Determination of the correlation distance for spaced antennas on multipath HF links and implications for design of SIMO and MIMO systems.

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In spatial diversity systems, two or more spaced antennas are employed at the receiver location. Then when the signal at one antenna is fading, the stronger signal at another antenna can be chosen.

In SIMO (Single Input Multiple Output) and MIMO systems, space-time coding is used to enable greater reliability and/or greater link capacity. For SIMO an antenna array is employed at the receiver location and for MIMO systems antennas arrays are employed at both transmitter and receiver locations and space-time coding is utilised.

For all these methods, it is important that the receiving (or transmitting) antennas are sufficiently far apart that the fading is relatively independent for each transmitter receiver path as otherwise little advantage is gained.

The most important contribution to the fading is generally that of the time-varying irregularities so that it is important to model these in any simulation.

Method

The correlation distance for spaced antennas, as used in these systems, has been determined using the Leeds-St.Petersburg HF simulator. In this simulator, the channel simulation for the multipath HF ionospheric sky wave random channel is based on the most general theory of HF wave propagation in the real fluctuating ionosphere.

(V. Gherm, N. N. Zernov and H.J. Strangeways, Propagation model for transionospheric fluctuating paths of propagation in a wideband ionospheric fluctuating reflection channel: Physically based software simulator of the transionospheric channel, Radio Science, Vol. 40, No.1, RS1003, doi:10.1029/2004RS003097, January 2005)

The complex phase method (or modified Rytov's approximation) is employed. This accounts for the main effects of HF propagation in the disturbed ionosphere: ray bending due to the inhomogeneous background ionosphere and scattering by random ionospheric irregularities including diffraction by localised inhomogeneities. The Earth's magnetic field effect on the irregularity shape is taken into account through the anisotropic spatial spectrum of the ionospheric turbulence

The propagation paths are determined using a Nelder-Mead homing-in algorithm together with a 3D ray-tracing model which takes into account the effect of the geomagnetic field on the refractive index and also permits horizontal gradients of electron density to be included. This enables simulation of the multimoded wideband ionospheric HF channel for both background and stochastic (time-varying irregularities) electron density components for any transmitter and receiver locations and taking into account both magneto-ionic modes for all the ionospherically reflected paths. The random realisation of a pulsed signal propagated through the fluctuating ionosphere is represented as the following Fourier integral in the frequency domain

$$E(\mathbf{r},t,t) = \sum_{n \to \infty} \int_{-\infty}^{+\infty} P(\omega) T_n(\mathbf{r},\omega,t) R_n(\mathbf{r},\omega,t) e^{-i\omega t} d\omega$$

- **E** is the field at the point of observation **r**, represented by the sum **n** of propagating ionospheric modes;
- **P** is the spectrum of the transmitted pulse;
- $\mathbf{T}_{\mathbf{n}}$ is the transfer function of the **n**-th mode in the background ionosphere;
- \mathbf{R}_{n} are the random functions (also called phasors), which account for the effects of the ionospheric electron density fluctuations on each mode.

The irregularities are modelled to have an anisotropic inverse spatial spectrum given by: $(2^{-p}/2)^{-p}/2$

$$B_{\varepsilon}(\vec{k}, s) = C_{N}^{2} [1 - \varepsilon_{0}(s)]^{2} \sigma_{N}^{2} \left(1 + \frac{\kappa_{tg}^{2}}{K_{tg}^{2}} + \frac{\vec{k}_{tr}^{2}}{K_{tr}^{2}} \right)$$

 $K_{tg}=2\pi/l_{tg}$; $K_{tr}=2\pi/l_{tr}$ where l_{tg} and l_{tr} are the outer scales of the turbulence tangential and transverse to the geomagnetic field direction respectively. *p* is the spectral index.

The wideband HF simulator can output realisations of the received signal at the receiver in both fast and slow time.

This can also enable correlation between spaced antennas to be determined assuming frozen in drift of the irregularities.

For antennas spaced in the direction of irregularity velocity drift, for spacings up to a few wavelengths, it is assumed that the spatial variation of the received signal can be modelled in the drift direction using the simulated slow time variation and the known drift velocity.

Based on a simple model of scattering from an inhomogeneous and time-varying ionosphere, a spatial correlation function p(d) normalised to unity at d = 0 may be derived to show the dependence of CW signals at two antennas spaced at a distance d

$$p(d) = \exp(-d^2/2\sigma_1^2)$$

At a separation $d = \sigma_1$ the correlation is 0.61 and at $d = \sqrt{2}\sigma_1$, it is 0.37. We will take this latter distance as the "diversity separation distance" or "correlation distance"

(See CCIR Report 266-6)

As a first example, consider a North South path from 50° to 62° latitude at 0° longitude in the IRI Ionosphere with an East-West drift of the irregularities of 0.5 km/s. The carrier frequency is 9 MHz and the signal bandwidth is 20 kHz. The standard deviation of the relative electron density fluctuations is $2x10^{-5}$. The outer scale of the irregularities is 5 km in the transverse direction and 15 km in the geomagnetic field direction. The spectral index is given by p =3.7 The E and F layer reflected paths exist for both magneto-ionic modes and all 4 paths are included to determine the signal strength at the receiver location.



The correlation coefficient at antennas spaced by distances up to 3.2 km is determined over the fast (propagation) time which enables the difference in correlation coefficient between the E and F modes to be seen.





The figure shows the variation of the signal strength of both ionospherically reflected E and F paths for a 10 second period. Both magneto-ionic modes are included for both the E and F reflected paths.



The figure shows how the correlation coefficient falls of with antenna separation for both reflected E and F modes. It is clear that the fall-off is faster for the F mode and thus this mode decorrelates over a shorter distance. Note that because of the small number of points, the correlation coefficient has been "unbiassed" at each lag by dividing by the number of products taken in determining it. This explains why the maximum for the E-reflected mode is not at zero lag.

Second Example: Low and high angle F modes



The left figure shows the received signal strength for a path at 12.5 MHz consisting of low and high angle F reflected modes (both o and x) against fast and slow time. The right figure shows the corresponding correlation distance against fast time. Two consecutive pulses with a separation of 30 ms in fast time are shown. Using two pulses enables the period between consecutive pulses, where inter-symbol interference could occur, to be properly modelled. The variance of the electron density irregularities is 0.0004. The correlation distance is of course greater when a reflected mode pulse is received than for the time interval between the pulses.

The correlation coefficient is fairly similar between the low and high angle F modes. This is in contrast to the last example where the two modes there (E and low angle F) showed a significant difference in correlation coefficient and correlation distance.



This figure shows the same path through the same ionosphere as the previous plot except that the variance of the electron density irregularities is reduced to 0.0001. This increases the correlation coefficient and the correlation distance between spaced antennas.



Conclusions

The correlation of multipath ionospherically reflected signals is quite complex and will vary during the duration of a dispersed pulse.

The spatial correlation at the receiving antenna array depends strongly on the variance of the electron density irregularities.

Each mode (e.g. 1Eo or 1Fx) shows "fading" due to the time-varying irregularities

Paths reflected from the F region generally show poorer correlation at spaced antennas than E region reflected paths. This is likely to result from the larger absolute changes in electron density in the F as opposed to the E layer

Although it might be supposed that correlation between spaced receiving antennas would be increased by receiving additional modes this is not necessarily the case. E.g lowering the transmission frequency to an enable an additional E layer reflection may not decrease the spatial correlation at the receiver as the E layer mode added is likely to show better correlation between the spaced antennas than the F mode. Moreover decreasing the carrier frequency to enable the E mode will reduce the SNR which will also result in poorer channel capacity for a SIMO/MIMO link.

More work is required to validate the fading results from the simulator against observed fading characteristics for different multimode/link scenarios and frequencies and to extend the simulator determinations to a wider variety of multipath scenarios (e.g 1/2/3-hop) and different receiving antenna arrays and their orientation to the drift velocity direction.