Performance of Channel Prediction for Wireless Downlink Packet Systems

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Abstract - Channel prediction is an appealing approach to mitigate channel mismatch in wireless downlink packet systems. Channel mismatch arises due to the delay in the feedback loop. Both synthetic and measured channels were used to assess the accuracy of channel prediction for various ratios of specular to diffuse power. The power spectrum was estimated rather than assumed known. It has been found that high ratios (K factors) greater than ten are necessary for prediction greater than one wavelength. K factors of measured channels gave prediction accuracy similar to that of the synthetic channel given by the same K factor.

I. INTRODUCTION

Downlink wireless packet systems use channel knowledge to adapt transmission rate on packet by packet basis as the channel fluctuates. A key part of the downlink access scheme is the scheduler, which uses this knowledge to transmit to mobiles when their channel capacity is high, and defers when it is not. The channel is estimated at the mobile from downlink pilots and fed back regularly on the uplink. By the time the information is ready to be utilized at the base station, several milliseconds may have passed since the measurement was taken. This delay is the sum of the measurement interval, uplink MAC, transmission, and internal processing delays. Although we are considering a frequency duplexed system, it may be noted that even in a time duplexed system, there will be a delay between when the uplink pilots are transmitted, and when downlink transmission begins. Depending on the speed of the mobile, the delay, and the channel’s spatial/temporal properties any information will be out-of-date or stale to varying degree. Two issues arise: first the scheduler makes ‘wrong’ decisions, and second the transmission rate must be backed off to ensure that this rate does not exceed the actual channel capacity. To illustrate the latter, Figure 1 from [1] shows the probability of the transmission exceeding the channel capacity. A small fixed back off is set at 2 dB, and fading follows the Jakes model. In the figure as the velocity increases so does the probability of outage. To maintain multi-user gains the channel must be slowly varying, and this typically implies low mobile velocity.

Channel prediction has been proposed, to support mobile velocities. If a mobile could feed back a predicted version of the channel, the gains by the described feedback system could be maintained. It is customary to model the narrowband channel as a sum of Doppler shifted plane waves. A process governed by this model is wide sense stationary (second order stationary), and is a predictable auto-regressive process, satisfying a homogenous difference equation. The optimum all-zero FIR filter may be obtained by solving the Yule-Walker equations. All that is necessary are past samples of the channel and the power spectrum or equivalently the autocorrelation of the process. In theory, prediction may be made arbitrarily far into the future without error.

The nature of the power spectrum affects the predictability of the process. It has been observed that the probability density function (pdf) of the received signal envelope may be approximated by the Rayleigh distribution. The Rayleigh pdf is the distribution of the envelope of a complex Gaussian process, which in turn arises from a sum of random plane waves. This leads to two different physical interpretations. The first interpretation states that the received signal consists of plane waves from certain number of dominate scatterers. Over a short distance their angles of arrival and amplitudes would be constant, and linear phase shift in distance would result. The Doppler spectrum thus consists of line spectra. With super-resolution techniques only N+1 samples are necessary to identify N sinusoids. For example Andersen et. al. [2] used ESPRIT to identify the 10 sinusoids in the channel over an estimation window of 4.5 wavelengths and predict ahead 20 wavelengths with an error under 5%. In the second interpretation, there are an infinite number of waves leading to a continuous spectrum. In the widely quoted Jakes model, plane waves arrive uniformly in the horizontal plane. Teal and Kennedy [3] show that if there is a small error in the knowledge of the field, prediction is limited to a fraction of a wavelength. Since measurements of the channel are noisy and opportunity to sample the channel is limited, it is important to determine whether the channel may be better described by the first or second interpretation.

Several authors have investigated channel prediction, but only a few have tested their algorithms on measured data [4-6]. Explicitly relating predictability to the nature of the measured channel has received little attention in the literature. We may expect actual channels to be a mixture of the two extremes, having some specular components as well as a certain amount of diffuse power. The Rician model is an example of this with a single specular component, and has a single parameter known as the K factor, which specifies the ratio between the specular component power and diffuse power. High resolution Fourier based plots of Doppler spectrum are presented which demonstrate Rician modeling. In this paper, the
predictability of the radio channel is shown for a wide range of channels as represented by the Jakes and Rician models, and for specific channels measured in rural Lakehurst, New Jersey.

II. JAKES AND RICIAN CHANNELS

In the discrete scatterer model (DSM), the channel may be modeled as a sum of \( N \) discrete Doppler shifted plane waves:

\[
h(t) = \sum_{m=1}^{N} a_m \exp(jkvt \cos \theta_m),
\]

(1)

and the sampled received signal is

\[
s[n] = \sum_{m=1}^{N} a_m \exp(j \frac{2\pi}{f_s} kv \cos \theta_m) + \eta[n],
\]

(2)

where \( \theta_m \) is the angle between the direction of motion and the incoming plane wave, \( a_m \) is the complex amplitude, \( k \) the wave number is \( 2\pi/\lambda \), and \( \eta \) is additive white Gaussian noise. If the plane waves are associated with scatterers which are distant from the receiver then over small displacement \( a_m \) and \( \theta_m \) will be constant.

For the Jakes model (actually due to Clarke [7]), the pdf of \( \theta_m \) and phase angle are uniformly distributed \([0, \pi]\) and the autocorrelation \( r_{\text{Jakes}}(\tau) \) is the Bessel function \( J_1(2\pi F_\tau \tau) \). The Rician model is the sum of the Jakes process along with a specular component at Doppler frequency \( w_1 \):

\[
f_{\text{rician}}(t) = f_{\text{jakes}}(t) + \sqrt{K} \exp(jw_1 t),
\]

(3)

where the K factor is the ratio of the specular power over the random power. The autocorrelation \( r_{\text{Rician}}(\tau) \) is \( J_0(2\pi F_\tau \tau) + K \text{exp}(jw_1 \tau) \).

To generate the fading process, the method by Smith [8] is utilized, where a Gaussian process is multiplied by the appropriate power spectrum, and the inverse FFT taken to obtain the correlated time sequence. It should be mentioned that generating the Jakes process with a small number of sinusoids, results in a process which deviates from the desired statistical properties [9].

III. YULE-WALKER EQUATIONS

The Yule-Walker equations for \( P \)-th order filter, predicting \( R \) steps ahead may be written as:

\[
\begin{bmatrix}
  r(0) & r(1) & \cdots & r(P-1) \\
r^*(1) & r(0) & \cdots & r(P-2) \\
\vdots & \vdots & \ddots & \vdots \\
r^*(P-1) & r^*(P-2) & \cdots & r(0)
\end{bmatrix}
\begin{bmatrix}
w_1 \\
w_2 \\
\vdots \\
w_P
\end{bmatrix}
=
\begin{bmatrix}
r^*(R) \\
r^*(R+1) \\
\vdots \\
r^*(R+P)
\end{bmatrix}
\begin{bmatrix}
w_p \\
w_{p-1} \\
\vdots \\
w_1
\end{bmatrix}
\]

The solution \( w \) may be found as

\[
w = R^{-1}b.
\]

Since the autocorrelation is not known \( r \) is replaced with its sample estimate. An estimator of the autocorrelation for a window of \( J \) samples is given by:

\[
\hat{r}[m] = \frac{1}{J-m} \sum_{n=m}^{J-1} s[n+m]s^*[n], m < J
\]

(6)

This estimate has no bias, but the variance grows with increasing \( m \). In the second so called biased estimator, a window is applied

\[
\psi[m] = \left(1 - \frac{m}{J}\right),
\]

(7)

\[
\hat{r}_b[m] = \psi[m] \hat{r}[m] = \frac{1}{J} \sum_{n=m}^{J-1} s[n+m]s^*[n], m < J.
\]

\( \psi[m] \) is known as the Bartlett window which reduces the variance. Further averaging in the frequency domain can reduce the variance at the expense of resolution. However, best results for the given window lengths were found without sacrificing additional resolution. To quantify the performance of the predictor, the mean square (MS) error is defined for the predicted signal \( \hat{s}[n] \) and actual signal \( s[n] \):

\[
\hat{s}[n] = \sum_{k=1}^{J} w[k] s[n-k - R + 1]
\]

\[
\sigma^2 = \frac{\sum_{n} |s[n] - \hat{s}[n]|^2}{\sum_{n} |s[n]|^2}.
\]

(8)

(9)

IV. MEASURED DATA

Narrowband measurements were taken at Lakehurst Naval Air Engineering Station, NJ. Detailed properties of the MIMO and wideband channel are given in [10] and [11]. The area is characterized by some gentle terrain variation, with open fields, and pine trees. There are several very large hangars which formerly housed transatlantic dirigibles. Of historical significance, it is the site of the 1937 Hindenburg crash. The carrier frequency was 2.5 GHz, the channel was sampled at 3 ms intervals, and measurements were taken at approximately 25 mph. The recorded SNR was generally high around 30 dB. Antennas were omni-directional horizontally polarized, with 8 dBi vertical gain and mounted on the roof of the van. Distance between transmitter and receiver varied from 500 to 1000 m.

V. PREDICTION ON SYNTHETIC & MEASURED DATA

The prediction problem is shown in Figure 2. The autocorrelation is determined from \( J \) samples, and \( P \)
previous samples are used in a FIR filter to predict R-steps ahead. All quantities in samples may also be expressed in wavelengths such that \( J_s = J/\lambda \), in samples where \( \lambda \) is the sampling rate. Let the prediction interval be the distance predicted in wavelengths up to some low MS error. The following example provides a sense of scale of the prediction interval. If velocities are moderate such as \( v = 10 \) m/s, and the delay is short eg. 2 ms, then the prediction interval needs only to be \( 0.13 \) \( \lambda \) at \( f_s = 2 \) GHz. Under these conditions from Figure 1, \( p \) is 0.38. Prediction could improve the throughput of the downlink packet system, by reducing \( p \) for a fixed back-off, or reducing the back off for fixed \( p \).

For the synthetic data the sampling frequency \( f_s = 500 \) Hz, \( v = 10 \) m/s or 36 kph, \( f_d = 67 \) Hz, \( P = 10 \), \( w_1 = \pi f_d \), and SNR is 30 dB. The MS error was largely independent of value of \( w_1 \). Prediction accuracy usually saturated with low filter order, but for the filter order not be an issue, \( P \) was left at 10. Figure 3 shows the predictability of the channel with values of K corresponding to channel ranging from diffuse to nearly specular. As expected, prediction becomes more accurate for higher values of \( K \). The prediction interval (with MS error up to .1) for Jakes is only \( 0.28 \lambda \), in agreement with Teal and Kennedy. Yet with \( K \) factors up to 4 dB prediction is still limited to about \( 0.4 \lambda \). K factors 10 dB or higher are needed for prediction greater than \( 1 \lambda \). Figure 4 shows the same curves as Figure 3, but with slight improvement due to doubling the estimation window from 13 to 27 \( \lambda \). K factors greater than 6 dB are needed for predicting beyond \( 1 \lambda \). Using larger windows is expected to break the stationary assumption as shadow-fading spatial scale is on the order of 10 to 20 \( \lambda \) in urban areas.

The Lakehurst channels were processed as follows: for each value of \( R \), filter coefficients were generated once with \( J \) approximately 25 \( \lambda \), prediction was run over 100 samples, and the MS error computed. The process was iterated over several values of \( R \). Figure 5 gives the MS error vs. \( R \) for four measured links at Lakehurst. Of these links three are non-line-of-sight (LOS), and one is LOS. The \( K \) factors of all links have been estimated via the moment method \[12\]. Interestingly, the \( K \) factor appears to be a good indicator of predictability. The prediction accuracy of the measured channel is close to that of the synthetic channel with the same \( K \) factor.

VI. DOPPLER SPECTRUM

Figures 6 and 7 give Doppler spectrum for a non-LOS and LOS location respectively. The spectral estimator is given by

\[
\tilde{S}_D(w) = \left| \frac{1}{64N_{\text{sample}}} \sum_{n=1}^{N_{\text{sample}}} \sum_{i=0}^{N_{\text{sample}}} w_b[n] y[i+n] e^{i2\pi w t} \right|^2
\]

where \( w_b \) is the Blackman window, \( y[i,n] \) is the n-th sample of the narrowband channel between the i-th transmit receive pair. Since 8 transmitters and 8 receivers were available 64 different spatial realizations were used to reduce the variance. The processing forms a synthetic array with an aperture on order of 10 m, when \( N_{\text{sample}} \) is 400. Figure 6 shows a large peak at \( f_d \) and some smaller peaks around 30 to 50 Hz. Figure 7 shows one large peak. Supporting the use of the Rician model, both figures show a low level apparently continuous spectrum between +/- \( f_0 \) As for the discrete scatterer model as seen in Figures 6 and 7 it is impossible to determine the number of scatterers \( N \), from even with a 10 meter array!

VII. PRACTICAL IMPLICATIONS & CONCLUSION

In CDMA 2000 EV-DO there is 2.5 slot, or 4.1 ms delay from the measurement to the downlink slot. Using the rule of thumb \( f_s = 1/(20*\lambda d) \), prediction may be beneficial when the mobile velocity exceeds 4.2 mph, but below 25 mph (prediction interval of \( 0.3 \lambda \) at 1.9 GHz). If coherence distances are actually doubled as reported in \[13\], prediction may be maintained up to 50 mph. At high mobile velocities, hybrid ARQ and incremental redundancy (IR) allow packets to finish early if a portion is received successfully, thus gaining back what was lost due to increased fade margins. Yet this gain is only partial, as \[14\] compares performance at 2 mph to 13 mph showing a loss of 67% without HARQ but only 33% loss with HARQ/IR. Note that with on-time channel feedback or prediction, gains are not just maintained, but system throughput increases with mobile velocity.

In this paper we have studied how the channel’s power spectrum, when it must be estimated rather than assumed known, affects the predictability. High \( K \) factors were found to be needed for prediction greater than a wavelength. The effect of estimation window length was investigated, showing only slight improvement with doubling. The measured \( K \) factor appeared to be indicator of predictability, that is, prediction intervals of measured data were similar to those of the synthetic data given by the same \( K \) factor. Having demonstrated the importance of an accurate propagation model for the evaluation predictive techniques, we suggest a simple generalization of the Rician model. This model allows more than one coherent (non-fading) wave. In this case the spectrum can be split into two parts \( S(S) = S_{\text{discrete}} + S_{\text{continuous}} \) with \( K' \) the ratio of their powers. Note that \( S_{\text{discrete}} \) is easy to predict and \( S_{\text{continuous}} \) is difficult. The estimated \( K' \) factor is an attempt at obtaining \( K' \).
References:


Figure 1: Outage probability $p$ because of higher SNR in the fed back channel as compared to actual channel. $	au$ is the delay.
Figure 2. Rayleigh faded channel, and prediction windows.

Figure 3. MS error vs. $R$ for Jakes & Rician channels, $J=13\lambda$.

Figure 4. MS error vs. $R$ for Jakes & Rician channels, $J=27\lambda$. 

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.
Figure 5. LOS and non-LOS links measured in Lakehurst. MS error vs. prediction interval $R$, $J=25\lambda$, $P=10$.

Figure 6. Doppler spectrum of a non-LOS link.

Figure 7. Doppler spectrum of a LOS link.