AN ASSESSMENT OF HF NVIS RADIO SYSTEM RELIABILITY

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ABSTRACT
High Frequency Near Vertical Incident Sky wave (HF NVIS) radio system in sense of increasing inland waterways and sea waterways safety in states of emergency is considered. Assessment of HF NVIS link performance by means of transmission errors is performed by technique of communication link analyses. The result of analyses is link budget which is implemented, together with other modeling techniques, in standard procedure of HF radio system reliability prediction. Analysis shows that performances of HF NVIS radio should be concerned when planning emergency communication system.

KEYWORDS
HF NVIS radio system, radio link analysis, system reliability prediction

PROCJENA POUZDANOSTI HF NVIS RADIOSUSTAVA

SAŽETAK
Razmotren je HF NVIS radiosustav u cilju povećanja sigurnosti na plovnim putovima u izvanrednim stanjima. Tehnikom analize komunikacijske veze izvršena je procjena radnih svojstava HF NVIS radiosustava u pogledu pogreške pri prijenosu. Njezin rezultat je proračun veze koji je zajedno s ostalim tehnikama modeliranja primijenjen u standardnom postupku procjene pouzdanosti HF radiosustava. Provedena analiza pokazuje da pri planiranju komunikacijskog sustava za izvanredna stanja u priobalju treba uzeti u obzir prikazane značajke HF NVIS radiosustava.

KLJUČNE RIJEČI
HF NVIS radiosustav, analiza radioveze, procjena pouzdanosti sustava

1. INTRODUCTION

Reliable information transmission and determination are basis for sea traffic safety. For this purpose various professional (private) mobile radio system networks which implements radio communications and radio determinations at waterways has been developed. Among them HF radio system, with carrier wave frequency band from 2 MHz to 30 MHz, has unique feature; communication beyond line of sight is provided without using radio relay equipment. That is the result of reflection phenomena, by means of refraction with effect of reflection, of HF radio wave from ionosphere. However, such sky wave is exposed to complex solar and terrestrial environment interaction which implies that such HF radio link is not reliable in all conditions. In spite of that, HF radio does not require expensive terrestrial and/or satellite infrastructure and it is perspective radio communication technology from beginning of 20th century that is constantly developed. Procedures for HF radio link reliability improvement are listed in [1]:

- Advanced signal processing has been introduced to cope with the fading and intersymbol interference and to increase the data rates on these narrowband channels.

- Network protocols have automated, on the basis of real-time ionosphere sounding, the task of finding usable frequencies, medium access control (MAC), data link control, relay management and route selection.

Depending on propagation characteristics of HF radio wave it is possible to establish link of different range as shown in Figure 1 in accordance with [2] and [3]. Sky wave transmitted slant upwards reflects by ionosphere at heights of several hundreds kilometers backwards to the Earth surface. In this way several hundreds kilometers communication range is achieved, but requires use of a radio wave frequency that will propagate under the instantaneous ionospheric and terrestrial conditions. At some operating frequencies communication with nearby nodes may not be possible, because those frequencies penetrate the ionosphere at the step takeoff angle required for short-range communication. Skip distance is the minimum achievable distance where sky wave, for a given operating frequency, is returned to the Earth. The skip zone is area of the Earth's surface bounded by skip distance in all directions with transmission point in its center.

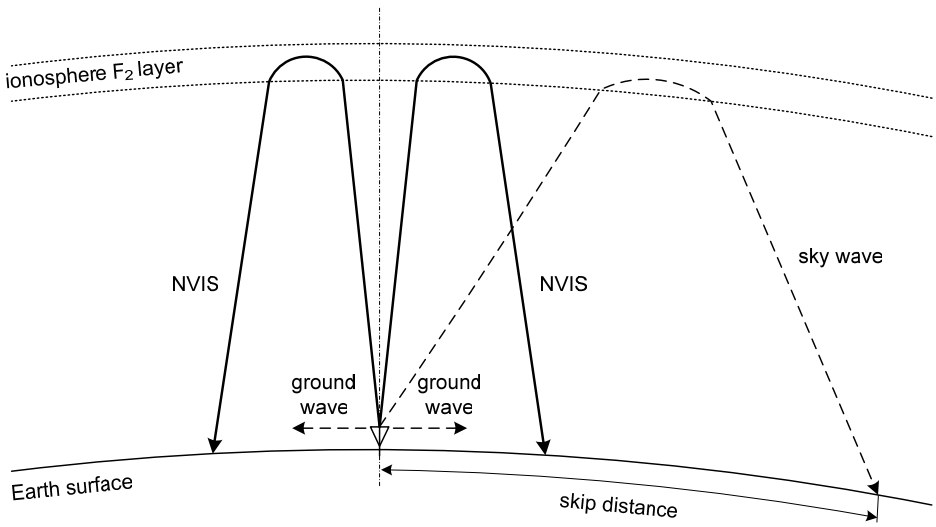


Figure 1. HF radio wave propagation characteristics
Source: [2] and [3]

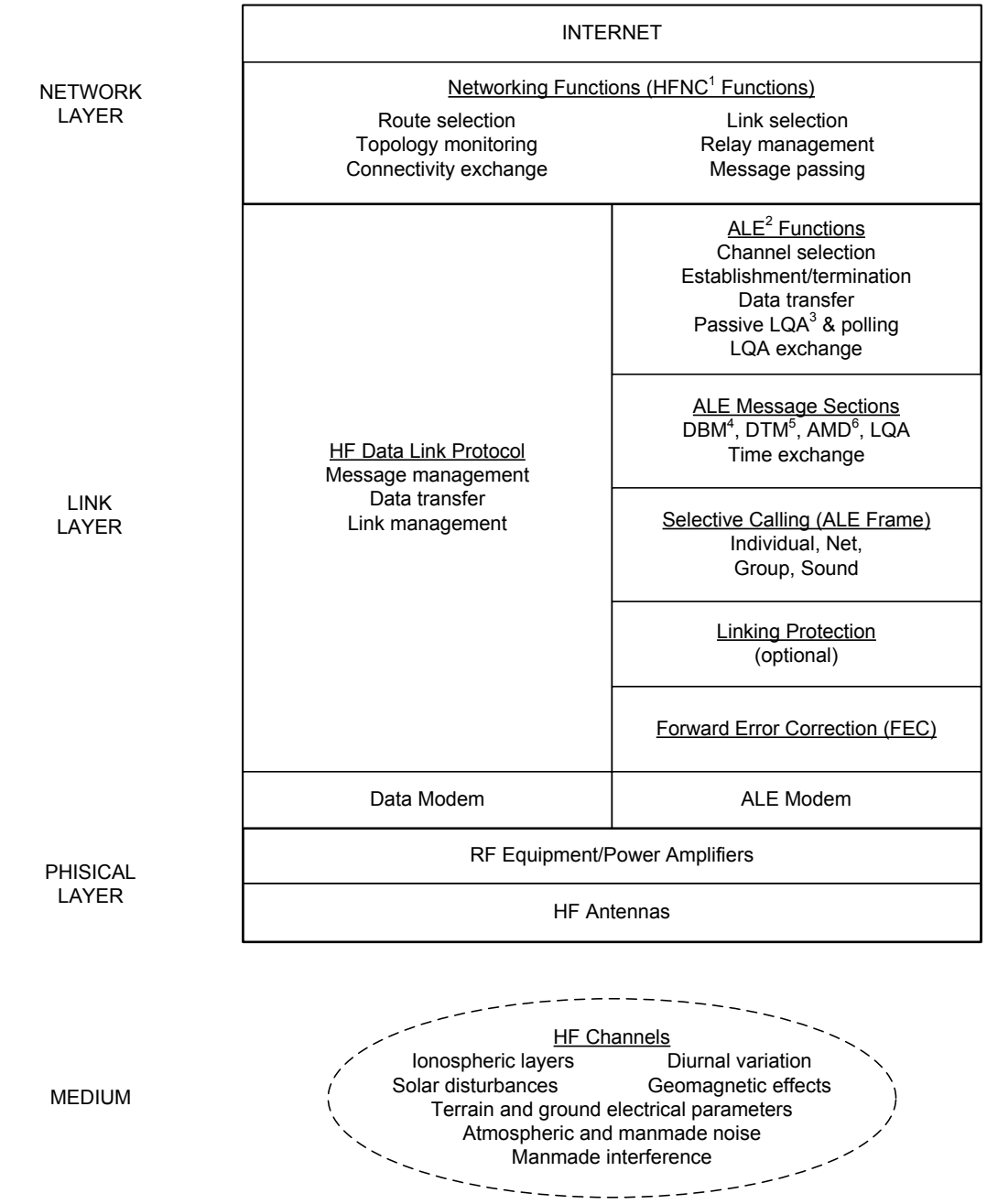
Ground wave propagates without ionosphere participation which results with range that does not extend much past beyond line of sight. Radio wave with linear vertical polarization has communication range of approximately hundred kilometers, more over the sea surface propagation and less over the land propagation. Ground wave coverage zone do not include skip zone, but it is limited with natural and man made obstacle. In accordance to [4] it is far simpler to use ground wave than sky wave while in its propagation usually occurs attenuation and delay only. Sky wave in addition to experiencing much greater attenuation and delay variability, also suffers from fading, Doppler frequency shifting, spreading, time dispersion and delay distortion.

Near vertical incident sky wave (NVIS) occurs by launching near vertical sky wave which, after ionosphere reflection, returns near vertical to the Earth's surface. Such propagation path results in circular coverage zone with transmitting point in its center independent of involved Earth's surface part characteristics. Communication range from few tens to few hundreds of kilometers is achieved. In such case skip zone practically disappears, but interference with ground wave is possible. Therefore appropriate operating frequency and antenna selection for NVIS is crucial.

Main goal of this paper is to assess HF NVIS reliability like economical supplement to existing private mobile radio networks in waterways safety system. In so doing crucial fact is that zone coverage of such radio network includes well-indented coast and/or highland coastal.

2. HF NVIS RADIOSYSTEM

Radio system is usually divided into transmitter, radio channel and receiver subsystem which transfer or detect information by means of electromagnetic wave. The automated HF radio station includes controlled single side band transceiver with transmission equipment (antennas, transmission lines, antenna tuning units, antenna couplers, etc.), Automatic Link Establishment (ALE) controller with modem and data modem with controller. Where the station is part of radio network it includes networking controller. ISO OSI HF radio system referent model up to network layer is shown in Figure 2 in accordance with [3].



1 HFNC - HF node controllers
2 ALE - automatic link establishement
3 LQA - link quality analysis
4 DBM - data block message
5 DTM - data text message
6 AMD - automatic message display

Figure 2. HF radio system hierarchical layers
Source: [3]

HF antenna and medium interface in radio channel subsystem depends on propagation path characteristics. Where sky wave of large or small (NVIS) range is used crucial role has ionosphere, which consists of non homogenous and anisotropic layers of ionized rare gas molecules in outer part of Earth's atmosphere. Magneto plasma's structure and characteristics primary depend on solar and geomagnetic activity. Typical mid-latitude electron density distribution against height for moderate solar activity is shown in Figure 3 in accordance with [2] and [4].

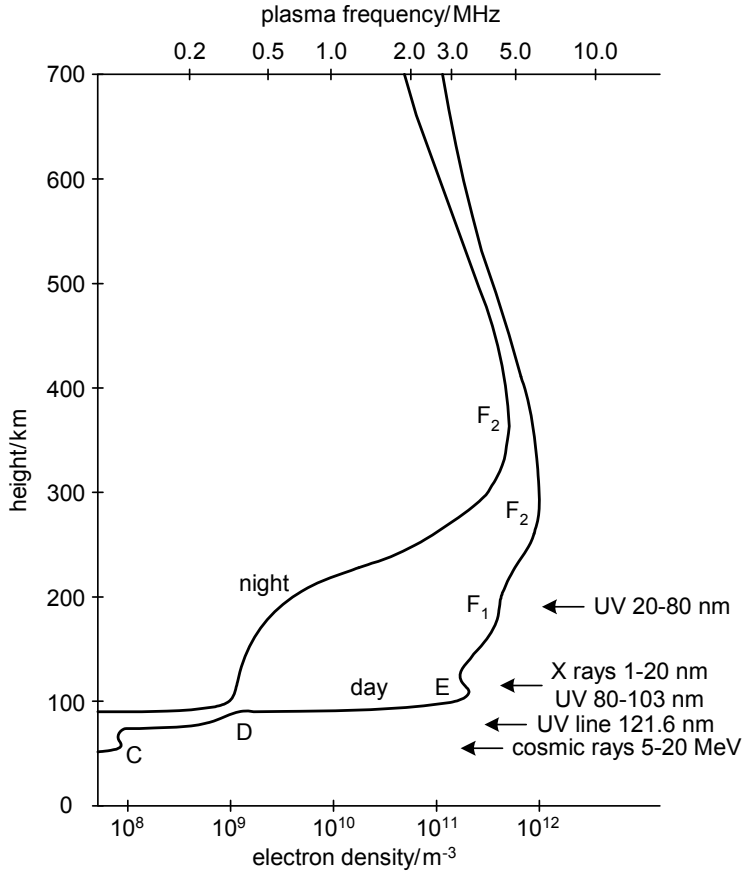


Figure 3. Typical mid-latitude electron density profiles for moderate solar activity
Source: [2] and [4]

For NVIS radio link, in accordance to [2], the most important is F_2 layer. The maximum ionization in that layer occurs at approximate height from 200 km to 500 km above the Earth's surface with electron density from $5 \cdot 10^{10}\,m^{-3}$ to $1 \cdot 10^{12}\,m^{-3}$ which depends on the Sun's activity, season, latitude and local time. NVIS radio link Maximum Usable Frequency (MUF) equals to F_2 layer critical frequency (plasma frequency as shown in Figure 2); for mid-latitude is mostly in 2 MHz to 10 MHz range. Due to geomagnetic field ionosphere layer is anisotropic and given range of critical frequency is valid only for ordinary mode of vertical sky wave propagation. While propagation direction is vertical, electric field vector of linear horizontal polarized wave is parallel with geomagnetic field vector. Commonly for NVIS radio link polarization mismatch loss, with average value of 3 dB, is taken into consideration. Thus, major absorption loss, inversely proportional to square frequency, originates in D layer where reaches up to 20 dB value. The best operating frequency for NVIS radio link lies within small pass band (frequency window), sometimes only 1 MHz to 2 MHz wide, where MUF from given range is its upper bound.

Sporadic E_s layer effects can widen the available frequency window considerably, but occurrence of the phenomena is extremely difficult to predict. Unlike that, ionospheric storms

have effects of reducing the available frequency window, lowering F_2 layer critical frequency and increasing D layer absorption.

Practically, MUF for NVIS radio link and received signal strength is independent from transmitter and receiver distance up to 400 km approximately. When relatively small range is used it is possible to neglect the effect of Earth's surface curvature. In addition to, it is impossible to sky wave multipath propagation, but it is likely that sky wave and ground wave interference will occur. Use of horizontal polarization of vertical sky wave successfully suppresses such interference and contributes for reduction of received noise level.

From technical point of view for establishing NVIS radio link the major issue is efficient carrier wave frequency selection and implementation of wideband linear horizontal polarized antenna with mainly radiation in zenith direction. When using adaptive HF radio system, working frequency is selected within ALE procedure in accordance with results of direct ionosphere soundings. If mobile NVIS radio link is used, usually due to vehicle and antenna small dimensions related to wavelength in considered band, there will be small electromagnetic wave efficiency for required characteristics. Researches for increasing data rate and optimization of NVIS antenna mounted on vehicle, vessel or airplane is maintained. Intention is to increase, by means of complex modulation, transmission rate from 2.4 kbit/s (at most 4.8 kbit/s) up to 16 kbit/s in standard HF NVIS 3 kHz bandwidth channel. Among examined antenna types, as presented in [5], the best results for NVIS shipboard application are realized with adjustable capacity loaded square loop antenna.

3. HF NVIS RADIO LINK BUDGET

Link budget is complete representation of signal power level variation within the radio communication system. In so doing, all its components, sources of noise, sources of electromagnetic interferences and other effects over the radio link are included. According to [6] link budget is prerequisite for design of specific radio system and its reliability assessment.

Most frequently HF NVIS transmitter output signal power level is in range from several tens to several hundreds watts. In accordance to [3] and [7] HF NVIS antenna gain is in range from 2.5 dB_i to 7.5 dB_i where lower value is applied to antenna in mobile radio communication system. That implies equivalent antenna gain with transmission equipment loss included. Free-space basic transmission loss, L_{bf} expressed in decibels, according to [4] is:

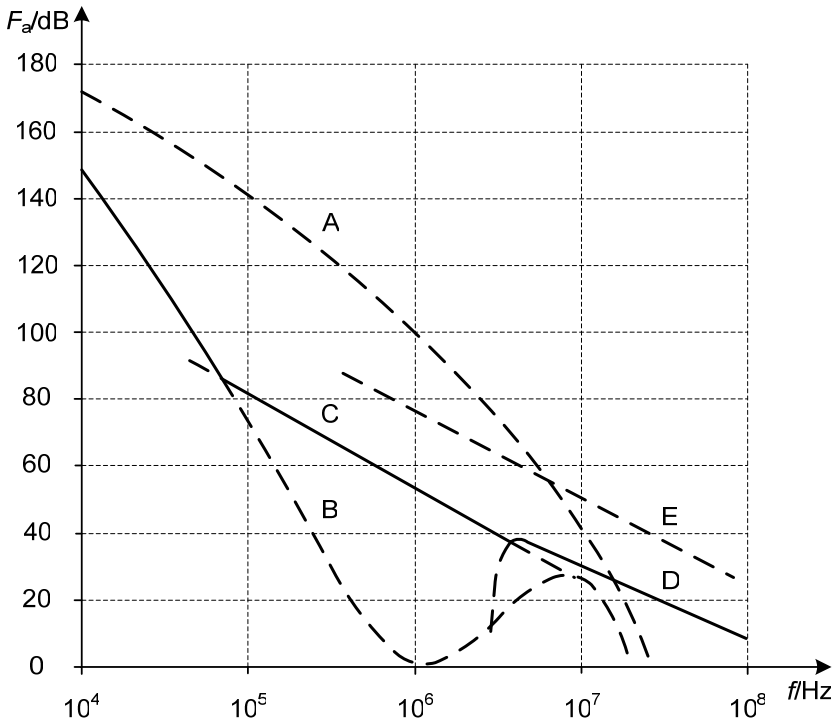
$$L_{bf} = 32.44 + 20\log(f) + 20\log(d) \qquad (1)$$

where frequency f is in MHz and transmission distance d is in km. Free-space basic NVIS transmission loss mean value according to (1) is 101.5 dB at signal frequencies 2 MHz and 10 MHz and at transmission distances 2×500 km and 2×200 km respectively. NVIS wave power loss due to absorption in ionosphere D layer is from 10 dB to 20 dB and received wave depolarization loss reaches up to 3 dB. Totally median power level of wanted signal at receiving antenna output is −88 dB_W as shown in Figure 5.

In accordance to [8] available noise power from an equivalent lossless antenna, P_n expressed in decibels referred to 1 W is:

$$P_n = F_a + 10\log(B) + 10\log(kT_0) = F_a - 169.2\,\text{dB} \qquad (2)$$

where external noise factor F_a is in decibels, receiving system bandwidth $B = 3$ kHz, Boltzmann's constant $k = 1.38 \cdot 10^{-23}$ J/K and reference temperature $T_0 = 290$ K. In Figure 4 various sources external noise factor frequency dependence is shown in accordance with [8].



A - atmospheric noise, value exceeded 0.5% of time
B - atmospheric noise, value exceeded 99.5% of time
C - man-made noise, quiet receiving site
D - galactic noise
E - median business area man-made noise
Solid line - minimum noise level expected

Figure 4. External noise factor frequency dependence
Source: [8]

If atmospheric noise, man-made noise and galactic noise is taken into consideration then total external noise factor mean value is $F_a = 45.9$ dB and according to (2) available noise power from an equivalent lossless antenna is $P_n = -123.3$ dB_W.

In [9] required signal-to-noise ratio in HF system predetection point is specified. When amplitude modulated voice transmission is obtained, required carrier-to-noise ratio (CNR) of 6 dB, 15 dB and 33 dB corresponds to grade of service “just usable”, “marginally commercial” and “good commercial” respectively. For digital 8-PSK modulation and data rate 2400 bit/s, required CNR is 10 dB and with fading condition 15 dB for bit error ratio (BER) less than $1 \cdot 10^{-2}$. It is clear that BER is possible to decrease additionally with appropriate channel coding in order to achieve error detection and correction. Due to combined and uncorrelated signal’s and noise’s intensity fluctuation value of 11.5 dB is added to mean value of required *CNR* = 15 dB. Since HF radio system is affected with far more external then internal noise level, receiver noise factor is ignored. Required median signal power level is -96.5 dB_W at receiving antenna output as shown in Figure 5.

Obviously, for HF NVIS radio system considered, radio link margin is 8.5 dB. That result is provided for transmitting and receiving antennas gain $G_t = G_r = 5$ dB_i and for transmitted power $P_t = 100$ W. Experimental results for HF NVIS radio link at Northern Ireland area are published in [7]. Those results validate radio link model presented in this paper.

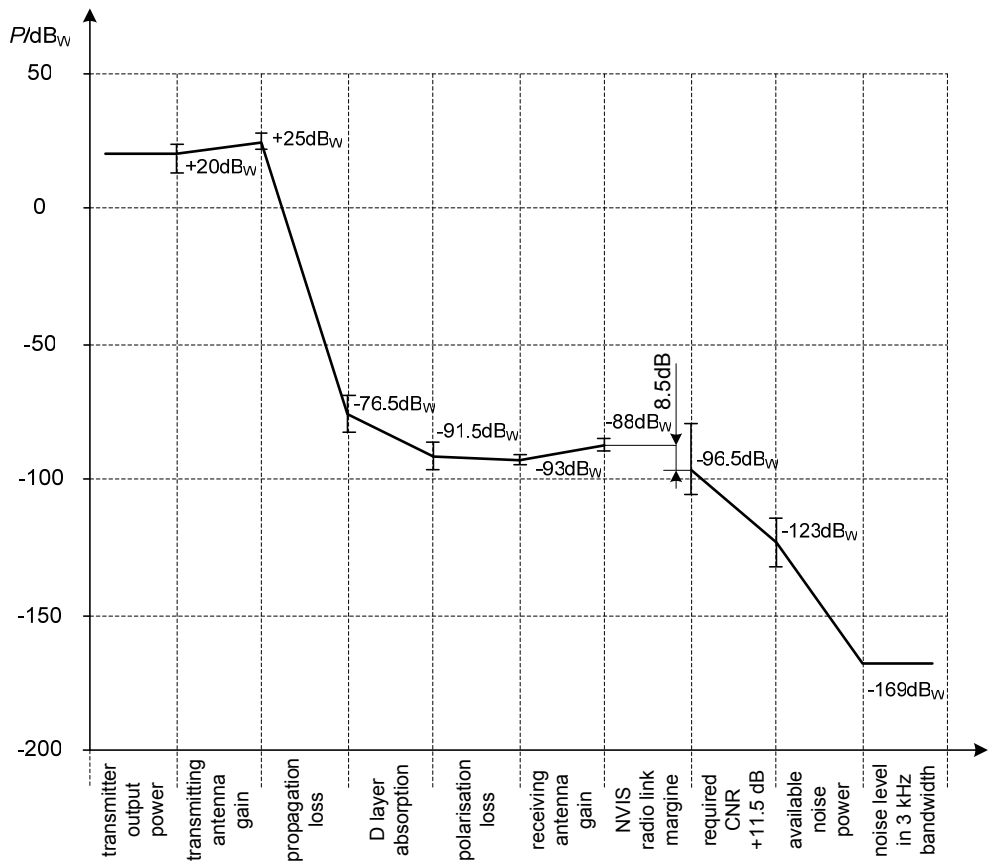


Figure 5. ***HF NVIS radio link budget***
Source: authors

4. HF NVIS RADIO SYSTEM RELIABILITY

In general, ITU defines reliability as probability that a specified performance is achieved. In [10] recommended methods for basic circuit reliability (BCR) assessment are given. BCR is defined as reliability achieved at a single frequency. Those procedures are applied for HF NVIS radio link considered.

Median available receiver power of wanted signal, S is determined by HF NVIS radio link budget and in accordance to [11] as:

$$S = -88 \text{ dBw} \tag{3}$$

According to [8] median noise factor for atmospheric noise, F_a(A), man-maid noise, F_a(M) and galactic noise, F_a(G), is determined respectively as:

$$F_a(\text{A}) = 38.7 \text{ dB} \tag{4.a}$$
$$F_a(\text{M}) = 45.8 \text{ dB} \tag{4.b}$$
$$F_a(\text{G}) = 14.7 \text{ dB} \tag{4.c}$$

Median resultant signal-to-noise ratio, S/N according to [10] is:

$$S/N = S - 10\log\left[10^{\frac{F_a(\text{A})}{10}} + 10^{\frac{F_a(\text{M})}{10}} + 10^{\frac{F_a(\text{G})}{10}}\right] - 10\log(B) + 204 \tag{5}$$

and inserting values from (3) and (4), for bandwidth $B = 3$ kHz, equals to:

$$S/N = 34.6 \text{ dB} \tag{6}$$

Signal-to-noise deviation from mean value is random event and for that statistical quantity it is possible to determine deciles. Upper (lower) decile is ratio of random variable value which is exceeded 10 % (90 %) of time and its mean value, expressed in decibels.

In accordance with [10] signal upper decile deviation (day-to-day), $D_u(S_d)$ is specified at operating frequencies 2 MHz and 10 MHz and latitude less than 60° as:

$$D_u(S_d) = 8 \text{ dB} \tag{7.a}$$

and signal upper decile deviation (within-the-hour), $D_u(S_h)$ as:

$$D_u(S_h) = 5 \text{ dB} \tag{7.b}$$

In accordance with [8] lower decile deviations of atmospheric noise, $D_l(\text{A})$, man-made noise, $D_l(\text{M})$ and galactic noise, $D_l(\text{G})$, are determined respectively as:

$$D_l(\text{A}) = 5.5 \text{ dB} \tag{8.a}$$
$$D_l(\text{M}) = 9 \text{ dB} \tag{8.b}$$
$$D_l(\text{G}) = 2 \text{ dB} \tag{8.c}$$

Upper decile deviation of resultant signal-to-noise ratio, $D_u(\text{SN})$ according to [10] is:

$$D_u(\text{SN}) = \\ = \left\{ \begin{array}{l} D_u^2(S_d) + D_u^2(S_h) + \\ + 20\log\left[\left(10^{\frac{F_a(\text{A})}{10}} + 10^{\frac{F_a(\text{M})}{10}} + 10^{\frac{F_a(\text{G})}{10}} \right) \Big/ \left(10^{\frac{F_a(\text{A}) - D_l(\text{A})}{10}} + 10^{\frac{F_a(\text{M}) - D_l(\text{M})}{10}} + 10^{\frac{F_a(\text{G}) - D_l(\text{G})}{10}} \right) \right] \end{array} \right\}^{1/2} \tag{9}$$

where inserting values from (4), (7) and (8) equals to:

$$D_u(\text{SN}) = 12.5 \text{ dB} \tag{10}$$

In accordance with [10] signal lower decile deviation (day-to-day), $D_l(S_d)$ is specified at operating frequencies 2 MHz and 10 MHz and latitude less than 60° as:

$$D_l(S_d) = 6.5 \text{ dB} \tag{11.a}$$

and signal lower decile deviation (within-the-hour), $D_l(S_h)$ as:

$$D_l(S_h) = 8 \text{ dB} \tag{11.b}$$

In accordance with [8] upper decile deviations of atmospheric noise, $D_u(\text{A})$, man-made noise, $D_u(\text{M})$ and galactic noise, $D_u(\text{G})$, are determined respectively as:

$$D_u(\text{A}) = 5.5 \text{ dB} \tag{12.a}$$
$$D_u(\text{M}) = 9 \text{ dB} \tag{12.b}$$

$$D_u(\mathrm{G}) = 2\ \mathrm{dB} \tag{12.c}$$

Lower decile deviation of resultant signal-to-noise ratio, D_l(SN) according to [10] is:

$$D_l(\mathrm{SN}) = \\ = \left\{ \begin{array}{l} D_l^2(S_d) + D_l^2(S_h) + \\ + 20\log\left[\left(10^{\frac{F_a(\mathrm{A})+D_u(\mathrm{A})}{10}} + 10^{\frac{F_a(\mathrm{M})+D_u(\mathrm{M})}{10}} + 10^{\frac{F_a(\mathrm{G})+D_u(\mathrm{G})}{10}}\right) \Big/ \left(10^{\frac{F_a(\mathrm{A})}{10}} + 10^{\frac{F_a(\mathrm{M})}{10}} + 10^{\frac{F_a(\mathrm{G})}{10}}\right)\right] \end{array} \right\}^{1/2} \tag{13}$$

where inserting values from (4), (11) and (12) equals to:

$$D_l(\mathrm{SN}) = 13.4\ \mathrm{dB} \tag{14}$$

Basic circuit reliability, *BCR* expressed in percent according to [10] is:

$$BCR = 130 - \frac{80}{1 + \dfrac{S/N - (S/N)_r}{D_l(\mathrm{SN})}} \quad \text{for} \quad S/N \geq (S/N)_r \tag{15.a}$$

$$BCR = \frac{80}{1 + \dfrac{(S/N)_r - S/N}{D_u(\mathrm{SN})}} - 30 \quad \text{for} \quad S/N < (S/N)_r \tag{15.b}$$

where *S*/*N* from (5) is median resultant signal-to-noise ratio, and $(S/N)_r$ is required signal-to-noise ratio.

Dependence of basic circuit reliability considered HF NVIS radio link on required signal-to-noise ratio, in accordance with (15.a), is shown in Figure 6. It is obvious that considered HF NVIS radio system is entirely reliable if required signal-to-noise ratio equal or less then 12.3 dB and for required signal-to-noise ratio equal to 15 dB basic circuit reliability is 97.5 %.

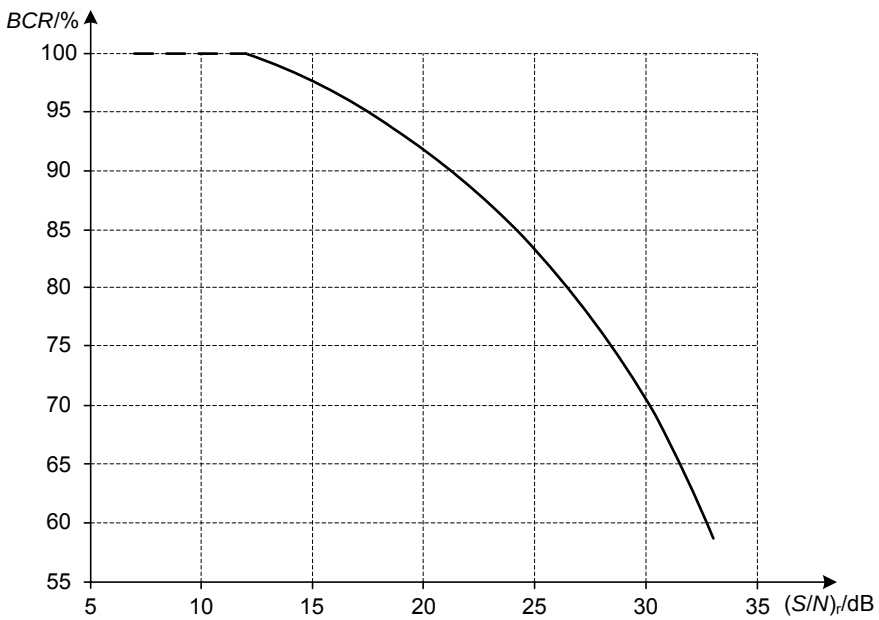


Figure 6. HF NVIS radio system reliability
Source: authors

5. CONCLUSION

Presented results of modeling and analyses confirm that HF NVIS radio system performs reliable communications with circular coverage zone, from few tens to few hundreds of kilometers in radius, completely independent of involved Earth's surface physical characteristics. In so doing for successful radio link establishment crucial is carrier wave frequency selection in accordance with current ionosphere conditions and selection of efficient linear horizontal polarized antenna with mainly radiation in zenith direction. Such economical alternative and/or supplement to existing systems HF NVIS radio system can contribute to waterways safety in case of well-indented coast and/or highland coastal. Further research should be dedicated to existing data rate enhancement and optimization of HF NVIS antenna mounted on vehicle, vessel or airplane.

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