REAL TIME CHARACTERISATION OF THE MOBILE MULTIPATH CHANNEL

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ABSTRACT

This paper introduces the concept of characterisation of the mobile multipath channel in real time, using a model of the channel based on processes which vary more slowly than the channel itself. A key application of the concept is channel prediction. Some of the key constraints on the range of accurate channel prediction are presented. In particular, the number of paths comprising the multipath, the proximity of scatterers to the mobile, and the effects of rough surface scattering are discussed.

INTRODUCTION

The Real Time Characterisation Concept

The presence of multiple path propagation between a transmitter and a receiver is a principal cause of unreliability of digital mobile radio systems. In particular, the mobile nature of the receiver, transmitter and other objects in the environment causes the channel characteristics to change continually.

The usual approach in designing systems to operate over fading channels has been simply to allow a large fade-margin when calculating the power budget. Although simple, this technique however produces far more interference than is necessary, with consequent inefficiencies in channel re-use, reduces the running time of battery operated mobile transmitters, and results in higher levels of electromagnetic radiation exposure to users. Another approach is to introduce diversity into the system, in either time, frequency, space or polarisation. If the receiver can be supplied with several replicas (or a redundant coding) of the information signal transmitted over independently fading channels, the probability that all the signal components fade simultaneously is reduced considerably.

This paper discusses a different approach to the problem of fading channels based on characterisation of the channel *in real time*. Such a characterisation is based on recognition of the fact that while the fading which is characteristic of the mobile radio channel is very rapid, the processes underlying this fading may vary much more slowly. These processes can be used to construct a model with slowly varying parameters.

There are two main applications for such a characterisation. The first application is in channel prediction. The second application, improved channel adaptation, is not discussed here.

Channel Prediction

If the behaviour of the channel is known, the performance of a system using the channel can be optimised for the particular conditions being experienced at that instant. This optimisation may take the form of change in transmission timing, frequency, power level, modulation type, and coding, as well as some implementations of Multiple Input, Multiple Output (MIMO) systems.

Many such schemes have been proposed, but the difficulty of obtaining *up to date* channel information at the transmitter in the case of a time varying channel does not appear to have been adequately addressed in the literature. If the channel is changing the channel state information available to the transmitter will be outdated, unless the channel behaviour can be predicted a short time in advance of the behaviour actually occurring. Such channel prediction was first proposed in [1], but has been presented by several researchers, including [2] and [3].

Real time channel characterisation can enable such prediction. Samples of the channel information are acquired as the mobile moves through its spatial trajectory. These samples can be used to estimate the parameters of the model. If the model has been chosen appropriately, and the parameters vary more slowly than the channel itself, then they can be used to extrapolate the channel behaviour beyond the region of the measurements.

Content of this Paper

In this paper, a simple model is presented, and used as a basis for identifying the factors which limit reliable channel prediction. This paper reports only the results of these investigations. For detailed derivations, the reader is referred to [4]. Significant limitations which are not discussed here, include the effects of scatterer extent, and macroscopic changes in the scattering environment, such as shadowing. These are discussed briefly in [2].

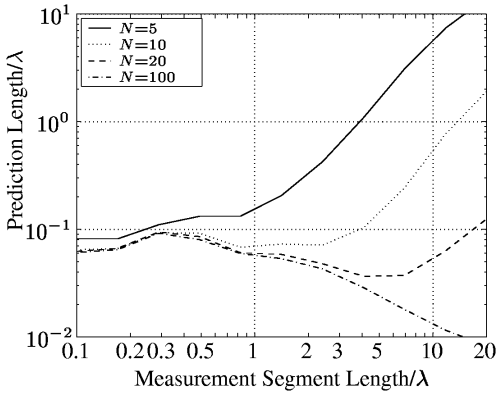


Figure 1: Prediction Performance versus Measurement Segment Length using a subspace method (PCLP) for different numbers N of far-field sources.

CHANNEL MODELS

A very commonly used baseband multi-ray propagation model for specular multipath is

$$r(t) = \sum_{n=1}^{N} \zeta_n(t) s(t - \tau_n(t)) e^{-j\omega_c t} + \eta(t), \tag{1}$$

where N is the number of propagation paths, $s(t)$ and $r(t)$ are the transmitted and received signals respectively, ω_c is the carrier frequency, $\zeta_n(t)$ and $\tau_n(t)$ are the gain and delay associated with the n-th propagation path, and $\eta(t)$ is a noise process. This model is here used as a basis for exploring the critical factors which limit the viable range of channel prediction. It should first be noted that despite the utility of this model, it incorporates the significant assumption that the multipath is specular, and that there are a finite number N of propagation paths.

Narrowband Far-field Model

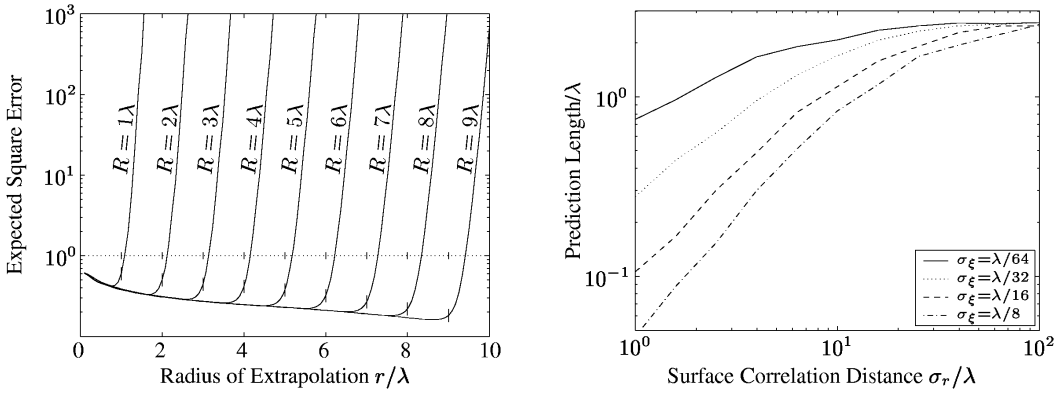
There are further simplifying assumptions which are frequently made to this model. If the channel is narrowband, the delay $\tau_n(t)$ is only detectable as a change in the *phase* of the signal. The delay $\tau_n(t)$ can be expressed as a *relative* delay, via a Doppler frequency $\varpi_n = vk \sin\theta_n$ where v is the mobile travel speed, k is the wave number of the carrier, and θ_n is the angle between the normal to the direction of travel, and the direction of propagation of the n-th path. If the nearest scatterer is distant from the mobile, and the mobile is not accelerating, then both $\varpi_n(t)$ and $\zeta(t)$ do not change rapidly with time, and it so a model has been constructed for which the parameters do not vary rapidly, thus allowing channel prediction.Using discrete samples, the channel model may be expressed as

$$h_m = \sum_{n=1}^{N} \zeta_n e^{jm\varpi_n} + \eta_m, \tag{2}$$

a form which allows reliable parameter estimation using subspace methods of spectral estimation. One of the implications of the Wold decomposition theorem [5] is that this model is equivalent to an auto-regressive (AR) model. Investigating the validity of the assumptions used to derive this model, using analysis, simulation and measurement, leads to some valuable insights into the feasibility of channel prediction. Presented here are the key findings from these investigations. The methods used are detailed in [4].

Predictability Criteria

Once the parameters of the model have been estimated (from data measured in what is here called the *measurement segment*, they can be extrapolated into the future to predict the channel (in the *prediction segment*). Various criteria for the performance of this channel prediction have been proposed. The one used here in most cases here is the distance (in wavelengths) for which the difference between the predicted and the actual signal envelopes is within 20% of the root mean square value of the channel transfer function in the measurement segment.



(a) (b)

Figure 2: (a) The expected error in the reconstructed field as the radius of the extrapolation increases, for various radii of known field. (b) The influence of rough surface correlation distance on predictability of the channel, for various values of roughness. In this scenario, the number of scattering surfaces $N = 5$, the received SNR is 20dB, the number of measurements $M = 40$, the trajectory length is 6λ. The angles of incidence on the rough surface are uniformly distributed.

LIMITING FACTORS

Number of Paths

For a simulated and a measured channel, the prediction length is presented in Fig. 1 as a function of the length of the measurement segment. A key observation is that the prediction length only begins to rise when the number of independent real data values is larger than the number of real parameters to be estimated. Large measurement segments are impractical, since paths will not remain unmoving over trajectories of many wavelengths, so if the number of paths is large, prediction over distances of more than a few wavelengths may not be achievable. The same conclusion can be drawn from consideration of the Cramer Rao Bound on the variance of the parameter estimates (for details see [6]). Hence the number of paths which contribute a significant proportion of the available energy can be seen to be *pivotal*.

The fact that many properties of a channel (such as correlations, probability density etc.) may be reliably simulated with a small number of discrete sources has led many researchers to believe that in a typical scenario there are only a small number. This is in fact a *non sequitor*, and the experimental evidence suggests that in many situations there are many sources [e.g., 7].

A bound which is relevant to the diffuse field situation (in effect where N is infinite) can be derived by consideration of the Helmholtz wave equation. It is shown in [8] that if a narrowband field is known to within relative error ϵ inside a region of radius R, then the number of paths which can be detected is $2N + 1$ where

$$N = \arg\min_{\mathcal{N}>0} \Big(\sum_{n>\mathcal{N}} |J_n(kR)| < \epsilon \Big), \tag{3}$$

where $J_n(.)$ is the $n-$th order Bessel function of the first kind, and a similar result holds for the case of a three dimensional field known inside a given spherical region. In other words, the illusion that there are only a small number of paths inside any given region is complete. This result is adapted in [4] to show that that the expected square error in extrapolating the field to a distance r which is outside of this known region ($r > R$) is given by

$$\sum_{n=-\infty}^{\infty} \frac{J_n^2(kr)}{J_n^2(kr_1)} \tilde{\Psi}(r_1, -n) \tag{4}$$

where $\tilde{\Psi}(.,.)$ is the Fourier transform in azimuth of the correlation function of the error process representing the uncertainty in the field, and r_1 is any radius $r_1 < R$. An example correlation function was used to produce Fig. 2(a). It can be seen the error incurred when extrapolating field beyond the known region rapidly becomes prohibitive.

Proximity of Scatterers

The parameters associated with sources near the trajectory of a moving receiver may vary rapidly, violating the requirement that the parameters allow extrapolation into the future. This rapid variation can be removed by using models which

explicitly consider the location of near-field scatterers. However, the parameters of such models are difficult to estimate using the measurements acquired from a single trajectory. Most methods of estimating the parameters of the model (2) begin by first estimating the covariance matrix of the data observed at some set of location on the mobile trajectory. It is easy to show that

$$E\{h_{m_1} h^*_{m_2}\} = E\left\{\sum_{n=1}^{N} |\zeta_n|^2 e^{j\varpi_n(m_1-m_2)}\right\}. \tag{5}$$

The covariance can be estimated by averaging several such terms, even though only one measurement is available from each location, since (5) clearly depends only on the *difference* between m_1 and m_2. In the case of models which include the location of near-field scatterers, this invariance property does not hold, and only one sample of the covariance is available. Hence, parameter estimation of near field models with a single "pass" is very much more difficult than for far-field models.

Surface Roughness

It is shown in [9] that, given certain assumptions, the ratio of the power of the diffuse component caused by roughness in the surface of a surface, to the power of the specular component is given by $\mathcal{J}^2$, where the Rayleigh parameter $\mathcal{J} = 2k\sigma_\xi \sin\psi$, ψ is the grazing angle of the reflection, and σ_ξ is the depth (standard deviation) of the surface roughness. The correlation between the *diffuse component* of signals reflected from a rough surface and measured at two different points can be approximated by

$$\mathcal{K}(\boldsymbol{R}, \boldsymbol{R}') \approx e^{-jk\Delta_{R_0}} W(\Delta_{\boldsymbol{r}_0}), \tag{6}$$

where Δ_{R_0} is the difference in the total path length between the source and the two receiving points $\boldsymbol{R}$ and $\boldsymbol{R}'$, $\Delta_{\boldsymbol{r}_0}$ is the separation of the points of specular reflection, and $W(\Delta_{\boldsymbol{r}_0})$ is the correlation between the surface height at the two points of specular reflection. The results of a simulation based on these equations is shown in Fig. 2(b). Note that all of the surface roughness conditions presented in the figure qualify as smooth according the the Rayleigh criterion ($\mathcal{J} < \pi/8$), and are likely to be encountered in many practical situations. The degradation from the situation with smooth scatterers is very obvious and significant.

CONCLUSIONS

In principle, characterisation of the mobile channel in real time, using an appropriate channel model, allows channel prediction. There are however, significant limitations to be validity of the model which are likely to be encountered in practice. These include the presence of a large number of paths, scatterers near the receiver, and the effects of rough surface scattering.

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