System and Measurements for Analysis of Near Vertical Ionospheric Skywave Propagation in the High Frequency Range

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Abstract *– Design and testing of a system able to characterize the quality of radio link in high frequency range are presented with the objective of providing a starting point for efficient planning of data communication over restricted areas belonging to the territory of Romania. A swept spectrum analyzer cored setup was used in parallel to a Software Defined Radio platform cored setup that enabled determination of capabilities and limitations in describing essential parameters of the momentary availability of data radio link. Ionospheric channels used in experimental session were chosen based on nowcasting data provided by the European Ionosondes System for a radio link 100 km long. The results confirm the necessity of real time description of the ionospheric channel for best performance and stable data rate communication in highly variable conditions of ionospheric behavior.*

Keywords – *ionospheric channel, signal to noise ratio, NVIS, critical frequency, Software Defined Radio*

1. INTRODUCTION

When satellite communication and cellular networks become unusable due to local disasters or catastrophes, a convenient emergency tele-communication alternative is the use of high frequency (HF) range. Such relief alternative which is generally quickly deployable needs however a previous careful planning which should start by taking into consideration the study of the specific ionospheric propagation conditions over the area of interest. They will highly depend on location, but also on hour of the day, season and momentary solar activity.

For geographical areas with radius of about 150 km it has been demonstrated that the use of a single 100 W base station emitting in HF band in near vertical incidence skywave (NVIS) propagation conditions will ensure a reliable signal strength [1]. Typical ionospheric HF channel problems are connected to fading, dispersion and noise. Presently, for data transmission in HF channel some advanced modulation techniques or automatic repeat quest (ARQ) technique are applied [2].

NVIS communication is based on the idea that the radio coverage over very short distances by reflection back from the ionosphere is assured if the emitted waves were launched nearly vertically (70^0-90^0). Practically, to cover a circular area around a transmitter starting to its immediate proximity, the wave should be launched from a certain angle (elevation angle) upwards.

NVIS propagation quality is highly sensitive not only to ionospheric behavior but also to some parameters of the transmission and receiving antennas. For example, at the emission the most important parameters are elevation angles and optimum antenna height – which affects the radiation pattern, while at receiver the most important thing is the optimization of the antenna to a high signal-to-noise (SNR) value [1]. Recently in-depth studies were devoted to the consistent improvement of NVIS communication from the antenna point of view. Ground effects on transmitting radiation pattern were systematically analyzed [3], proposal of efficiency increasing by use of transmitting directional antenna arrays were made [4] and use of diversity reception or multiple-input-multiple output (MIMO) principles at receiver antenna were proposed [5]. Such approaches are however beyond the objectives of present work but will be considered in our further research.

In NVIS conditions, HF signal is reflected back to earth by the most outer layer of the ionosphere, denominated as F2 layer. Therefore, description of this layer's parameters is crucial. For HF radio links the most important are the critical frequency f0F2 – which shows the maximum ordinary radio wave frequency able of vertical reflection from F2 layer back to earth and the maximum height of the layer, hmF2. Besides, the maximum usable frequency (MUF) indicates the highest value of the frequency, which guarantees radio wave propagation on an oblique ionospheric route.

The predicted values of f0F2 and MUF in present work were extracted for the location of interest from the real-time database provided by the European Dias project [6]. The height hmF2 was extracted from the International Reference Ionosphere 2007 [7] – a model which was demonstrated to be reliable enough if compared to measurements [8].

By using calculations of the form described in [9] one can apriori assess the link budget for the desired radio-link and design the practical connection.

In case of HF-NVIS communication, data transmission rate and bit error rate depend on signal quality at reception. An important indicator is in this context SNR. In [10] the channel availability is determined based on SNR using two threshold levels (3 dB and 6 dB). Thus the first considered case is that in which 70% of time segments (a period of analysis contains 10 segments each lasting 1s) present SNR> 3dB, while the second case is that in which 50% of time segments present SNR> 6 dB.

Present work is devoted to description and experimenting of a system transmitting and receiving HF-NVIS signals between two locations 100 km apart in Romania for which a preliminary analysis of radio link quality is made. The received signal level and SNR are determined by theoretical and experimental means in parallel. Subsection 2.1 of the paper presents the calculation methodology proposed by ITU-R P.372-8 [11] recommendation and in subsection 2.2 the measurement procedures and systems are described. The evaluation results are discussed in detail in Section 3 and finally the conclusion conduct to the idea of experimental measurements needed for proper planning of local HF communication coverage.

2. MATERIALS AND METHOD

2.1. Theoretic evaluation of received signal and noise power levels for NVIS propagation case

Recommendation ITU-R P.372-8 mentions as main sources of noise in the HF range [11]: atmospheric noise (F_A), the noise produced by human (F_c) and galactic noise (F_D). The median values of the noise produced by humans are classified into four categories [11]: A - business, B - residential, C - rural and D - quiet areas. The noise power can be expressed by [9], [11]:

$$P_n[dBW] = F_a[dB] + B - 10\lg(kT_0) \qquad (1)$$

where k represents the Boltzmann constant ($1.38\cdot10^{-23}$J/), T_0 is the environmental temperature (T_0=290 K) and B is given by the receiving bandwidth b expressed in kHz as follows [9]:

$$B = 10\lg b \qquad (2)$$

and F_a represents the noise figure of the receiving system, being characterized by the external noise factor and by the receiver noise factor (F), as follows [9], [11]:

$$F_a[dB] = F[dB] + 10\log(10^{\frac{F_A[dB]}{10}} + 10^{\frac{F_C[dB]}{10}} + 10^{\frac{F_D[dB]}{10}}) \qquad (3)$$

The values of the main components of external noise factor for a quiet rural environment are presented in Table 1.

Tabel 1 External noise in the frequency range 2-10 MHz for a quiet electromagnetic rural environment [11]

Frequency [MHz]	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**
F_A[dB]	5	12	20	23	24	29	30	31
F_C[dB]	45	40	37	36	32	27	26	24
F_D[dB]	0	10	38	37	36	34	32	30

The received signal power (P_{rec}) depends on transmitted power (P_{em}), on the gains of the emission antenna (G_{em}) and receiving antenna (G_{rec}), on radio frequency cables losses (L_{RF}), on the free space path losses (L_{FSL}) and on additional losses (L_{ad}) caused by the ionospheric propagation mechanism:

$$P_{rec}[dBW] = P_{em}[dBW] + G_{em}[dBi] + G_{rec}[dBi] - L_{RF}[dB] - L_{FSL}[dB] - L_{ad}[dB] \qquad (4)$$

Free space path losses depend on distance passed by the electromagnetic wave (d) and on the frequency (f). For d expressed in km and frequency in MHz path loss is given by [9]:

$$L_{FSL}[dB] = 32.44 + 20\lg d + 20\lg f \qquad (5)$$

The path length of the electromagnetic wave ($d = d_1 + d_2$) can be appreciated if the height of F2 ionospheric layer (hmF2) and the distance between the two locations (D) of the transmission and receiving antenna is known. Thus if d_1 and d_2 are considered equal (Figure 1) then:

$$d = 2\sqrt{\left[\left(\frac{D}{2}\right)^2 + (hmF2)^2\right]} \qquad (6)$$

From Figure 1 one can calculate the elevation angle (θ):

$$\theta = \arctan\left(\frac{2 \cdot hmF2}{D}\right) \tag{7}$$

Knowing the radiation patterns of the transmitting and receiving antennas and the elevation angle (θ) one can determine the gains of two antennas (G_{em} si G_{rec}) on the direction of communication.

Additional losses caused by ionospheric propagation in NVIS conditions specifically depend on attenuation of waves in D layer of the ionosphere. This attenuation is inversely proportional to the square of the frequency and occurs especially during the day, with the highest amplitude at midday. It is estimated that D layer attenuation is between 10 and 20 dB [9].

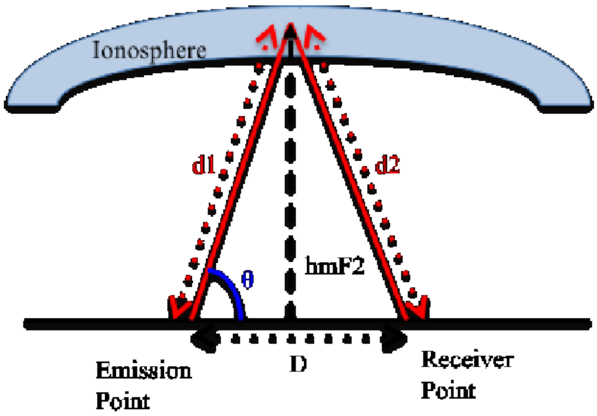

Fig. 1 – Geometric scheme of NVIS propagation of HF waves

2.2. Experimental evaluation of power and of signal to noise ratio at the reception in NVIS propagation case

In order to experimentally assess the received power and the noise level two measurement systems were used. The first one was based on a swept spectrum analyzer and the second one was based on a Software Defined Radio (SDR) receiving platform with real-time response. Radio communication in NVIS conditions took place between Sibiu city – transmission (coordinates: Latitude: 45.7828, Longitude: 24.1452) and Lupsa village – reception (coordinates: Latitude: 46.3774, Longitude: 23.1737), which was located 100 km distance away in straight line.

The frequencies of the used channels were determined from nowcasting values of critical frequency foF2 and MUF, as extracted from [6] for the time and place of the experiment.

2.2.1. Ionospheric sounding system with swept spectrum analyzer at receiving point

Ionospheric sounding system included the emission and the reception set-ups. All operations performed at both the transmitter and receiver were software-controlled for the automation of the sounding process. Special software applications were built under Lab Windows CVI 2012 programming environment [12].

The transmission set-up was composed of the software driven signal generator Rohde & Schwarz SM 300, a power amplifier AR 50W 1000B and a crossed dipole antenna Harris RF-1938 (optimal for NVIS communication in the distance range 10-400 km) elevated at 8.6 m above the ground on a sectional mast of the form of a low loss coaxial feed line. The command software allowed setting of the desired list of emission frequencies, choosing of signal levels, the duration of each channel emission and the time of start and stop of the emission sessions.

The receiving set-up comprised of Rohde & Schwarz FSH3 spectrum analyzer and a broadband dipole antenna Diamond W330 elevated at 6 m above the ground. The use of broadband antenna provided a standing wave ratio (SWR) bellow 1.5 in the band of interest 2-10 MHz. Signal strength measurement was made using “Channel Power” mode of the analyzer. The software enabled reception of a set of ionospheric channels, the setup of the spectrum analyzer‘s parameters (frequency, sweep time, frequency resolution, frequency span, sweep mode, type of detector, amplitude reference level), the control of the channel bandwidth, the establishment of the recording time for each channel and start and stop moments of the recordings. Figure 2 presents a view of the power amplifier AR 50W 1000B, the FSH3 spectrum analyzer and the signal generator SM 300 while in Figure 3 a picture of the positioning of the Diamond W330 broadband antenna used at the reception was posted.

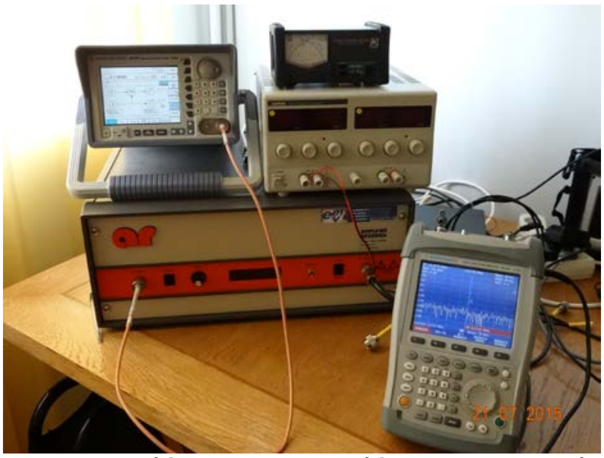

Fig. 2 – Picture of the main components of the transmission set-up for NVIS communication experiment

Using of a swept spectrum analyzer for monitoring of HF channels has several limitations due to settings needed for proper measurements. For reception of a low-amplitude channel one needs an improving of the analyzer’s sensitivity by lowering the analyzer resolution bandwidth (RBW). This however conducts to an increase of the sweep time (SWT). For example, if the FSH3 analyzer is set to RBW=100 Hz then the displayed noise of the analyzer (DANL) will be approximately -120 dBm, but for the correct operation SWT must be at least 5 s. This constriction implies that the spectrum analyzer cannot measure rapid variations of the received signal. This is why this set-up was used in present experiment just for monitoring slower changes in the signals of ionospheric channels. From this perspective the operational analyzer settings were: channel bandwidth= 3 kHz, SWT = 5s, RBW = 100Hz, detector type = Root Mean Square (RMS). The software provided a result file of type *.txt which included the channel central frequency, the power level and the time of the recording.

Ionospheric channel measurement was performed for 24 hours long, with a periodicity of 30 min when samples at each 5 s were recorded for as long as 3 min.

Fig. 3 – Receiving wideband antenna Diamond W330 installed at Lupsa site

2.2.2. Ionospheric sounding system with real-time response of receiving SDR platform

One specific problem encountered in HF communications is the rapid variations of the received signal amplitude due to fading. Knowledge and characterizing of these variations could lead to a better adaptation of transmitted signal characteristics (bandwidth, transfer rate) to the ionospheric channel status.

To monitor rapid changes of the signal level we proposed the use of a SDR platform with real-time measurement capabilities. A SDR platform from National Instruments - Universal Software Radio Peripheral (NI USRP) was chosen and it was software controlled by an application developed in GNU Radio [13]. Therefore, at emission we used a NI USRP 2952 platform (with the RF emission board model LFTX 0-30 MHz) and at reception a NI USRP 2932 platform (with the RF receiving board model LFRX 0-30 MHZ). At emission the signal was amplified by the power amplifier AR 50W 1000B and conducted to the dipole antenna Harris RF-1938. The receiving antenna was again the broadband model Diamond W330. In Fig. 4 the two platforms NI USRP can be viewed.

Receiving of the frequency span of interest could be achieved by appropriate setting of the sampling frequency of the SDR platform. From this perspective GNU Radio application provided the possibility of monitoring of a wider range of frequencies in the first stage (200 kHz in our case) and then in the second stage, by decimation (reducing of the sampling frequency), of a narrow band (10 kHz) - which could be evaluated in detail. The complex signal in file format **.dat could be recorded on the short term (between 1 min. and 2 min.) in either of the two stages of processing. Saved data file was then processed by an application developed in MATLAB, specially written for this purpose which enabled: transformation of data file from format **.dat in format ***.m; evaluation of the signal power, of the noise power and of the SNR with different bandwidths (by changing the corresponding frequency windows) and in different bands of the frequency range recorded by NI USRP platform.

The analyzed receiving situations included two emitted signal types: a continuous wave – just carrier (narrow band analysis) and a waveform encoded by the method Orthogonal Frequency Division Multiplexing (OFDM) with 64 subcarriers having bandwidths of 2 kHz and 4 kHz. By establishing adequate resolution in the time domain and in the frequency domain one can extract significant conclusions regarding short-term variation of received signal parameters.

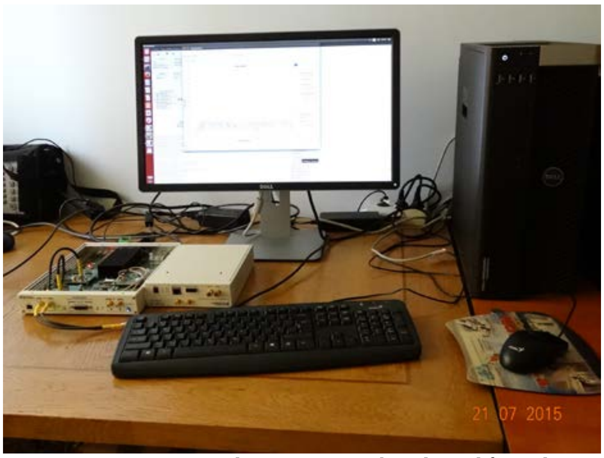

Fig. 4 –NI USRP 2952 and NI USRP 2932 boards used for real-time capabilities

3. RESULTS AND DISCUSSION

Fig. 5 shows the variations over 24 hours – in universal time (UTC) (which is 3 hours delayed from local time) of MUF and of critical frequency foF2 for the day of 9 July 2015. The nowcasting values of foF2 and of MUF frequencies were extracted from the European Ionosonde System (EIS) through Dias Project [6] – which provide systematic real-time measurements of the upper atmosphere in Europe. Respective data were used as reference for analyzing the radio link frequency range in the experiment.

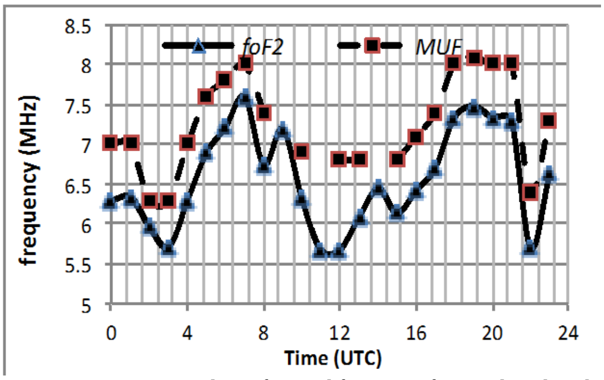

Fig. 5 – Nowcasting values of critical frequency foF2 and predicted values of maximum usable frequency for the radiolink Sibiu-Lupsa on 9 July 2015

The height of F2 layer at the middle distance of direct path between Sibiu and Lupsa, on 9 July 2015 at midday was 332.7 km [7]. Applying relationship (7) of subsection 2.1 it resulted and elevation angle $\theta=81.5^0$, that is equivalent to an opening angle of the radiation from the antenna $2\alpha=17^0$.

The radiation pattern of the emission antenna Harris RF 1938 is shown in Fig. 6 [14]. For the radiating angle of 17^0 and for operating frequencies between 2-12 MHz one can observe that the antenna gain varies between 0-6 dBi. In the range 4-8 MHz the antenna gain is almost constant around 5 dBi.

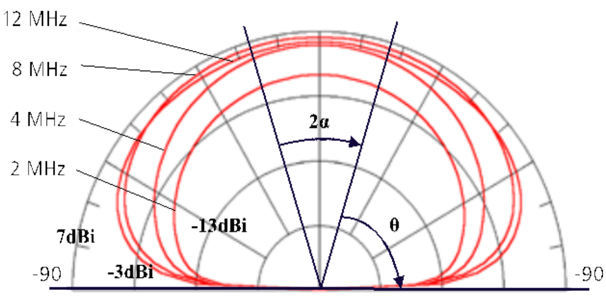

Fig. 6 – Radiation pattern in elevation plane for RF 1938 antenna [14]

Fig. 7 traces the received power levels during the day of 9 July 2015 for the three frequencies used in the experimental radio link. In case of those measurements the receiving system containing the swept spectrum analyzer R & S FSH3 was used.

Taking MUF as reference, one expects, looking at Fig. 5, that frequencies higher than 7.6 MHz would propagate only between 4.00-8.00 UTC and between 17.00-21.00 UTC. Fig. 7 in parallel shows that exactly during those periods of time the signal on 7.6 MHz exceeds a power level of -95 dBm. During the night hours, i.e. 0.00-3.00 UTC and 22.00-24.00 UTC the rule that the lowest frequency (5.2MHz) propagates the best is obeyed, since all this time the received signal is highest at this frequency, followed by the one on 6.7 MHz and then by 7.6 MHz. During midday, when the absorption in the D-layer of the ionosphere becomes very large, all signals are consistently decreased, and mainly the largest one, on f=6.7MHz. The impact of the D-layer absorption is observable in Fig. 5 in the period 9.00-13.00 UTC (which correspond to local time 12.00-16.00), when the received power on all frequencies is lower than -95 dBm.

The most intense signal received at Lupsa was obviously the one on 6.7 MHz, which was very good received both during morning hours and during afternoon and evening. The signals power on 5.2 MHz and 7.6 MHz showed very similar behavior with the exception of the night hours.

By applying the algorithm described in section 2.1 and for a forward power value of 20 W at emission, one obtains the data presented in Table 2. For attenuation due to D layer propagation a dissipation of 20 dB power was considered (noon). Comparing the measured values with these theoretical ones, it can be noted that the calculated values exceeded by more than 15 dB the experimental ones for all three frequencies.

Table 2 Total losses and received power level obtained by theoretical calculation for frequencies used in the experimental radio link

Frequency [MHz]	5.2	6.7	7.6
Total Loss [dB]	126.3	122.3	123.6
Received Power [dBm]	-83.3	-79.5	-80.6

Short-term measurements were made at midday using real-time capabilities of the set-up based on NI USRP platform on a central frequency of 6.7 MHz. The received signal was recorded over short periods of time (approximately 1 minute) and then analyzed by the special MATLAB code. The forward powers were 20 W and 10 W.

In Fig. 8 is represented the variation of the ratio between the received actual momentary signal power and its maximum value over the monitored period (normalized signal). Over 1 min significant variations in signal strength are observed and also short periods when the signal may disappear (decreases greater than 40 dB).

Figure 9 indicates the variation of SNR for a channel bandwidth of 3 kHz for noise power determination. The maximum SNR was 17.46 dB and mean SNR was 7.646 dB. Figure 10 indicates SNR variability for a channel bandwidth of 6 kHz. A significant change is observed, because in this case maximum SNR was 0.72 dB and mean was -7.12 dB. Weight of signals contributing to the noise power by increasing the channel bandwidth is given primarily by other emissions present close to frequency of 6.7 MHz in the spectrum. This is evidenced in Fig. 11 where it can be seen that other channels were present in the band of 10 kHz in the very proximity of our intended sinusoidal carrier signal.

By applying the calculation algorithm in section 2.1 the data in Table 3 were obtained in case of a forward power of 20 W at 6.7 MHz radio link. This time the calculation overestimated again the real SNR.

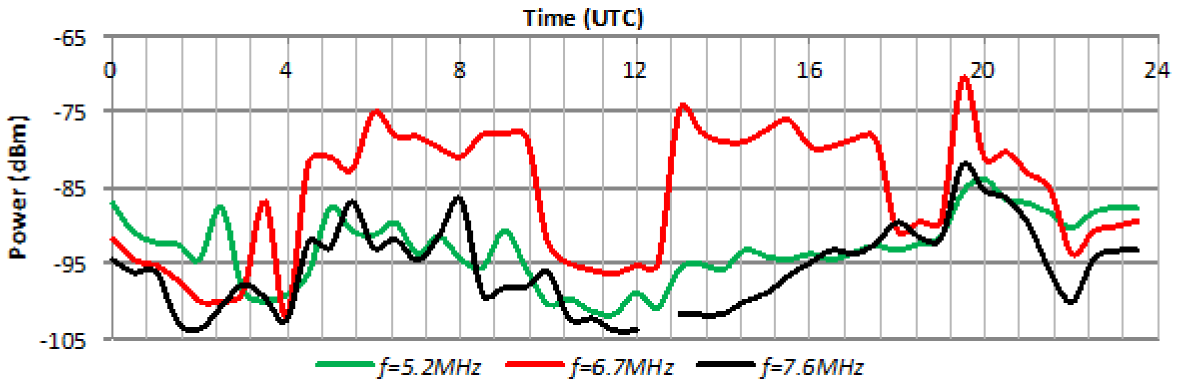

Fig. 7 Power levels of three NVIS signals received at 100km distance from Sibiu, from where they where emitted at 20W, during 9 July 2015

This may be explained by the fact that the calculation algorithm does not take into account possible adjacent channels present in the proximity of the signal. In the algorithm, the change of the channel bandwidth is contributed only by enlargement of the noise power level, as observed in expression (2).

Table 3 Signal to noise ratio and noise power values measured for two different channel bandwidths

Channel bandwidth [kHz]	3	6
Noise Power [dBm]	-96.5	-91.3
Signal Noise Ratio [dB]	17	11

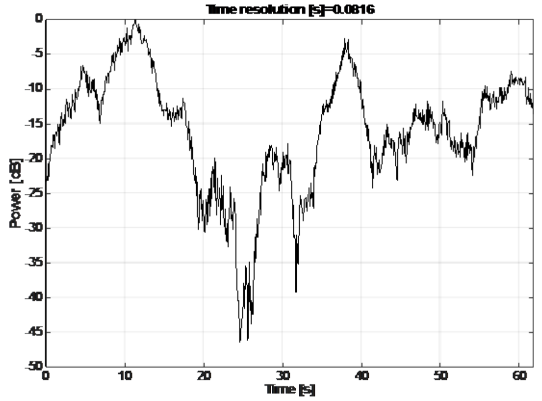

Fig. 8 – Normalized power variation over 1min for the sinusoidal carrier signal at 6.7 MHz

In Fig. 12 the received power spectrum is presented for an emission of OFDM signal having a 4 kHz bandwidth and 64 subcarriers. The transmission was made at midday of 9 July 2015 (ionospheric propagation conditions less favorable) on a center frequency of 6.7 MHz with a power of 20 W. The time variation of the normalized received power of the OFDM signal is presented in Fig. 13 over a time period of 70 s of recording. Over the first 60 seconds the power variation didn't exceed 6 dB proving that in worse propagation conditions the OFDM channel can be stable. By reducing the OFDM signal band to 2 kHz a forward power reduced to 10 W power still allowed a stable reception (Fig. 14).

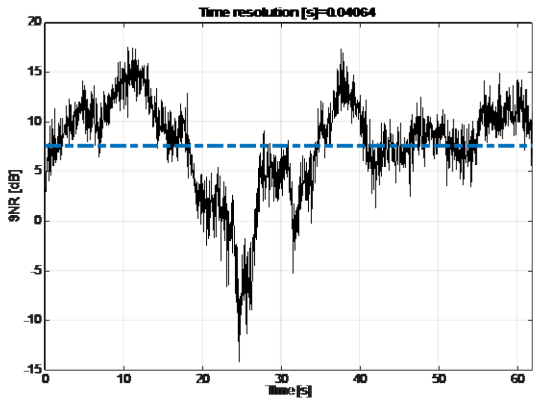

Fig. 9 – The variation of SNR over 1min recorded for a sinusoidal carrier signal and the calculated noise level for 3 kHz bandwidth

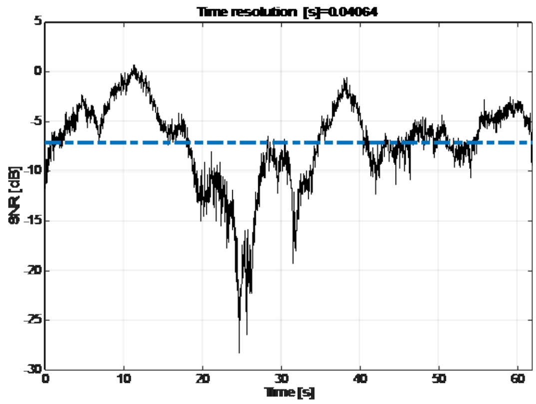

Fig. 10 – The variation of SNR over 1min recorded for a sinusoidal carrier signal and the calculated noise level for 6 kHz bandwidth

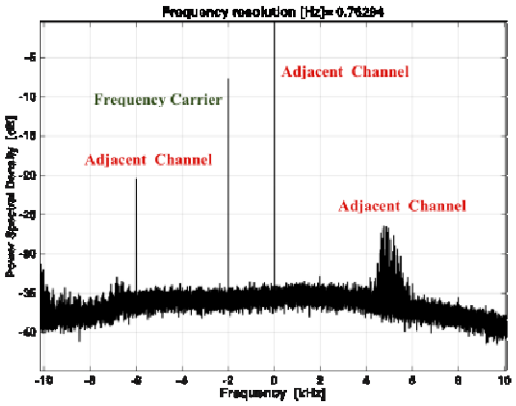

Fig. 11 – Adjacent channels in a bandwidth of 20 kHz

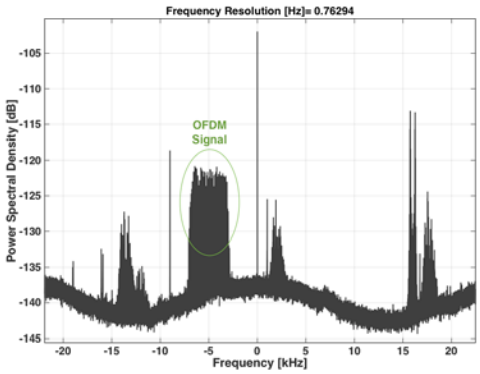

Fig. 12 – Spectrum of the received OFDM signal at 4 kHz channel bandwidth / 64 subcarriers, for a transmitted power of 20W

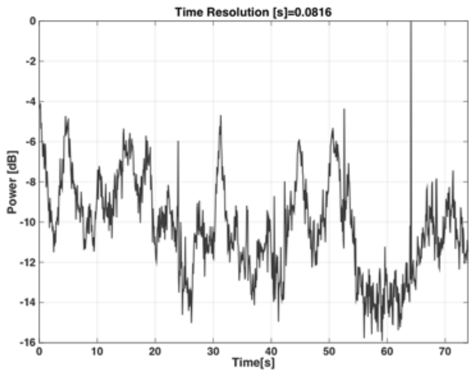

Fig. 13 – Normalized OFDM channel power variation in case of 4 kHz bandwidth and 64 subcarriers for transmitted power of 20W

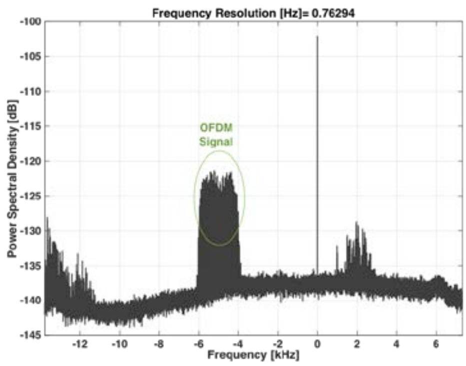

Fig. 14 – Spectrum of the received OFDM signal at 2 kHz channel bandwidth / 64 subcarriers, for a transmitted power of 10W

4. CONCLUSIONS

The paper analyzes the performance of HF-NVIS communications between two locations in Romania from two perspectives: a theoretical one, based on the calculations extracted from ITU-R P.372-8 [11] recommendation and an experimental one, based on measurements which made use by two different set-ups. The first measurement set-up was contained a swept spectrum analyzer with limited performance and the second one used a SDR platform with real-time capabilities.

Using the spectrum analyzer imposed restrictions given by limited sweep time setting and the displayed noise. For example, for the FSH3 analyzer used in experiments, for a resolution bandwidth of 100 Hz the sensitivity could not be higher than -120 dBm while the sweep time could not be decreased bellow 5s. The increase of the frequency resolution lead to increased noise levels in the channel if close to the frequency of interest there are strong adjacent channels present (a common encountered situation in HF range). Short sweep time required for proper measurement of fast variations of the signal strength could not be decreased at reasonable values to capture such behaviors.

Digital platforms with real time response, due to good resolution in both time and frequency, greatly improve reception performance of ionospheric channels that are characterized by strong variations in time. NI USRP platform testing showed that in less favorable propagation conditions the received carrier signal is properly captured in NVIS conditions for transmitted powers of 10-20 W and, the same is true in the case of transmitting OFDM waveform in standard channels of 3 kHz bandwidth. In addition, the real-time acquisition capability of the platform allows complex signal analysis by determination of indicators such as error vector magnitude, bit error rate, etc.

Comparison of measured values with theoretical calculations showed that the first ones are generally overestimated for signal strength and signal to noise ratio at the reception. This is explained by variation of transmission conditions due to ionospheric propagation mechanism and by the presence in the receiving location of strong adjacent channels that are not considered by the calculation algorithm.

Experimental session results underline the need of local ionospheric channel characterization by measurements both over short periods and long periods of time. In this way one can get reliable adjustment of signal characteristics when strong variability of HF radiation to ionospheric behavior is encountered and as a consequence the communication could be considerably improved.

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