Directional Measurement of HF Spectrum Occupancy

Cornel Balint
Dept. of Communication
Politehnica University Timisoara
Timisoara, Romania
cornel.balint@upt.ro

Aldo De Sabata
Dept. of Measurements and Optical Electronics
Politehnica University Timisoara
Timisoara, Romania
aldo.de-sabata@upt.ro

***Abstract* — Results concerning spectrum occupancy in HF range as function of the direction of signals arrival are reported. In addition to time and frequency, the influence of the spatial dependence on spectrum occupancy is analyzed. Spectrum occupancy is computed using an energy detection criterion. Parallel measurements of HF signals have been made using software defined radio equipment, a reference omnidirectional broadband antenna and two type of HF directional antennas. Measurements results prove that directional antenna can bring additional gain in terms of spectrum occupancy data and can offer more free frequency bands for an opportunistic transmission in an emergency communications system.**

Keywords—HF, spectrum occupancy, software defined radio, directional antennas

I. Introduction

Radio communications in the High Frequency (HF) range (3-30 MHz) are subject to national and international regulations and standards [1, 2]. The spectrum is heavily occupied by broadcast transmissions, individual users, fixed and mobile communications and various services such as time and frequency references, ionosphere sounding signals for scientific purpose and propagation forecast, heating, ISM etc. The spectrum occupancy is large also because propagation of HF electromagnetic waves takes place not only in line-of-sight but also through one or several bounces between the ionosphere and Earth, allowing for very long distance coverage. However, the free electron density in the ionosphere is highly variable at several time scales (hourly, daily, seasonally, yearly and according to the cycles of the Sun), so that wave propagation is affected and consequently communications in the HF range are notoriously unreliable.

Despite the above described variability, communications in the HF range are widespread due to simplicity of the equipment needed for transmission (transmitter and antenna) and reception (receiver). This makes the ionospheric channel the solution in case of long-range broadcasting or communications for regions that lack infrastructure, or where terrain forbids line-of-sight links, in emergency situations and in troop deployment in the battlefield.

Spectrum occupancy (SO) measurements in the HF range have been performed for a long time now in various parts of the world (see e.g. [3, 4]). Knowledge of the SO allows authorities to better regulate frequency allocation and constitutes the foundation for building models for long- and short-term prediction [5, 6, 7] that are beneficial for secondary spectrum users in the cognitive radio paradigm [8]. The majority of reported SO measurements involved isotropic antennas. However, some older references indicate that some important information is lost in this way: differences in noise floor or SO measured with directional antennas at the same spot in various directions have been found [9, 10, 11]. These differences have been explained by the time and space dependent ionization of the D layer due to the current position of the Sun, by the azimuthal variation in the density of signal sources and by the azimuthal variation of the propagation conditions.

Knowledge of the HF SO is important in other fields, such as in Electromagnetic Compatibility for the Automotive industry, since modern cars are equipped with various devices that are critical for safety, but are sensitive to electromagnetic fields from low frequency to millimetric waves [12, 13]. This work is motivated by this application too.

In this paper, we report SO results obtained with two directional antennas at the location of Timişoara, Romania: a loop antenna and a directional 4-elements Yagi antenna. Measured isotropic SO at the same location has been discussed in [14, 15]. By using a loop antenna that is oriented with the surface of the loop in the vertical plane, SO can be measured for vertically polarized waves according to the radiation pattern of the antenna, with a maximum on a given axis (e.g. north-south, east-west etc.).

While this result is different and less sharp than the one obtained with an antenna array, it is, for the best of the authors' knowledge, the first attempt to estimate the azimuthal SO at the considered location. By contrast, measurement with the Yagi antenna provides directional information. However, in this case the measurement frequency band is limited by the antenna.

In the next Section, the receiving equipment, including antennas, are presented and the definition of the SO, based on an energy criterion, is outlined. In Section III, measurement results concerning azimuthal distribution of noise and SO are reported and discussed. Conclusions are drawn in the last Section.

II. Antenna and Receiving Equipment

SO measurements have been performed using a SDR equipment interfaced with a host computer. The SDR we used was a Dual RF Transceiver model NI USRP 2950R, equipped with Xilinx Kintex-7 (410T) FPGA and a PCIe – MXI Express Interface USRP RIO to host computer.

To operate the SDR equipment in the HF range, an extension LFRX (Low Frequency RX) USRP Daughterboard had to be added on each input channel, that provided the operational frequency range from DC to 30MHz.

The system has been controlled and operated under Ubuntu Linux and the GNU radio environment, allowing to set the received frequency and the desired bandwidth and to

978-1-5386-5925-0/18/$31.00 ©2018 IEEE

record complex samples of the acquired signal. Furthermore, signal processing procedures could be conveniently applied.

The measurement of SO has been done using one omnidirectional antenna as reference and two directional antennas. As reference antenna we have used a Diamond WD 330 J omnidirectional broadband antenna that performs well in the entire HF domain.

The first directional antenna was a small loop antenna, also known as magnetic loop [16]. It is designed to be highly portable and is quick and easy to set-up. The loop antenna is tuned using a variable capacitor, which makes the reception narrow-band. The simulation of this antenna plotted in Fig. 1 shows that the radiation pattern has a null along the loop axis and a maximum in the loop plane. Narrow nulls can be used for blocking specific signals or noise or for direction finding. The simulation shows a gain of +1.63dBi and a minimum gain of -6.46dBi along the loop axis and an angle of the main lobe about ±45º at -3dB, which led to the setting of a 45º antenna orientation step in the measurement setup.

The second directional antenna we used for measurements was a 4-element Yagi directive antenna model DHF-6, an antenna well known in the world of ham radio. According to the manufacturer specifications, the antenna has a gain of 7.5 dBi, front to back ratio 15 dB, and front to side ratio 25 dB. Even though this antenna is a multiple narrow band antenna, designed for radio amateur bands, as receive antenna it performs well also for all frequencies in HF band for vertically polarized waves.

To have consistent results concerning spectrum occupancy irrespective of the antenna type used for measurement, we performed an antenna and receiver calibration. We included in the SDR receiver a multiplication by constant block and set this constant to have the same signal level for each antenna we used.

The acquisitioned signal (records) had a duration t_r (e.g. t_r=10 seconds) and a bandwidth B_r (e.g. B_r=1 MHz) centered on a frequency f_c from the HF band. Every record has been split off-line in sub-records of duration τ (e.g. 1 second). Each record has been repeated by rotating the antenna with an angle of 45°, resulting 8 azimuthal positions: N, N-E, E, S-E, S, S-V, V and N-V.

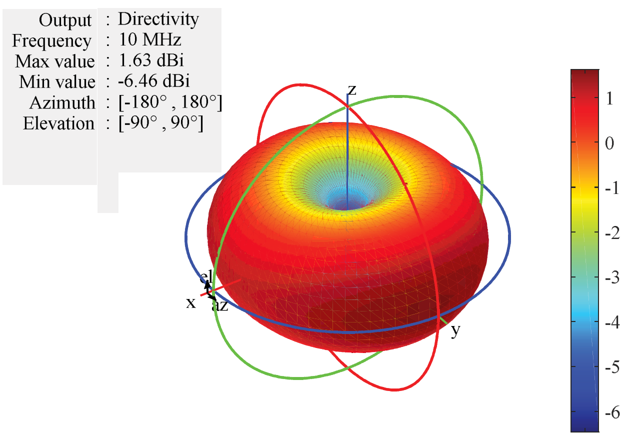

Fig. 1. 3D radiation pattern of loop antenna at 10 MHz

These sequences have been repeated N times with a period T (e.g. T= 120 seconds) for a certain duration, e.g. 1 hour. The short time averaged power spectral density of each sub-record has been numerically calculated, based on the Discrete Fourier Transform and the Parseval theorem.

Each sub-record has been split into several sub-bands of bandwidth B=3 kHz (the remaining frequencies at the edges have been discarded). The value of B has been selected for convenience, as required by the communications network [5, 15]. We calculated the SO on each cell having a duration τ and a bandwidth B, i.e. $SO(t_{mn}, f_k)$, where f_k denotes the center frequencies of the k-th sub-band.

The calculation of the SO has been based on an energy detection criterion [15], which relies on a threshold depending on frequency $T(f)$. A cell has been declared occupied (i.e. SO=1) if at least one sample in the power spectrum was greater than the threshold and free (i.e. SO=0) in the opposite case.

The threshold can be written as [7]:

$$T(f) = W(f) + M \tag{1}$$

where $W(f)$ is the noise floor and M is a fixed margin [17].

Ionosphere communications are affected by cosmic, atmospheric, and man-made frequency-dependent noise. A value M=8 dB has been chosen as a convenient compromise between misdetection and false alarm.

The average over time of the spectrum occupancy at frequency f_k yields the *duty cycle* of a sub-band:

$$DC(f_k) = \langle SO(t, f_k) \rangle_t \tag{2}$$

The average over frequency of SO at t_{mn} time (record m, sub-record n) gives the *congestion* of the 1-MHz channel:

$$CC(t_{mn}) = \langle SO(t_{mn}, f_k) \rangle_f \tag{3}$$

Measurement results of the above introduced quantities are reported in the next Section.

III. Azimuthal Measurements Results

To assess the differences between the signals received with the omnidirectional antenna and the directional antenna (oriented to east), Fig. 2 shows the frequency spectrum of the two signals, for the central frequency of 7 MHz in the case of directive antenna oriented to N-V. The spectrum for other directions is comparable, but with small modifications.

Some notable differences are observable around 6.65MHz, 7 and 7.2MHz, proving that the azimuthal variation in the distribution of signal sources and the azimuthal variation of the propagation conditions can lead to differences in received signals level and to different SO for different angles of arrival of the signals.

The noise floor $W(f)$ used in (1) to find the threshold for energy detection criterion is computed by splitting the signal total bandwidth into several small sub-bands (e.g. B=1KHz), and finding the bandwidth having the minimum energy, i. e. the sub-band containing only noise.

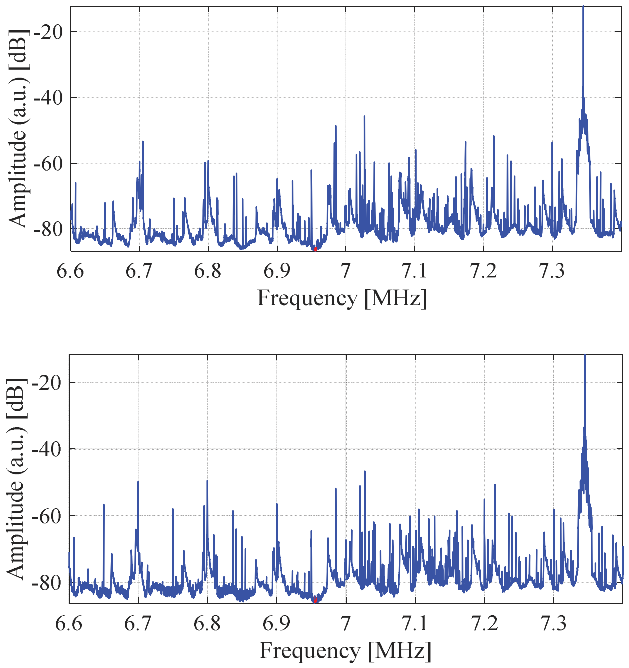

Fig. 2. Frequency spectrum for a signal received on May 7, 2018 at 18 h (GMT+2) with omnidirectional antenna (top) and loop antenna (bottom)

HF noise is still a matter of great concern in the literature [18, 19]. Fig. 3 plots a detail of the signal in Fig. 3 in blue, showing the minimum energy sub-band in red. As expected, the use of a directive antenna should confirm a different level of noise depending on the azimuth angle of the antenna. Fig. 4 plots the observed noise floor as function of the azimuth angle for three different frequencies, for the Yagi antenna. A maximum noise floor is observable at N-E, E and S-E for the specified frequencies respectively. The differences in noise floor in Fig. 4 are about 2-2.5 dB and reach a maximum of 4dB.

For the received signals we compute the duty cycle and congestion according to (2) and (3). Figure 5 plots the duty cycle over a number of 50 records for omnidirectional and directive antenna for a frequency band of 3KHz. In Fig. 6 congestion over 1MHz bandwidth around 7 MHz is plotted.

Both Fig. 5 and Fig. 6 show that the directional antenna can bring additional information in terms of SO. The use of a directional antenna increases the possibility of finding an opportunity to transmit both in the time domain (duty cycle) and in the frequency domain (congestion).

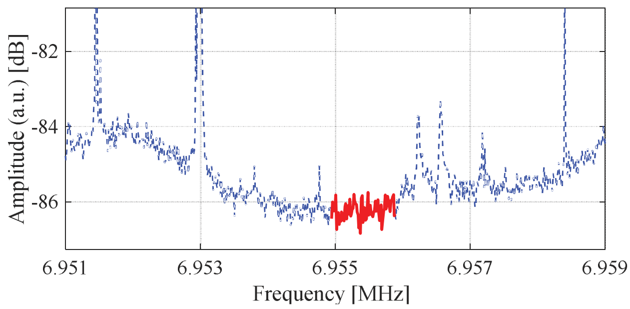

Fig. 3. Ilustration for noise floor computing: minimum energy subband in red

The measurements of SO and congestion on 1MHz bandwidth covering the frequency range from 5 to 10 MHz, as function of directional antenna azimuth angle are presented in Table 1.

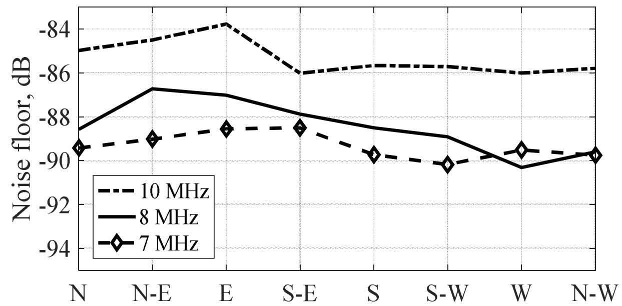

Fig. 4. Noise floor at 6, 7 and 10MHz versus antenna azimuth angle

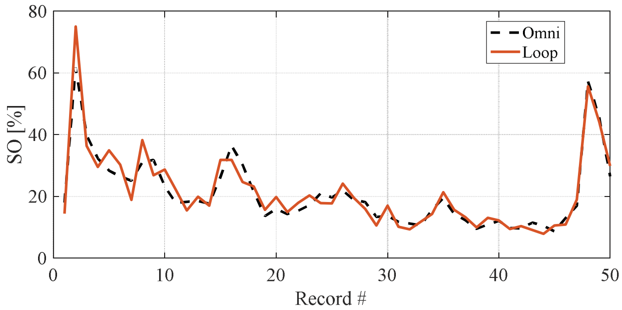

Fig. 5. Duty cycle over 50 records for omnidirectiona and loop antenna

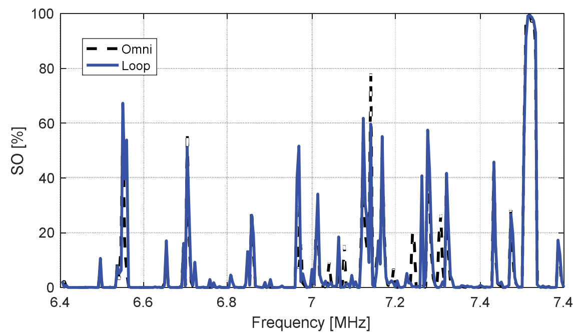

Fig. 6. Congestion in the frequency band around 7MHz

TABLE I. CONGESTION FUNCTION OF ANTENNA AZIMUTH (%)

	4.5-5.5 MHz	**5.5-6.5 MHz**	**6.5-7.5 MHz**	**7.5-8.5 MHz**	**8.5-9.5 MHz**	**9.5-10.5 MHz**
Reference	18	33	36	51	54	53
N (0º)	18	34	36	52	53	53
NE (45º)	17	32	35	50	52	52
E (90º)	17	31	33	49	50	50
SE (135º)	16	30	32	47	50	49
S (180º)	17	31	33	49	51	51
SV (225º)	18	32	34	50	52	52
V (270º)	18	33	36	51	54	53
NV (315º)	18	33	36	51	54	53

The antenna referred in Table 1 is the directional Yagi antenna. Similar results are obtained using the loop antenna, but in this case, due to the antenna characteristics, the figures are smaller and show a symmetry for azimuth positions that differ by 180°.

Fig. 7 plots in polar coordinates the congestion over the 7MHz frequency band for the Yagi antenna compared to omnidirectional antenna.

Fig. 7 shows that congestion is lower for narrower bands, which can be explained by the azimuthal and frequency variation signal sources.

IV. CONCLUSIONS

The paper presents results on SO in HF range as function of the azimuth angle of the directional antenna.

SO dependence of time and frequency is extensively studied in the literature, but there are extremely few references to the spatial influence on SO in HF band.

This paper is an attempt to estimate the azimuthal SO at the considered location, using directional antenna. Signals from the reference omnidirectional broadband antenna and the directional HF antenna have been acquired in parallel, using a two channel SDR USRP equipment. SO was computed using energy threshold criterion.

Although the directional antennas in the HF range are not easy to build, measurements results demonstrate that this worth the effort since directional antenna can bring additional knowledge in terms of SO and can provide a more efficient use of spectrum.

The directional antennas can, in addition, increase the link budget of the communication system by increasing directivity antenna gain in the desired direction and reducing interference from other directions.

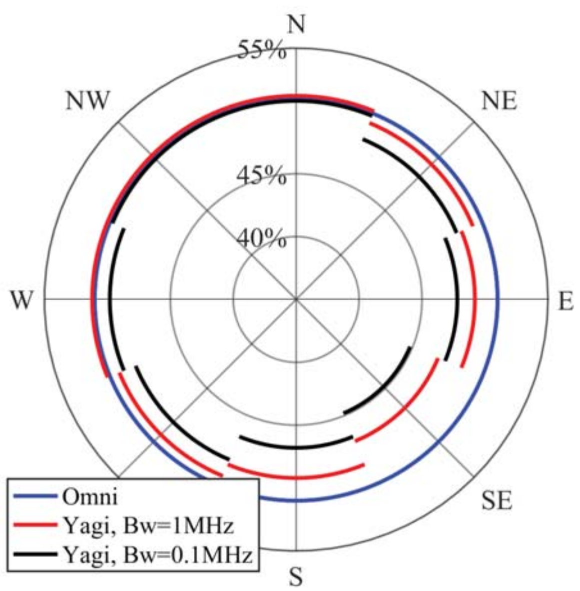

Fig. 7. Congestion in the frequency band around 7MHz for two bandwidth, for 1 second sub- record, May 17, 2018, 19.15 local time

ACKNOWLEDGEMENT

This work was supported by a grant of the Romanian Ministery of Research and Innovation, CCDI-UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0917 / contract number 21PCCDI/2018, within PNCDI III

REFERENCES

[1] Romania, The National Table of Frequency Allocations, Edition: Nov. 2009, updated: July 2010 and October 2011, http://www.ancom.org.ro/en/uploads/links_files/NTFA_ROMANIA-2009+modif-2010-2011_en.pdf, accessed July 8, 2018

[2] "Handbook on Spectrum Monitoring", ITU, 2011

[3] G. H. Hagn, R. H. Stehle, L .O. Harnish, "Shortwave broadcasting band spectrum occupancy and signal levels in the continental United States and Western Europe", IEEE Transactions on Broadcasting, vol. 34, no. 2, pp. 115-125, June, 1988

[4] D. J. Warner, S. Bantseev, N. Serinken, "Spectral occupancy of fixed and mobile allocations within the High-Frequency Band", Proc. 12th IET Conf. on Ionospheric Radio Systems and Techniques, pp. 4-9, 2012

[5] Md. G. Mostafa, E. Tsolaki, H. Haralambous, "HF spectrum occupancy time series models over the Eastern Mediterranean region", IEEE Trans. Electromagnetic Compat., vol. 59, no. 1, pp. 240-248, 2017

[6] H. Haralambous, H. Papadopoulos, "24-Hour neural networks congestion models for High-Frequency broadcast users", IEEE Trans. on Broadcasting, Vol. 55, No. 1, pp. 145-154, 2009

[7] C. A. Pantjiaros, P. J. Laycock, G. F. Gott, S.K. Chan, "Development of the Laycock-Gott occupancy model" IEE Proc. – Comm. Vol. 144, No. 1, pp. 33-39, 1997

[8] Y. Chen, H.-S. Oh, A survey of measurement-based spectrum occupancy modeling for cognitive radios, IEEE Comm, Surveys & Tutorials, Vol. 18, No. 1, First Quarter, pp. 848-859, 2016

[9] A. J. Gibson, L. Arnett, "Azimuthal distribution of noise and interference at HF", Eighth International Conference on Antennas and Propagation, IET, Edinburgh, UK, pp. 356-359, 1993

[10] T. Canat, J. Caratori, C. Goutelard, " Time modelling of HF interferences, Fifth International Conference on HF Radio Systems and Techniques, IET, Edinburgh, UK, pp. 19-1..19-18, 1991.

[11] C. A. Pantjiaros, L. V. Economou, G. F. Gott, P. J. Laycock, "Variation of HF spectral occupancy with azimuth in the UK", Seventh IET Int. Conf. on HF Radio Systems and Techniques, pp. 19-24, 1997.

[12] T. Rybak, M, Steffka, Automotive Electromagnetic Compatibility, New York: Kluwer Academic Pub., 2004.

[13] J. Hasch, E. Topak, R. Schnabel, T. Zwick, R. Weigel, C. Waldschmidt, "Millimeter-wave technology for automotive radar sensors in the 77 GHz frequency band", IEEE Trans. Microw. Theory Techn., vol. 60, no. 3, pp. 845-860, Mar. 2012.

[14] C. Balint, A. De Sabata, P. Bechet, S. Miclaus, Joint Spectrum Availability measurement in the 4.5–10.5 MHz HF band, DOI: 10.1109/EMES.2017.7980422 Conference: 2017 14th International Conference on Engineering of Modern Electric Systems (EMES), 2017, Oradea, Romania.

[15] C. Balint, A. De Sabata, Measurements of Short-Time Spectrum Occupancy for Ionospheric Propagation, 22nd IMEKO TC4 International Symposium, 2017, Iasi, Romania.

[16] C. Balanis, Antenna Theory: Analysis and Design, second edition, John Wiley and Sons, 1997. Chapter 5.

[17] A. De Sabata, C. Balint, P. Bechet, S. Miclăuş, "USRP based HF spectrum occupancy measurements at two locations in the western part of Romania", International Symposium on Signals, Circuits and Systems ISSCS, July 2014, Iaşi, DOI: 10.1109/ISSCS.2017.8034876

[18] 16 J. E. Giesbrecht, "An empirical study of HF noise near Adelaide Australia," 11th International Conference on Ionospheric radio Systems and Techniques (IRST 2009), Edinburgh, 2009, pp. 1-5, DOI: 10.1049/cp.2009.0086

[19] J. Giesbrecht, R. Clarkez and D. Abbott, An Empirical Study of the Probability Density Function of HF Noise, Fluctuation and Noise Letters, Vol. 6, No. 2 (2006) L117-L125, World Scientific Publishing Company