AN EFFICIENT IONOSPHERIC PROPAGATION SIMULATOR FOR HIGH FREQUENCY SIGNALS

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The use of High-Frequency (HF) propagation in the ionosphere is still prevalent for applications such as long-range communication, target detection and commercial broadcasting. The advancement of data communication using HF, and the introduction of HF digital radio broadcasting places a greater demand on the frequency bandwidth supported by the ionospheric propagation channel [1]. The ability to acquire the behavior of the channel and the knowledge of how the channel will affect the propagating signals in advance is imperative to ensure the reliability, and maintain adequate performance, of modern wide-bandwidth HF systems. Thus, there is an ever increasing need for an efficient wide-bandwidth ionospheric propagation simulator [2].

In this paper, an efficient ionospheric propagation simulator will be presented. This propagation simulator is focussing on one of the most undesirable characteristics of HF signal that is the variability of the signal levels arriving at the receiver, otherwise known as fading. A theoretical model for fading of HF signals and efficient algorithms for calculating the fading signals have been developed, which will be used in implementing the ionospheric propagation simulator. Possible applications for this efficient simulator include real-time channel evaluation and frequency management system, as well as forming a test-bed in testing various fading mitigation techniques. In particular, it is intended that the simulator be used to investigate the fading mitigation possibilities that are afforded by modem HF techniques such as frequency hopping. In the following sections, a brief treatment on the development of the propagation simulator, along with preliminary simulation and experimental results, will be included.

IONOSPHERIC PROPAGATION SIMULATOR

The ionospheric propagation simulator is based on the theoretical model of signal fading in the ionosphere. The major advancement in the theoretical model is an analytical expression for the fading effects and it results in an efficient algorithm for the real-time prediction of signal fading in a given ionosphere.

The two main contributors to the fading of HF signal propagating in the ionosphere are: polarization and amplitude. Each phenomenon is modelled separately and later combined to form the core of the propagation simulator.

Polarization fading model

Polarization fading occurs because of the rotation of the polarization plane of the wave in a process known as Faraday rotation. Two characteristic waves, the Ordinary (O) and the Extraordinary (X), traverse through the ionosphere in slightly different path and phase speed. Since they are both circularly polarized and opposite in direction, the resultant wave arriving at the receiver will have different polarization compare to that of the initial wave. The dynamic nature of the ionosphere causes the ever-changing polarization of the wave at the receiver, resulting in the effects of fading.

The effects of polarization fading is modelled by using perturbation techniques to calculate the change in the phase path due to the irregularity in the ionosphere. The phase path, P, is the distance travelled by a constant phase front of a wave, and it is given by

$$P = \int \mu \, ds = \int \mu^2 \, dg, \tag{1}$$

where μ is the refractive index along the ray path element ds, and the group path element is $dg = \frac{ds}{\mu}$. Under Fermat's principle, the phase path variation away from the ray path is second order ($\delta P = 0$). This implies the change in phase path due to irregularity in the ionosphere can be evaluated along the ray path of the ionosphere without irregularity

$$\delta P = \int_{\text{regular}} \delta\mu \, ds = \int_{\text{regular}} \mu\delta\mu \, dg \tag{2}$$

where the irregularity in the ionosphere is represented as the variation in the refractive index $\delta\mu$. The integral in (2) can be evaluated to produce an analytical expression for the change in phase path due to the irregularity in the ionosphere, and thus allows for rapid calculation of the phase path perturbations. Further speed enhancement is possible by using the improved frequency offset method [3]. The frequency offset method is the use of equivalent frequencies for the O and X wave to take account of magnetic field effects. It is a first order approximation in that the shift of wave frequency in the absence of magnetic field yields the same ray path quantities as the unchanged frequency in the presence of the field.

The polarization fading model has been shown to produce fast and accurate algorithm for the prediction of polarization fading compared to a full numerical ray-tracing algorithm [4].

Amplitude fading model

Amplitude fading is caused by the movement of large scale irregularity in the ionosphere. Depending on the position of the irregularity, the ionosphere will effectively becomes a concave or convex reflection layer for HF signals, which causes a focussing or defocussing effects on the received signal. As the irregularity is travelling along, there will be a variation on the strength of the received signal.

The effects of amplitude fading can be modelled by using a parabolic approximation to Maxwell's equations [5]:

$$-2jk_0 \frac{\partial U}{\partial g} + \frac{\partial^2 U}{\partial t^2} + k_0^2 \xi(g,t) U = 0, \tag{3}$$

where k_0 is the background wave number, U is the complex modulation of the wave in the unperturbed ionosphere, ξ represents the refractive index and its irregularity and it is a function of g and t, which are the longitudinal and transverse coordinates respectively as defined in the local coordinate system along the central path of the wave. This is shown in Fig.(1). Equation (3) is a complexified version of diffusion equation and can be solved by Green's functions method. The analytic solution is used in the model to describe the fluctuation of the signal amplitude as the wave propagates through the irregular ionosphere. Alternatively, for large length scales, the amplitude fading can be calculated using ray tracing.

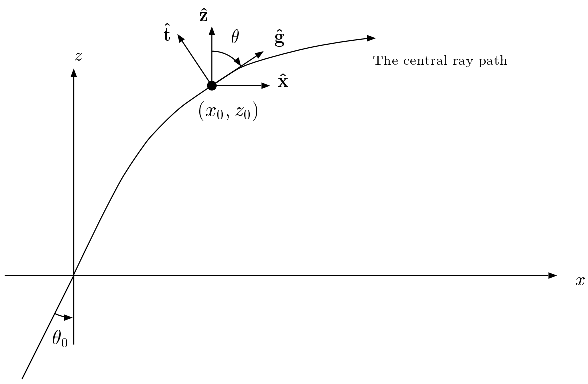

Figure 1: Local ray coordinate system

Simulator implementation

The implementation of the ionospheric propagation simulator involves combining the two fading models described above, and incorporating an efficient numerical ray tracing package, HASELX [6], that will generate the required ray paths. By using an accurate homing algorithm [7], path quantities such as phase path distance can be used within the models to calculate the received signal strength.

SIMULATION RESULTS

Simulation is done for a path over a distance of 1289 km (Alice Springs to Darwin), and for a wide-bandwidth signal of 500 kHz between 8 MHz and 8.5 MHz. The ionosphere is modelled as a single Chapman layer with the parameters obtained from the International Reference Ionosphere (IRI) model. In the simulator, the ionosphere irregularity is a periodic sinusoidal modulation on the electron density, with the parameters being the scale length of the irregularity, speed of propagation, and the maximum relative variation on the electron density.

Fig.(2) shows the simulation results for the 1289 km path. It is important to note that in this simulation only the low ray is present, as the operating frequencies are below that of the critical frequency of the chapman layer. The received signal suffers from the short-term fading with sharp nulls that is caused by the polarization fading. A longer term fading with smaller variation can be observed by comparing the level of the peaks. Notice there is an orthogonality between the vertical and horizontal channel for the sharp nulls, as expected for fading due to the rotation of the polarization vector at the receiver. Looking at the received signal over the whole bandwidth of 500 kHz, one could observe the frequency selective behavior of polarization fading. According to the results, the polarization bandwidth of the ionospheric channel is around 160 kHz. This is an extremely important observation, especially for systems that are relying on wide bandwidth channels for proper operation.

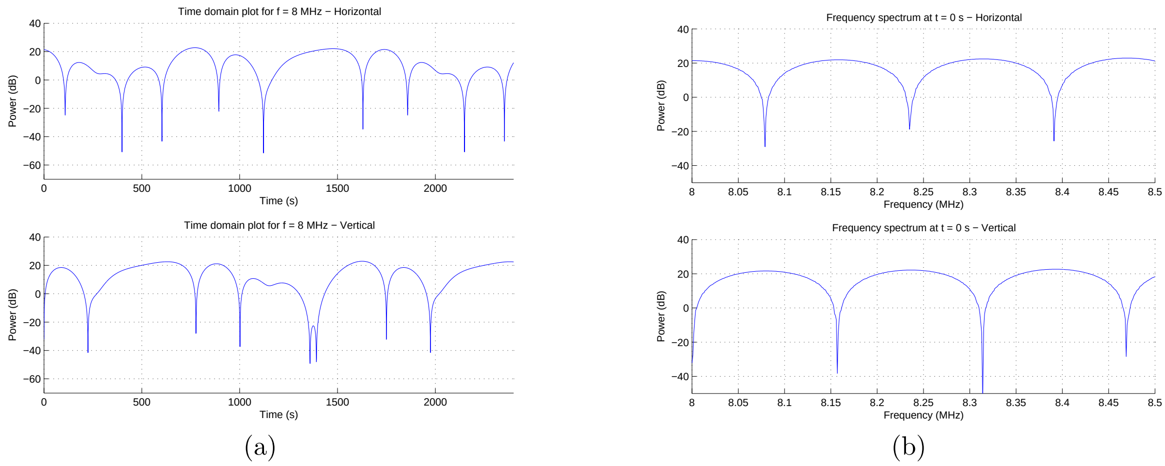

Figure 2: Simulation results for the irregularity parameters - Scalelength = 350 km, speed = 250 m/s, maximum variation in electron density = 5%. (a) Time evolution of received signal at 8 MHz, with top and bottom graphs showing the horizontal and vertical channel respectively. (b) Received signal over the whole 500 kHz bandwidth at time = 0s, with top and bottom graphs showing the horizontal and vertical channel respectively.

EXPERIMENTAL RESULTS

To verify the validity of the propagation simulator, signals propagating in the real ionospheric channel have been observed. The equipment used in obtaining the data is the compact channel probe. Main constituents of the channel probe include a workstation equipped with a wide-band digital receiver and the active crossed-dipole antennas. The compact crossed-dipole active antenna provides the capability to simultaneously monitor both horizontal and vertical polarization.

In fig.(3), the fading behavior of a 9.66 MHz signal over a path of 1900 km (Brandon to Adelaide) is shown. Notice that both short-term fading and long-term fading behavior is observed in the received signals. Closer observations have revealed that polarization fading is occurring at some instances, where a peak in the horizontal channel corresponds to a null in the vertical channel.

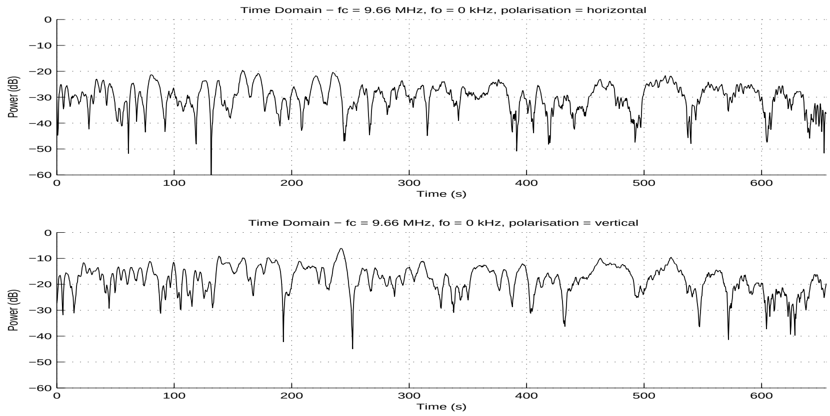

Figure 3: Fading behavior of a 9.66 MHz over a 1900 km path. Top graph shows the signal received at the horizontal antenna. Bottom graph shows the signal received at the vertical antenna.

DISCUSSION AND FUTURE WORK

The ionospheric propagation simulator is able to simulate the effects of polarization and amplitude fading on a received signal. Although some of the finer details of fading is not captured by the propagation simulator, the important features of the signal fading are corresponding to that of a real ionospheric channel. Further development is required to take into account of a more general ionospheric irregularity and disturbances.

When fully developed, the ionospheric propagation simulator will form a test-bed for mitigation techniques to combat signal fading. Mitigation techniques such as polarization diversity and frequency diversity have the potential to overcome the effects of signal fading.

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