TOWARD A PROPER MODEL OF THE PORTABLE INDOOR MICROWAVE CHANNEL

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SUMMARY

Certain common assumptions and practices developed for modeling outdoor mobile and fixed microwave channels are fundamentally incorrect if applied to wideband, microwave channels indoors or in urban areas. This paper explains the problems and lists requirements for channel models for radio LANs which support portable terminals. Specific modeling techniques are recommended. The paper concludes with some observations concerning real-time channel simulators.

INTRODUCTION

Among other things, an RF channel model is a concise statement of opinion. Since the classical laws of electromagnetic wave propagation were described by Maxwell in 1873, one might think sufficient time has passed for opinions to have converged to near-perfect unanimity. Such is not the case, of course.

While they presumably agree on the basic physics, engineers often find themselves at odds on almost everything else, especially the validity of the various approximations which are necessary to make computations feasible. It is all too easy to casually violate some obscure assumption which underlies a familiar formula.

The next section is a brief, very loose review of certain basic concepts; it is intended merely to remind the reader (especially the reader who has not recently thought about channel models and multipath) and set a stage for what follows.

BASICS

A variable may be viewed as random until one learns underlying principles which allow its precise prediction and, thereafter, may be viewed as deterministic. Discrepancies between predictions and measurements may be attributed to additional random variables (noises).

One of the mathematical entities often used to (partially) characterize scalar random variables is the amplitude probability density. Loosely speaking, it specifies how likely the variable is to assume any particular value available to it. It says nothing about time behavior. That is, it says nothing about how long the variable lingers near a particular value it has assumed, nor whether it jumps discontinuously from one value to the next, etc.

The most common tools for characterizing the time behavior of random variables are correlation functions or, equivalently, power spectra. Crosscorrelation functions specify the degree to which the values assumed by one variable depend on those assumed by another variable, i.e., their tendancy to affect each other.

These tools are statistical quantities, i.e., they involve ensemble averages. An ensemble average is an average over all possibilities, weighted by their probabilities. In nonstationary cases, these probabilities are time dependent. Both stationary and nonstationary random variables can be functions of time or space or both. Moving a measuring device through a static field produces a time varying measurement.

In applications like long-distance point-to-point microwave links, atmospheric refraction can bend radio waves so as to produce a more-or-less continuous range of arrival times at the receiver. Multipath can also result from reflection from solid objects like building walls or the ground. In the first case the scatterer is air and it is appropriate to view the multipath as randomly fluctuating in time and to characterize it probabilistically. In the second case the scatterer is solid and the multipath may be better viewed as static and deterministic.

Echoes, almost by definition, are highly correlated, in both time and space, with each other and with the original signal.

Adaptive radios adjust themselves over time to account for changes in their environments. The adjustment may consist of switching to a new antenna, new coefficients for an equalizer (echo canceller) or beam former, etc. Typically, some delay appears between the environmental change and the corresponding adjustment; the faster a radio adapts the better. Adaptation typically requires some sort of computation.

In the old days, mobile radios did not adapt. It was not practical to include computers as components of mobile equipment. Computers were much bigger than mobile radios. The problem of interest was to design radio systems which tolerated typical multipath as gracefully as possible rather than systems which recognized and adapted to specific situations. Thus arose the question, "What is typical multipath and how shall it be simulated to support design of nonadaptive mobile radio systems"?

In references one and two, and, in fact, in most of the channel modeling literature, the channel offered as typical and relevant is a spatially averaged one. The spatial averages appear in the guise of ensemble averages; the ensemble of possibilities is the ensemble of all locations. As Clarke puts it,

> "The angular brackets denote "the average of" the quantity they enclose, and in this case may be thought of as an ensemble average over all the situations implied by the assumed statistics of [the phases and angles of arrival of the incoming plane waves]."[1]

The angles are assumed uniform on [0,2pi) which is true only for spatial averages. At first this seems ideal --- after all, mobile radios should work in as many locations as possible. However, an effect of this spatial averaging is to decorrelate quantities depending on the angles. This hides the detailed local structure of standing wave patterns --- structure that adaptive mobile radios exploit.

Consider, for example, the simple case of a stationary transmitter and receiver and a single, solid reflector somewhere in (otherwise) free space. The angles of arrival of the line-of-sight (direct) ray and the reflected ray have fixed, definite values, as does their phase difference. The channel impulse response is static. If we smoothly move the receiver to a new location, then the channel smoothly changes in an easily calculable and measurable way. While the transmitter remains fixed, we may take the viewpoint that a static field of impulse responses is being sampled by our moving receiver. These impulse responses are all related; they are all determined by the arrangement of the transmitter and reflector. If the transmitter moves, the impulse responses all change together in a systematic, predictable way: the field of channels is correlated in space and time. Returning to previous positions reproduces previously observed channels because the scatterer is solid.

Averaging together the complex channel impulse responses at many different locations generally gives a zero result. Averaging their magnitudes gives a nonzero result (a spatially averaged power delay profile), but is it typical in any meaningful way? Since radios must always be in one place at a time, no radio can ever experience a spatially averaged channel. Only by coincidence will a spatially averaged power delay profile resemble one which applies at any definite location, even one of the locations being averaged. A nonadaptive radio optimized against such an average could, conceivably, perform poorly against the individual channels. What is much worse is that use of simulators derived via inappropriate spatial averaging deprives adaptive radios of the correlations they need to function.

INDOOR MICROWAVE CHANNELS

In an urban environment, the main distinction between indoors and outdoors is the presence or absence of a ceiling. Urban terrain tends to be planiform, i.e., composed of planes. Walls, floors, sidewalks, etc. --- planes are characteristic of man-made structures. Man also has a strong tendency to smooth the planes and to arrange them orthogonally. To a centimeter or millimeter wave, a typical drywall surface appears as does a large, polished, partially-silvered mirror to light.

Reflection, then, tends to be an efficient deliverer of radio power over substantial distances within microcells --- distances over which power scattered in more dispersive ways may decline to insignificance. Consequently, indoor, high frequency channel impulse responses and power delay profiles tend to have dominant spikes representing discrete reflections. These spikes appear over a continuous component which is due to nonspecular scattering.

Since urban surfaces are like flat mirrors to millimeter waves, we can speak of reflected images of sources: there is a one-to-one correspondence between the images seen by a receiver and the incoming (quasi-) plane waves or echoes which impinge on its antennas. These plane waves cause the spikes in the channel impulse response (and correspond one-to-one with them). The plane waves create a standing wave pattern of troughs and peaks in space. If the transmitter and the reflectors are stationary, then so is the standing wave pattern. As explained above, we should not view such a pattern as structureless --- it has information which can be exploited.

Some important concepts about high frequency indoor or urban multipath are illustrated by an optical analogy. Suppose you are somewhere within a building whose walls and floors are made of glass. Each wall or floor partially transmits and partially (specularly) reflects incident rays (quasi-plane waves). Both transmission and reflection involve some attenuation.

Somewhere else in the building, someone lights a match. You see many images of the match: each image is generated by reflections from certain surfaces and transmissions through others. The number of images above some threshold brightness is finite and remains constant as you execute small motions of your head. If you move your head far enough, at least one of the bright images will disappear as it moves beyond an edge of some reflector, or a new image will appear at an edge. In this way, you can map out the boundaries of your current image-set domain. An image-set domain is the volume in which a certain set of images can be seen, i.e., certain plane waves are incident upon the receiver. For each frequency, the standing wave pattern within a domain is a three-dimensional fabric woven by the phasors which represent the amplitudes and delays of the plane waves.

Indoor microwave impulse response magnitudes tend to have spikes (quasi-plane waves from particular large reflectors) above a more-or-less continuous component which is due to general scattering and a multitude of weak images. Of course, individual scatterers contribute to the channel impulse response according to the power they redirect into the receiver's antenna; scatterers far from directional beams can be ignored.

REQUIREMENTS FOR WIDEBAND INDOOR CHANNEL SIMULATORS IN THE CENTIMETER AND MILLIMETER WAVEBANDS

The discussion above leads to the following explicit requirements. It seems inescapable that indoor simulators be time-dependent and that simulation runs last long enough to test candidate designs against all the situations of interest.

1 They must preserve the space- and time-correlated nature of indoor multipath.

2 They must realistically simulate the effects of pedestrian-like motions indoors, including random translational and rotational accelerations. In particular, the phases and amplitudes of the major echoes (the tall spikes) must change together to realistically represent the motion. Image set domains must be respected, e.g., images must appear and disappear appropriately.

3 They must be able to serve multiple antenna designs, i.e., simultaneously simulate several suitably correlated channels and accept antenna pattern specifications.

4 Despite 1 and 2 above, the simulators must express characteristics typical of a range of buildings, rather than enshrine a single example.

SIMULATOR TECHNOLOGY

There are many existing software simulation systems which might be augmented and utilized. For example, reference three puts forth a detailed formalism which could be extended to meet the requirements above. A suitable simulator capable of exercising real radios in real time might be constructed with programmable filters using ACT/SAW (acoustic charge transfer/surface acoustic wave) devices [4].

REFERENCES

[1] R. H. Clarke, "A Statistical Theory of Mobile-Radio Reception," Bell System Tech. Jour., pp957-1000, July-August 1968.

[2] W. C. Jakes Jr., ed., "Microwave Mobile Communications", John Wiley & Sons, New York, 1974.

[3] S. C. Seidel and T. S. Rappaport, "Simulation of UHF Indoor Radio Channels for Open-Plan Building Environments", IEEE 40th Vehicular Technology Conference, pp. 597-602, 1990.

[4] An information packet of commercial and technical literature on programmable F.I.R. filters using ACT/SAW technology and their use as equalizers is available from Electronic Decisions Incorporated, 1776 East Washington Street, Urbana, Il, 61801; telephone 1-217-367-2600.

ADAPTIVE RADIOS AND CHANNEL ENSEMBLES

* We must design to an average over an ensemble of channels

* In the old days, radios just endured multipath and designers worked against spatially averaged channels

* Radios are always somewhere in particular --- they never see a spatially averaged channel

* Tiny computers can now be inserted in portable radios to make them adaptive to particular locations

* $\langle f(x) \rangle$ is generally not the same as $f(\langle x \rangle)$: you should not design an adaptive radio system against spatially averaged channels

* Spatial averaging decorrelates discrete echo phases

* In reality, discrete echoes are highly correlated in both time and space --- equalizers can exploit these facts

THE HIGH FREQUENCY URBAN OR INDOOR MICROCELLULAR RADIO CHANNEL

* Urban and indoor environments are planiform

* Walls smoother than a quarter wavelength are (partial) mirrors and create images

* Channel impulse response magnitudes are spiky due to discrete echos (quasi-plane waves)

* Receivers are generally embedded in a frequency-dependent standing wave pattern

* Multipath, discrete reflections, standing wave patterns, spiky channels, images, multiple incoming plane waves --- all these describe the same phenomenon: echoes from planar surfaces

THE OPTICAL ANALOGY

* If you are in a glass house and

* A match is lit in another room, then

* You see a finite number of images above some threshold brightness

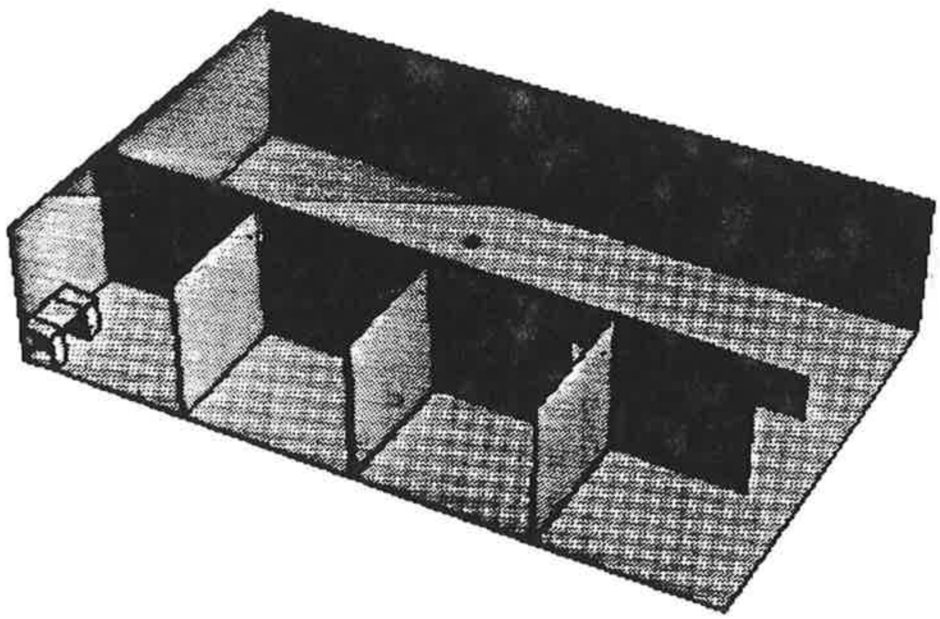
* You are in an Image Set Domain (ISD)

* The number of images remains constant as you move your head through small motions

* Loosing or gaining an image at a mirror edge defines the boundaries of your current image set domain

* High frequency microcells are composed of image set domains and they are generally rather large compared to a wavelength

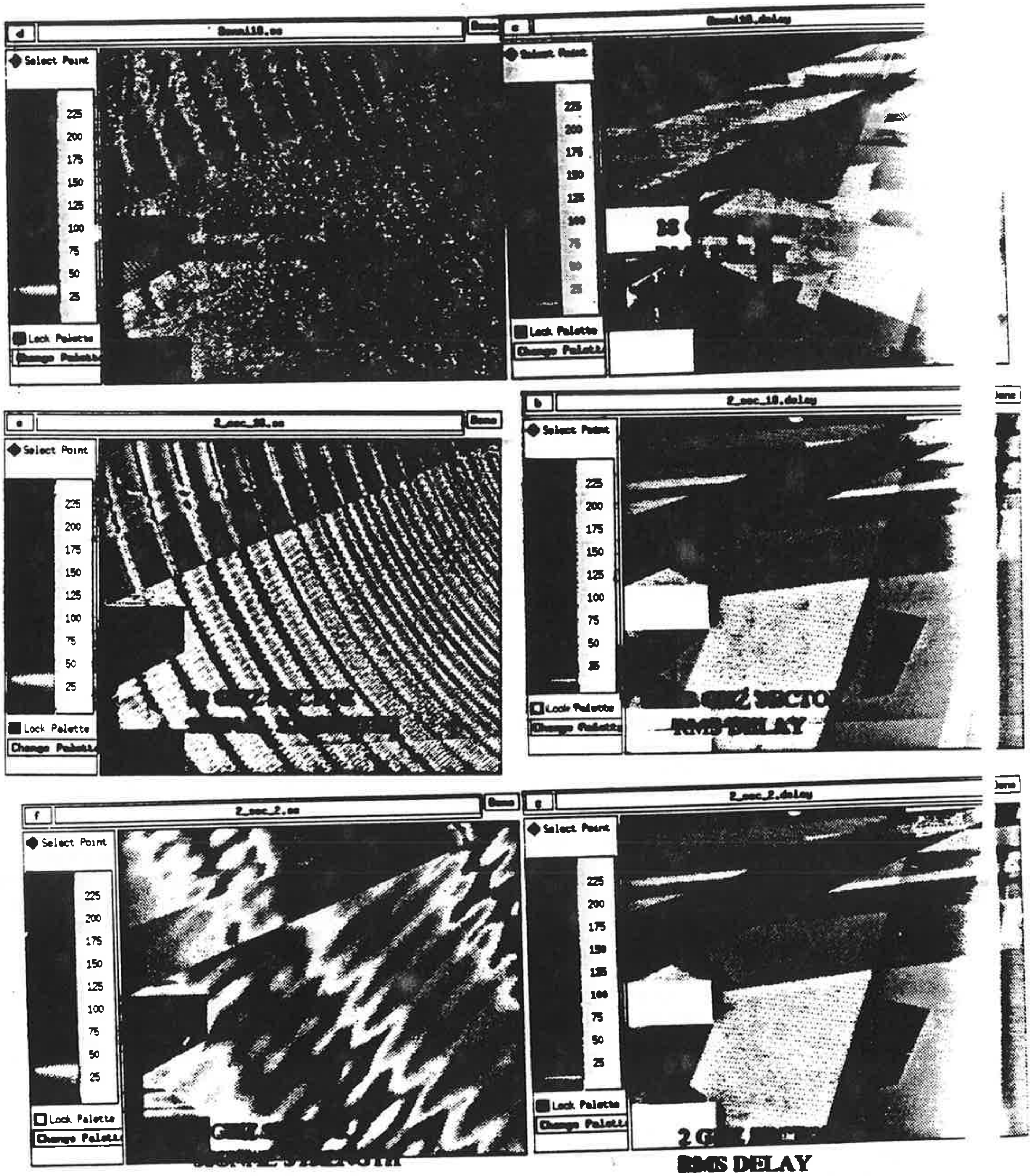
* Within an image set domain, the standing wave pattern is quite regular; a sort of 3-D fabric



18 GHZ OMNI

18 GHZ SECTORIZED

2 GHZ SECTORIZED



SIGNAL STRENGTH

RMS DELAY SPREAD