IONOSPHERIC HF CHANNEL MODELING AND END-TO-END HF SYSTEM SIMULATION

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Abstract: **HF frequency band, lying within 1.6-30 MHz, is very important from data communications point of view and is unique in its property that it is refracted by the ionosphere. The main advantage of HF communications is their ability to enable data transmission over very long distances using ionospheric propagation paths without any preexisting infrastructure, making them suitable for many applications. This paper presents a detailed study regarding the modeling of a low latitudes and moderate conditions channel and its integration in an end-to-end system using the software environment VSS from National Instruments in co-simulation with MATLAB. This channel model considers that the channel fading is characterized by a Rayleigh distribution, which assumes that the magnitude of a signal passing through a communications channel will vary randomly. The ionospheric channel model is simulated through the MATLAB block, using the specific parameters of the low latitudes and moderate conditions channel, according to the Recommendation ITU-R F.1487. The simulation results illustrate the received signal attenuation level at the receiver after its propagation through the modeled ionospheric HF channel.**

Keywords: *HF channel modeling, ionosphere, co-simulation, NI AWR VSS, MATLAB.*

I. INTRODUCTION

High Frequency (HF) communications term describes a communications system that uses the HF band for transmissions. The HF band, lying within 1.6 - 30MHz, also called shortwave, is very important from data communications point of view and is unique in its property that it is refracted by the ionosphere [1].

This type of communications offers two great advantages. Firstly, they offer the ability to communicate over very long distances using ionospheric propagation paths without any preexisting infrastructure making them suitable for many applications and secondly, in HF communications there is no need for a satellite to communicate with a point beyond the line of sight [2]. Thus, HF radio is considered the main means of communications for countries in which a reliable access to satellite links is not available during wartime [3].

A successful HF transmission using sky wave propagation depends on the conditions of the ionosphere. HF communications are affected by different types of ionospheric variations, including: seasonal variations, variations with latitude and variations due to Solar Cycle and therefore data transmission over HF represents a challenging task [4].

This paper presents a detailed study on modeling of an ionospheric HF channel and its integration in an end-to-end system using the software environment Visual System Simulator (VSS) from National Instruments in co-simulation with MATLAB. In particular, this paper focuses on low latitudes and moderate conditions channel model. The channel fading is characterized by a Rayleigh distribution which assumes that the magnitude of a signal passing through a communications channel will vary randomly.

The ionospheric channel model is simulated through the MATLAB block, using the specific parameters of the low latitudes and moderate conditions channel, according to the Recommendation ITU-R F.1487 [5]. A great amount of mathematical research has been performed in simulating HF channels. In [6], the HF channel is characterized with two fundamental parameters: the coherence bandwidth and the coherence time. In this study the channel model is a simplified version of the Vogler and Hoffmeyer's model and does not take into account the altitude and propagation conditions.

The originality of this study consists in analyzing the way in which the characteristics of an HF channel implemented based on the Watterson model for low latitudes and moderate conditions are fluctuating. Time and money saving is achieved and any error can be corrected without costs if such a model is considered before transmitting information on the real channel.

The technological development of communications services in the past few years, shows an increasing interest for transmissions operating at high frequencies. Military use and interest in high frequency band is increasing as higher data rates become practical [7].

The remainder of the paper is organized as follows. Section 2 presents the short wave transmissions followed by the Watterson channel model description and the implementation of the low latitudes and moderate conditions channel model. The implementation details of the end-to-end system using National Instruments AWR Visual System

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Simulator (NI AWR VSS) is described in Section 3. Simulation results concerning how the transmissions on short waves are affected are presented in Section 4. Finally, Section 5 concludes the paper.

II. CHARACTERIZATION OF THE TRANSMISSIONS ON SHORT WAVES

The HF band, lying within 1.6 - 30MHz, is a major part of the shortwave band of frequencies and therefore communications at these frequencies are also called shortwave. Shortwave radio is used for communications at long distance, through the phenomenon known as sky wave propagation, in which the radio waves are reflected or refracted back to Earth from the ionosphere. The multiple reflections of the sky waves make possible long distance communications, which is the main advantage of the ionospheric propagation.

HF communications systems represent a viable solution to support special applications services, like those in military tactics or those needed in emergency situations.

Besides all the advantages, the HF channel has its own limitations and challenges. One of the main disadvantages is the fact that HF is defined as a multipath fading channel, meaning that a received signal may be comprised of components arriving at the receiver via multiple paths, at different times because of the different path lengths. Another disadvantage is the fact that data transmission over HF represents a challenging task because the HF channel is affected by Doppler spread and shift, multi-path and different sources of noise (manmade noise, atmospheric noise and galactic noise). Therefore, the success of a HF transmission using the sky wave propagation depends on the conditions of the ionosphere [1].

The ionosphere is divided into three main layers, classified based on their electron density: D, E and F. D layer, the lowest layer of the ionosphere, is the least important from the point of view of HF wave propagation. The E-region plays an important role in supporting sky wave communications at shorter distances (<2000 km). The F-region consists of two layers known as F1 and F2. The F2 layer, the highest layer of the ionosphere, generally has the greatest electron density and its ionization varies diurnally, seasonally and with the sunspot cycle. The F2 region is principally involved in reflecting signals which support long range HF sky wave propagation [8].

The layers of the ionosphere are different during day and night and they act like silver mirrors which reflect or refract the wave depending on its frequency. Once the waves enter the Ionosphere they are refracted back to Earth by their interaction with the Ionosphere's free electrons. The electromagnetic waves will be refracted as they pass through regions with significant ionization gradients; this is due to the variation of the electron density with height in the ionosphere.

The influence of the magnetic field determines the splitting of the electromagnetic wave once it arrives into the ionosphere in two waves: ordinary and extraordinary [9].

The ionosphere varies with the solar cycle, solar flares, season and during any given day and therefore it isn't a stable medium that allows the use of the same frequency throughout the year, or throughout one day. The solar radiation strikes the atmosphere more obliquely during the day, with increasing latitude, so the daily production of free electrons and the intensity of radiation decrease with increasing latitude.

The high frequency spectrum plays an important role for radio applications and therefore channel simulators are widely used to evaluate the performance of HF communications system. A great amount of mathematical research has been performed in simulating HF channels. In [6], the HF channel is characterized with two fundamental parameters: the coherence bandwidth and the coherence time. In our study the channel model is a simplified version of the Vogler and Hoffmeyer's model [10] and does not take into account the altitude and propagation conditions.

In the simulation of the HF ionospheric channel, the ITU-R approved Watterson Gaussian scatter model known as Watterson model is widely used. This model assumes that the channel fading is described by a Rayleigh distribution. The Watterson channel model is based on a tapped delay line, with n taps, each one representing an ionospheric propagation path as shown in Figure 1. Each tap consists of two magneto-ionic components, each of them being modeled as a complex Gaussian random process with a given gain and frequency shift. Each magneto-ionic component is modeled by a Gaussian Doppler spectrum, with a given standard deviation. Therefore, a tap is characterized by a bi-Gaussian Doppler spectrum, which consists of two Gaussian functions in the frequency domain.

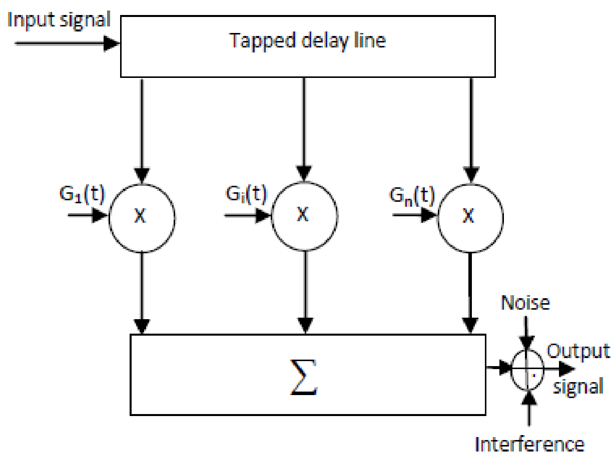

Figure 1: Block diagram of the Watterson HF channel model

The Watterson channel cannot be obtained by simply generating a Rayleigh channel with a bi-Gaussian Doppler spectrum. As a solution, two independent Rayleigh channels are generated, each one with a frequency shifted Gaussian Doppler spectrum. To obtain the Watterson channel model with a bi-Gaussian Doppler spectrum the two independent Rayleigh channels are added together.

The International Radio Consultative Committee (CCIR) Recommendation [5] recommended a list of HF channel conditions, defined as "Poor", "Moderate" and "Good" channels. Each of these channels is described with their values of differential time delay and frequency spread for different latitudes. This paper focuses on the simulation of a Poor, Low Latitudes and Moderate Conditions channel model used in quantitative testing of HF modems, according to the Recommendation ITU-R F.1487 [5].

As the ordinary and extraordinary waves propagate through different routes, this model consists of two independently fading paths of equal frequency spreads and equal power, each one consisting of two magneto-ionic components. It is assumed that the magneto-ionic components have no frequency shift and equal variance, meaning that in this case the magneto-ionic splitting is neglected. As a result, on each tap the bi-Gaussian Doppler spectrum can be replaced by a Gaussian Doppler spectrum.

The HF channel is modeled through MATLAB language and simulated using the MATLAB block from VSS environment.

First step in implementing a Low Latitude, Moderate Conditions channel model consists in the initialization of the simulation specific parameters. The signal entering the MATLAB block is chosen to be a BPSK modulated signal and for binary PSK the symbol rate is always equivalent to the bit rate. There is a dependency relationship between the bandwidth and data transmission rate that should be correlated. A 3 kHz analog channel, as in this case, can easily accept 1200 bits/sec, therefore, a bit rate of 1200 bits/sec was chosen for the HF channel corresponding to a symbol rate of 1200 symbols/sec.

According to Recommendation ITU-R F.1487, the path delays for the low latitudes and moderate conditions channel are 0 ms and 2 ms and the frequency spread is 1.5 Hz. The maximum Doppler shift is equal to 1 for all ITU-R HF channel models in order to obtain the correct frequency spreads.

Further, other parameters like the number of frames, the number of samples per frame and the sample period are properly established.

In the second step, a Rayleigh fading channel object is constructed using a dedicated function which constructs a multiple path fading channel object that models each path as an independent Rayleigh fading process. Then, a Gaussian Doppler spectrum object is created and assigned to the Doppler Spectrum property of the channel created.

In the third step the signal is filtered through the channel and added with AWGN (Additive White Gaussian Noise). The signal obtained after the AWGN noise was added is saved as a matrix, this being the only output format supported by the MATLAB block.

To simulate the HF channel using the MATLAB block, the .m file is modified as a standard function, in order to accept arguments and return the result. Hence, a function is declared in the first executable line of the code, which accepts as inputs the sample period, maximum Doppler shift, the path delays and the average path gains and returns the output.

The connection between the MATLAB block and the **.m* file is made by calling the **.m* file as a function from RUNCMD field existing on the MATLAB Commands tab. The block allows the user to introduce the number of input and output ports using the NINP and NOUT parameters, i.e. how many inputs and outputs has the application. Using the matrix variables denoted by 'in' and 'out', we are able to pass samples to MATLAB, respectively to retrieve samples from MATLAB. In this case, the variable 'in' represents the BPSK signal coming from the transmitter and entering the MATLAB block. Therefore, after the signal is processed through each block belonging to the transmitter, it will enter the MATLAB block, where the channel effects are applied over the signal and then the signal will pass through each block belonging to the receiver.

III. MODELING THE TX-RX SYSTEM USING NI AWR VSS

In a radio communications system, functional blocks are necessary to ensure at transmission: processing of information from the information source, its transformation in electromagnetic waves and its transmission in space and at the reception, recovery of the initial information. We begin with the presentation of each component of the transmitter block diagram, followed in the same manner by the description of the receiver block diagram.

3.1 RADIO TRANSMITTER

The main tasks of a transmitter are to create, modulate and transmits the RF signal through space to the receiver. The transmitter provides capturing of the information which is then transformed into electrical signals. Next step consists in information coding, the superimposing of it on the carrier signal through the modulation process and is ensured, through amplification, the necessary energy for signals propagation through electromagnetic waves, which are radiated by the transmission antenna.

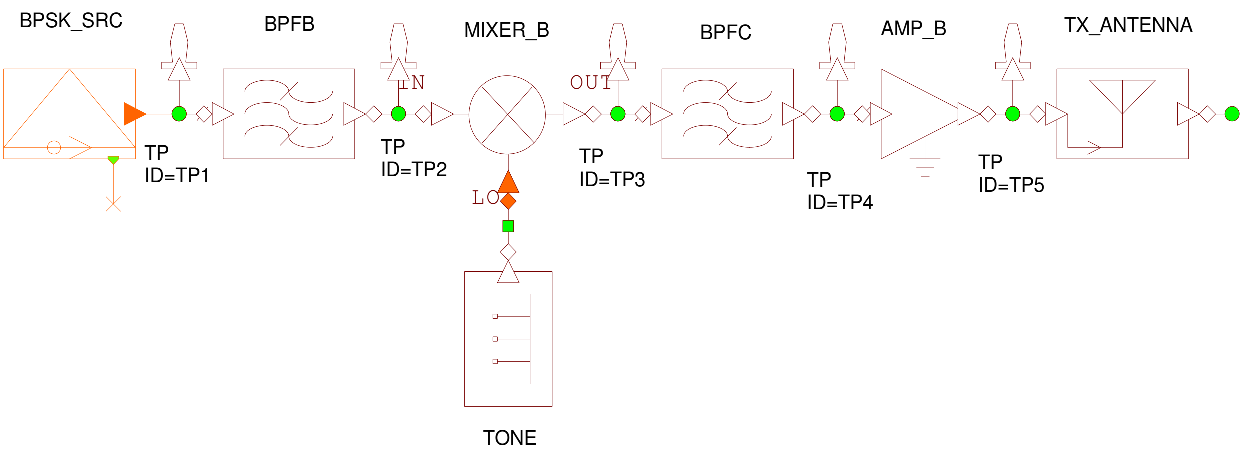

Figure 2: Transmitter block diagram

In dimensioning of components we chose standard values frequently used in communications at high frequencies:

BPSK modulated signal (**BPSK_SRC**): This block is used to produce a BPSK signal with a pseudo-random bit sequence. For beginning, a symbol rate of 1200 symbols/second, as mentioned earlier, and a center frequency of 455 kHz (standard value for AM radio) are chosen.

Band Pass Filter (**BPF**): The BPF is used before the mixer to stop passing the undesired harmonics. A channel of 3 kHz wide and a central frequency of 10 MHz are considered, therefore the lower edge of the pass-band and the upper edge of the pass-band are set according to Table 1:

Frequency at the input of the filter	Bandwidth around the central frequency	Lower and upper edge of the pass-band
455 kHz	1.5 kHz	453.5 kHz 456.5 kHz

Table 1: Lower and Upper edge of pass-band

Mixer: After the signal is filtered, it is mixed with the local oscillator to up-convert the carrier frequency. The local oscillator provides a frequency for mixing with the signal that is fed to the mixer, to get the intermediate frequency. At the transmitting side takes place the so called "up-conversion", defined as the sum of the two frequencies. Here the optional output frequency range is set to 10 MHz and the bandwidth around the center frequency is set to 3 KHz.

The center frequency for the local oscillator is calculated according to equation (1):

$$f_{mixer,c} + f_{LO,c} = 10 \text{ MHz} \quad (1)$$

Replacing the value of the center frequency of the mixer in equation (1), we obtain:

$$f_{LO,c} = 9545 \text{ kHz}; \quad (2)$$

BPF: The BPF is used after the mixer to stop passing of the undesired harmonics. The general purpose of the filters used in transmitter is to “clean up” its output and therefore this filter is used to remove noise, spurious signal and as was mentioned earlier, to remove undesired harmonics. Knowing that the frequency at the output of the mixer is 10 MHz, the lower edge and the upper edge of pass-band are set according to Table 2:

Frequency at the input of the filter	Bandwidth around the central frequency	Lower and upper edge of the pass-band
10000 kHz	1.5 kHz	9998.5 kHz 10001.5 kHz

Table 2: Lower and Upper edge of pass-band

RF power amplifier: Here, the signal power is amplified before it is fed to the antenna. After the RF signal is amplified, it is sent to the transmitter antenna so that it can be transmitted over a broader area. Here, the lower and upper limit of the RFI frequencies to generate is set equal to the lower and upper edges of pass-band: {9998.5, 10001.5}.

Transmitter antenna (**TX antenna**): The antenna receives the RF signal from the power amplifier and translates this RF power into electromagnetic waves so that the signal can be propagated through the air. For the antenna gain a standard value of 7dB is set.

3.2 RADIO RECEIVER

At the receiving end all the steps performed at the transmission end are reversed in order to recover the information. The receiver captures electromagnetic waves, selects electrical signals from the channel containing the useful information, amplifies them and then through detection extracts the information signal.

The receiver is basically a low noise amplifier that down-converts the incoming signal. It converts the RF signal to a lower frequency, called intermediate frequency.

Receiver antenna (**RX antenna**): The antenna is considered one of the most important elements in a radio circuit, as it ensures capturing of electromagnetic waves. The signal received by the RX antenna is filtered by a BPF and then amplified using a LNA, to improve the SNR before it is fed to the mixer for down converting the frequency. A standard value of 7dB is set for the antenna gain and a value of 600km as the distance from the transmitter.

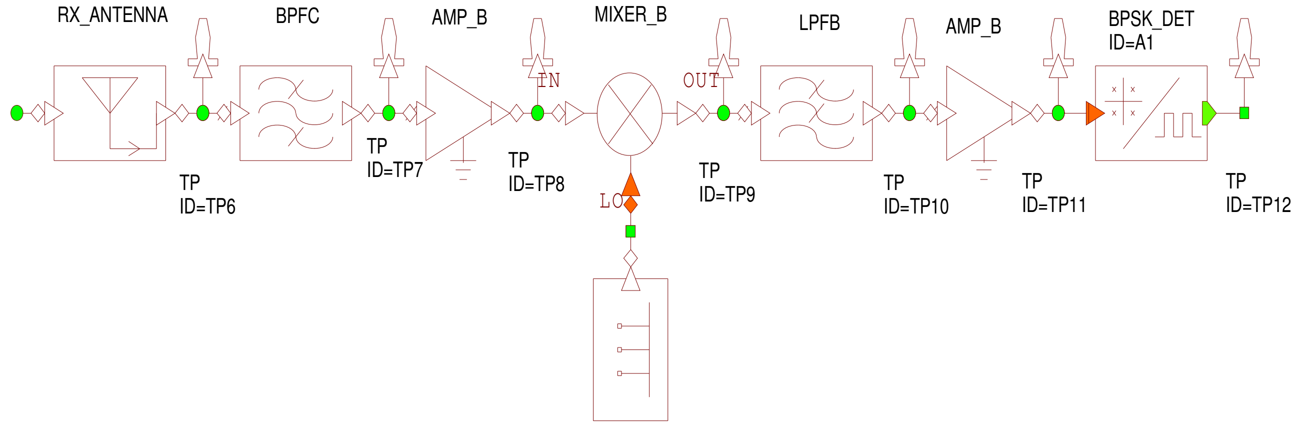

Figure 3: Receiver block diagram

RF Filter (BPF): The signal is filtered through RF filter which allows passing only the frequency in the pass-band and blocks the RF signals that are outside the pass-band. For this paper a BPF was chosen to reduce strong out-of-band signals and image frequency response. The upper and lower edges are calculated as follows in Table 3:

Frequency at the input of the filter	Bandwidth around the central frequency	Lower and upper edge of the pass-band
10000 kHz	1.5 kHz	9998.5 kHz 100001.5 kHz

Table 3: Lower and Upper edge of pass-band

Low Noise Amplifier (**LNA**): The task of the low noise amplifier is to increase the weak signals without contaminating them with noise. LNA plays an important role in achieving good reception sensitivity. The lower and upper limit of the RFI frequencies to generate is set equal to the lower edge and the upper edge of pass-band: {9998.5, 10001.5}.

Mixer: The amplified signal is then fed to the mixer, along with the output of the local oscillator, producing the so called intermediate frequency (IF) signal. At the receiver part takes place the so called "down-conversion" operation, defined as the difference of the two frequencies. Here, the bandwidth around the center frequency is set to 3 kHz and the center frequency of the local oscillator is calculated according to the equation (3):

$$|f_{mixer,c} - f_{LO,c}| = 455 \text{ kHz} \qquad (3)$$

Replacing the value of the center frequency of the mixer in equation (2), we obtain:

$$f_{LO,c} = 10455 \text{ kHz}; \qquad (4)$$

Low Pass Filter (**LPF**): The task of this filter which is placed at the input of IF amplifier is to eliminate the mixer products that could affect the performance of the IF amplifier. In the case of the LPF, the pass-band corner frequency is set to 3 kHz.

IF amplifier: The signal at the output of the filter is fed to the IF amplifier providing enough signal amplification so that the signal to be properly detected. The lower and upper limit of the RFI frequencies to generate corresponds to the values: {9998.5, 10001.5}.

BPSK Detector: extracts the information signal.

IV. SIMULATION RESULTS

The purpose of this paper is to implement an ionospheric channel on short waves and to integrate it into an end-to-end system using VSS in co-simulation with MATLAB.

Before integrating the HF channel in the end-to-end system, it is simulated as a standalone application using MATLAB environment.

In the standalone application, a signal randomly generated is modulated using a BPSK modulation and then filtered through the channel by applying the channel effects. A BPSK modulation was chosen because it is commonly used for HF channel simulations and it is considered the simplest form of PSK. After modeling the channel in MATLAB we can analyze the impulse response of a transmission on HF at low latitudes and moderate conditions, with the corresponding delay between the two paths, according to ITU-R F.1487. The impulse response is illustrated in Figure 4. Each stem represents one multipath component. The red component has the smallest delay value while the blue component has the largest delay value.The green curve represents the bandlimited channel response.

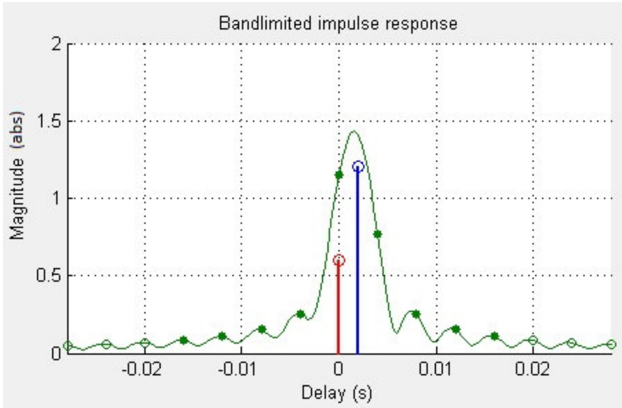

Figure 4: Impulse Response according to the low latitudes and moderate conditions

By integrating the modeled HF channel in the end-to-end system, the .m file simulated as a standalone application must be modified as a standard function. After the .m file is properly modified, it is called from the MATLAB block which recognizes as input the signal coming from the transmitter antenna.

In order to better observe the effects of the simulated HF channel a comparison between the signal that enters the MATLAB block and the signal at the output of the HF channel is realized. The transmitter antenna receives the RF signal from the power amplifier and translates this RF power into electromagnetic waves so that the signal can propagate through the air.

The signal transmitted by the transmitter antenna, illustrated in Figure 5, represents the input signal of the MATLAB block.

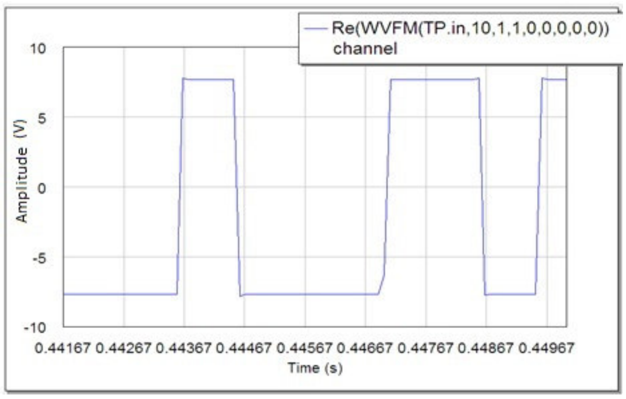

Figure 5: Signal transmitted by the transmitter antenna

The signal at the output of the simulated HF channel is illustrated in Figure 6.

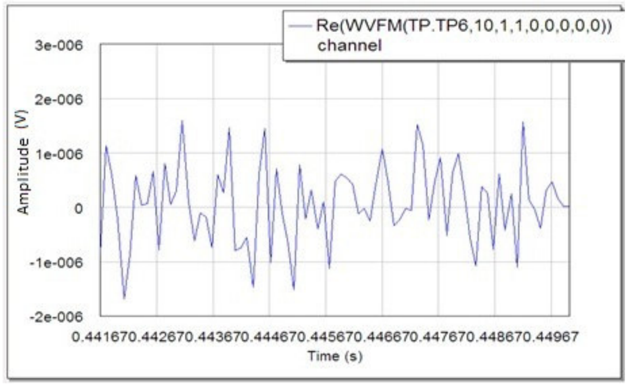

Figure 6: The signal at the output of the HF channel

Simulation results indicate that the HF propagation through ionospheric reflection is characterized by multipath propagation and fading. The transmitted signal travels through different paths between the transmitter and receiver. Each of these paths has a different length resulting in different time delays. Rayleigh fading assumes that the magnitude of a signal passing through a communications channel will vary randomly. Therefore, after passing through a Rayleigh channel the strength of the received signal decreases with the square of the distance between the transmitter and the receiver.

V. CONCLUSIONS

For several years, HF radio has provided reliable communications services throughout the world. Communications systems using the HF band represent a viable solution to support special applications, like those needed in military tactics or emergency situations. Moreover, HF radio is considered the main means of communications for countries where a reliable access to satellite links is not available during wartime.

This paper presents a detailed study regarding the modeling of an ionospheric HF channel and its integration in an end-to-end system using the software environment VSS from National Instruments in co-simulation with MATLAB, aiming at analyzing the effects on a transmission in the HF band. In particular, this paper focuses on the low latitudes and moderate conditions channel model.

The propagation of HF waves through ionospheric reflection is characterized by multipath propagation and fading. The channel model considers that the channel fading is characterized by a Rayleigh distribution, which assumes that the magnitude of a signal passing through a communications channel will vary randomly.

Analyzing the fluctuation of the characteristics of an HF channel implemented based on the Watterson model for low latitudes and moderate conditions are fluctuating represents an important aspect of this study.

The ionospheric channel model is simulated through the MATLAB block, using the specific parameters of the low latitudes and moderate conditions channel, according to the Recommendation ITU-R F.1487. Including the MATLAB block modeling the ionospheric channel within the VSS environment enables a comprehensive end-to-end simulation of a communications system operating in the HF band.

As that higher data rates become more practical, the technological development of communications services in the past few years shows an increasing interest for transmissions operating at high frequencies, mainly for military use. Therefore, using such simulation tools and appropriate HF channel models may save time and money, as any errors can be corrected without costs if such models are considered in an end-to-end system before transmitting information on the real HF channel.

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