Electromagnetic Compatibility (EMC) Analysis Approach for Band Migration to Provide Spectrum for the President's Spectrum Initiative

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Abstract— **When communication systems operating in one band must be moved to another band occupied by existing (incumbent) systems, an electromagnetic compatibility (EMC) analysis is used to evaluate the viability of spectrum sharing and frequency reassignments. The analysis starts with gathering all of the transmitter and receiver parameters of both systems. The correct propagation model for different geometric scenarios is then used to accurately estimate the signal strength of the interfering signal and determine the noise level of the victim receiver. If the separation distance is not adequate to reduce the interfering signal to an acceptable level, then the necessary frequency dependent rejection (FDR) must be determined. Finally, the interference-to-noise ratio (I/N) can be calculated which will allow a determination of frequency separation versus separation distance from the FDR curves.**

I. Introduction

In support of the President's Spectrum Initiative [1], the Institute for Telecommunication Sciences (ITS) has been tasked to conduct an exit evaluation for several bands in the radio frequency spectrum. This exit evaluation considers the sharing of spectrum via the migration of entrant systems operating in one band to another band where incumbent systems are operating. In order to perform such an evaluation, it is necessary to conduct an electromagnetic compatibility (EMC) analysis to evaluate spectrum sharing and frequency reassignments. Regulatory agencies need to perform EMC analyses to address potential interference problems between users of the crowded electromagnetic spectrum. ITS has examined the interference potential between various Federal communications systems that have been targeted for sharing common spectrum.

It is important to use the correct propagation model for different geometric scenarios to determine the signal strength of the interfering signal. Use of the wrong propagation model could result in either predicting interference when no interference is present or not predicting interference when interference is actually present. As a result, the interference mitigation technique that is applied could either overcompensate or not provide enough compensation. This could result in an overly expensive mitigation solution or unexpected interference. An example is the use of free-space loss, which does not include physical phenomena such as the surface wave and the effects of ground on the antenna performance in the prediction of transmission loss. The propagation effects of diffraction and troposcatter are also not included in free-space loss. ITS has developed many specific radio-wave propagation models [2] to meet the requirements for EMC analyses and other applications over several decades and distributes them freely to other Federal agencies and the U.S. Military.

II. Interference Analysis Approach

The analysis starts with gathering all the transmitter and receiver parameters of the systems that are currently in the frequency band and the systems that are planning to move into this band. The EMC analysis is necessary to evaluate the compatibility of all systems that are planned to occupy the band.

The parameters needed for an interference analysis are first gathered for receivers and transmitters. Transmitter information includes: transmitter power, operating frequency, modulation information, emission bandwidth (with roll-off of the emission spectra at the band edges), antenna gain, patterns, and feed losses. Receiver information includes: operating frequency, receiver sensitivity, receiver bandwidth with sufficient information for the receiver rejection characteristics outside of the receiver bandwidth, and desired signal-to interference ratio (S/I) for adequate performance, in addition to the antenna parameters of gain and patterns.

The propagation loss incurred as a result of the separation distance between an interference source (transmitter) and a victim (receiver) is one mechanism for obtaining electromagnetic compatibility between them. To evaluate this mechanism, the analyst needs to calculate the radio-wave propagation loss between the systems using an appropriate propagation model. Another mechanism would be the frequency dependent rejection (FDR) between the interference source and the victim receiver. In this case, the operating frequency, emission bandwidths, transmitter power, and antenna parameters are used for the interference source. The operating frequency, receiver bandwidth, receiver sensitivity, out-of-band rejection, and antenna parameters are used for the victim receiver.

The antenna orientation of the interference source and victim receiver, as well as the geometric orientation of the relative positions of the interference source and victim receiver, are also important for the calculation of separation distances. Additional parameters for the receiver would include a required signal-to-noise ratio (S/N) for the needed bit-error-rate or adequate performance metric.

A required interference-to-noise ratio (*I/N*) or desired signal to interference ratio (*S/I*) would also be needed to perform the interference analysis. This is where the type of modulation comes into play. Absent adequate interference interaction information between different modulations, a first cut at this would be to assume the *I/N* of either minus 6.0 dB or minus 10.0 dB. The minus 6.0 dB is used for general analysis of systems interference. The minus 10.0 dB is used where requirements are critical or there is a safety-of-life requirement. This is a simple but adequate approach, but more sophisticated procedures have been developed using the energy-per-bit-per-Hz-to-noise power ratio (E_b/n_0) to determine a more specific *I/N* criteria.

The analysis approach used here determines the *S/I*, *I/N*, and *S/N* based on the modulation type, the bandwidth, and the data rate. A digital system usually has a bit-error-rate requirement for proper operation and this bit-error-rate corresponds to a certain signal-to-noise ratio. There are tables and graphs with this information [3], [4]. The required bit-error-rate is sometimes associated with an E_b/n_0, where $N = n_0 B$ and B is the IF bandwidth, and n_0 is the noise per unit bandwidth. The relationship between required *S/N* and E_b/n_0 is:

$$\frac{E_b}{n_0} = \frac{B}{R}\frac{S}{N}$$

where R is the information or signaling rate in bits per second, and S is the signal power. The BER curves allow us to determine the E_b/n_0 values and calculate the S/N necessary to meet the required system performance [3].

After obtaining all parameters of the systems involved, the analysis scenarios are set up by first deciding what interference interactions are going to take place. Knowing the deployment procedures for each of these systems allows the analyst to set up a range of possible interference distances and antenna heights at which the different geometric scenarios of the systems will occur. Radio waves propagate differently over these different scenarios, because of the different distances and antenna height combinations involved. The basic phenomena that can occur over these scenarios and that will affect these radio waves include: refraction, diffraction, line-of-sight (LOS) propagation, and troposcatter. For each of the scenarios, propagation models were selected that would result in the best prediction of radio-wave propagation loss between the candidate interference sources and the victim receivers, with consideration for different distances and antenna heights.

III. Computation of the Received Interference Signal Levels

Four propagation models were used to determine the basic transmission loss and received signal levels: the ITS Irregular Terrain Model (ITM), the ITS Undisturbed-Field Model, a free-space loss model, and a free-space loss model minus 6 dB along the slant range. The analysis did not include terrain. This is a worst case for an interference analysis, since the loss is at a minimum for the spherical smooth Earth when compared to the case when there is terrain present. The minimum propagation loss is what should be used to assure that the interference analysis provides the maximum possible interference signal level prediction.

The ITM is a good method for medium to long distances with antenna heights of up to 3,000 meters, and it includes LOS, diffraction, and troposcatter phenomena over a spherical Earth.

The Undisturbed-Field Model includes LOS phenomena at medium and close-in distances less than 6.8 km, and for low antenna heights less than 10 meters [5]. It includes the direct and reflected waves as well as the surface wave. The surface wave is an important component of the total electromagnetic wave at close-in distances, even at the higher frequencies [5]. The distance of 6.8 km is used because the Earth can be assumed to be flat at a frequency of 1800 MHz out to a distance of 6.8 km [5]. The Undisturbed-Field Model will include all of the destructive and constructive interference behavior over a real smooth-Earth environment which will appear on a plot of received signal versus distance with many oscillations (Figures 1 and 3 for close-in distances).

Figures 2 and 4 don't show the constructive and destructive interference, since it doesn't occur at the longer distances, but for distances less than 6.8 km the vertical and horizontal scale factors on these plots make it indiscernible. Rather than trying to determine the exact received signal level at a specific distance (which may be difficult due to the frequency of oscillations and lobe structure), it is advisable to take the envelope of the maximum received signal level predicted by this model for a worst case analysis. The height of the maximums (distance between the average value of received signal level and the maximum value of received signal level) can be as much as 6.0 dB over perfectly conducting ground. The maximum value of this excursion over average ground is about 4.0 to 5.0 dB.

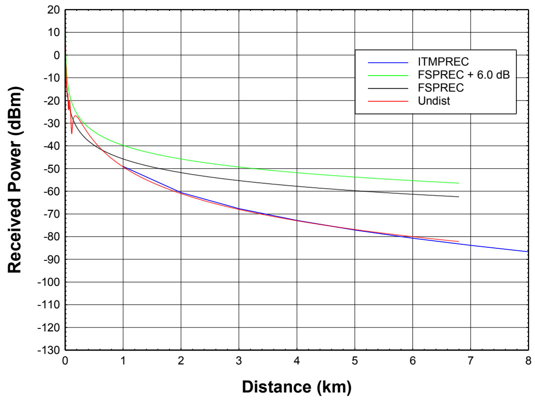

Fig. 1 Received power versus distance for close distance, low transmit antenna (h_t = 2.0 m, h_r = 5.0 m)

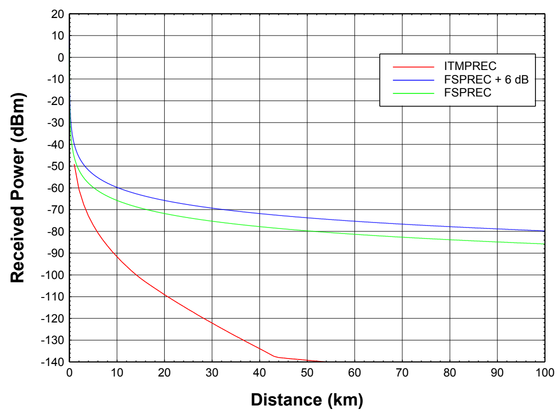

Fig. 2 Received power versus distance for far distance, low transmit antenna (h_t =2.0m, h_r = 5.0m)

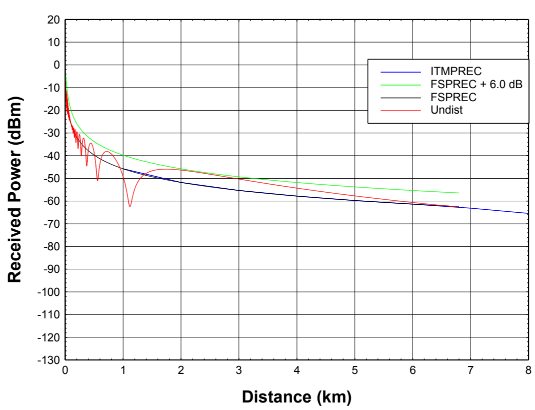

Fig. 3 Received power versus distance for close distance, high transmit antenna (h_t = 20.0 m, h_r = 5.0 m)

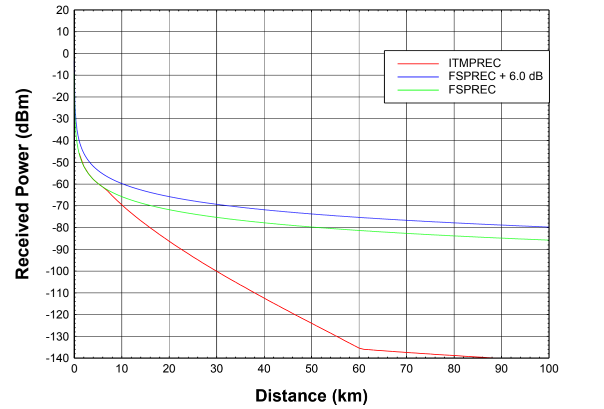

Fig. 4 Received power versus distance for far distance, high transmit antenna (h_t = 20.0 m, h_r = 5.0 m)

The remaining two received signal prediction techniques are the free-space signal method and the free-space signal level plus 6 dB. The free-space signal level plus 6 dB method results in absolute maximum signal level that follows the maximum signal level predicted by the Undisturbed-Field Model. The free-space signal level plus 6 dB model is more suitable than a free-space signal level model, and takes into account the maximum possible interference signal level due to constructive and destructive interference phenomena predicted by the Undisturbed-Field Model. This would provide a safety factor for limiting the maximum possible interference power. This is demonstrated by the plots in Figures 1 and 3 for the Undisturbed-Field Model. This phenomenon occurs in LOS scenarios. The free-space models do not take into account any propagation phenomena other than the spreading loss that occurs in free space.

One must be careful in choosing the correct propagation model for EMC analysis. There are situations where the Undisturbed-Field Model should be used in preference to the two free-space models. Figure 3 demonstrates that the predicted received interference signal level for the Undisturbed-Field Model is less than the received signal level predicted by the free-space plus 6 dB model for distances greater than 3 km, and would be more accurate for distances above 3 km. However, for distances less than 3 km the Undisturbed-Field Model has lobes in the received signal power predictions, which are real, but are difficult to use as a general limit for maximum signal if the exact distance is not known. These lobes are bounded by the free-space signal level plus 6 dB model. In this case, the free-space plus 6 dB model would be better to use for distances less than 3 km. The Undisturbed-Field Model is a more accurate model than the free-space plus 6 dB model, so it would result in lesser separation distances for avoiding interference than the other free-space models for distances greater than 3 km and less than 6.8 km. The Undisturbed-Field Model has been verified with measured data and other accurate propagation prediction techniques [5], [6].

For distances less than 3 km the Undisturbed-Field Model predicts the exact received signal level, but the free-space plus 6 dB model follows the envelope of the varying signal level, so in this case it would be better to use the free-space plus 6 dB model rather than be concerned about the actual locations of the peaks and nulls in the received signal level. The amount of FDR required would also be less for a fixed distance.

Figures 2 and 4 for the far distance scenarios demonstrate that the received signal level for the ITM model is much less than that for the two free-space models. This would allow much reduced separation distances and frequency dependent rejection for avoiding interference. The ITM model has been verified with measured data and other accurate models. It takes the presence of ground into account in addition to diffraction around a spherical Earth. The ITM model also takes into account troposcatter propagation.

IV. Noise Level Predictions for the Analysis

The noise level (in dBm) of the victim receiver in the analysis can be determined from the equation:

$$Noise(dBm) = -174 dBm / Hz + NF(dB) + 10\log(BW(Hz))$$

where:

NF(dB) is the noise figure in decibels and

BW(Hz) is the bandwidth in Hertz.

The received signal power from a desired transmitter is given by:

$$P_{rec}(dBm) = P_t(dBm) + G_t(dBi) + G_r(dBi) - Loss(dB) - LossT(dB) - LossR(dB) - FDR(dB)$$

where

P_{rec} is the received signal power from the desired transmitter or the interference source in dBm,

P_t is the transmitted signal power from the desired transmitter or the interference source in dBm,

G_t is the gain of the antenna at the desired transmitter or the interference source in dBi,

G_r is the gain of the antenna at the receiver in dBi,

Loss is the propagation loss between the desired transmitter (interference source) and the receiver in decibels,

LossT is the loss between the transmitter (interference source) and the antenna that it provides energy to, which includes cable and feed losses,

LossR is the loss between the receiver and the receiver antenna, which includes cable loss, and

FDR is the frequency dependent rejection in decibels.

V. Prediction of the Required Frequency Dependent Rejection

If the separation distance is not adequate to reduce the interfering signal to an acceptable level, then it is necessary to apply FDR. FDR is the signal loss calculated from the transmitter and receiver frequency differences, emission bandwidth of the transmitter, and filter characteristics of the receiver. FDR is the ability of a receiver to reject a specific interfering signal at a frequency offset from the receiver's center frequency. FDR is a measure of the signal attenuation between a transmitter and receiver as a function of the frequency offset between the transmitter and receiver. FDR defines the necessary frequency separation between the receiver and interferer to avoid interference. It also can be used to determine the physical separation distance required, at a given frequency separation, to avoid interference. The plots of Figures 5 through 8 are examples taken from a single scenario for an entrant transmitter and incumbent receiver. The plots were calculated using the received interference signal power, and the *S/I*, *S/N*, and *I/N* ratios for the example scenario.

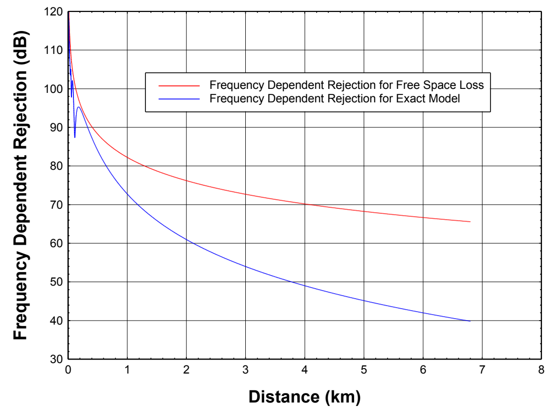

Fig. 5 FDR versus distance for close distance, low transmit antenna (h_t = 2.0 m, h_r = 5.0 m) for both the free-space loss model and the Undisturbed-Field (Exact) Model

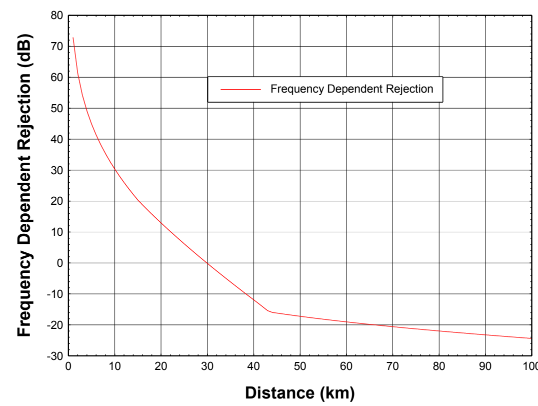

Fig. 6 FDR versus distance for far distance, low transmit antenna (h_t =2.0m, h_r = 5.0m)

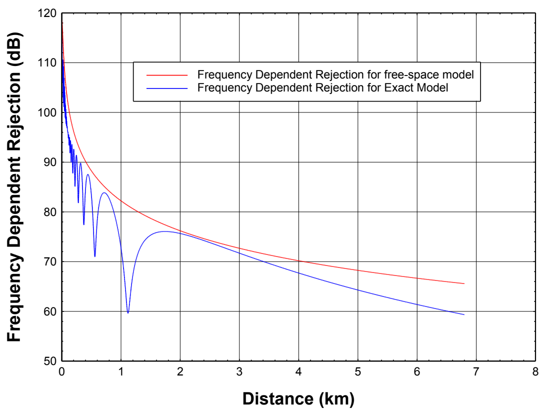

Fig. 7 FDR versus distance for close distance, high transmit antenna (h_t = 20.0 m, h_r = 5.0 m) for both the free-space loss model and the Undisturbed-Field (Exact) Model

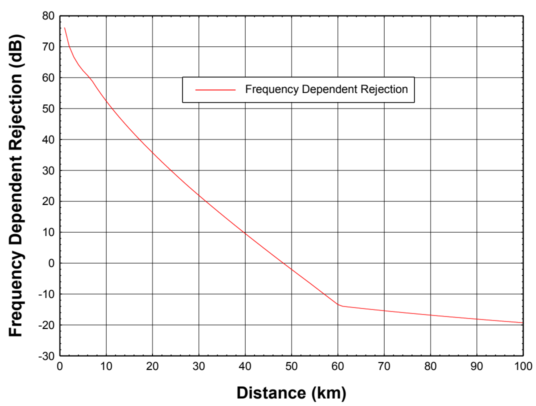

Fig. 8 FDR versus distance for far distance, high transmit antenna (h_t = 20.0 m, h_r = 5.0 m)

The required FDR was calculated for each interferer/receiver pair as a function of separation distance (Figures 5 through 8).The FDR achieved as a function of the transmitter and receiver parameters mentioned previously and the frequency offset was also calculated (Figure 9). As a result we have now estimated the potential interference rejection for this entrant transmitter into the incumbent receiver.

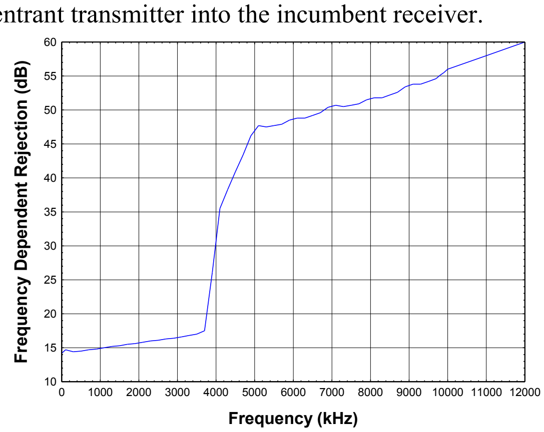

Fig. 9 Example plot of FDR versus frequency offset for entrant transmitter and incumbent receiver

The FDR required to bring the interference signal level down to meet the *I/N* and *S/N* requirement is given by:

$$FDR(dB) = P_r(dBm) - N(dB) - \frac{I}{N}(dB)$$

$$\frac{S}{N} = \frac{E_b}{n_0}\frac{R}{B}$$

$$\frac{I}{N}(dB) = \frac{S}{N}(dB) - \frac{S}{I}(dB)$$

The *S/N* = 7.3 dB was computed from the E_b/n_0 = 7.0 dB, the data rate *R* = 8.0 Mbps, and the bandwidth *B* = 7.5 MHz [1]. The bit-error-rate (BER) curves will allow for the calculation of the SNR at a given *S/I*. The E_b/n_0=7.0 dB was obtained from the curves in [1] for a pre-correction value for *BER* of 10^{-3} and QPSK modulation with an *S/I* = 20 dB. The resultant *I/N* is -12.7 dB. The FDR computed from the equation is a function of distance since the received power P_r is also a function of distance, so the plots in Figures 5 through 8 are a function of distance.

Figure 9 is an example of the FDR computed for the example entrant transmitter/incumbent receiver pair based on their parameters. For the entrant transmitter this would include the emission bandwidth with roll-off of the emission spectra at the band edges and beyond. For the incumbent receiver the information includes the receiver bandwidth with sufficient information for the receiver rejection characteristics outside of the receiver bandwidth.

VI. THE EMC METRIC OF FREQUENCY SEPARATION VERSUS SEPARATION DISTANCE

From *S/N* and *S/I*, the *I/N* can be calculated which will allow a determination of frequency separation (Δf) versus separation distance from the FDR curves (Figures 10 and 11). For a given separation distance between the entrant interferer and the incumbent receiver, a minimum frequency offset must be maintained. If the entrant interfering transmitter antenna were at a 2 meter height (Figure 10), it could operate at a frequency that is only 4.5 MHz from the incumbent receiver with a 6 km separation distance. If the incumbent receiver is operating at a frequency that is 12 MHz away from the entrant interference source, the entrant transmitter at a rooftop height of 20 meters (Figure 11) would have to be at least 6 km away from the incumbent receiver to avoid a harmful interference level. At greater distances, the frequency offset between the two systems can be less; at greater than 36 km, the two devices can operate on the same frequency (Figure 11).

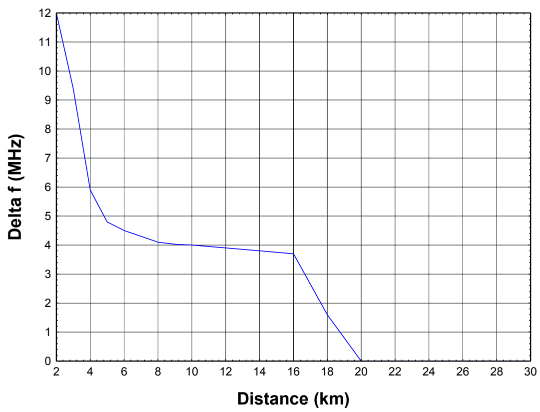

Fig. 10 Example plot of frequency offset versus separation distance for low transmitter antenna height (h_t = 2.0 m)

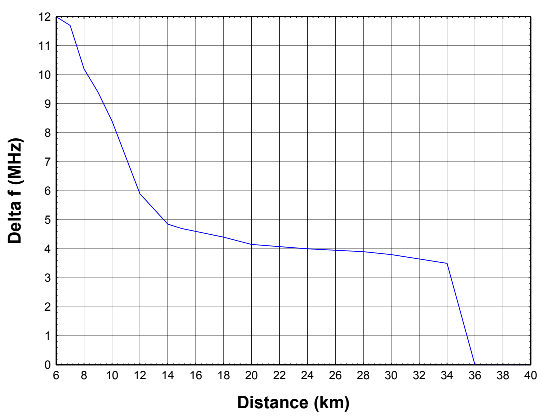

Fig. 11 Example plot of frequency offset versus separation distance for high transmitter antenna height, (h_t = 20.0 m)

VII. CONCLUSION

Two important items to be incorporated into an EMC analysis of digital communication systems are the effects on the specific modulation in a digital receiver and the correct propagation loss prediction models.

The interference effects on digital communication systems have been addressed by taking into account the specific digital modulation of the incumbent receiver. Taking the digital modulation into account permits specific S/I and I/N ratios based on E_b/n_0 to provide a more precise determination of interference thresholds.

It is important to incorporate both the effects on the specific modulation in a digital receiver and the correct propagation loss prediction models into the EMC analysis of digital communication systems. Taking the digital modulation into account allows a more precise determination of interference thresholds through calculation of specific signal-to-interference and interference-to-noise ratios based on E_b/n_0. Using the correct propagation model for different geometric scenarios allows a more accurate determination of the signal strength of the interfering signal.

Using the wrong propagation model can lead to either predicting interference when no interference is present or not predicting interference when interference is actually present. If more interference is predicted than actually exists, overcompensation could lead to expensive and unnecessary mitigation techniques. If interference is not predicted through the use of the incorrect model, unexpected interference may be encountered. An example is the use of free-space loss, which predicts transmission loss without including the surface wave, the effects of ground on antenna performance, or the propagation effects of diffraction and troposcatter.

Using the correct propagation models assures that interference is eliminated through application of the most appropriate and cost-effective mitigation techniques. Frequency, antenna heights, antenna characteristics, and the distances involved must be considered in selecting the correct propagation model. If an unsuitable model is chosen, the propagation prediction will be erroneous. ITS has developed many radio-wave propagation models to meet these various requirements; these models are freely distributed to other Federal agencies and the U.S. Military [2].

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