

Coverage Prediction for Digital Mobile Systems

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1. Introduction

The rapid growth in mobile communications systems over the past several years has led to increasing use of digital modulation techniques to transmit information. Whether it's cellular, PCS, paging, two-way mobile, or SMR trunking, essentially every aspect of mobile communication has been affected by the "digital revolution". Digital techniques allow much greater flexibility for encoding and processing information making possible more efficient and robust transmission than previously achieved with analog systems.

In designing any radio system, a fundamental task is to predict the coverage of a proposed system and determine whether the intended service objectives are met. Over the years a wide variety of approaches have been developed to predict coverage using what are known as propagation models. Propagation in this context simply means the transfer or transmission of signals from the transmitter to the receiver. Propagation modeling is an effort to predict what happens to signals en route from the transmitter to the receiver. Obviously the signal gets weaker, and everyone has experienced other signal impairments such as multipath fading. In large part the design of modulation techniques and radio system hardware, including antennas, is directed toward combating the signal impairments that happen during propagation.

The traditional approaches to propagation modeling which have been developed for analog systems were intended to only predict signal attenuation, or path loss, as the signal traveled from the transmitter to the receiver. While they have been adequate for most analog systems, for digital systems new techniques are needed which produce other information in addition to path loss. This information may actually be the controlling factor on system performance or coverage, even when the signal-to-noise ratio is well above the value otherwise necessary to achieve perfect reception.

In the following sections of this article, various approaches to propagation modeling will be discussed with a view towards their strengths and weaknesses when used with digital systems. The most incisive approach based on ray-tracing techniques will be used to explore some of the propagation factors which specifically affect digital system performance and coverage.

2. Empirical vs. Physical Propagation Models

The most common approaches to propagation modeling are:

- Empirical models which use measurement data to define a model path loss equation
- Physical models which use physical radio wave principles such as free space transmission, reflection, diffraction, etc. to model path loss

Each of these approaches is discussed below.

2.1 Empirical Models

In the VHF/UHF frequency bands, examples of an empirical propagation models are the FCC and ITU-R models [1,2]. The FCC uses propagation curves which were fitted to a set of signal strength measurements done at several locations in the United States. The propagation model as represented by a set of curves for different frequency bands shows field strength versus distance for a range of transmit antenna height above average terrain (HAAT) values. The ITU-R has similar curves based on height above average terrain as set forth in Rec. 370-6. The ITU-R method also provides for corrections to take into account “terrain roughness” or Δh , the 10% to 90% inter-decile terrain variation over the path. These models make use of measurement data instead of electromagnetic wave principles to define the prediction. As such, the FCC and ITU-R models are classic examples of purely empirical models.

Another model commonly used in mobile radio and cellular work is the Hata model[3] which is a set of equations based on measurements and graphs developed by Okumura[4]. This too is an excellent example empirical model.

Empirical models use what are known as “predictors” or “specifiers” in general statistical modeling theory. Predictors are parameters which have been found through statistical analysis to bear a relationship to (are correlated with) the quantity which is to be predicted. In econometric models,

the objective may be to predict gross national product (GNP). In doing so the model may use values for unemployment, disposal income, balance of trade, etc. as predictors. All of these factors may have been found to be correlated with GNP, but none of them directly *causes* GNP to go up or down. Similarly, in the field of psychology one may find a correlation between a child's IQ and the family annual income, but higher family income does not cause the child's IQ to be higher. There are other mechanisms at work. In medicine, mis-interpretation of the significance of empirical studies have lead to such absurd headlines as "COFFEE CAUSES CANCER". The textbook axiom is "*Correlation does not prove causality.*"

In the case of the FCC model, through statistical analysis a correlation was found between antenna HAAT and signal strength. But this was only correlation, not a causal relationship. Indeed, one could not conceive of a radio propagation mechanism where the simple average elevation value directly changes the magnitude of an electric or magnetic field at the receiver. The consequence of this approach is easily illustrated in Figure 1 and 2 which show two terrain profiles along a 25 km path separating the transmitter and receiver. The 3-16 km HAAT values (as specified in the FCC Rules) for the transmit and receive antennas is the same for both terrain profiles in Figures 1 and 2, but the field strength at the receiver will be much lower in Figure 2 due to the obstruction of the nearby hill. A similar example could be constructed for Δh in which a valley and a mountain along two paths both have the same inter-decile elevation variation, yet the field strength at the receiver on the path with the mountain will be much lower than on the path with the valley. The inability to explicitly account for particular features of the propagation environment is perhaps the greatest limitation of empirical, measurement-based models.

The accuracy and usefulness of such empirical models also depends on the environment where the original data for the model was taken and how universally applicable that environment is. A common problem is trying to use empirical models in areas where the propagation environment is widely different from the environment where the data was gathered. In the Hata model based on the work on Okumura, propagation path loss is defined for "urban", "suburban", and "open" environments. These correction factors in Okumura's work are an effort to refine the predictions, but unless the characteristics of "urban", "suburban", and "open" for your study area are reasonably similar to those in Japan where the measurement data was taken, these finer-grained classifications may not be of much use.

In spite of their limitations, empirical models such as the FCC, ITU-R, and Hata models are still widely used because they are simple and allow rapid computer calculation. They also have a certain

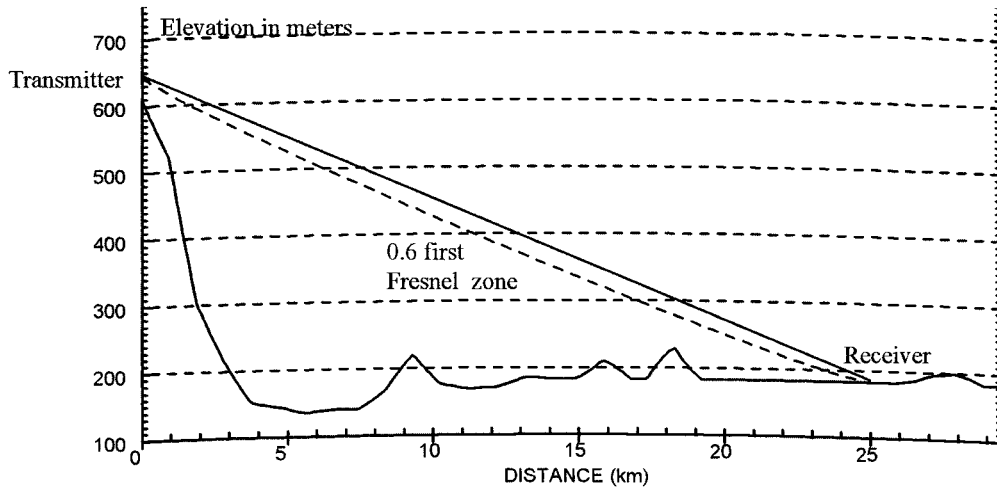


Fig. 1. Line-of-sight radio path over a terrain profile.

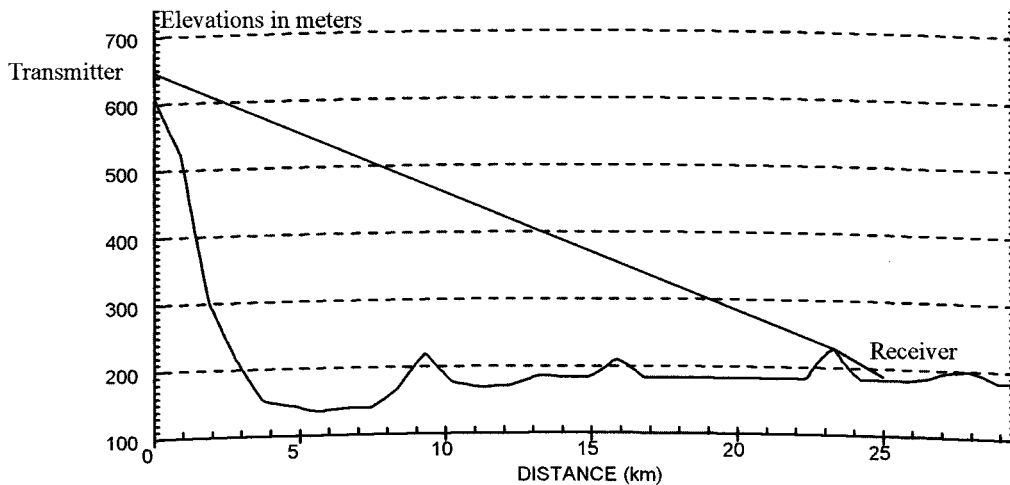


Fig. 2. Obstructed radio path over a terrain profile.

“comfort” factor in that people using them in certain circumstances over time have come to know what to expect and make their own ad-hoc “corrections” to the prediction values provided by the model. When the propagation environment is fairly homogeneous and similar to the environment where the model measurements were taken, an empirical model can achieve reasonably good prediction results.

With the recent advent of automated field strength measurement systems with GPS position logging, it is now relatively easy to acquire vast amounts of measurement data. This has led to the use of custom empirical propagation models which are path loss equations or formulas “tuned” for a given system, or even for a given transmitter or cell base station within a system. With such extensive use of measurement results, however, it’s appropriate to question whether these models are really

prediction methods at all when in essence the answers are used to “predict” the answers. In spite of their heavy reliance on measurement data, such customized models will still fail to adequately account for propagation environment features such as the hill in Figure 2.

As pointed out in the Introduction, digital communication systems require a wider variety of information from propagation models than just signal strength to predict coverage and performance. With empirical models, each new category of information represents another set of measurements which has to be taken. As an example, RMS delay spread (defined later) has recently become a routinely used factor in predicting the performance of wideband digital communication systems. For an empirical model to be useful for such systems, another set of measurement data using a channel sounder would have to be acquired and appropriate statistical analysis done to determine statistically significant predictors of RMS delay spread. All the same limitations of empirical modeling pointed out above would still apply, but when signal strength and RMS delay spread predictions are both considered as separate dimensions in the prediction problem, the difficulties of the empirical approach multiply. This problem is aggravated as other information types such as signal fading statistics are added. As the amount of data increases, the attraction of the empirical modeling approach diminishes.

2.2 Physical Propagation Models

Unlike empirical propagation models, physical models don't use measurement data for predictions but instead rely on physical laws governing the interaction of electromagnetic waves with the physical elements of the propagation environment. Fundamentally, all of these interactions can be derived from the Maxwell's equations[5].

To be effective, physical models require detailed descriptions of the elements of propagation environment for their predictions. For this reason, the weakness of physical models is that they require extensive databases of information (terrain elevations, building wall locations, surface material characteristics, etc.) which in turn require significant computer resources to take all this information into account to perform the required propagation calculations. To reduce this problem, simplified descriptions of the propagation environment are usually employed. A typical example is representing an obstructing mountain ridge like that shown in Figure 2 as a single isolated “knife-edge”. The effect of a single knife-edge on the signal is readily found from classic diffraction theory to provide a field strength prediction at the receiver. The problem is whether a real mountain ridge can be accurately modeled as a knife-edge. Clearly, no mountain ridge is really a knife-edge. Other methods to more accurately represent the mountain ridge have been used. In each case where a new model of the

obstacle was employed, the physical principles governing the effect of the "model" obstacle on the radio waves were known.

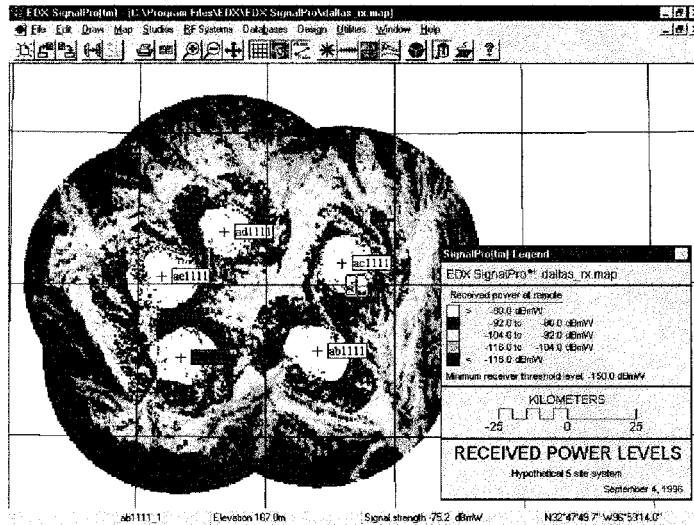


Fig. 3. Received power prediction using a single path model.

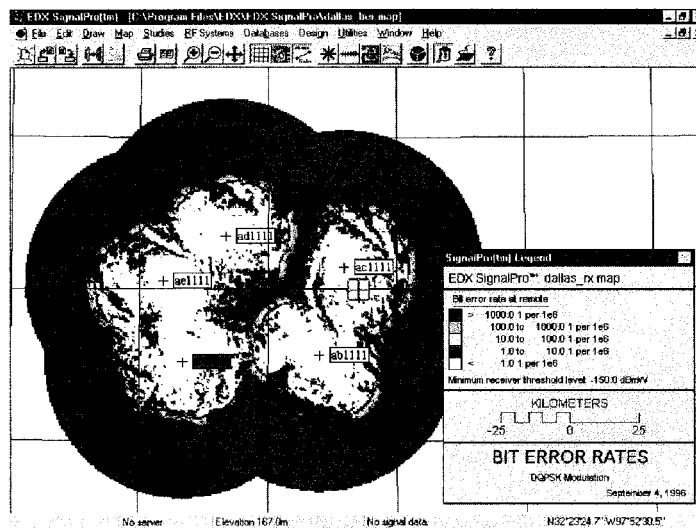


Fig. 4. Bit error rate prediction.

receiver. Models such as TIREM and Longley-Rice are examples of physical models which predict signal strength using a single propagation path.¹ Even using the assumption that signal energy arrives at the receiver via a single path only, useful results can still be obtained. Figure 3 shows a map of

The important aspect of physical propagation models, and their primary distinction from empirical models, is that they attempt to predict the field strength at a precise point in space by considering the specific propagation environment circumstances involved. For this reason they can be regarded as *site-specific* models. Given a particular transmitter and receiver location, and the propagation environment, a site-specific physical model will provide a tailor-made prediction of the field strength at that point, and as will be shown, other channel response characteristics. Site-specific physical propagation modeling is the approach used here to explore coverage prediction for digital mobile radio systems.

3. Traditional Single Path Propagation Models

Commonly used propagation models attempt to predict the signal strength at the receiver by calculating the path loss for a single radio propagation path from the transmitter via a great circle route to the

¹ Strictly speaking, TIREM and Longley-Rice are not pure physical models since measurement results have been used to "tune" certain parameters in each model.

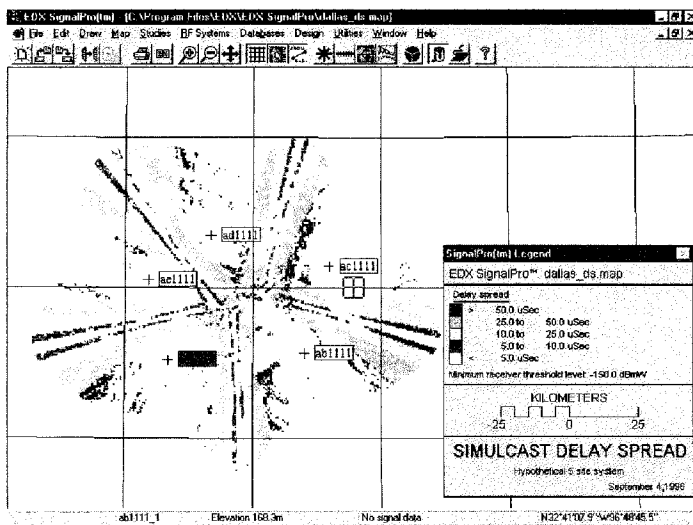


Fig. 5. Simulcast delay spread prediction.

maps of simulcast delay spread can also be readily created as shown in Figure 5. Such maps are especially useful for digital paging systems where time delay and frequency offsets can be assigned to each transmitter to re-locate and control the interference areas. Software prediction tools such as EDX SignalPro™ that provide this capability allow the system designer to quickly evaluate many different offset configurations from a notebook or desktop computer without making time-consuming and expensive field measurements to interactively assess and adjust these parameters.

While single path prediction methods are a very useful starting point, for modern digital systems the answers can sometimes be inadequate or even misleading as will be shown in the following sections.

predicted received power levels for a five transmitter system using the TIREM model. With receiver signal power predicted, and knowing the system noise, digital modulation type and data rate, it is straightforward to display maps of bit error rate (BER) as shown in Figure 4. By taking into account relative propagation path length delays from various transmitters, and their relative signal strengths,

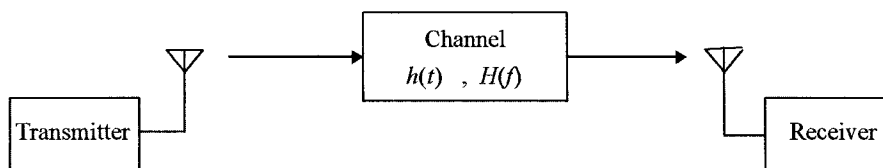


Fig. 6. Propagation channel model.

4. Multi-Ray Models - Propagation as a Channel Filter

An instructive and useful way to look at the propagation mechanism is to consider it as a filter, and the propagation path itself is a channel containing this filter, as illustrated in Figure 6. The notations $h(t)$ and $H(f)$ shown in Figure 6 are standard engineering terms for the *transfer function* of the filter. The transfer function is simply a way of describing what happens to the signal as it passes through the filter. Common descriptions such as “8-pole Butterworth” denote a particular filter transfer function.

The propagation channel filter transfer function certainly has attenuation (the familiar path loss), but it also has other characteristics which can have important effects on the signal that is detected at the receiver.

How do we find the other characteristics of this filter? One approach is to find all the ways the signal can travel from the transmitter to the receiver, rather than just assuming it gets there via a single path as we did above. If we take into account all the ways the signal arrives at the receiver, we have completely described the filter transfer function. An approach to the problem is the multi-ray or “ray-tracing” method.² The multi-ray concept is illustrated in Figure 7. Signals leaving the transmitter encounter a wide variety of objects on the propagation environment including buildings, mountains, the ground, vehicles, etc. The signals can “bounce” (reflect and diffract) off these objects and get to the

² Ray-tracing is the most common approach here but other electromagnetic field calculation methods, such as FDTD or method-of-moments, which attempt to provide a complete description of the signal at the receiver could potentially be used.

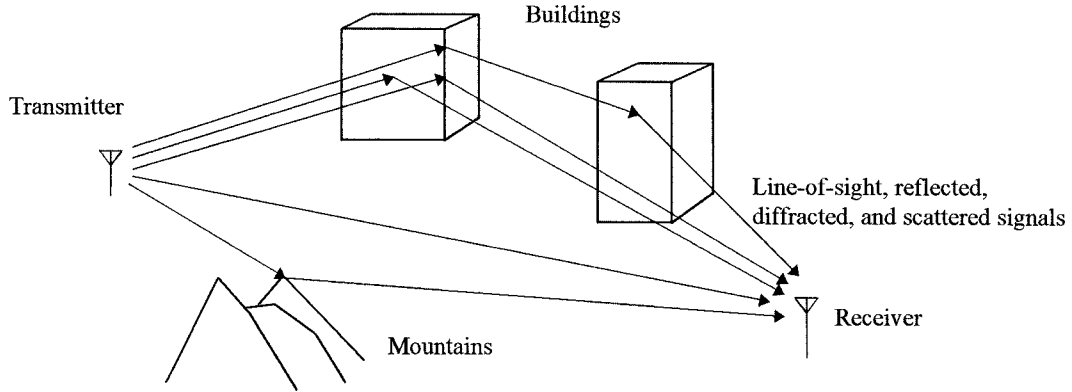


Fig. 7. Channel model based on multipath signals arriving at the receiver.

receiver via many different paths. This is multipath propagation, and causes the familiar signal fading at the receiver which every mobile radio engineer has experienced.

Using some mathematics, we can develop a way to use these rays to find the transfer function, $h(t)$, of the channel filter. First let's look at the case for the single path to the receiver. In this situation we have only path loss so we can write a simple equation for the signal strength at the receiver. Under these circumstances, the signal at the receive antenna terminals, E_r , would be the same as the signal at the transmitter except weaker. This can be written as:

$$E_r = AE_t \exp(-j\omega t + \theta) \quad (1)$$

where E_r is the (complex) electric field voltage or magnetic field current at the receive antenna, E_t is the magnitude of the transmitted signal (voltage or current), ω is the carrier frequency in radians, and t is time. The multiplicative factor A is the propagation loss while θ is some phase delay or phase shift introduced by the channel. The expression " $\exp(-j\omega t + \theta)$ " is just a convenient way to describe the transmitted carrier wave in this case. For simplicity only the electric field will be represented in the following equations with the understanding there is an associated magnetic field.

If the channel is now considered as a filter with some lowpass impulse response, that impulse response would be given by:

$$h(t) = A\delta(t - \tau)\exp(-j\theta) \quad (2)$$

where the “ $\delta(t - \tau)$ ” means there is impulse in the channel response at time $t = \tau$. A sinewave signal at frequency ω leaving the transmit antenna would arrive at the receiver reduced in amplitude by factor A , shifted in phase by θ , and delayed by τ seconds where the delay is a direct function of the path length from the transmitter to the receiver. Such a model of the transmission channel is applicable for free-space propagation conditions where the signal energy arrives at the receiver directly (via one path) from the transmitter.

If the channel consisted of two transmission paths for the transmit energy to arrive at the receiver (for example, with the addition of a single ground reflection), the channel impulse response would be the sum of the effect of the two paths:

$$h(t) = A_1\delta(t - \tau_1)\exp(-j\theta_1) + A_2\delta(t - \tau_2)\exp(-j\theta_2) \quad (3)$$

This is the impulse response of the so-called "two-ray" channel model. If we have N possible transmission paths, $h(t)$ becomes:

$$h(t) = \sum_{n=1}^N A_n \delta(t - \tau_n) \exp(-j\theta_n) \quad (4)$$

This is the channel impulse response to the receiver at a particular coordinate point in space $p_2(x_2, y_2, z_2)$ from the transmitter located at some other coordinate point $p_1(x_1, y_1, z_1)$. The more general impulse response as a function of this geometry can thus be written as:

$$h(t, p_1, p_2) = \sum_{n=1}^{N(p_1, p_2)} A_n(p_1, p_2) \delta(t - \tau_n(p_1, p_2)) \exp(-j\theta_n(p_1, p_2)) \quad (5)$$

where the number, amplitude, phase and time delay of the components of the summation are a function of the location of the transmit and receive antenna points in the propagation space.

The channel impulse response given by (5) is for a single static point in space. For mobile communication, the receiver is often moving and that motion can affect the phase relationship of the components of (5) in a way which may be important to digital data being transmitted over the

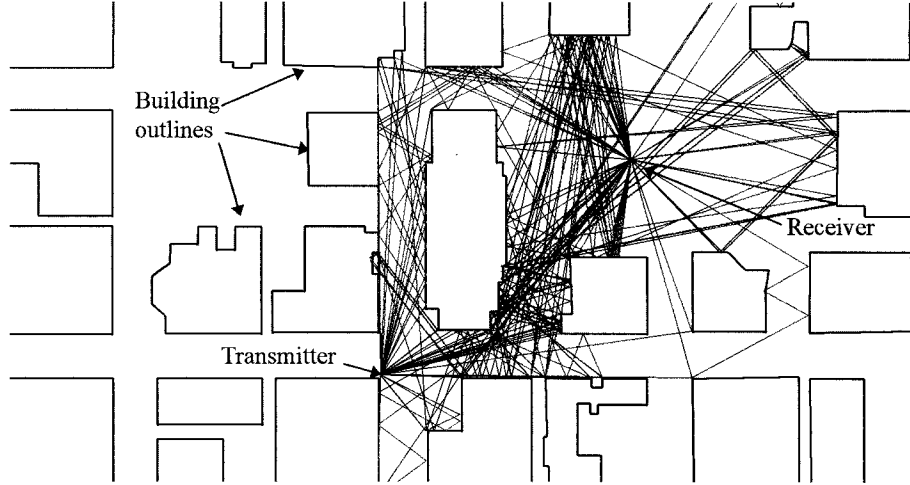


Fig. 8. Ray-tracing study in an urban area.

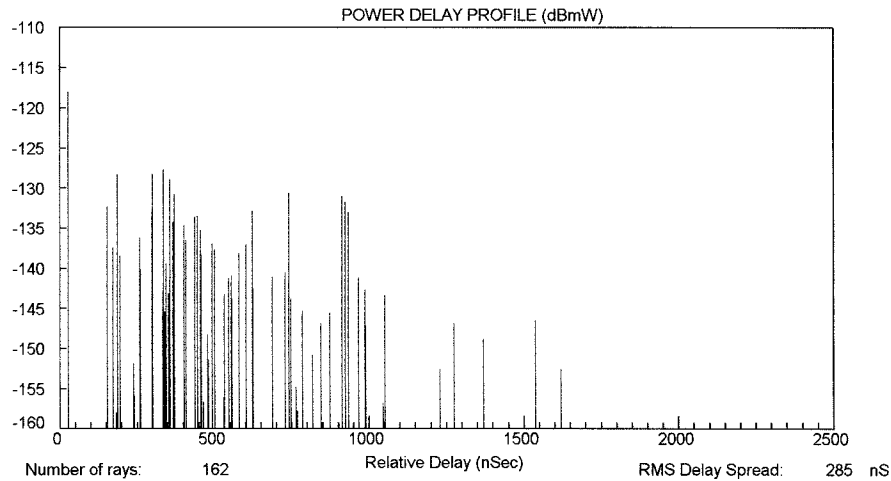


Fig. 9. Channel impulse response for propagation channel in Figure 8.

channel. This motion will result in a frequency or Doppler shift of the received signal which will be a function of speed and direction of motion, and the angle of arrival of the signal energy. Equation (5) can be modified to include Doppler shift and thus account for this motion as follows:

$$h(t, p_1, p_2) = \sum_{n=1}^{N(p_1, p_2)} A_n(p_1, p_2) \delta(t - \tau_n(p_1, p_2)) \exp(-j\theta_n(p_1, p_2) + \Delta\theta_n(p_1, p_2)) \quad (6)$$

where $\Delta\theta_n$ is a phase displacement due to the motion. It should be kept in mind that this is motion of either the transmitter or receiver *relative to every other element in the propagation environment*. The transmitter or receiver may be fixed, but a signal from a moving reflection source (such as a moving

bus) may resulting in a non-zero $\Delta\theta_n$ for a particular component of (6). For a mobile receiver, $\Delta\theta_n = (2\pi vt / \lambda) \cos(\varphi_n - \varphi_v)$ where φ_n is the arrival angle of the n^{th} ray component, v is the speed of motion, φ_v is the direction of motion, and λ is the wavelength³.

In general, the amplitudes A_n and phase shifts θ_n , will be functions of the carrier frequency ω because they are controlled by the interaction of the transmitted energy with the features of the propagation environment. Inserting the frequency dependence into equation (5) gives:

$$h(t, p_1, p_2, \omega) = \sum_{n=1}^{N(p_1, p_2)} A_n(p_1, p_2, \omega) \delta(t - \tau_n(p_1, p_2)) \exp(-j\theta_n(p_1, p_2, \omega)) \quad (7)$$

We can now apply this approach to a practical situation. Figure 8 shows an overhead drawing of a downtown area with several buildings. The multiple rays from the transmitter to the receiver are shown reflecting and diffracting off the buildings. A detailed description of the methods involved in such “ray-tracing” can be found in [6]. If we were to plot the channel filter impulse response for this case as given by equation (7) we would have the graph shown in Figure 9. This comprehensive description of the propagation channel filter (often called a power delay profile) includes not only path loss information but several other characteristics of the propagation channel. Now that we have the filter response, how do we use it to predict coverage or performance in a digital system?

5. Digital Errors due to Multipath Propagation

Errors in a digital system occur when the receiver mistakenly interprets a 0 for a 1 or vice versa. The receiver needs to make a decision about which value it has received. If the only signal the receiver has to work with is a perfect replica of the transmitted signal, it could make this decision flawlessly every time and there would be no errors. But it doesn't have a perfect replica to work with. First, and most common, there is noise introduced by the receiver and perhaps external sources. As we've determined from equation (7) and Figure 8, there are also a lot of other signals arriving at the receiver which can confuse the detection process and cause an error. The effect of noise on the error rate

³ The ray angle of arrival and the direction of mobile motion can both be interpreted here as azimuth angles relative to True North.

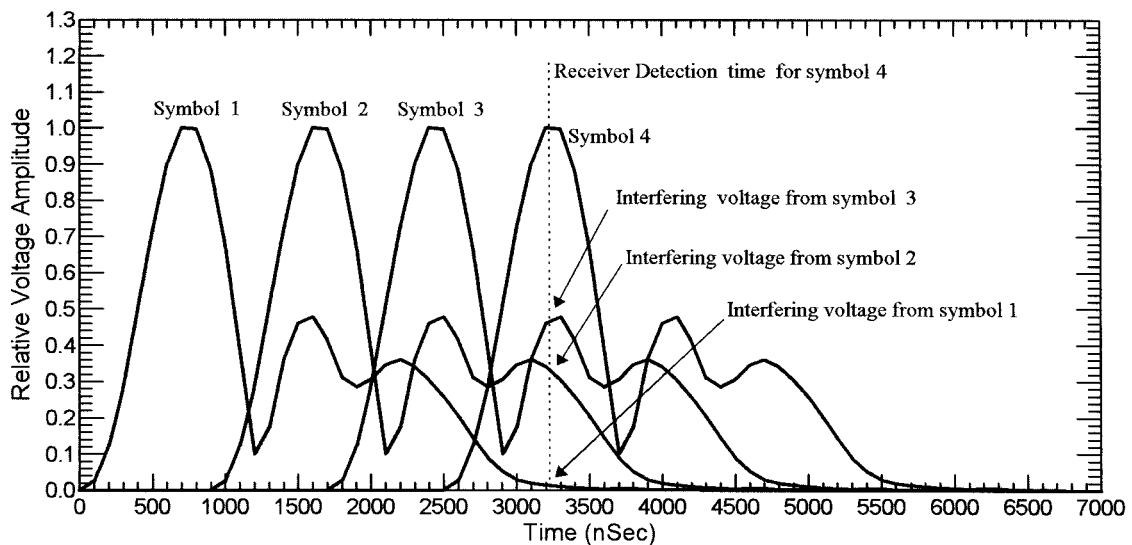


Fig. 10. Inter-symbol interference in transmitted symbol 4 due to previously-transmitted pulse.

performance is well known and exhaustively treated in communication engineering textbooks. We will thus focus on the errors due to the multipath signals.

Let's say we want to transmit a series of digital pulses or symbols over a propagation channel like that shown in Figure 9. We will assume our digital pulse as been smoothed off with a filter at the transmitter so it uses less bandwidth. When it gets to the receiver it looks like the first pulse waveform in Figure 10. There is a strong peak in the signal which comes from the strongest ray arriving at the receiver, but there are also other peaks in the signal due to reflected signals arriving at some later time.

Now what happens we send a second pulse, and a third and a fourth? As Figure 10 shows, when the receiver tries to detect the fourth pulse, the decision is corrupted by reflected energy from pulses transmitted earlier. This is known as inter-symbol interference (ISI). For a given data rate and propagation channel response, it can result in error rates which make the signal totally unusable even if the average signal power is more than adequate to overcome errors due to receiver noise. You could raise your transmitter power to 10 Megawatts and your received data would still be full of errors!

Because increasing transmitter power doesn't reduce these errors, the unfortunate misnomer describing them as "irreducible errors" is sometimes used. In fact, using various techniques in the receiver such as channel equalizers, many multipath-related effects can be reduced before the signal reaches the decision making process. A common example is the European digital cellular system called GSM which has a data rate of about 270 kbps and uses an equalizer in the handset to improve performance in multipath conditions. Even more sophisticated are the handsets for CDMA cellular

systems which use so-called RAKE receivers where the multipath energy is actually *constructively combined* to improve overall fading performance. On the other end of the scale is a European short range telephone technology called DECT which has a data rate of 1 Mbps but uses no equalizer. DECT systems are known for having performance problems in multipath urban areas even when the signal strength at the receiver is well above the level needed for acceptable error rates if only noise were present.

An approach to explicitly calculating error rates for this type of intersymbol interference can be found in [7], however, it requires detailed knowledge of the multipath components. For this reason, some simplified ways of describing the degree of multipath in the channel have been devised. One of the most common is RMS delay spread. The RMS delay spread, σ_τ , is a statistical measure of the amount of time dispersion or spreading found in the multipath signal. Formally, it is calculated as the second central moment of a power delay profile such as that illustrated to Figure 8.

The RMS delay spread, σ_τ , is calculated as follows:

$$\sigma_\tau = \left[\sum_{n=1}^N (\tau_n - \bar{\tau})^2 p(\tau_n) \right]^{\frac{1}{2}} \quad (8)$$

where the mean value of the power delay profile is

$$\bar{\tau} = \sum_{n=1}^N (\tau_n) p(\tau_n) \quad (9)$$

and

$$p(\tau_n) = \frac{A_n^2}{\sum_{n=1}^N A_n^2} \quad (10)$$

A_n is the amplitude of ray n , τ_n is the time delay to ray n , and N is the total number of rays.

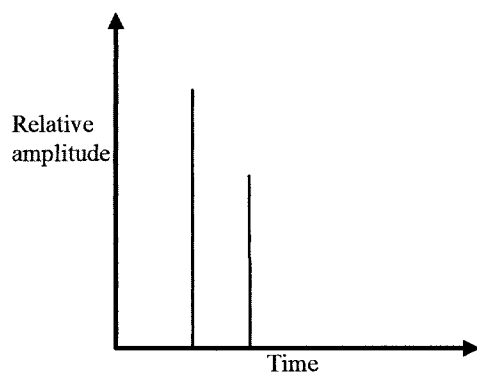


Fig. 11.

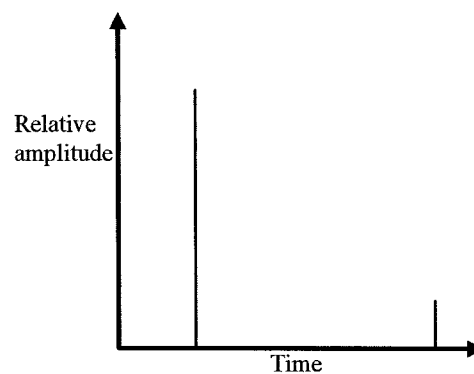


Fig. 12.

Using a single number like RMS delay spread to find error rates is often misleading because the statistical averaging process glosses over important details about when the multipath energy arrives and what its magnitude and phase are. These factors are treated in [7], but cannot be addressed looking at RMS delay spread alone. As an example, Figures 11 and 12 show two simple power delay profiles with two rays each. One has a strong echo delayed a short period of time after the main signal; the other has a much weaker multipath echo delayed a much longer period of time. Both channel responses will have exactly the same RMS delay spread value, but by using the comprehensive analysis in [7] it can be shown that the channel in Figure 11 will produce a high error rate dominated by multipath while the channel in Figure 12 will have a much lower error rate controlled primarily by noise. For this reason, convenient measures of channel time dispersion like RMS delay spread should be used with caution and recognized for the significant approximations they represent.

As mentioned above, the data rate is important in determining whether multipath will cause errors. Reviewing Figure 10, if we envisioned a lower data rate (much greater pulse width), then all of the multipath signals would have come and gone before the decision time for the next pulse and no errors would occur due to multipath. Depending on the data rate and the time delays for the multipath, there may or may not be errors due to this effect. For reflections along city streets multipath delays on the order of several hundred nanoseconds may occur. With longer range systems reflection paths from mountains may result in path delays of several microseconds. Indoor wireless systems where multipath comes from reflections off relatively closely-spaced interior walls, delay times on the order to 10 to 100 nanoseconds are found. Using RMS delay spread (a quantity in time), a common rule-of-thumb says that if the RMS delay spread is greater than 1/5th the time between the digital symbols or pulses, then errors due to multipath may be significant if no equalizer or other correction device is used in the receiver.

6. Digital Errors Due to Random FM or Doppler Shift

Again referring to Figure 10, if we envision even lower data rates where all multipath reflections have died out you might think that no errors would be introduced in the system due to the propagation channel filter. If the receiver is stationary (and the propagation environment is unchanging), that's true. But if the receiver is moving another kind of error can occur which actually gets worse as the data rate is *lowered*.

Errors due to random FM arise in narrowband transmissions due to the phase shift of the carrier from one symbol to the next. If the data transmission rate is high, the amount of phase change which is possible from one symbol to the next, even with high mobile speeds, is still very small so that errors due to random FM are not important compared to errors from amplitude fading in noise and errors due to inter-symbol interference. For coherent detection, depending on the receiver carrier reference recovery techniques, the random phase changes can be tracked so that errors due to random FM are minimized or reduced to zero. Random FM errors are therefore of primary concern for mobile systems with relatively low data rates which employ differential modulation and detection techniques.

The usual analysis of random FM errors assumes that the signal is arriving from a single direction and the mobile is moving in a direction φ relative to the arrival angle of the signal. Under these conditions, the Doppler frequency f_d (frequency shift) for a given mobile speed is:

$$f_d = \frac{v}{\lambda} \cos\varphi \quad (9)$$

where v is the speed of the mobile in meters per second. In determining error rates, the traditional assumption is that the worst case Doppler frequency, $f_d = v / \lambda$ occurs and leads to a error rate which will depend on the modulation type. In a complex environment with energy arriving from many different directions as illustrated in Figure 8, the rate of phase change, and hence frequency deviation, can vary considerably. In fact, a phase change of 180° can occur in deep fades over an arbitrarily short distance increment resulting in a finite probability of infinite frequency deviation[8].

Rather than make the assumption about random FM deviation, the site-specific physical ray-tracing channel model provides detailed information about the arrival angles of signals at the mobile unit. The specific nature of the phase shift may be estimated and used to find f_d . To simplify the analysis, an average value of f_d can be found and use in a similar way as RMS delay spread to estimate

when errors due to random FM become important. For this purpose the term $f_d T_s$ is used where T_s is the duration of the transmitted symbol. The term $f_d T_s$ is an angle error and has the units of cycles. For example, an $f_d T_s$ of 0.1 represents a phase error introduced by the channel of 36 degrees.

When considered together with the errors due to inter-symbol interference, the overall error rate picture looks something the drawing in Figure 13. For a given signal-to-noise ratio, modulation type, propagation channel, and mobile speed, as data rate increases errors increase due to ISI. As the data rate decreases, errors increase due to random FM. In between, the error rate is largely a function of noise.

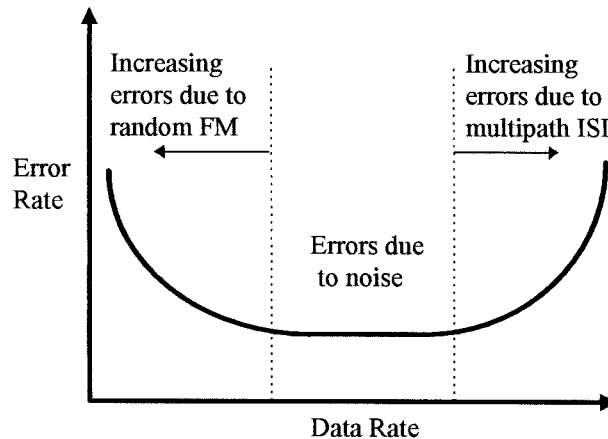


Fig. 13. Error rate trends for digital mobile systems with propagation channel multipath and random FM effects.

7. Conclusions

The contrast between empirical measurement-based models and physical propagation models for predicting the coverage of digital mobile systems has been presented. While empirical models are simple, they don't explicitly take into account many important elements of the propagation environment, and don't currently include information about channel delay spread or random FM which are important to predicting error rates in many kinds of digital systems.

Physical propagation models in the form of ray-tracing offer a means of acquiring the necessary propagation information for predicting the performance of digital systems in any given environment. However, to make predictions, physical models rely on detailed descriptions of the environment and require relatively intensive calculations. Ever increasing computer processor power and storage space for data make the calculations required by physical models less burdensome. Physical modeling such as ray-tracing therefore offers the best way forward for predicting coverage and error rate performance in current and future digital systems.

The digital system performance results presented here have generally assumed that no techniques are used in the receiver or system to combat the linear distortions caused by the propagation channel. With modern receiver design and the increasing economic feasibility of using sophisticated DSP chips in handsets, long-known techniques for countering channel impairments can now be widely employed. Nevertheless, it will remain important to model the channel accurately to gain insight into the magnitude of channel impairments which must be addressed by hardware and system designs, and to assess the overall efficacy of those designs.

8. References

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