheric channels in order to implement efficient waveforms in the HF range"

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CONTENTS OF DOCTORAL THESIS

INTRODUCTION

The critical importance of high-frequency (HF) communications is underscored by its indispensable role in areas where traditional communications infrastructures are either lacking or compromised. These scenarios include remote geographical locations, maritime environments and emergency and disaster relief missions, for which rapid deployment of communications systems is vital.

However, despite its extensive applications, the field of HF communications faces considerable challenges due to the highly unpredictable and variable nature of the ionosphere. A number of factors, including solar activity, time of day and atmospheric conditions, can have a significant impact on the ionospheric propagation of HF signals, leading to unpredictable quality and reliability of communications.

In the Ukrainian conflict, HF communications have been of great help, providing reliable long-distance connectivity and resistance to electronic warfare tactics. Its versatility and ability to integrate with modern communications systems improved operational coordination and supported humanitarian assistance.

This PhD thesis aims to investigate state-of-the-art Software Defined Radio (SDR) technology, which provides flexibility in configuration and control over radio functions and parameters. The innovative use of SDR technology enables real-time monitoring and adjustment of communication parameters, facilitating increased radio link performance despite variable ionospheric conditions.

The work has 212 pages, representing the current state of knowledge and personal contributions, structured in 9 chapters, 3 research directions, 8 studies, plus 128 figures, 5 tables and 99 bibliographical references.

The theoretical foundation of this research is based on the principles of electromagnetic wave propagation in the ionosphere, a fundamental component of HF communications. This involves understanding the complex interactions between radio waves and ionospheric layers, which are affected by variables such as electron density, electromagnetic fields and solar radiation. The main focus of this study is on the concept of

Near Vertical Incidence Wave Propagation (NVIS). This technique uses radio waves with a large angle of incidence, which are reflected back to the Earth by the ionosphere, allowing reliable medium-range communications without the need for repeater stations.

Integrating orthogonal frequency division multiplexing (OFDM) into the theoretical framework offers a substantial advantage. OFDM is an advanced digital modulation technique that splits a radio spectrum into multiple orthogonal signals of closely spaced subcarriers, each carrying a portion of the user's data. This method significantly improves bandwidth utilization and minimizes interference, making it particularly effective in ionospheric communications, where multipath propagation predominates. Further advances in this study stem from the integration of digital signal processing (DSP) tools and techniques, which are essential for analyzing and streamlining the signal processing tasks inherent in software-defined radio (SDR) technology. The use of GNU Radio, a comprehensive set of open source software development tools, allows practical application of complex DSP algorithms without requiring extensive custom hardware. Combining this toolset with Python programming allows researchers to rapidly prototype and test new communication strategies and waveforms. This combination of GNU Radio and Python facilitates a dynamic and flexible approach to the development and enhancement of SDR-based communication systems, ensuring that they can effectively adapt to diverse requirements and operational environments.

The synergy between DSP, GNU Radio, Python and SDR results in a solid platform for the investigation and development of HF communications. By leveraging these technologies, research can overcome the limitations of traditional radio systems, enabling efficient communications capable of overcoming the specific challenges of the ionospheric transmission environment. This comprehensive approach not only underpins the theoretical aspects of the study, but also provides a practical way to implement advanced communication solutions tailored to the particular requirements of HF ionospheric communications.

This paper presents three strategic research directions, and the personal contributions aim at analyzing in detail the parameters underlying the development of applications that systematically overcome the current limitations of ionospheric HF communications.

The first research direction focuses on the implementation of a complex SDR system designed to assess and analyze HF noise and to examine the availability of ionospheric channels over variable bandwidths. By developing a versatile platform for measuring and analyzing the noise characteristics prevailing in ionospheric channels, the work will provide essential information about the sources and impact of noise, thus paving the way for robust HF communication strategies. In addition, this first approach also aims to investigate the impact of bandwidth variability on noise profiles, thus enabling improved bandwidth allocation for efficient HF communications.

Starting from the fundamental understanding of noise characteristics, the second research direction focuses on the improvement of the signal-to-noise ratio (SNR), its detailed analysis and the implementation of an adaptive system to keep the SNR values at an optimal level. By exploiting the advantages of SDR technology, dynamic analysis and real-time adaptation to SNR variations can be achieved. This active adaptation aims not only to preserve but also to improve channel availability and data transfer, which are essential for reliable HF communications.

The third and final research direction aims at using advanced technologies to evaluate and test waveforms to improve data transfer rates under NVIS conditions. The objective is to implement and test an SDR-based system using OFDM technique. By analyzing and making OFDM waveforms more efficient, this study will attempt to overcome the limits achievable in

HF communications, aiming to significantly increase the data transfer rate and communication quality.

The thesis contributes to research in the field of HF communication systems by promoting the development of more robust and efficient communication technologies. The results of this research have the potential to innovate HF communications, improving the reliability and quality of long-distance communications. This work not only supports a wide range of practical and scientific applications, but also lays a foundation for future innovations in telecommunications and beyond, aligning with the continuing evolution towards more connected and resilient communication networks.

In conclusion, this thesis presents a comprehensive approach to the implementation of SDR technology to address the fundamental challenges posed by HF ionospheric communications. By advancing knowledge in the field of noise analysis, SNR and waveform enhancement, this work aims to set a new benchmark for the efficiency and reliability of HF communication systems, contributing significantly to the development of applications in the fields of telecommunication and radio technology.

Objectives and research directions

The research approach in this PhD thesis is structured around three main directions, each of which is designed to explore and innovate the field of shortwave radio communications using SDR technology. The overall objective is to improve the reliability, efficiency and data handling capabilities of HF communication systems over the ionosphere, with particular focus on NVIS propagation. The research will pursue various aspects of ionospheric communication channels such as noise analysis, signal-to-noise ratio evaluations, and the implementation of spectrally and power efficient waveforms to improve data transmission rates and radio link reliability. The following details the objectives of each research direction in this thesis.

Research direction 1: Implementation of an SDR system for HF noise assessment and availability analysis of ionospheric channels with variable bandwidths

The first research direction focuses on the implementation and testing of an SDR system for analyzing noise in ionospheric channels. This includes the following objectives:

- ✓ *Implementation and testing of an SDR system for noise analysis*: Development of a versatile SDR platform for measuring and analyzing the prevailing noise characteristics in ionospheric communication channels. This system will be essential for the identification of noise sources and their impact on the reliability of HF communications.

- ✓ *Analysis of existing noise in ionospheric channels with varying bandwidths:* Investigate how different bandwidths affect the noise profile of ionospheric channels. This will allow determining the optimal bandwidths for different link scenarios, increasing the efficiency of HF communications.

- ✓ *Analysis of ionospheric channel availability using channel noise level as a criterion:* Evaluation of ionospheric channel availability by examining how different noise levels affect channel usability. This approach will present information about the reliability of ionospheric channels under different conditions, contributing to the development of noise mitigation strategies.

Research direction 2: Strategies to improve the efficiency of NVIS communications by analyzing SNR using SDR technology.

The second research direction advances the research by focusing on analyzing the variation of SNR as a function of different factors and implementing an adaptive system to keep the SNR as high as possible in the ionospheric channels. Studies will include:

- ✓ *SDR-based SNR analysis*: Implementation and testing of an SDR-based system to analyze SNR variations within ionospheric channels. This analysis will form the basis for strategies to improve the quality of received signals.

- ✓ *Ionospheric channel availability as a function of SNR:* Examining how SNR levels influence ionospheric channel availability. This will help to understand the correlation between SNR and ionospheric channel performance from the perspective of increasing data transfer rate.
- ✓ *Adaptive system for SNR enhancement:* Development of an adaptive system capable of dynamically applying HF radio link realization strategies based on real-time SNR evaluations. This system aims to ensure improved quality indicators for HF radio links even under difficult ionospheric conditions.

Research direction 3: Deployment and testing of advanced waveforms to improve HF data communications under NVIS propagation conditions.

The third research direction involves the implementation and testing of an SDR-based system for HF data communications in NVIS propagation scenarios, with a focus on improving data transfer rates and reducing error rates. The objectives are as follows:

- ✓ *SDR-based system for data communications in the HF range:* Implementation and evaluation of an SDR-based communication system designed for efficient data transmission over ionospheric channels using OFDM top OFDM waveforms. This work will examine the potential of SDR technology to improve reliability and data transfer rate in the HF range.

- ✓ *Analysis of OFDM waveforms in the context of HF propagation for speed improvement and error reduction:* design, implementation and testing of OFDM-based waveforms in the context of HF propagation to increase the transfer rate and reduce packet errors. This includes performance evaluation of OFDM technology in terms of the parameters underlying its formation.

- ✓ *Investigation of methods to increase packet throughput by increasing bandwidths in the context of HF propagation*: Implementation and testing of channel aggregation techniques with the aim of increasing available bandwidths in ionospheric propagation, resulting in increased throughput in HF communications. This research aims to improve the overall reliability of communications by reducing the aggregation of multiple narrowband channels into a single channel.

Through these interconnected research directions, the investigation in this PhD thesis aims to substantially advance the understanding and usability of ionospheric channels for reliable, efficient and high-quality HF communications. By harnessing the flexibility and innovation potential of SDR technology, the study aims to address and overcome the inherent challenges of ionospheric communications, paving the way for significant advances in global communication systems in various domains.

Research Direction 1 - Implementation of an SDR system for HF range noise assessment and availability analysis of ionospheric channels with variable bandwidths e

Study 1 - Design and implementation of an HF band noise measurement system based on SDR platforms

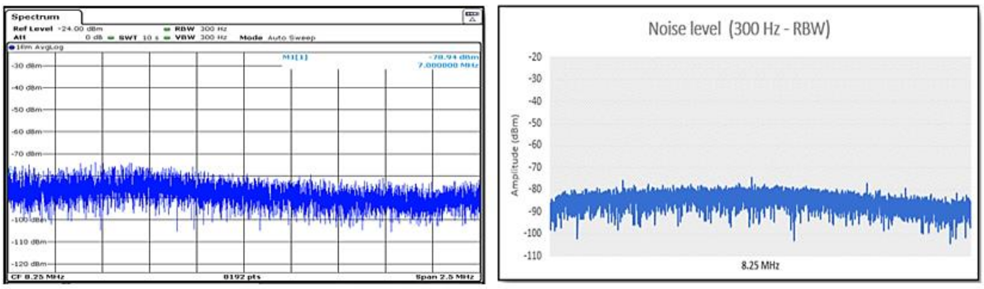
Materials and methods

A system based on software defined radio stations has been designed to record the level of man-made noise (MMN). For a real time monitoring of the noise level, a high performance SDR platform from National Instruments - Universal Software Radio Peripheral (NI USRP) model 2932 and equipped with a LFRX RF LFRX board in the frequency band 0-30MHz was chosen. The software component of the system was realized using a workstation on which the Linux operating system (Ubuntu 20.04) was installed. A Rohde&Schwarz broadband active antenna (HFH2-Z6E + IN600) was also used to measure the electric field strength. In order to accurately determine the acquisition times and coordinates of the location where the measurements were performed, a GPS module was connected to the SDR equipment and its implementation was realized using a script developed in Python.

Results and discussions

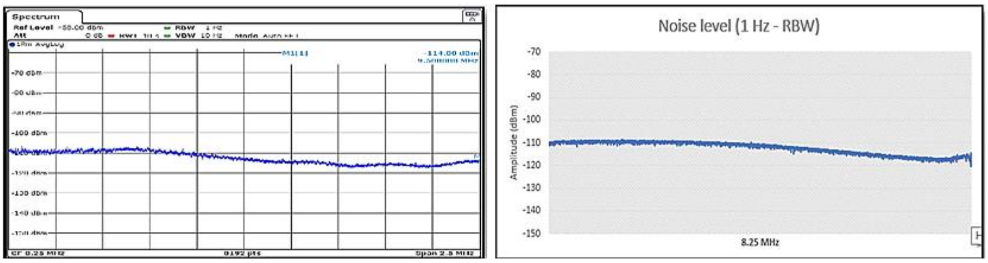
Initially, in the test part, a preliminary measurement was made using an acquisition time of 2 seconds for each frequency, with a 2 second pause in between, and a repetition interval of 10 minutes over a period of one hour. This means that four "name".dat files will be saved every 10 minutes. The files were named with the date and time of acquisition and also the center frequency, bandwidth and resolution. To process the data and display the results, custom Python scripts were created to load the saved files and plot the results graphically.

In the following figures, detailed comparative analyses between the spectral analyzer and the proposed measurement system have been developed. In Fig. 1(a,b), the noise level was measured for the frequency of 8.25 MHz with a frequency resolution (RBW) of 300 Hz.



(a) (b)

Figure 1 - Noise level at 8.25 MHz - (a) Spectrum analyzer, (b) SDR system (300 Hz RBW, 2.5 MHz bandwidth andă)



(a) (b)

Figure 2 - Noise level at 8.25 MHz - (a) Spectrum analyzer, (b) SDR system (1 Hz RBW, 2.5 MHz bandwidth)

In the second step (Figure 2), the noise level was measured for 1 Hz resolution. The SDR system is limited due to the 8192 points in the FFT, but, using the same values, the representation was normalized to 1 Hz by applying the formula $10 \cdot \log_{10}$ (RBW). In both cases, the values are comparable, resulting in the system displaying correct results for the next sets of measurements.

In the measurement recommendations it is proposed to measure the WGN by using a spectral analyzer equipped with an RMS type detector and applying the 20% method. Then, the noise level be normalized to an RBW of 1 Hz and expressed in dB over kTB. The following figures show the implementation results of this method using the system implemented with SDR.

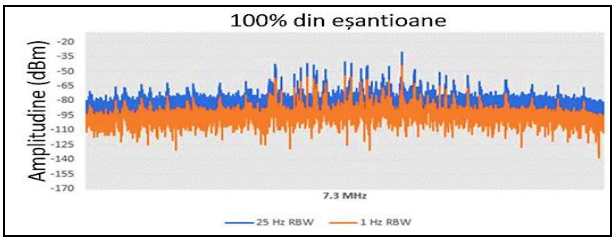
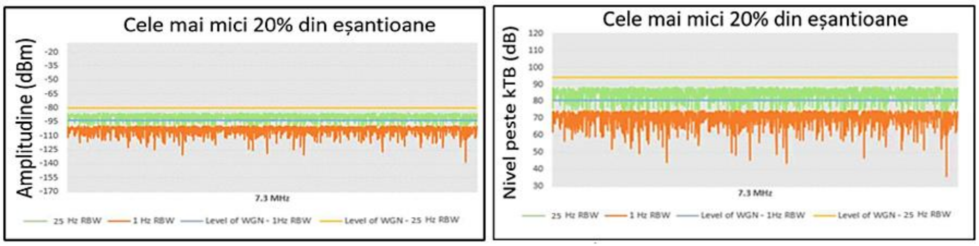


Figure 3 - SDR noise measurement at 7.3 MHz (all samples)



(a) (b)

Figure 4 - SDR noise measurement at 7.3 MHz (a) lowest 20% of samples, (b) representation over kTB

Figures 3, 4(a,b) show a measurement performed at 7.3 MHz. The representation has a bandwidth of 200 kHz. The resulting frequency resolution is approximately 25 Hz (at 8192 FFT points). The results shown are obtained after normalizing to a bandwidth of 1 Hz. As can be seen, the band is not emission-free. In order to determine the correct noise level at this frequency, the highest 80% of the samples were removed and only the lowest 20% were kept.

Study 2 - Amplitude probability density method for measuring high-frequency noise in ionospheric channels

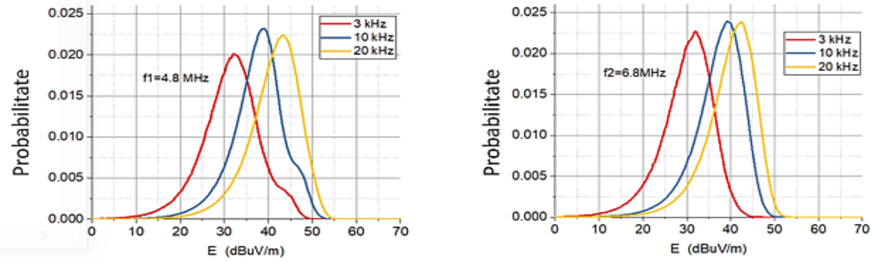
Materials and methods

The monitoring system implemented in this study consists of a Rohde&Schwarz FSVR 7 spectral analyzer, an R&S HFH2-Z6E active antenna and a laptop serving as the central control unit. On this laptop a custom Python application was configured specifically designed to manage the spectrum analyzer operations. This software not only facilitates control of the device, but also streamlines the data collection process, making it more efficient by automating data acquisition.

Results and discussions

Figure 5(a) shows the APD noise histogram for the center frequency of 4.8 MHz, for which the three bandwidths of the ionospheric channel have been considered. Figures 6(b) and 7 show similar representations for the center frequencies of the ionospheric channel at 6.8 MHz and 8.8 MHz, respectively. All these exemplified measurements were made in the middle of the day at 13:40 local time.

As expected, it can be seen that as the channel bandwidth increases, the E-field strength of the noise also increases. It should be noted that the values obtained are comparable with similar results reported in the literature for urban areas [36]. At a channel bandwidth of 3 kHz, a range of electric field level, E = (30-40) dBμV/m, is obtained. At a 10 kHz bandwidth, E = (38-45) dBμV/m, and at a 20 kHz bandwidth, E = (43-48) dBμV/m.



(a) (b)

Figure 5 - APD of HF noise electric field strengths in the ionospheric channel at center frequencies of (a) 4.8 MHz, (b) 6.8 MHz

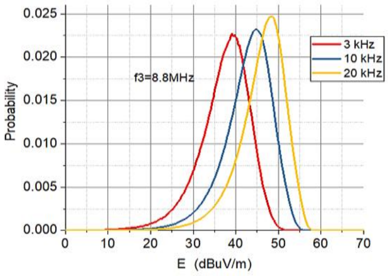
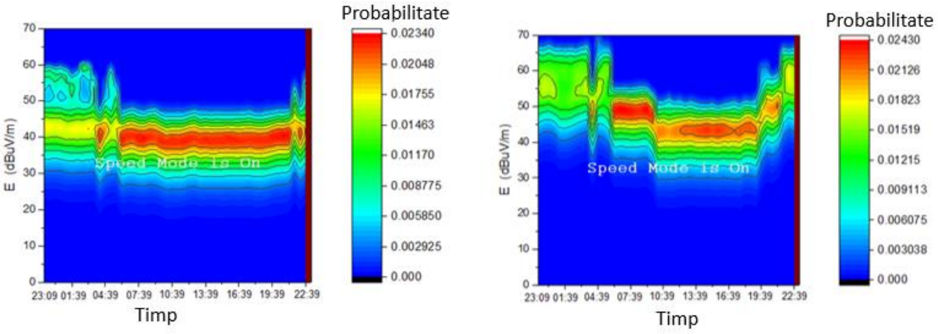


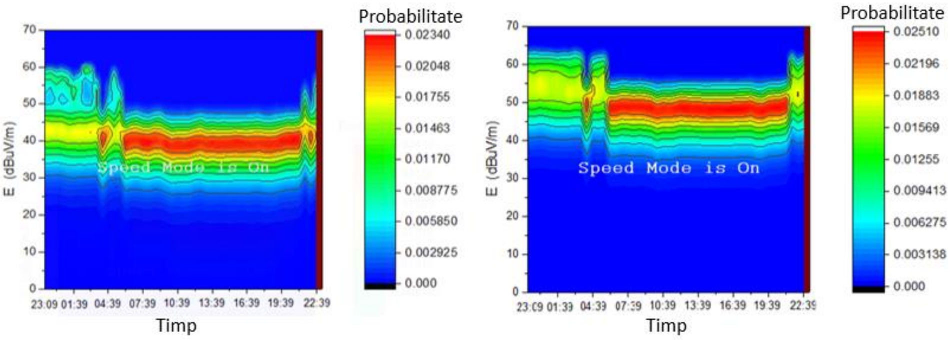
Figure 6 - APD of the HF noise electric field strengths in the ionospheric channel at 8.8 MHz center frequency

The shape of the APD plot was preserved in all the cases illustrated in Figures 5 and 6. Figures 7 and 8 show the time evolution of the electric field strength E in the ionospheric channel over 24 hours. Figs. 7(a) and 8(a) refer to a 3 kHz bandwidth, while Figs. 7(b) and 8(b) show a 20 kHz bandwidth. In the analyzed figures, two center frequencies were chosen, as shown, 4.8 MHz and 8.8 MHz, respectively. For all the exposed cases, it can be seen that in the time interval (05:00-21:00) the noise in the ionospheric channel exhibits a relatively constant field strength. At the center frequency of 4.8 MHz and channel bandwidth of 3 kHz an electric field strength of less than 40 dBμV/m is present, while in a channel with 20 kHz bandwidth the field strength increases by about 10 dB. Similar behavior can be observed for the 8.8 MHz center frequency. It is interesting to note that in the time interval (20:00-05:00) significant variations in the E-field level occur. Relatively high field levels of about 70 dBμV/m can also be observed. Consequently, this time range could create difficulties in achieving reliable communications at the frequencies investigated. The maximum likelihoods extracted from the APD histograms are at values of 0,023.



(a) (b)

Figure 7 - Variation of E field strength over 24 hours on a channel with a bandwidth of (a) 3 kHz (b) 20 kHz, at a center frequency of 4.8 MHz



(a) (b)

Figure 8 - E field strength variation over 24 hours on a channel with a bandwidth of (a) 3 kHz (b) 20 kHz, at a center frequency of 8.8 MHz

If in Figures 5 and 6, for which the duration of the analysis was 2 minutes - in the middle of the day, no noticeable differences were observed, when measurements were made over 24 hours, essential differences were found between the different ionospheric channels.

Research direction 2 - Strategies to improve the efficiency of NVIS communications by analyzing SNR using SDR technology

Study 3 - Design, implementation and testing of an automated system for SNR assessment of ionospheric channels

Materials and methods

An SDR platform with real-time monitoring capability was used to monitor rapid variations in signal level. Thus, an SDR platform from National Instruments - Universal Software Radio Peripheral (NI USRP), controlled by an application developed in the GNU Radio environment, was chosen.

The broadcasting system configuration was realized using a laptop running the Linux operating system (Ubuntu 20.04) connected to a NI USRP 2932 platform, equipped with a LFTX 0-30 MHz LFTX 0-30 MHz radio frequency transmitter board. The system also contains a Rohde & Schwarz BBA 150 power amplifier and a Diamond W330 broadband dipole antenna mounted in an inverted "V" shape. This antenna configuration was chosen for its NVIS propagation characteristic.

Similarly, the receive setup used the same laptop-USRP configuration, connected to a multi-band (3-30MHz) HF T2FD T2FD antenna, also arranged in an inverted "V" shape. The NI USRP 2932 platform is equipped this time with an LFRX 0-30 MHz model LFRX 0-30 MHz radio frequency receiver board. To improve the reception quality, a 9:1 balun and non-inductive terminating resistors were used, achieving a VSWR of less than 2 over the entire HF spectrum.

Results and discussions

The system evaluation was performed in three steps: (1) transmission and reception calibration using reference spectral generators and analyzers, (2) back-to-back testing of the system under controlled laboratory conditions, and (3) verification of the system operation under real NVIS propagation conditions.

In the first phase, a signal generator was connected to a receive (RX) channel of the USRP equipment with a coaxial cable. The R&S FSVR spectrum analyzer served as reference equipment for calibrating the amplitude levels. This setup allowed the amplitude and frequency response of the SDR system to be evaluated. To accomplish this, the frequency of the generated signal was varied between 3 and 30 MHz in 1 MHz steps, and the signal amplitude was varied from -90 dBm to -30 dBm in 5 dB steps. Figure 9 shows the test stand under laboratory conditions.

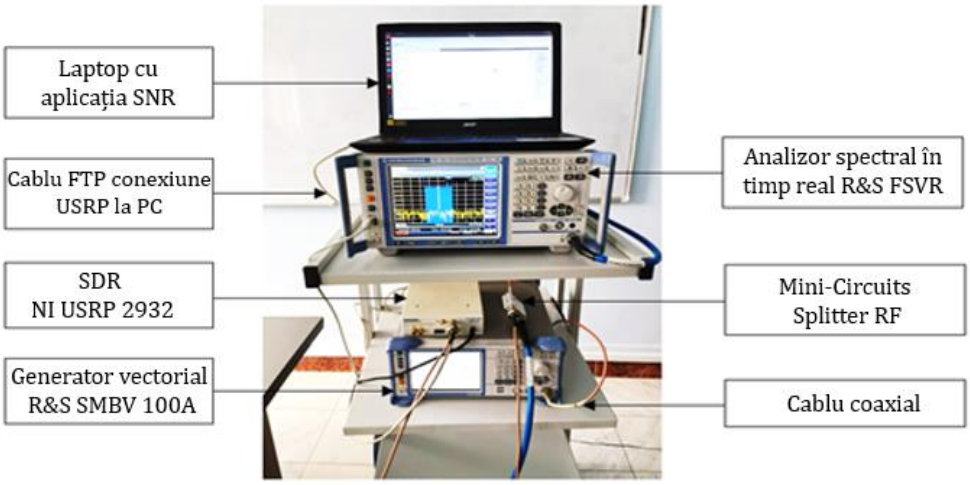


Figure 9 - Test stand under laboratory conditions

The power level calibration was performed on a 3 kHz bandwidth, generating a sinusoidal signal with different power levels. As can be seen, after adjusting the parameters, the power level of the channel measured with the GNU Radio application is similar to the one measured with the reference spectral analyzer.

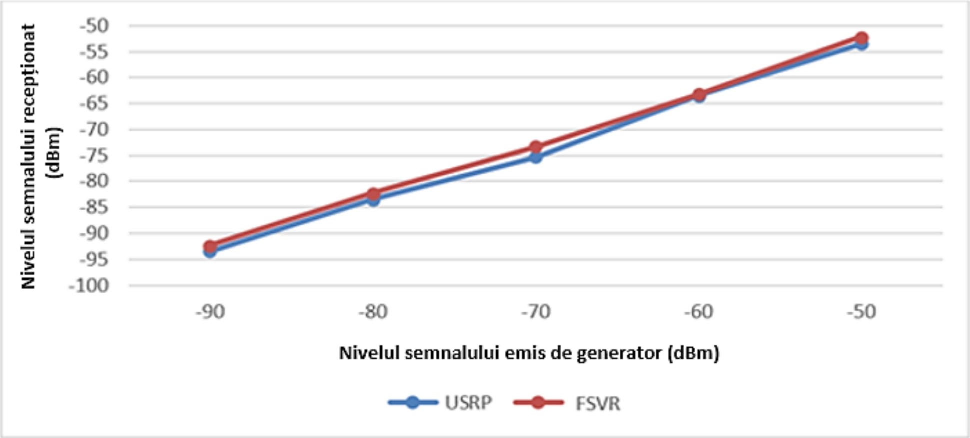


Figure 10 - Comparative power measurement (FSVR-USRP) for an ionospheric channel with 3kHz bandwidth

Back-to-back testing involved connecting the USRP transmitter system directly to the USRP receiver system with a coaxial cable. During this test, a series of 30 frequencies in the HF range were transmitted over 2 hours. This procedure allowed a faithful synchronization of the two systems and also ensured that the linearity of the signal amplitude was maintained at the receiving end.

The radio link under NVIS conditions for the real testing of the system was realized between the transmitting point installed in Sibiu (coordinates: Latitude: 45.7828, Longitude: 24.1452) and the receiving point installed in Sângeorz-Băi (coordinates: Latitude: 47.3826, Longitude: 24.6559), located at a distance of about 180 km in a straight line (Figure 11).

Figure 11 - Transceiver system locations

In order to configure and verify the correct operation of the system, remote control of the receiving system from the transmitter's location was chosen, using a "remote control" application available for Linux operating systems. The transmission was realized using 2 HF frequencies (6.7 MHz and 7.3 MHz), by generating a continuous unmodulated sinusoidal signal, and amplified with a power of 60W. The transmit-receive duration for each frequency was set to 2 seconds and the interval between two consecutive transmissions was set to 4 seconds. The frequency list, both transmit and receive, was repeated every 15 minutes for 6 hours.

Figure 12 shows the received power levels over 6 hours for the frequencies 6.7 MHz and 7.3 MHz at 3 kHz bandwidth. It can be seen that the signal starts to decrease from 18:00 pm for the 6.7 MHz frequency and from 18:45 pm for the 7.3 MHz frequency. They also reach the noise floor (-95 dBm) after 20:30 pm for the 6.7 MHz frequency and after 19:30 pm for the 7.3 MHz frequency.

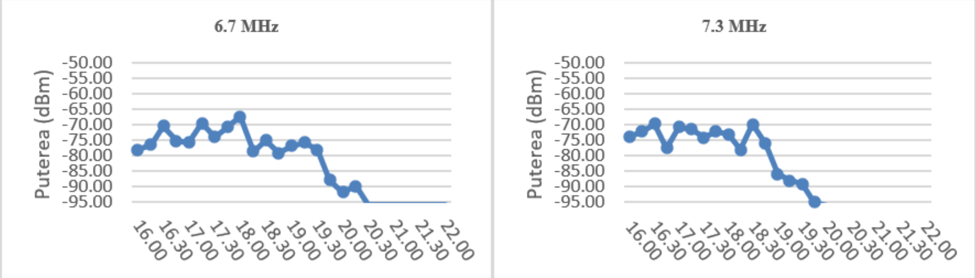


Figure 12 - Reception signal strength variation for 6.7 MHz and 7.3 MHz at 3 kHz channel bandwidth

Using the application realized in GNU Radio, the SNR value was calculated for the same periods and for the same 3 kHz bandwidth. The results reflect SNR variations due to changes in signal strength and noise. Considering an SNR level of at least 5 dB, it can be stated that, in the time interval during which the measurement was carried out, for an ionospheric channel with a bandwidth of 3 kHz, the channel availability is only between 16:00 pm and 18:00 pm for the 6.7 MHz frequency and between 16:00 pm and 18:45 pm for the 7.3 MHz frequency.

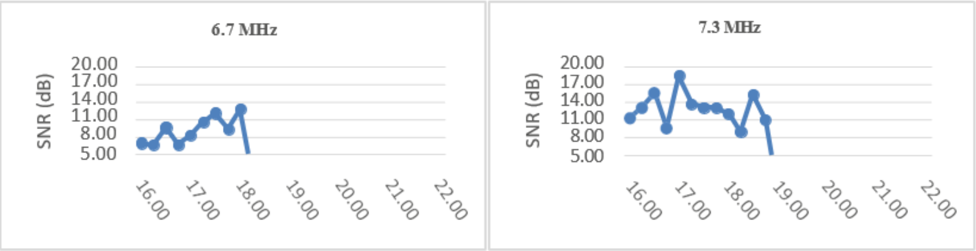


Figure 13 - Reception signal-to-noise ratio variation for 6.7 MHz and 7.3 MHz frequencies at 3 kHz channel bandwidth

Figure 13 shows the variation of the measured signal-to-noise ratio for a 10-minute continuous emission on the carrier frequency of 5.7 MHz using three different bandwidths. As expected, the SNR decreases with increasing channel bandwidth. If we analyze the availability of the ionospheric channel as a function of SNR value, it can be seen that, for a minimum SNR value of 5 dB, the availability is about 95% for an ionospheric channel bandwidth of 3 kHz and drops considerably to less than 50% for a channel bandwidth of 24 kHz. This underlines the fact that extending the channel bandwidth to achieve a higher data transfer rate needs to be analyzed very carefully from the SNR degradation perspective.

Study 4 - Evaluation of ionospheric channel availability under NVIS conditions by signal-to-noise analysis

Materials and methods

For SNR analysis, the same SDR USRP platforms/systems as in previous studies were used. The radio link under NVIS conditions for this study was also established between the city of Sibiu, Sibiu county and the city of Sângeorz-Băi, Bistrița-Năsăud county (Figure 14).

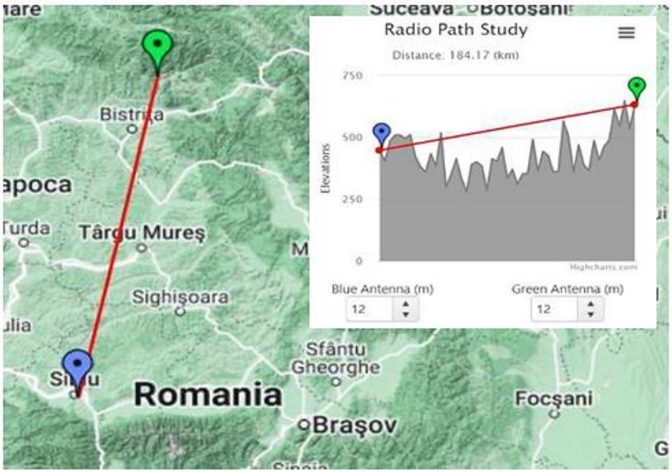


Figure 14 - Transceiver system locations [94]

Thus, both for the configuration of the transmitting and receiving system, a laptop/PC was used on which the Linux operating system (Ubuntu 20.04) was installed, connected to a NI USRP 2932 platform. Both systems were connected to dipole antennas installed in inverted "V" for propagation under NVIS conditions.

Results and discussions

In the first stage, measurements were performed using the 5.7 MHz frequency. A sinusoidal signal with a power of 40 W was emitted on this frequency. The emission duration was set to 2 seconds, with an interval between measurements of 5 minutes over 24 hours. Reception monitoring was performed using the same parameters (frequency and time) for a channel bandwidth of 3 kHz.

The signal emitted on this frequency was detected at reception only between 08.00 AM and 17.00 PM. The ionospheric channel became unavailable immediately after sunset, continued to be unavailable during the night and became available again after sunrise. Therefore, this frequency is available in the intervals with increased ionization levels during the daytime. At the same time, it was observed that the noise power level had little variation, below 5 dB, throughout the measurements and remained below the -85 dBm threshold.

Using the application configured in GNU Radio to measure SNR, the variation over 24 hours was calculated for a 3 kHz bandwidth. It can be seen that this channel has periods of time even during the day when availability is low. For an SNR threshold of 5 dB, the channel availability during 24 hours was only 30% of the time, and for a threshold of 10 dB the availability was 16%.

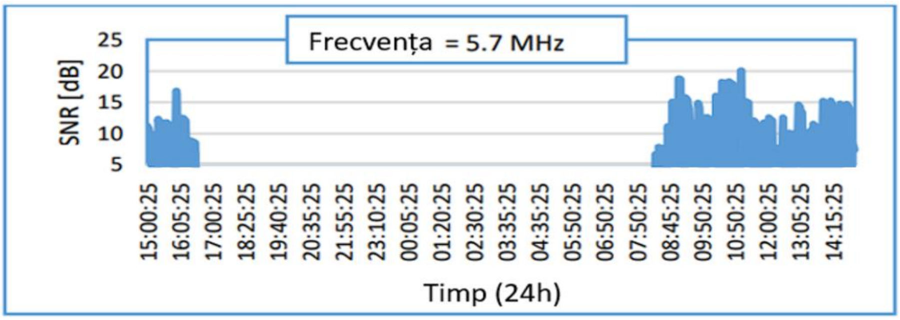
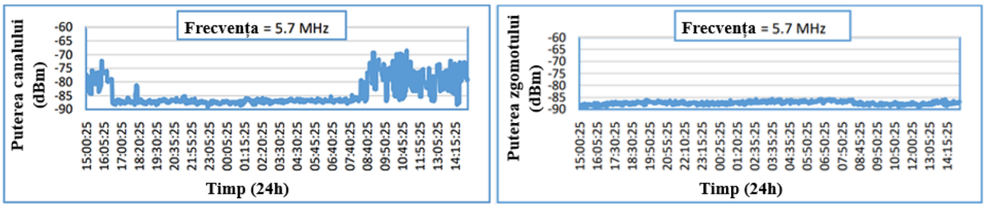


Figure 15 - SNR level measured every 5 minutes for 2 seconds - 24 hours



(a) *(b)*

Figure 16 - Signal power level (a) and noise power level (b) received every 5 minutes for 2 seconds - 24 hours

Next, a 3-hour time duration analysis was performed in the most favorable time slot (09.00 AM - 12.00 PM). Figures 17 and 18 show the signal strength, noise power and SNR for this time slot. A significant variation in channel power is noticeable. Also the SNR varies quite a lot even for 5 minutes between measurements. As can be seen, between one measurement and the next, in most cases there are significant differences. The SNR variation over the whole range was between 2 dB and 20 dB. For a 5 dB threshold, the channel was available 78% of the time, for a 10 dB threshold availability was 54%, and for a 15 dB threshold availability was only 17%.

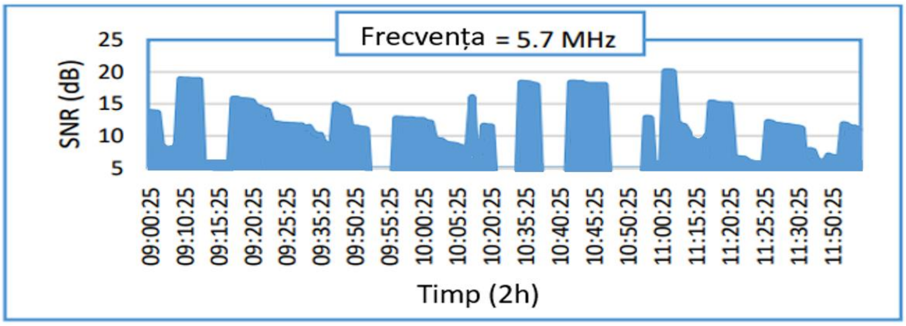
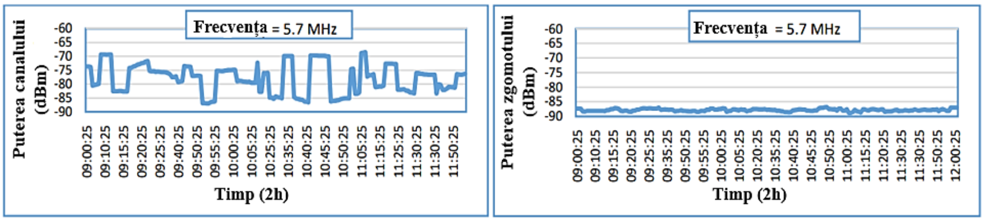


Figure 17 - SNR level measured every 5 minutes for 2 seconds - 2h



(a) *(b)*

Figure 18 - Signal power level (a) and noise power level (b) at reception measured every 5 minutes for 2 seconds - 2h

Study 5 - Adaptive signal-to-noise based adaptive HF radio channels using SDR technology

Materials and methods

The transceiver system has been designed to provide an adaptive radio link in the HF range using SDR platforms. By controlling all parameters via software, the process of adapting frequency, bandwidth and transmission power could be automated, which simplifies the establishment of a stable and reliable communication link.

The radio communication system was configured using the NI USRP-2932 SDR platform, capable of receiving and transmitting signals over a wide range of frequencies, including HF. This SDR platform is an ideal solution for the development of an adaptive radio link in the HF range, due to its superior flexibility and functionality, as well as low cost. Digital signal processing has been realized with the help of a processing system and Python programming language.

Results and discussions

This system has been developed to implement adaptive radio link technology using SDR and to support the development of a software-defined radio station specific protocol to improve the performance of radio communication systems, particularly in the HF domain. As wireless networks continue to expand and evolve, there is an urgent need to develop appropriate HF protocols for military, government and other applications. Adaptive techniques play an important role in ensuring reliable and efficient operation of HF links.

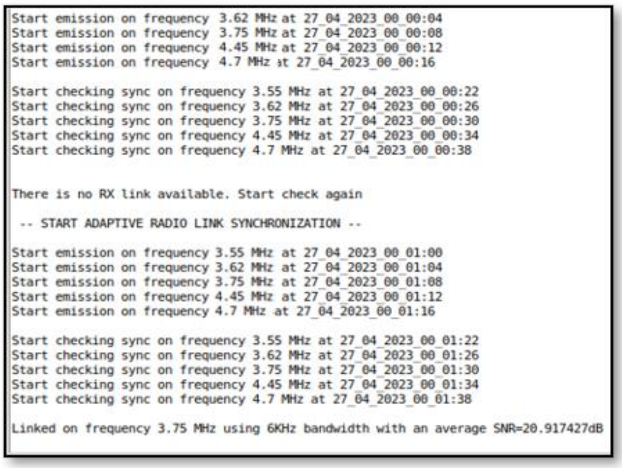
This methodology, implemented in the present system, is the prerequisite for ensuring the realization of data links at the highest possible data rates for radio links in the HF range.

Based on the resulting parameters, established at each station, an OFDM communication protocol adapted to these parameters will be implemented in the next development phase.

In order to verify the correct operation and the ability of the system to adapt according to the SNR level in each situation, the system was tested in the laboratory for different operational scenarios as follows:

Test 1: The radios were turned on randomly at different times (Figures 19 and 20).

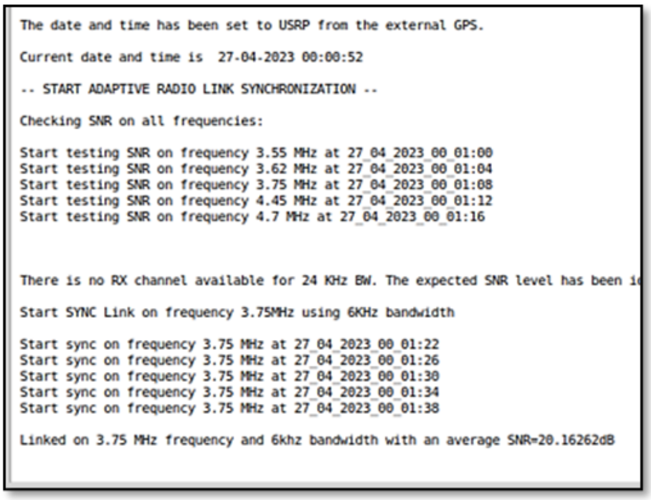
In this case, the master station was started 5 minutes before the slave station. The applications for both master and slave stations try to synchronize every minute. Since the slave station was not turned on, the master station transmitted every minute, waiting for a synchronization signal from the slave station. When the slave station was also turned on, it measured the SNR level for the frequencies in the list and transmitted on the frequency with the best SNR and frequency deviation corresponding to the optimal bandwidth.



```
Start emission on frequency  3.62 MHz at 27_04_2023_00_00:04
Start emission on frequency  3.75 MHz at 27_04_2023_00_00:08
Start emission on frequency  4.45 MHz at 27_04_2023_00_00:12
Start emission on frequency  4.7 MHz at 27_04_2023_00_00:16

Start checking sync on frequency 3.55 MHz at 27_04_2023_00_00:22
Start checking sync on frequency 3.62 MHz at 27_04_2023_00_00:26
Start checking sync on frequency 3.75 MHz at 27_04_2023_00_00:30
Start checking sync on frequency 4.45 MHz at 27_04_2023_00_00:34
Start checking sync on frequency 4.7 MHz at 27_04_2023_00_00:38


There is no RX link available. Start check again

 -- START ADAPTIVE RADIO LINK SYNCHRONIZATION --

Start emission on frequency 3.55 MHz at 27_04_2023_00_01:00
Start emission on frequency 3.62 MHz at 27_04_2023_00_01:04
Start emission on frequency 3.75 MHz at 27_04_2023_00_01:08
Start emission on frequency 4.45 MHz at 27_04_2023_00_01:12
Start emission on frequency 4.7 MHz at 27_04_2023_00_01:16

Start checking sync on frequency 3.55 MHz at 27_04_2023_00_01:22
Start checking sync on frequency 3.62 MHz at 27_04_2023_00_01:26
Start checking sync on frequency 3.75 MHz at 27_04_2023_00_01:30
Start checking sync on frequency 4.45 MHz at 27_04_2023_00_01:34
Start checking sync on frequency 4.7 MHz at 27_04_2023_00_01:38

Linked on frequency 3.75 MHz using 6KHz bandwidth with an average SNR=20.917427dB
```

Figure 19 - First synchronization performed to establish optimal link parameters with the main radio station

As can be seen in the test case, the radios have established connection on 3.75 MHz frequency and 6 kHz bandwidth. After the first synchronization, if the radios are not switched off and remain in IDLE mode, they will re-synchronize after a predefined time, initially set to 30 minutes.

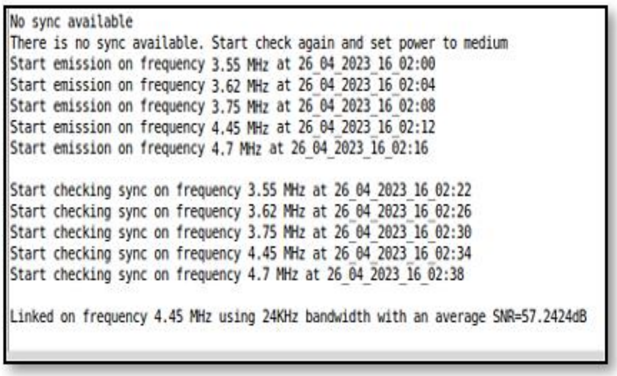


```
The date and time has been set to USRP from the external GPS.

Current date and time is  27-04-2023 00:00:52

-- START ADAPTIVE RADIO LINK SYNCHRONIZATION --

Checking SNR on all frequencies:

Start testing SNR on frequency 3.55 MHz at 27_04_2023_00_01:00
Start testing SNR on frequency 3.62 MHz at 27_04_2023_00_01:04
Start testing SNR on frequency 3.75 MHz at 27_04_2023_00_01:08
Start testing SNR on frequency 4.45 MHz at 27_04_2023_00_01:12
Start testing SNR on frequency 4.7 MHz at 27_04_2023_00_01:16



There is no RX channel available for 24 KHz BW. The expected SNR level has been i

Start SYNC Link on frequency 3.75MHz using 6KHz bandwidth

Start sync on frequency 3.75 MHz at 27_04_2023_00_01:22
Start sync on frequency 3.75 MHz at 27_04_2023_00_01:26
Start sync on frequency 3.75 MHz at 27_04_2023_00_01:30
Start sync on frequency 3.75 MHz at 27_04_2023_00_01:34
Start sync on frequency 3.75 MHz at 27_04_2023_00_01:38

Linked on 3.75 MHz frequency and 6khz bandwidth with an average SNR=20.16262dB
```

Figure 20 - First synchronization performed to establish the optimal parameters of the link to the slave radio

Test 2: The radios were randomly turned on at different times and perform the second synchronization, being conditioned to change power.

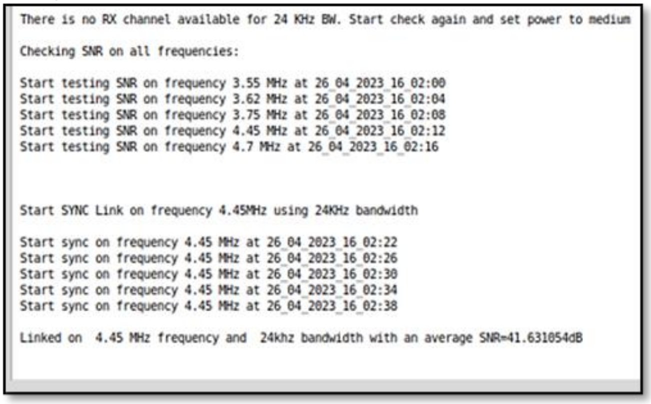
From the second synchronization, the system will also adjust its transmit power, trying to go from the lowest power to the highest power that will provide 24 kHz bandwidth. If, even at high power, there is not an acceptable SNR for the 24 kHz band, it will gradually reduce the bandwidth to 3 kHz.



```
No sync available
There is no sync available. Start check again and set power to medium
Start emission on frequency 3.55 MHz at 26_04_2023_16_02:00
Start emission on frequency 3.62 MHz at 26_04_2023_16_02:04
Start emission on frequency 3.75 MHz at 26_04_2023_16_02:08
Start emission on frequency 4.45 MHz at 26_04_2023_16_02:12
Start emission on frequency 4.7 MHz at 26_04_2023_16_02:16

Start checking sync on frequency 3.55 MHz at 26_04_2023_16_02:22
Start checking sync on frequency 3.62 MHz at 26_04_2023_16_02:26
Start checking sync on frequency 3.75 MHz at 26_04_2023_16_02:30
Start checking sync on frequency 4.45 MHz at 26_04_2023_16_02:34
Start checking sync on frequency 4.7 MHz at 26_04_2023_16_02:38

Linked on frequency 4.45 MHz using 24KHz bandwidth with an average SNR=57.2424dB
```

Figure 21 - Second synchronization to establish the optimal parameters for the link to the main radio station, including transmission power

As can be seen, the radios were automatically connected with medium transmit power (because at low power the SNR was below the minimum SNR for the 24 kHz bandwidth), using the optimal frequency of 4.45 MHz for an SNR that allows a 24 kHz bandwidth.

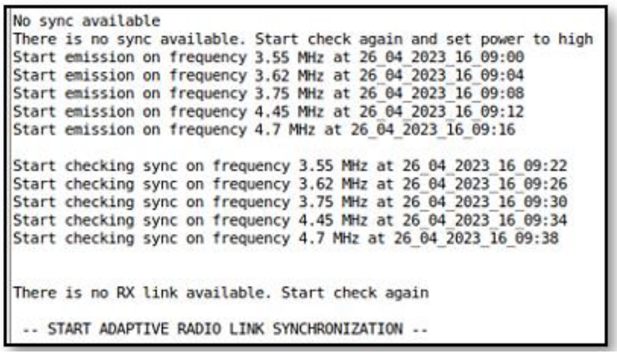


```
There is no RX channel available for 24 KHz BW. Start check again and set power to medium

Checking SNR on all frequencies:

Start testing SNR on frequency 3.55 MHz at 26_04_2023_16_02:00
Start testing SNR on frequency 3.62 MHz at 26_04_2023_16_02:04
Start testing SNR on frequency 3.75 MHz at 26_04_2023_16_02:08
Start testing SNR on frequency 4.45 MHz at 26_04_2023_16_02:12
Start testing SNR on frequency 4.7 MHz at 26_04_2023_16_02:16



Start SYNC Link on frequency 4.45MHz using 24KHz bandwidth

Start sync on frequency 4.45 MHz at 26_04_2023_16_02:22
Start sync on frequency 4.45 MHz at 26_04_2023_16_02:26
Start sync on frequency 4.45 MHz at 26_04_2023_16_02:30
Start sync on frequency 4.45 MHz at 26_04_2023_16_02:34
Start sync on frequency 4.45 MHz at 26_04_2023_16_02:38

Linked on  4.45 MHz frequency and  24khz bandwidth with an average SNR=41.631054dB
```

Figure 22 - Second synchronization to set the optimal parameters of the link to the slave radio station, including transmission power

Test 3: The radios were randomly switched on at different times and perform a third synchronization and cannot establish the link on any frequency.

It may happen that for a given resynchronization, the radio link cannot be established even at full power. In this case, the synchronization attempt will be repeated every minute in the same way as when a station is not turned on, but now all three power levels will be checked: low, medium and high.



```
No sync available
There is no sync available. Start check again and set power to high
Start emission on frequency 3.55 MHz at 26_04_2023_16_09:00
Start emission on frequency 3.62 MHz at 26_04_2023_16_09:04
Start emission on frequency 3.75 MHz at 26_04_2023_16_09:08
Start emission on frequency 4.45 MHz at 26_04_2023_16_09:12
Start emission on frequency 4.7 MHz at 26_04_2023_16_09:16

Start checking sync on frequency 3.55 MHz at 26_04_2023_16_09:22
Start checking sync on frequency 3.62 MHz at 26_04_2023_16_09:26
Start checking sync on frequency 3.75 MHz at 26_04_2023_16_09:30
Start checking sync on frequency 4.45 MHz at 26_04_2023_16_09:34
Start checking sync on frequency 4.7 MHz at 26_04_2023_16_09:38


There is no RX link available. Start check again

 -- START ADAPTIVE RADIO LINK SYNCHRONIZATION --
```

Figure 23 - Repeat synchronization until an acceptable SNR level is identified - master radio station

Research Direction 3 - Implementation, analysis and evaluation of advanced waveforms for improved HF data communications under NVIS propagation conditions

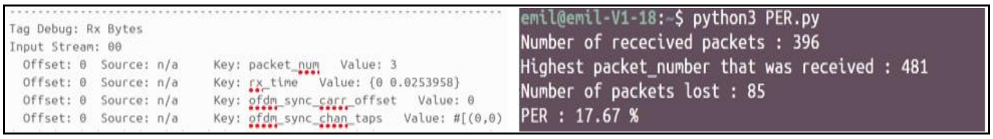
Study 6 - Implementation and testing of an SDR system for OFDM transmissions under HF-NVIS propagation conditions

Materials and methods

GNU Radio is an open source software development kit for planning, simulating and implementing different types of communication systems. It uses a block-based structure, where each block performs a specific task, such as filtering, modulation or coding. Users can modify the target configuration to suit their needs, combining these blocks to build complex signal processing and communications workflows. While it can simulate entire communications systems, GNU Radio's real potential is realized when combined with SDR equipment such as NI/Ettus USRP. This hardware compatibility turns theoretical designs into practical applications. Taking these advantages into account, the following experimental research opted to implement the OFDM protocol using the GNU Radio software package. Thus, the conditions are created to easily simulate the operation of the communication system through software applications depending on different parameters, but also to perform tests under real conditions by connecting to SDR equipment.

Results and discussions

In order to evaluate the packet error rate of the OFDM system for HF radio communications with NVIS propagation, an application was designed to analyze the labeling information of each received packet. This method allowed clear packet monitoring during the reception process. A Python script was then used to parse this text file, calculating the total number of packets received against the expected number of packets, which was deduced from the value of the last packet received. The packet error rate was then calculated as the ratio of the number of packets lost to the number of packets expected, expressed as a percentage.



```
Tag Debug: Rx Bytes
Input Stream: 00
  Offset: 0  Source: n/a     Key: packet_num   Value: 3
  Offset: 0  Source: n/a     Key: rx_time   Value: {0 0.0253958}
  Offset: 0  Source: n/a     Key: ofdm_sync_carr_offset   Value: 0
  Offset: 0  Source: n/a     Key: ofdm_sync_chan_taps   Value: #[(0,0)
```

```
emil@emil-V1-18:~$ python3 PER.py
Number of rececived packets : 396
Highest packet_number that was received : 481
Number of packets lost : 85
PER : 17.67 %
```

(a) *(b)*

Figure 24 - PER analysis: (a) Visualization of label information; (b) PER calculation

By varying the SNR values, the efficiency of the system was tested, with a focus on the PER calculation as a function of the packet length and the modulation scheme used for the OFDM subcarriers (BPSK, 8PSK, 16QAM).

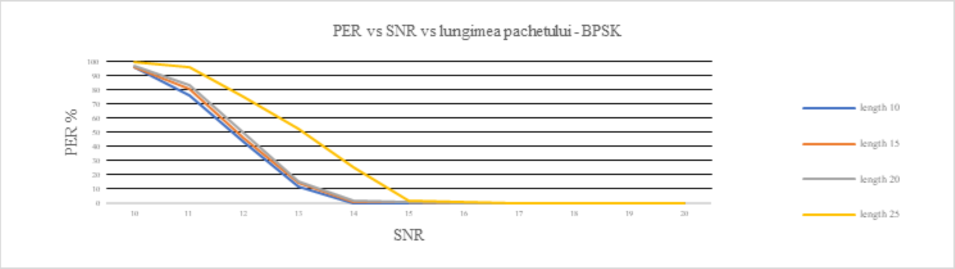


Figure 25 - PER versus SNR versus packet length for OFDM with BPSK modulation

According to Figure 25, it can be seen that when using BPSK modulation for OFDM subcarriers, data can be received if the SNR is at least 10dB. If the SNR is 15dB or higher the data packets are received at 100%. However, for packet lengths greater than 20, it is observed that the losses increase substantially.

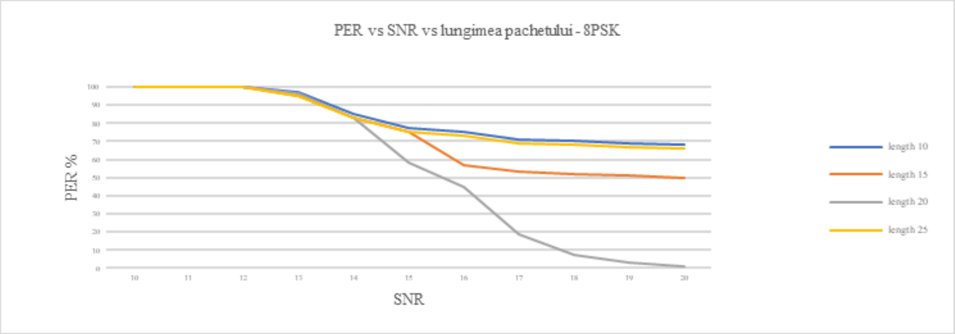


Figure 26 - PER versus SNR versus packet length for OFDM with 8BPSK modulation

Optimal packet lengths are about 20 when using 8PSK modulation. For higher or lower values the PER increases considerably. As the modulation factor increases to 3, the minimum detection level also increases to 12-13dB.

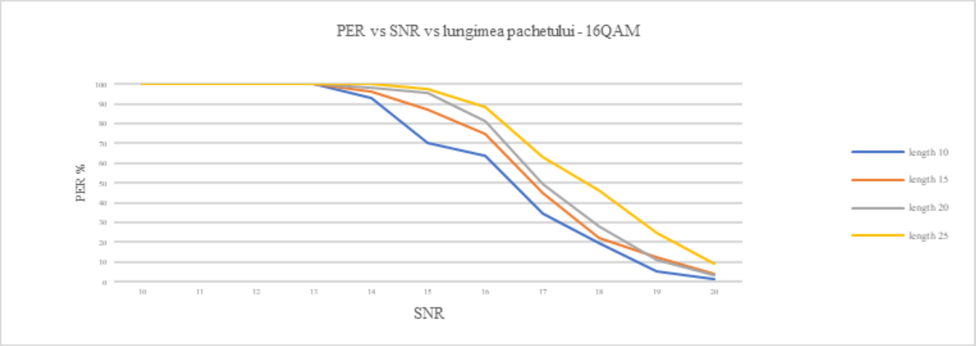


Figure 27 - PER versus SNR versus packet length for OFDM with 16QAM modulation

The next test revealed that the use of OFDM with 16QAM modulation also resulted in variations of the PER with packet length. These variations increased with packet length (Figure 27). The minimum detection level in this case was with an SNR of 13-14 dB.

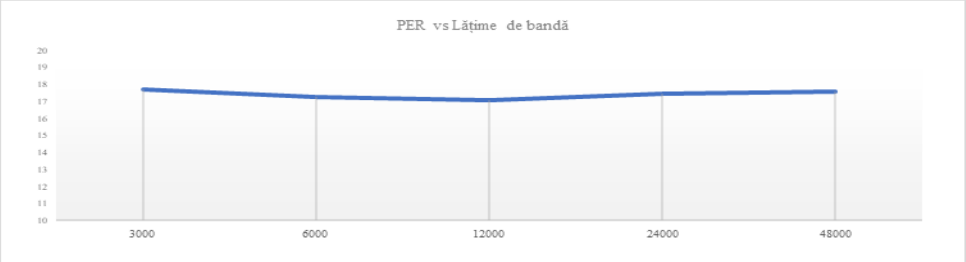


Figure 28 - PER versus bandwidth for packet length =10, OFDM with 16QAM modulation and SNR of 18dB

The next step was to analyze whether there are changes in PER when changing the bandwidth, keeping the same SNR and packet length. The result shows that, in the simulation, the variations are almost non-existent when increasing the bandwidth, if the same SNR is maintained. However, in the real case, the varying characteristics of the ionospheric channel may change the PER even if the transmit power is increased to maintain the SNR. This hypothesis results from tests under real NVIS propagation conditions.

In order to realize the tests under real conditions, a proprietary transmission application was realized using Python that integrated the script configured in GNU Radio. This configuration was designed to transmit an OFDM modulated data file every 5 minutes over 24 hours. IQ data received during these transmissions was stored locally on the PC, while SNR values were measured and stored in a *.csv file. The whole process was performed under real conditions, using a USRP N210 transceiver configured with an ADC/DAC sampling frequency of 200 kHz.

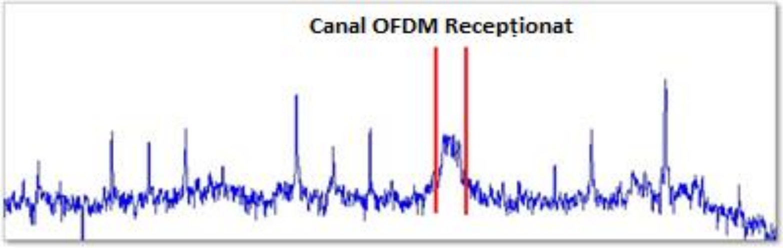


Figure 29 - Frequency domain reception and visualization of an OFDM channel

Study 7 - HF-NVIS data communications: OFDM transmission testing and optimization strategies

Materials and methods

The figure below illustrates the general framework of the OFDM technique implemented in GNU Radio. It comprises numerous subcarriers, represented by the vertical red lines in the middle of the blue lines. These subcarriers contain frequencies very close to each other, which are used for data transmission. The term guard subcarrier refers to the unoccupied spectrum present in an OFDM signal in order to prevent interference with adjacent channels.

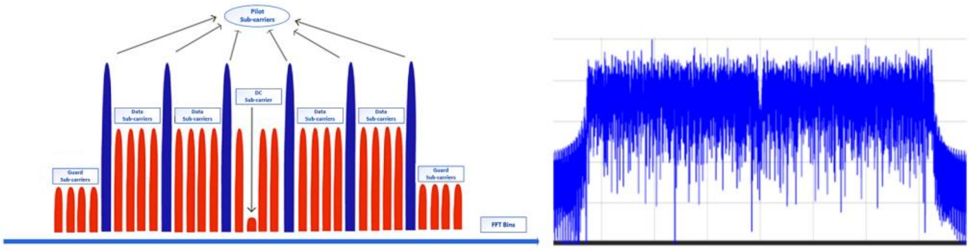


Figure 30 - Standard subcarrier allocation for an OFDM channel

In an OFDM system, pilot subcarriers are specially placed among the data subcarriers and are used for specific purposes, such as channel estimation to correct for distortion or fading that affects the signal during transmission. They provide a reference signal that can be used by the receiver to determine how the channel is affecting the data subcarriers and to adjust the receiver accordingly. The FFT dimension refers to the individual frequency slots within the OFDM signal, presented as the basis of each subcarrier line. Each FFT sample contains information for a particular subcarrier, and the FFT is used to multiplex the subcarriers at the transmitter and demultiplex them at the receiver.

There is also another component called guard interval in the time domain called cyclic prefix (Figure 31). The cyclic prefix is a copy of the end of the OFDM symbol added to the beginning of the OFDM symbol. It is used for two purposes. First, it provides a period during which the receiver can synchronize itself without having to ensure symbol to symbol switching. Second, the receiver receives a continuous signal representing the OFDM symbol, even if the symbol is scattered in time due to multipath propagation effects.

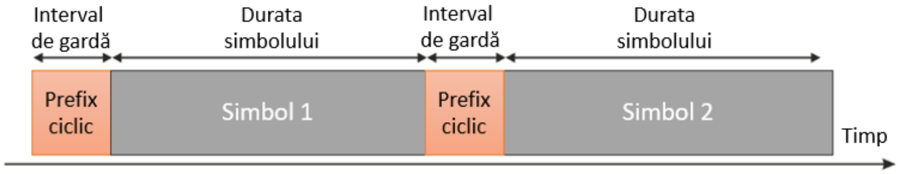


Figure 31 - Implementation of the guard interval in the time domain

A number of signal processing blocks are used to perform a variety of tasks in an OFDM implementation using GNU Radio. Some blocks can be seamlessly integrated into a signal flow graph and are provided as standard components within the GNU Radio library. Extensibility and reconfigurability by using custom blocks written in Python is one of the strengths of GNU Radio. This makes it possible to create specialized functions that cannot be included in the standard set of blocks. These custom blocks are then inserted into the GNU Radio flow similar to the standard blocks, providing a customized solution, while maintaining overall system consistency.

The implementation of the OFDM transceiver in GNU Radio (Figure 32) is divided into two main software applications: transmitter and receiver, adapted to the HF-NVIS communication channel/link.

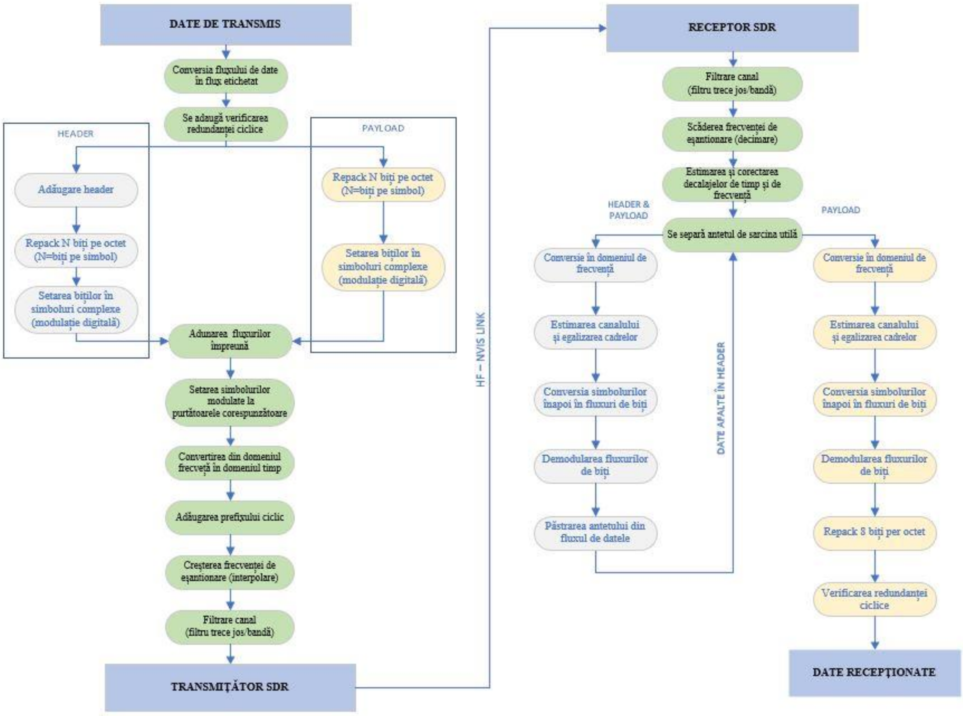


Figure 32 - Flowchart implementation used in GNU Radio for an OFDM transceiver

Results and discussions

Testing the performance of an OFDM channel with respect to packet error rate (PER) requires the modification of a number of distinct variables, including the number of subcarriers, the number of pilot signals, the amplitude of the pilot signals, the cyclic prefix length, and the modulation techniques applied to the subcarriers. The table below presents a set of variables for the purpose of OFDM system performance evaluation. The variables can be modified to check their influence on the PER, which is a measure to quantify how often data packets are not received correctly.

Total number of carriers	Carriers assigned as pilots	Busy data carriers	Cyclic prefix length	Digital Carrier Modulation
32	(-7,-4,4,7)	16	5-20	BPSK, QPSK, 8PSK,
64	(-21,-7,7,21) (-23,-17,17,23) (-10,-4,4,10)	48	5-20	BPSK, QPSK, 8PSK,
128	(-51,-8,8,51,)	112	5-20	BPSK, QPSK, 8PSK,

Table 1 - OFDM test specific settings

The test process allows a systematic variation of the analyzed parameters, while the PER evaluation allows to determine the impact of each element. This solution can be applied to achieve superior performance between data transfer rate and OFDM system reliability. In the following, the results of the tests carried out according to the changes of the OFDM system parameters are presented:

- Variation in cyclic prefix length

The cyclic prefix length is the length of the buffer region at the beginning of an OFDM symbol. It is used to protect against the effects of intersymbol interference caused by fading due to multipath propagation. Different sizes can be tested to identify the shortest usable prefix that provides sufficient protection without reducing the data transfer rate.

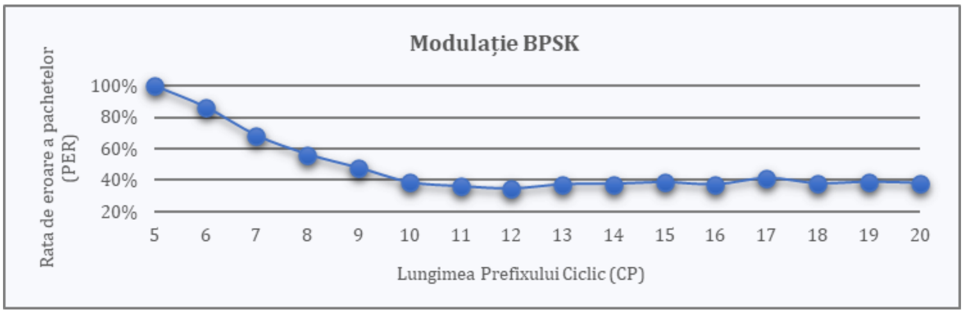


Figure 33 - PER vs CP for BPSK OFDM modulation

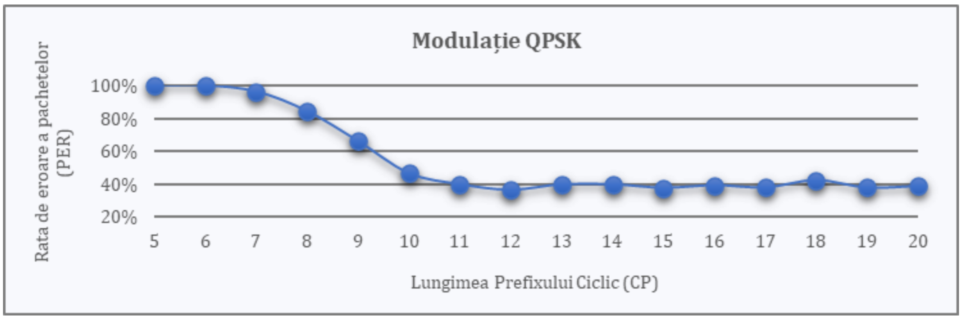


Figure 34 - PER vs CP for QPSK OFDM modulation

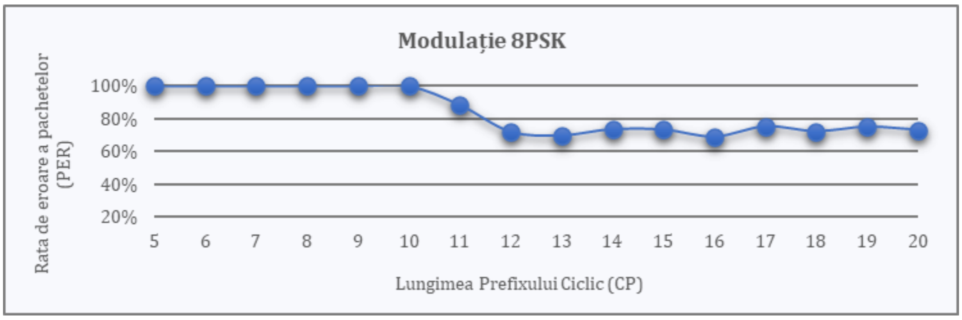


Figure 35 - PER vs CP for 8PSK OFDM modulation

The above figures illustrate the packet error rate (PER) as a function of cyclic prefix length for three distinct modulation schemes in an OFDM system: BPSK, QPSK and 8PSK.

In the case of BPSK modulation, the PER is about 100% when the CP length has value 5. If the CP length increases to the value of 6, the PER decreases significantly, which demonstrates that a minimum cyclic prefix length is required to achieve a lower error rate using BPSK modulation. PER continues to decrease as the CP length increases, but the rate of decrease slows down as the CP length extends beyond values 11 and 12, respectively.

QPSK modulation performed comparably to BPSK in terms of CP length. In contrast, for 8PSK modulation, there was a noticeable decrease in PER as CP length increased, but only after CP length 10. The decrease in PER remained relatively constant after the threshold value of 12, as for the other two modulations.

In conclusion, the value of the cyclic prefix length has to be adapted to both the propagation conditions and the type of modulation used, since the effect of the environment on the channel is different depending on the modulation.

➢ Distribution of pilot subcarriers

The graph labeled "PER vs. Pilot Subcarrier Distribution" illustrates the relationship between PER and pilot subcarrier distribution in an OFDM system. The plot shows three different sets of pilot subcarriers, each color-coded. The orange color is used to represent the pilot subcarriers at positions -21, -7, 7, and 21, the blue color is used to represent the pilot subcarriers at positions -23, -17, 17, and 23, and the green color is used to represent the pilot subcarriers at positions -10, -4, 4, and 10.

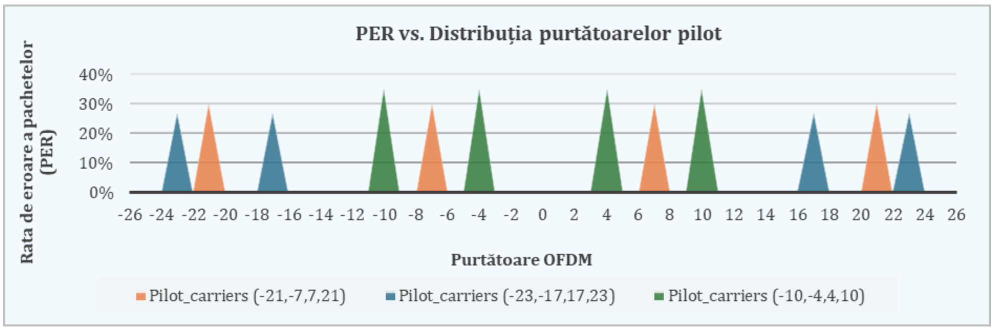


Figure 36 - PER vs Pilot subcarrier distribution

The first case, where the pilot subcarriers are arranged at positions -21, -7, 7, 21 (orange), characterizes a uniform distribution of the pilot subcarriers across the OFDM spectrum. The second case, where the pilot subcarriers are -23, -17, 17, 23 (blue color), expresses the situation where the four pilot subcarriers are placed at the two ends of the OFDM spectrum. The last case, where the pilot subcarriers are -10, -4, 4, 10 (green color) shows a higher concentration of pilot subcarriers around the middle of the frequency band. By analyzing the three cases, it can be seen that a wide uniform dispersion of the pilot subcarriers over the entire OFDM signal range facilitates more accurate channel estimation, which is beneficial in multipath environments. This can be seen by the PER value which is lower (case of pilot subcarrier distribution, orange color) and is specific to a channel that has a relatively uniform behavior in the frequency band.

- Test 3: OFDM subcarrier number variation

The figure below shows the correlation between PER and FFT size for three distinct modulation types. The FFT size, which corresponds to the number of subcarriers in an OFDM system, has a noticeable impact on the performance of the system, in particular in terms of its ability to handle interference and multipath propagation effects.

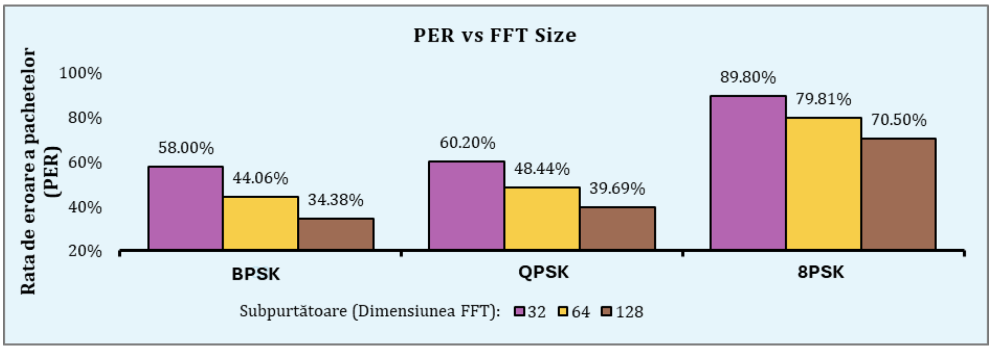


Figure 37 - PER vs FFT size for different digital modulations

The use of 32 subcarriers resulted in using the smallest FFT size with the highest error rates for all modulation types addressed. In contrast, the PER is reduced when the number of subcarriers is doubled from 32 to 64, regardless of the modulation type.

Study 8 - OFDM aggregation in HF communications using SDR technology: design and validation under laboratory conditions

Materials and methods

The test system was built using two USRP N210 software defined radio stations, connected back-to-back through a power attenuator to simulate communications under as realistic conditions as possible. Two laptops, each equipped with GNU Radio software, were used to develop and deploy the OFDM transmitter and receiver. This configuration allowed precise control and monitoring of the transmit and receive processes, enabling a thorough performance evaluation of the OFDM channel aggregation system in a controlled laboratory environment. The GNU Radio programming environment was used to develop and test the OFDM modulation and demodulation schemes required for efficient HF communication.

The channel aggregation OFDM technique was implemented using GNU Radio, supplemented with Python blocks developed specifically for this study. Methods included setting up the GNU Radio environment, building specialized computational blocks, and integrating and debugging these components into a controlled OFDM system.

Results and discussions

In the first adjacent aggregation experiment, the OFDM system was configured to efficiently utilize the available bandwidth by dividing it into closely spaced channels. The results show a clear and well-defined spectrum with no channel spacing, which indicates efficient spectrum utilization, as seen through the QT GUI Frequency Sink QT blocks.

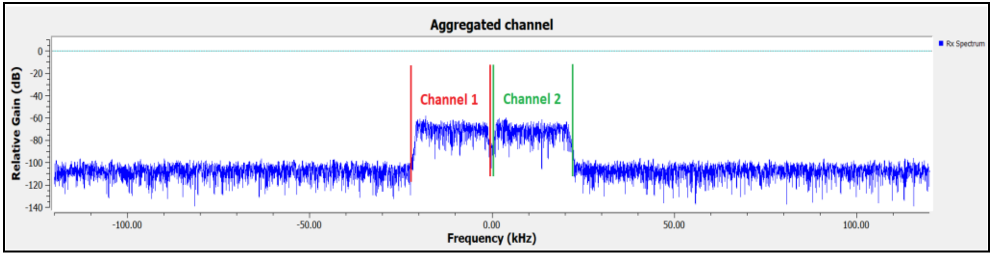


Figure 38 - Adjacent aggregation of two OFDM channels

An insight into the flexibility of the system in avoiding spectral regions affected by interference or regulatory constraints was provided by the non-continuous aggregation configuration, in which case the channels are distributed with spectrum spacing. In dynamic spectrum access scenarios, where certain frequency bands may be occupied or restricted, this form of aggregation is particularly useful.

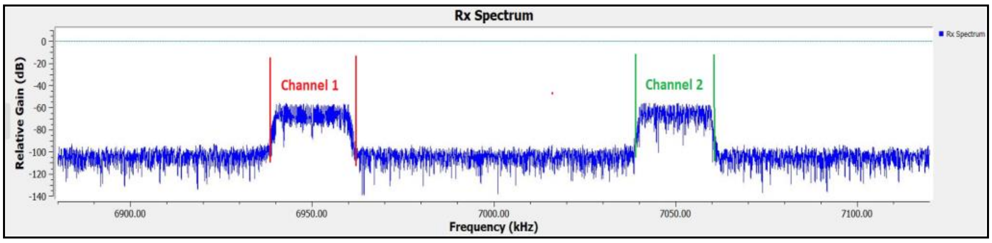


Figure 39 - Non-adiacent aggregation of two OFDM channels

The performance and behavior of the OFDM receiver in terms of contiguous and non-continuous aggregation are illustrated by visualizing the time-domain label with the received data. The effect of the settings on the channels in the OFDM system is also demonstrated by visualizing the time-domain label of the received data in the context of aggregation.

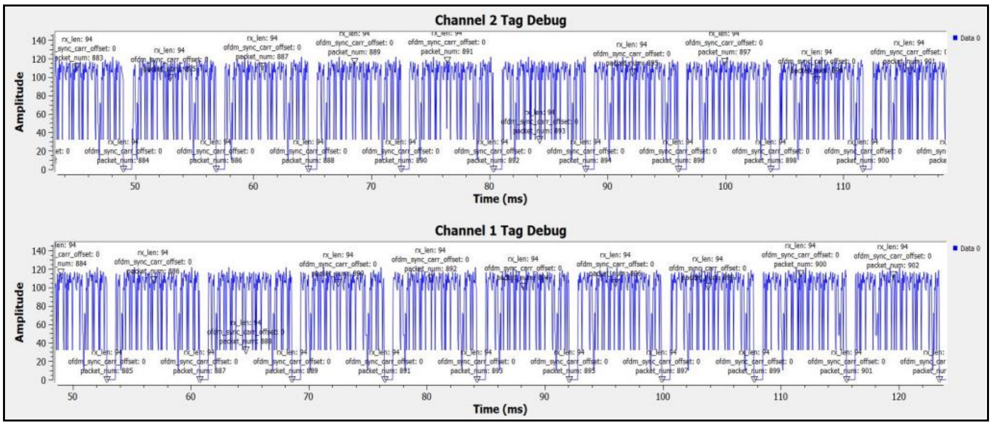
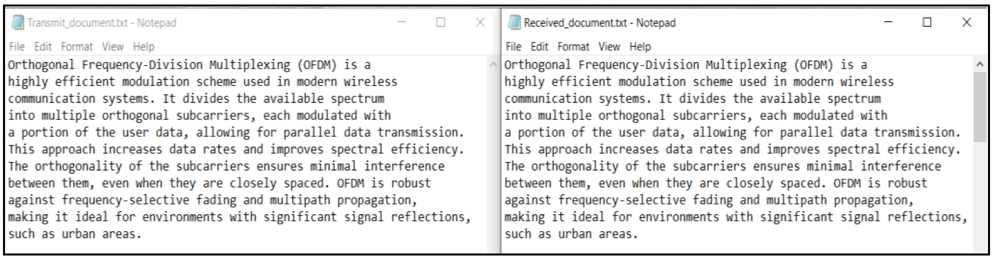


Figure 40 - Visualization of data received in the time domain by tag analysis

The test results demonstrate successful data reception using channel aggregation in both adjacent and non-adjacent channel scenarios, as can be seen in the time domain labeling plots, as well as in Figure 41 where both the transmitted and received data performed in a test are shown. The system demonstrated consistent packet reception with stable synchronization and minimal packet loss in both configurations.



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Orthogonal Frequency-Division Multiplexing (OFDM) is a
highly efficient modulation scheme used in modern wireless
communication systems. It divides the available spectrum
into multiple orthogonal subcarriers, each modulated with
a portion of the user data, allowing for parallel data transmission.
This approach increases data rates and improves spectral efficiency.
The orthogonality of the subcarriers ensures minimal interference
between them, even when they are closely spaced. OFDM is robust
against frequency-selective fading and multipath propagation,
making it ideal for environments with significant signal reflections,
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Figure 41 - Analysis of transmitted/received files on correct data remapping

The HF communication channel is highly variable and subject to many influences, caused by the ionospheric environment, interference and noise. These factors cause different levels of signal degradation for each channel. By using different modulation schemes on each OFDM channel, it is possible to increase the data transfer rate and robustness to the specific conditions of each channel. The overall spectral efficiency of the system can be maximized by adapting the modulation type to the specific SNR of each aggregated channel. If the SNR is high, higher order modulations can be used. This allows more efficient spectrum utilization and increases the overall data throughput. The implementation of different modulation types on each OFDM channel enables adaptive communication strategies.

With Adaptive Modulation and Coding (AMC), the modulation scheme can be dynamically adjusted based on real-time channel evaluations. This adaptability ensures that the system can respond to changing conditions, and continue to function and operate at higher efficiency. It also allows better utilization of available bandwidth and power resources, which is essential for long-distance HF communications. Figure 42 shows the results of an OFDM aggregation test in an HF data link using different parameters on each channel. One channel uses QPSK modulation and another channel uses 8-PSK modulation. The purpose of the test is to analyze the performance and reliability of these two modulation schemes when combined in a non-adiacent aggregation configuration for a fixed SNR of 15 dB.

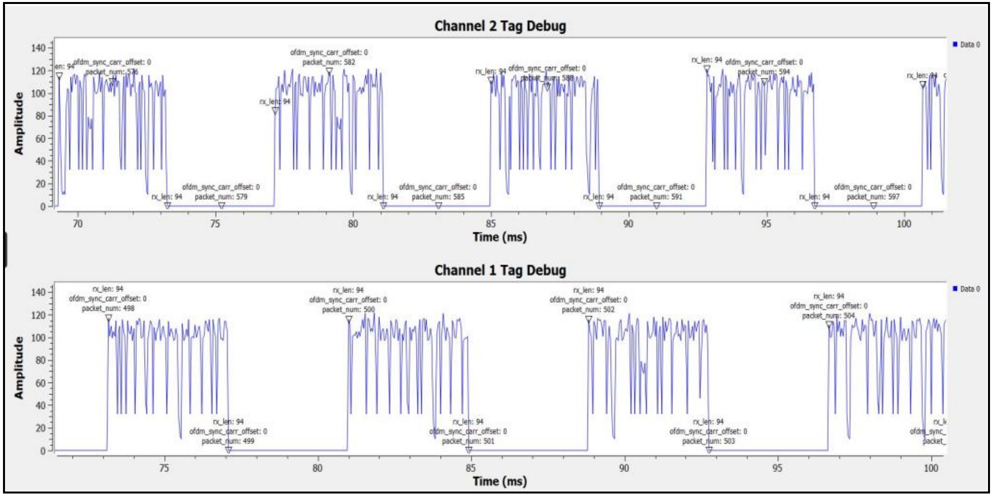

Figure 42 - Visualization of received time domain labels for QPSK (channel 1) and 8-PSK (channel 2) modulated channels

The QPSK modulated channel 1 is more robust and reliable, as shown by the packet reception and the lack of losses according to the received data (498-504 packets). The simpler modulation scheme of QPSK provides better resistance to noise and interference, thus ensuring stable communications for the set SNR level.

On the other hand, there are many lost packets when receiving packets (576-597 packets) on channel 2 using 8-PSK modulation. Although 8-PSK provides higher packet transmission rates (597 vs. 504), its higher sensitivity to signal degradation causes the packets to be less reliable. In low SNR radio frequency environment, the increased complexity of 8-PSK modulation, causes the system to be more susceptible to errors. This comparison emphasizes the importance of selecting appropriate modulation schemes for different channels to increase the performance in non-continuous OFDM aggregation and highlights the trade-off between data rate and robustness.

Final conclusions

The dynamic and evolving field of radio communications presents significant challenges in ensuring stable and reliable data transmission specific to ionospheric channels for HF transmissions. Due to the high variability characteristic of ionospheric propagation conditions, traditional HF communication systems are often inadequate, necessitating an innovative re-evaluation of the underlying technology. This research has investigated these challenges through comprehensive studies and implementations using SDR technology, which has the potential to support significant advances in ionospheric propagation radio communications.

The initial phase of the research consisted in the implementation of an SDR system designed for noise assessment in the HF frequency range. The effectiveness of this system for measuring and analyzing noise levels has been demonstrated, thus establishing a solid basis for future studies. The results indicated that the SDR system provides reliable and cost-effective performance at a low cost price compared to conventional spectral analyzers for which the cost is much higher. In addition, the research was extended to evaluate HF noise within ionospheric channels over different bandwidths. This analysis sought to determine how these bandwidths influence channel availability over time. Real-time data acquisition systems are capable of capturing the signal levels within these channels, thus providing a clear picture of how channel availability varies throughout the day as a function of bandwidth adjustments and the noise level corresponding to each transmission channel bandwidth.

In addition, the development of an adaptive HF communications system reflects the innovative nature of the research approach. This system utilizes SDR technology, the GNU Radio software environment and the Python programming language to dynamically control transmission parameters such as transmit frequency, bandwidth and power in response to real-time ionospheric conditions. This adaptability is essential for maintaining the integrity of communications in environments where ionospheric variability can have a strong impact on the received signal level. By monitoring and adapting to continuously changing conditions, the system ensures reliable and efficient HF communications.

Another notable aspect of this research is the practical testing of an HF data communications system using OFDM under NVIS conditions. Laboratory evaluations, implementations and real-world testing explore the performance of OFDM in the system, focusing on variables such as SNR, PER and transmission channel bandwidth. These tests confirm the performance of the system to maintain data integrity under varying SNR conditions and demonstrate the potential to achieve higher data transfer rates by adjusting the bandwidth.

This study has been followed up with a detailed analysis of the impact of varying OFDM parameters, including modulation type, FFT size, cyclic prefix length and pilot subcarrier positioning, on the overall performance of the HF communication system under NVIS propagation conditions. It clearly demonstrates that simpler modulation techniques such as BPSK result in lower error rates, indicating that less complex schemes can be advantageous under certain conditions. In the future, there is considerable potential for further improvement of OFDM systems through adaptive modulation and coding schemes capable of dynamically adapting to channel conditions and real-time traffic requirements.

The research concludes with a study on the implementation of OFDM waveform-specific channel aggregation to increase the data rate. Laboratory tests have confirmed successful data reception in both continuous and non-continuous aggregation scenarios, emphasizing its importance for HF communications. This innovation is crucial for applications requiring higher data transfer rates, such as advanced digital communication systems, and can significantly improve the reliability and efficiency of HF communication networks under variable channel conditions.

This research covers advances in both theoretical and practical aspects of HF communications, setting a benchmark for future innovations. The successful integration of adaptive strategies and advanced digital modulation techniques represents a significant step towards improving the performance of HF communication service. The results of the research undertaken in this PhD thesis contribute to the improvement of critical communication infrastructures, ensuring reliable performance under varying ionospheric conditions.

The PhD thesis has a multidisciplinary character and focuses on obtaining primarily experimentally demonstrated results with immediate applicability. The proposed waveform, based on the OFDM technique and test results, can be a starting point for the finalization of a communication protocol in the HF range under NVIS propagation conditions.

PhD thesis contributions

This PhD thesis makes a significant contribution to the field of data communications in the HF range. Through innovative research and implementation, this experimental and applied approach contributes to the understanding and utilization of HF ionospheric channels, improving both the reliability and efficiency of HF communications.

Research direction 1: Contributions on the implementation of an SDR system for HF noise assessment and availability analysis of ionospheric channels with variable bandwidths

The first research segment focuses on the development and testing of a specially designed SDR system for analyzing noise in ionospheric channels, following several key milestones:

- ✓ *Design and implementation*: The study involved the design and implementation of a flexible SDR-based measurement system, equipped with a wideband active antenna, designed to accurately measure white Gaussian Gaussian noise (WGN) in the HF frequency range from 2 to 12 MHz.

- ✓ *Measurement and testing*: This phase aimed to test and evaluate the settings against calibrated reference measurement equipment. Measurements were performed using the "20% method" to assess WGN levels in bandwidths up to 2.5 MHz.

- ✓ *Data analysis and validation: The* collected data on WGN levels were subjected to analysis, thus validating the performance of the SDR-based system in terms of its ability to record accurate noise measurements and to assess its potential impact on HF communications.

In addition, this line of research has investigated the impact of different bandwidths on the noise profile of ionospheric channels, identifying the optimal bandwidths for different HF communication scenarios. This effort has established rapid and viable methodologies for probing HF ionospheric channels, assessing channel availability through real-time data acquisition, and demonstrating the performance of the proposed method to improve the accuracy of the assessment.

Research direction 2: Contributions on strategies to improve NVIS communications by analyzing SNR using SDR technology

The second research direction complemented the previous study, focusing on the analysis of SNR with respect to various factors and the implementation of an adaptive system to maintain the highest possible SNR within the ionospheric channels. Key activities included:

- ✓ *SDR-based SNR analysis*: Implementation and testing of an SDR-based system to analyze SNR variations within ionospheric channels. This analysis formed the basis for strategies to improve the quality of received signals.

- ✓ *Ionospheric channel availability as a function of SNR:* Investigate how SNR levels influence ionospheric channel availability. This analysis contributes to the understanding of the correlation between SNR and channel performance in order to increase data transfer rates.

- ✓ *Adaptive system for SNR enhancement*: Development of an adaptive system capable of dynamically configuring HF radio link establishment options based on real-time SNR evaluations. This system aims to provide improved quality indicators for HF radio links even under difficult ionospheric conditions.

Research direction 3: Contributions on the implementation, testing and analysis of advanced waveforms for increasing the data transfer rate of HF communications under NVIS propagation conditions

The third research direction focuses on the implementation and testing of an SDR-based system for HF data communications in NVIS propagation scenarios, with the aim to improve data transfer rates and reduce packet error rates. Main objectives include:

- ✓ *SDR-based HF data communication system*: Implementation and evaluation of an SDR-based communication system designed for efficient data transmission over ionospheric channels using OFDM technology. This study examines the potential of SDR technology to improve reliability and data throughput in HF communications.

- ✓ *Testing and evaluation of OFDM waveforms under HF transmission channel conditions:* Analysis of OFDM waveforms as a method to increase the data transfer rate in HF communications. This includes evaluation of the performance of OFDM technology in terms of its underlying parameters.

- ✓ *Aggregation of narrowband OFDM channels:* The innovative concept of aggregating multiple narrowband OFDM channels into a wideband channel addresses the need to increase spectral efficiency and overcome the bandwidth limitations inherent in traditional HF systems. The system utilizes unused portions of the spectrum by combining several narrowband channels. Each of these channels operates on a different group of sub-carriers, which contributes to efficient utilization of the available spectrum space. In doing so, the system ensures that the spectrum is used to its full potential.

The benefits of the SDR technology were that by means of specific software applications, the transmitting side and the receiving side could be synchronized for automatic control of hardware components, automatic data acquisition and real-time data processing. The control of the signal parameters by means of software applications allowed to adapt the waveform characteristics to the dynamic behavior of the ionospheric channel and led to the improvement of the data transfer rate in the HF range. The results of the research showed that the waveform based on the OFDM technique can be a viable solution for data communications in the HF range under NVIS propagation conditions.

All these interconnected research contributions significantly improve the utilization of ionospheric channels for high-quality HF communications. By harnessing the adaptability and innovative potential of SDR technology, this thesis addresses and overcomes current challenges in ionospheric communications, paving the way for significant advances in HF communication systems.

Future research directions

The results of the experimental research realized in this thesis will serve as a basis for future projects aiming at the development of a fully operational radio communication system. The main objective is to design and implement a prototype HF radio station using advanced SDR technology. This system is intended to bring substantial improvements in HF communication capabilities and adaptability, in particular to NVIS propagation conditions. Key technical objectives include increasing signal reliability, adapting operating frequencies and improving the overall robustness of the system in varying ionospheric environments.

The first direction will be to design and build a dedicated SDR platform specifically adapted for HF communications. This platform will integrate state-of-the-art digital processing technologies to improve signal integrity and operational flexibility. A key element of this platform will be the development of a customized FPGA module. This FPGA will be specifically programmed to utilize the OFDM technique for adaptive data communications, allowing the radio system to dynamically adjust transmission parameters in real time according to prevailing ionospheric conditions. The development of this FPGA requires a complex integration of hardware and software to enable advanced modulation and coding schemes that can be adapted instantaneously to increase the efficiency and reliability of communications.

Real-world propagation testing of such a prototype HF radio prototype is essential. Therefore, another research direction will focus on conducting field tests to evaluate the performance of the system in various operational environments - from urban environments with high noise levels to remote areas requiring secure communications. These evaluations will help fine-tune system parameters such as frequency range, output power and bandwidth. In addition, they will ensure data integrity and continuity of communications under varying conditions. The data collected will be essential for refining the adaptive algorithms and transmission strategies of the system.

In addition to hardware development, substantial progress is needed in the software area, in particular the development of a user-friendly Graphical User Interface (GUI). This GUI will be designed to interact seamlessly with the HF radio station system, providing users with real-time updates on system status, environmental conditions and communications quality. The interface will allow for manual adjustment of settings and, more importantly, will provide automatic recommendations for optimal communication settings based on continuous analysis of transmission data and environmental feedback.

The graphical user interface will also include diagnostic tools to assist users in real-time troubleshooting. The intuitive design of the GUI will simplify complex operations, making the system accessible to a wider range of users and contributing to the efficient management of the HF radio station. The software application will support users, enabling them to operate and manage the HF radio station system efficiently without requiring in-depth technical knowledge of radio frequency communications or ionospheric propagation.

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