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Theoretical and Practical Aspects of Shortwave Broadcast Reception in the Baltics

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Introduction

Wireless communication systems including ionospheric radio have been through a rapid development within recent decades. Modern technology enables to connect different mobile networks with fixed owns. Furthermore, it is also possible to interconnect various types of wireless networks with working frequencies of several different parts of radio frequency (RF) spectrum. The extensive usage of RF spectrum has increased substantially the demand for more realistic channel models for the simulation environment. Development of RF networks from one side and mighty mathematical power of available application programs from the other have created a possibility to refine and reassure the existing methodology of modeling and planning of RF communications. Additionally, evidence can be found that indicate that in conjunction with modern methods of analysis, different conclusions may be reached to those commonly used today [1].

The ionospheric channel is a dispersive medium causing deterioration in quality of transmitted signal. The transmission quality depends the manner in which channel variation differ as a function of time of day and of link type. In order to meet necessary service margins at the receiver it is essential to explore the behaviour of the signal under various ionospheric conditions.

Each shortwave communication link exhibits unique characteristics, fade rates and depths, multi-path structure, noise levels, etc. and these parameters can be used to separate chosen transmission from the effects of other channels in the shortwave band. For communication planning purposes the information only on the mean value of the received shortwave signal is inadequate. The variations in time, space and frequency also have to be taken into consideration. Fading has important impact on the performance of the radio systems and on the type of modulation and coding that can be implemented effectively. Thus, a performance analyses for modulations over fading channels requires knowledge of the fading envelope statistics [2]. The notable restricting aspect in developing more sophisticated simulation environments has been the computational power and availability of proper equipment so far.

Fading statistics

By the term *fading* we normally mean undesired fluctuations of signal strength. By exploring the basic meaning of the concept of fading, by discussing the origin of fading in the shortwave systems, and by developing methods for treating quantitatively the rate of fading we shall be able to establish some measure for the limitation on system capacity by fading. This will then enable us to develop also quantitative measure of comparison between different systems in use. We can distinguish between various kinds of fading, defined according to their origin. The main causes of fading are:

- time changes of absorption and variations in electron density of ionosphere
- fluctuations of the ionospheric reflector
- changes of path length
- rotation of the axes of the received polarization ellipse (Faraday rotation).

These various cause lead to different depths of fading and range of fading rates (duration). The fading range is defined as the time interval between signal levels exceeded 10% and 90%. Knowledge of the distribution of fade duration as a function of fade depth is also a prerequisite for the evaluation of system outage and unavailability due to propagation on a given link [3]. Of particular interest in the context of mathematical modeling is the distinction between *slow* and *fast* fading. With slow fading signal traveling over long paths varies due primarily to changes in attenuation loss by surrounding environment. Rapid fading which varies over shorter distances form due primarily to changes in phase angles of different signal components (multipath). It is in common to use *Rayleigh* distribution to model fast fading channels and the *lognormal* distribution to model slow fading channels.

Rayleigh channel is the simplest fading model from the standpoint of analytical characterization. It is expected that the rapid fading channels are approximately Rayleigh-distributed. The derivation Rayleigh distribution can be viewed as the summation of a large number of vectors of low amplitudes whose phases have a uniform distribution. The probability density and the cumulative distribution are given by:

PDF: $$f(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad , \tag{1}$$

CDF: $$F(x) = 1 - \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad . \tag{2}$$

The *lognormal* distribution arises if the natural logarithm of a random variable has a normal distribution. The lognormal distribution has been used successfully in many applications to model the propagation, but also to model the failure rates of semiconductor failure rate mechanisms such as corrosion, diffusion, metal migration etc. In the case of time (for example slow fading durations), the log-normal distribution is used explicitly because the natural variable is time (in seconds or in minutes) and not their logarithm. The probability density and the cumulative distribution are given by:

PDF: $$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \frac{1}{x} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right], \tag{3}$$

CDF:
$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^x \frac{1}{t} \exp\left[-\frac{1}{2}\left(\frac{\ln t - \mu}{\sigma}\right)^2\right] dt = \frac{1}{2}\left[1 + erf\left(\frac{\ln x - \mu}{\sigma\sqrt{2}}\right)\right] . \tag{4}$$

This is the two-parameter lognormal distribution. In this case μ is denoting the mean of log(x) and σ is denoting the standard deviation of log(x), these are *not* the parameters of variable x. We find:

- the mean : $$\exp\left(\mu + \frac{\sigma^2}{2}\right) \quad , \tag{5}$$

- the standard deviation : $$\exp\left(\mu + \frac{\sigma^2}{2}\right)\sqrt{\exp(\sigma^2) - 1} \quad . \tag{6}$$

The distribution has different shapes for different combinations of μ and σ and it is appeared to be extremely asymmetrical. The distribution can vary significantly even though the parameter values do not vary greatly [5].

Analysis of the measurement data

We made an attempt to describe the statistical behavior of 5 shortwave signals at two receiving sites at mid-range distances of several hundred kilometers from transmitter. The observations were conducted in March 2008, in the Northern Latvia and in May 2008, in Northern Estonia. Monitoring receiver in use was Rohde & Schwarz ESMB with active monopole (rod) antenna and laptop computer equipped with monitoring software ARGUS. Shortwave propagation prediction program R&S Propagation Wizard was used for calculations S/N ratio and field strength at the receiver sites. Radio signals under study originated from European broadcasting stations below 10 MHz band. Monitoring was carried out for 5 frequency channels and for 5 noise background channels as well. Time series were 10 hours in length; each frequency was measured in 10 sec interval readings. Measurement results have been recorded, separated and analyzed in MATLAB environment. These samples where radio stations were disengaged have been eliminated.

In our observations we have dealt with relatively slow fading up to 15 min, what harmonies with that criterion of our previous measurements and modeling. Fading-related features of received signals were quantitatively characterized by depth of fading and fading period. Shortwave channel includes also noise from different sources: atmospheric, galactic and man-made noises. We refer composite spectrum of the signal and noise as multiplicative. Thus, in statistical terms the signal is associated with the envelope curve of the cumulative distribution function of multiplicative spectrum.

Complete 10-hour profile of propagation and channel quality variations were clearly typical of this period near the solar minimum. The histograms of measured field strength values were studied to determine if the field strength variations can be interpolate in some well-known probability distribution [4]. (The most commonly used probability distributions in junction radio wave propagation modeling are presented in Rec. ITU-R P.1057)

As with modeling in general, there are mainly two approaches that can be used to select a propagation model. First one we introduce here is the use of probability density functions (PDF) and the other is the use of cumulative distribution (CDF). The selection of a distribution was made with the aid of a computer and distribution fitting tools in MATLAB environment.

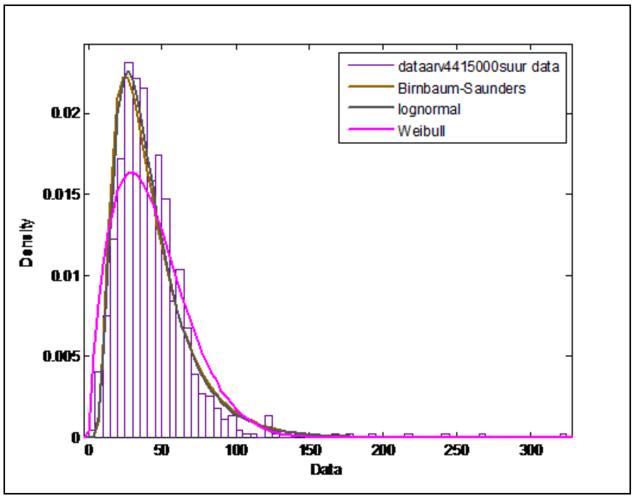

Fig. 1. There are three distribution models displayed for comparison (lognormal, Weibull and Birnbaum-Saunders) in this figure. A visibly large fraction of the empirical data (histogram of the signal 4.415 MHz) lies outside the Weibull distribution bounds

Initially, we assumed that the noise background would follow Rayleigh or Gaussian distribution, but there was no match amongst known distributions for these channels. However, the practical situation might be greatly influenced by transmitting and receiving antennas or noise source affecting the receiver sites.

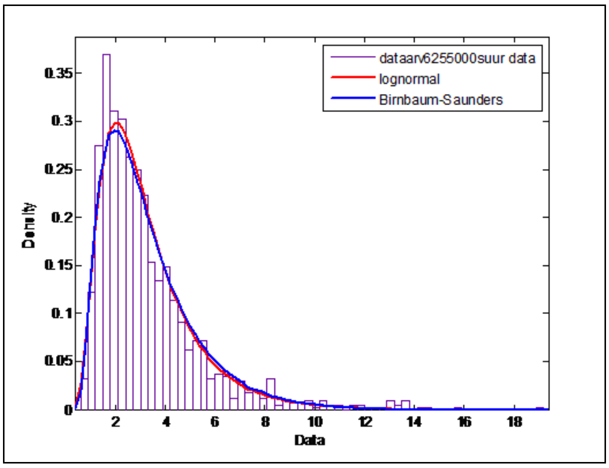

Fig. 2. The histogram of the empirical signal (6.255 MHz) has a shape of the lognormal PDF (mean value 42.9995 and variance 686.528)

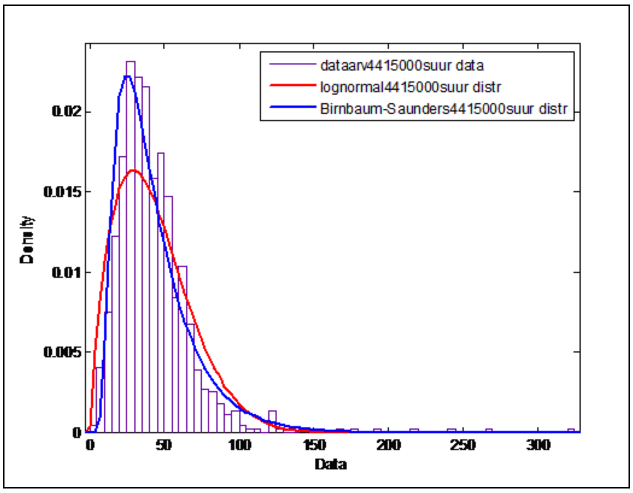

Fig. 3. The calculated histogram of the field strength of the measurement data and fitted curves of the Birnbaum-Saunders and lognormal PDF (f = 4.415 MHz)

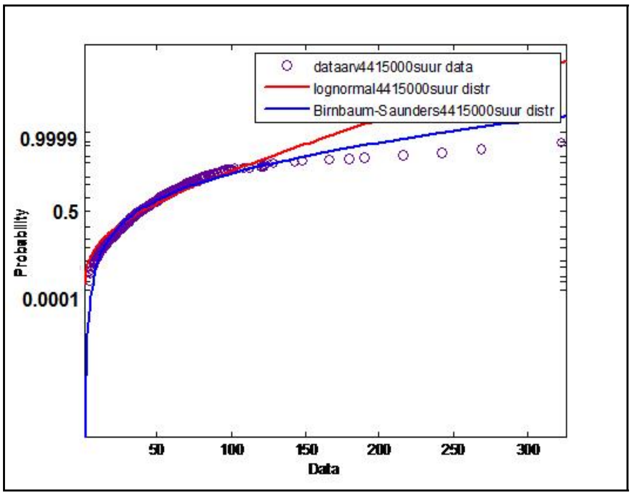

Fig. 4. The calculated histogram of the field strength of the measurement data and fitted curves of the Birnbaum-Saunders and lognormal CDF (f = 4.415 MHz)

In addition, previous studies showed a general lognormal distribution of received signal amplitudes. There were no significant differences found between channel variations in both receiving sites in the Northern Latvia and in Northern Estonia. Fig. 2 illustrates the histogram of the field strength measurement data of the 6.255 MHz signal. The observed channel features significant asymmetry. It is recognizable that histogram values follow approximately log-normal distribution. However, this was not applied to all frequencies. The striking feature on frequencies close to MUF was the Birnbaum-Saunders distribution that gave the closest mach with observation results.

In many cases the outcome fitting the measured field strength histograms to various distributions using MATLAB suggests the Birnbaum-Saunders distribution as the best match.

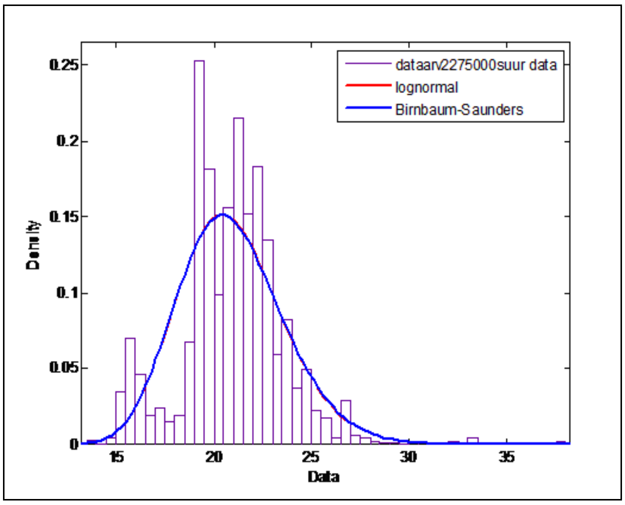

Fig. 5. The calculated histogram of the field strength of the measurement data (f = 2.275 MHz)

The shapes of Birnbaum-Saunders and lognormal PDF coincide on lower frequencies, as it is presented on the Fig. 5.

Birnbaum-Saunders distribution

The Birnbaum-Saunders distribution is applied to the independent, identically distributed random variables X_i with mean μ and variance σ^2. This distribution depends on two parameters $\alpha > 0$ and $\beta > 0$. The former is the scale parameter and the latter is the shape parameter of variable X. CDF of the B-S distribution has some compelling properties described in [9]. The parameter β is a scale parameter because, by definition, $X / \beta \sim$ B-S(α, 1). Also, β is the median for the distribution. The B-S distribution presents the *reciprocal property*; that is, $X^{1} \sim$ B-S(α, 1/ β), so thus this reciprocal is in the same family of distributions as the original random variable X. If X has a B-S distribution with parameters β and α, then $\left[\frac{1}{\alpha}\left(\sqrt{\frac{x}{\beta}}-\sqrt{\frac{\beta}{x}}\right)\right]$ has a standard normal distribution, and mean is given by:

$$\beta\left(1+\frac{\alpha^2}{2}\right), \tag{7}$$

standard deviation:

$$\alpha^2\beta^2\left(1+\frac{5}{4}\alpha^2\right). \quad (8)$$

We can interpret the random variable X as the time of link availability and distribution as probability that signal amplitude will stay in the certain level. Here Φ denotes the standard normal CDF and ω is a given threshold.

CDF:

$$F(t)=P(X\le x)=\Phi\left[\frac{1}{\alpha}\left(\sqrt{\frac{t}{\beta}}-\sqrt{\frac{\beta}{t}}\right)\right], \quad (9)$$

where $\alpha=\frac{\sigma}{\sqrt{\omega\mu}}>0;\beta=\frac{\omega}{\mu}>0.$

The PDF is given by:

$$f(t)=2\alpha\beta\sqrt{\frac{t}{\beta}}\left[1+\left(\frac{1}{\beta}\right)^{-1}\right]\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{1}{2\alpha^2}\left(\frac{t}{\beta}+\frac{\beta}{t}-2\right)\right] \quad (10)$$

The appearance of B-S probability density can differ considerably by varying α and β heuristically.

Conclusions and future work

The goal of this paper is to provide additional characteristics temporal variation of ionospheric channel, drawn from measurements in Tallinn suburban area and Northern Latvia. We investigated well-known distribution functions to find which one depicts calculated histogram the most and the present Birnbaum – Saunders distribution as an alternative approach to describe quantitatively fading-related features of shortwave communication channels. The B-S distribution is not used before in conjunction of ionospheric channel evaluation. As implied previously, there may be physical aspects that could suggest the choice of a specific model. The Birnbaum-Saunders introduces the channel reliability features. However, we can interpret reliability as extension of quality into time domain, that is how slowly or haw rapidly we can expect the channel to deteriorate. Lognormal and B-S distributions are both very flexible distribution functions and in some cases their shapes coincide.

However, more reliable conclusions can be made using larger sets of field strength measurement results. Our future research plans include also such types of studies.

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Authors of this study conducted monitoring in March 2008, in the Northern Latvia and in May 2008, in Northern Estonia. In most cases the derived a statistical model of channel variation from observed data sets verifies the log-normal nature of the signal amplitude distributions. However, in many cases the outcome fitting the measured field strength histograms to various distributions using MATLAB suggest the Birnbaum-Saunders distribution as the best match. The B-S distribution is not used before in conjunction with ionospheric channel evaluation. The variation in channel quality over time is an important characteristic of the ionospheric medium. Using the Birnbaum-Saunders distribution in conjunction of ionospheric data gives alternative approach for interpretation monitoring results and for channel simulation. Ill. 5, bibl. 5 (in English; summaries in English, Russian and Lithuanian).

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Авторы этого исследования в марте 2008 года провели мониторинг в Северной Латвии, а в мае 2008 года – в Северной Эстонии. В большинстве случаев получены статистические модели канала и наблюдаются отклонения от данных, полученных из распределения амплитуды сигналов. Во многих случаях результат установлен гистограммами при различных распределениях с использованием MATLAB, выбрав распределение Бирнбаума-Сондерза как лучшее. Распределение Б-С ранее не использовалось при исследвании влияния каналов. Качество канала в течении времени является важной характеристикой ионосферной среды. Использование распределения Бирнбаума-Сондерза при анализе ионосферных данных дает альтернативный подход интерпретации результатов мониторинга и моделирования канала. Ил. 5, библ. 5 (на английском языке; рефераты на английском, русском и литовском яз.).

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2008 m. kovo mėnesį atliktas trumpabangės transliacijos tyrimas šiaurės Latvijoje, o 2008 m. gegužės mėn. – šiaurės Estijoje. Tyrimui sudaryti statistiniai kanalo modeliai. Gauti nuokrypiai patikrinti pagal signalo amplitudės skirstinį. Sudarytos histogramos esant įvairiems skirstiniams. Naudojant programą MATLAB, nustatytas Birnbaumo ir Saunderso skirstinys kaip geriausias. Birnbaumo ir Saunderso skirstinys nebuvo taikytas tiriant kanalų įtaką. Il. 5, bibl. 5 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).