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Title Page Sample (not to actual size)

Top margin: $^1/_2$"

Center the title, initial caps, across the entire image area.

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8 $^1/_2$"x11" page

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Charts, equations, diagrams, pictures placed within copy flow, along with captions.

Keep text and graphics within a print area of 7 $^1/_2$" wide by 9 $^1/_2$" high

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Propagation Measurements and Models for Wireless Communications Channels

Jørgen Bach Andersen
Aalborg University and the Center for Personkommunikation
Theodore S. Rappaport
Virginia Tech.
Susumu Yoshida
Kyoto University

ABSTRACT: Wireless personal communications could in principle use several physical media, ranging from sound to radio to light. Since we want to overcome the limitations of acoustical communications, we shall concentrate on propagation of electromagnetic waves in the frequency range from some hundreds of MHz to a few GHz. Although there is considerable interest at the moment in millimeter wave communications in indoor environments, they will be mentioned only briefly in this survey of propagation of signals.

Propagation Results Influence Personal Communications

It is interesting to observe that propagation results influence personal communications systems in several ways. First there is obviously the distribution of mean power over a certain area or volume of interest, which is the basic requirement for reliable communications. The energy should be sufficient for the link in question, but not too strong, in order not to create cochannel interference at a distance in another cell. Also, since the radio link is highly variable over short distances, not only the mean power is significant; the statistical distribution is also important. This is especially true when the fading distribution is dependent on the bandwidth of the signal. Secondly, even if there is sufficient power available for communications, the quality of the signal may be such that large errors occur anyway. This results from rapid movement through the scattering environment, or impairments due to long echoes leading to inter-symbol-interference. A basic understanding of the channel is important for finding modulation and coding schemes that improve the channel, for designing equalizers or, if this is not possible, for deploying base station antennas in such a way that the detrimental effects are less likely to occur.

In this article we will describe the type of signals that occur in various environments and the modeling of the propagation parameters. Models are essentially of two classes. The first class consists of parametric statistical models that on average describe the phenomenon within a given error. They are simple to use, but relatively

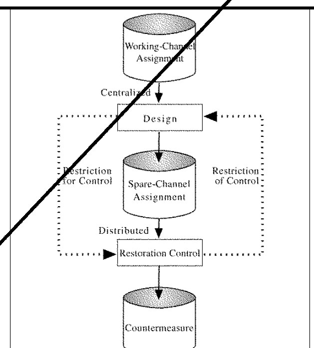

Figure 5-3 Cooperation between Control and Design

coarse. In the last few years a second class of environment-specific models has been introduced. These models are of a more deterministic nature, characterizing a specific street, building, etc. They are necessarily more time consuming to use, but are also more revealing concerning physical details and hopefully more accurate.

First some key parameters and the measurement of them will be discussed and then the different wireless environments will be treated. The latter topic is divided here into outdoor environments, indoor environments, and radio penetration from outdoor to indoor environments.

The Physics of Propagation

The mechanisms which govern radio propagation are complex and diverse, and they can generally be attributed to three basic propagation mechanisms: reflection, diffraction, and scattering.

Reflection occurs when a propagating electromagnetic wave impinges upon an obstruction with dimensions very large compared to the wavelength of the radio wave. Reflections from the surface of the earth and from buildings produce reflected waves that may interfere constructively or destructively at a receiver.

Diffraction occurs when the radio path between the transmitter and receiver is obstructed by an impenetrable body. Based on Huygen's principle, secondary waves are formed behind the obstructing body even though there is no line-of-sight (LOS) between the transmitter and receiver. Diffraction explains how radio frequency (RF) energy can travel in urban and rural environments without a LOS path. This phenomenon is also called "shadowing," because the diffracted field can reach a receiver even when it is shadowed by an obstruction.

Scattering occurs when the radio channel contains objects with dimensions that are on the order of the wavelength or less of the propagating wave. Scattering, which follows the same physical principles as diffraction, causes energy from a transmitter to be reradiated in many different directions. It has proven to be the most difficult of the three propagation mechanisms to predict in emerging wireless personal communication systems. For example, in urban microcellular systems, lamp posts and street signs scatter energy in many directions, thereby providing RF coverage to locations which might not receive energy via reflection or diffraction. The three mechanisms are illustrated in Fig. 1.

As a mobile radio moves throughout a coverage area, the three propagation mechanisms have an impact on the instantaneous received signal in different ways. For example, if the mobile has a clear LOS path to the base station, diffraction and scattering are not likely to dominate the propagation. Likewise, if the mobile is at street level in a large metropolitan area without a LOS to the base station, diffraction and scattering are most likely to dominate the propagation. As the mobile moves over small distances, the instantaneous received narrowband signal strength will fluctuate rapidly giving rise to small-scale fading. The reason for this is that the field is a sum of many contributions coming from different directions and since the phases are random, the sum behaves as a noise signal, i.e. Rayleigh fading. In small-scale fading, the received signal power may vary by as much as three or four orders of magnitude (30 or 40 dB) when the receiver is moved by only a fraction of a wavelength. As the mobile moves away from the transmitter over larger distances, the local average received signal will gradually decrease. Typically, the local average signal is computed over receiver movements of 5 to 40 wavelengths [1, 2, 3]. Figure 2 demonstrates the effects of small-scale fading and large scale signal variation for an indoor radio communication system. Notice in

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