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An Investigation of Measured and Simulated Wideband Channels with Applications to 1.25 MHz and 5 MHz CDMA Systems

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Abstract - **Fading of the wideband radio channel and its implications for CDMA RAKE receiver operation has been investigated using measured wideband impulse responses and simulations with an exponentially shaped channel model. The emphasis has been on systems with 1.25 MHz and 5 MHz bandwidth, and the reduction in fading variations as well as the increased complexity in terms of required RAKE correlator branches when increasing the bandwidth has been studied. An analysis of the consequences of fast power control has also been performed.**

I. INTRODUCTION

As the development of mobile communications systems moves on towards higher bandwidths and bitrates, a good and thorough understanding of the fundamentals of the radio channel at higher bandwidths is necessary. In this paper, the behaviour of the radio channel at bandwidths of 1.25 MHz and 5 MHz is investigated, with a focus on parameters of interest for CDMA systems. The basis for the analysis is wideband channel measurements performed at 1880 MHz and simulations using a channel model with an exponential power delay profile.

The questions this paper seeks to answer are the following:

- What are the typical quantitative reductions in channel fading when increasing the system bandwidth?

- How does the signal at the output of a RAKE receiver behave at different bandwidths and in comparison with the total received signal?

- What is the influence of power control?

- How many branches or RAKE fingers are necessary?

Previous work in this area include, among other, the article by Chan [1], where the power variations and RAKE receiver performance at 1.25 MHz and 10 MHz are investigated. The number of RAKE receiver fingers needed at different bandwidths to capture a certain percentage of the total power has been investigated by Martin and Faulkner [2]. Received signal levels and correlation properties are investigated by Kozono [3]. Iwai et al. [4] have investigated wideband signal fluctuations and path and spatial diversity for CDMA systems.

II. CHANNEL MEASUREMENTS

The wideband channel measurements have been performed at two locations in the city of Stockholm, Sweden, corresponding to two different environments. The location of the first was on a roof-top on the main building of Ericsson Radio Systems AB, in an environment best classified as a mixture of urban and suburban. 30 measurement locations at distances of 200-2000 m were selected. The second site was located in the central parts of Stockholm, in an urban environment with areas of open water. 41 measurement locations were used, at distances spanning 150 to 2500 m. Base station heights were 2-3 m above rooftop level, which for both sites was 20-25 m above ground level.

The mobile antenna was placed on top of a van, which was driven around on streets and highways in the area. Most of the measurements were acquired in non-line-of-sight conditions. Each measurement consists of 1430 consecutive complex impulse responses of length 109 ms, which were obtained via cross-correlation with a transmitted 511 bit PN-sequence clocked at 4.672 MHz. The sampling rate of the receiver, a HP 89441A Vector Signal Analyzer, was 6.4 MHz. With vehicle speeds of 30 to 90 km/h, the 1430 impulse responses would span a distance of 10-25 wavelengths at 1880 MHz.

The measured impulse responses were post-processed to bandwidths of 1.25 MHz and 5 MHz, with sampling rates of 1.6 MHz and 6.4 MHz respectively. Sampling rates are 1.28 times the bandwidths to avoid aliasing in the receiver. The level of the noise floor in the measured impulse responses was assessed, and all samples below a threshold level (set to about 6 dB above the noise level) were set to zero. Rather than using a threshold specified in relation to the strongest peak we chose to specify the threshold in relation to the median noise level, in a similar manner as described in [5].

The amount of time dispersion encountered in the two measurement environments can be assessed by studying Fig. 1, which displays the cumulative distribution functions (CDFs) of the rms delay spread.
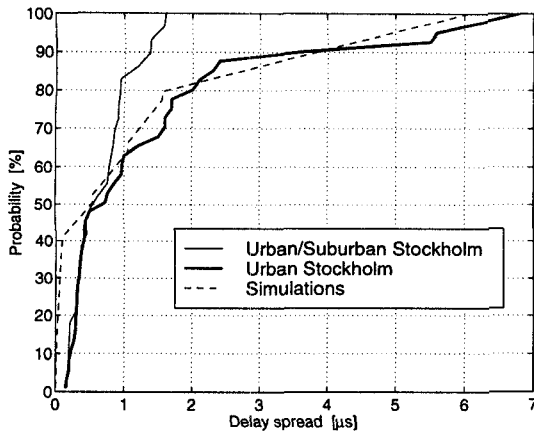
Fig. 1 Delay spread CDFs for measurements in urban Stockholm (thick) and urban/suburban Stockholm (thin). Also shown are the delay spread CDF from the simulations (dashed).

As is evident from the CDFs, the time dispersion in urban Stockholm is severe in some places. This is due to the open areas of water in the central part of the city, which allows radio waves reflected from distant buildings to propagate unobstructed over large distances. In locations where the direct wave is obstructed, this can generate severely time dispersive channels such as in the 20% of the locations where the delay spreads are in excess of 2 μs.

III. CHANNEL SIMULATIONS

The model for the wideband complex impulse response of the propagation channel was assumed to have the form:

$$h(\tau) = \sum_k a_k \exp(j\theta_k)\delta(\tau - \tau_k) \qquad (1)$$

where the a_k are real positive amplitudes, θ_k are the phase shifts of the incoming waves and τ_k are the propagation delays.

The modeling of the channel is restricted to reproduce the statistical behaviour of real signals in the complex impulse response together with the delay spreads observed at different propagation environments. The model is a modified version of the one presented in [6], and is based on the following assumptions:

- The average power delay profile (PDP) is exponentially shaped and has the following form for non-negative delay times

$$P(\tau) = \frac{P_o}{\gamma} \exp\left(-\frac{\tau}{\gamma}\right) \qquad (2)$$

where P_o is the total power and γ is the time-decay constant.

- The delay times τ (non-negative) are assumed exponentially distributed with a probability density function represented as follows

$$P_\tau\{\tau \leq \tau_0\} = 1 - \exp\left(-\frac{\tau_0}{\gamma}\right) \qquad (3)$$

- The fading of the taps is described by a Rayleigh distribution

$$P_r\{r \leq a\} = 1 - \exp\left(-\frac{a^2}{P_{mean}}\right) \qquad (4)$$

where P_{mean} is twice the variance of a.

- And finally the phase is uniformly distributed in the interval $[0,2\pi]$

$$P_\theta\{\theta \leq \theta_0\} = \frac{\theta_0}{2\pi} \qquad (5)$$

Each of the parameters τ_k, a_k and θ_k of the complex impulse responses are generated by random processes described by equations (3) to (5), which is done by letting the probabilities P_τ, P_r and P_θ take random values uniformly distributed in the interval [0,1].

In this way a set of non-equidistant exponentially distributed values of delay times is generated. They can lie arbitrarily near each other, which is equivalent to an arbitrary time resolution and system bandwidth. Because of this the user has to choose an adequate time resolution so that two consecutive taps in the PDP do not lie nearer than the inverse of the required bandwidth.

In order to simulate RAKE receivers with different system bandwidths it is necessary to filter the wideband complex impulse response generated by the described model down to the bandwidths of interest. The filtering was performed by means of an ideal lowpass filter and the regarded bandwidths were of 1.25, 2.5, 5, 10, 20 and 40 MHz.

To assess the fading behaviour of the channel and the performance of ideal RAKE receivers in different propagation environments several time-decay constants were considered, and corresponding delay spreads were derived. Observe that the delay spread will differ from the time-decay constant due to the discrete nature of the model and the exponentially distributed delay times. In Fig. 1 the delay spread CDF for the simulations is presented together with those obtained from measurements. The distribution is similar to the urban for larger delay spreads, but covers a wider range of low delay spreads.

IV. ANALYSIS OF MEASUREMENTS AND SIMULATION RESULTS

The total channel power is the sum of the power of each individual path (neglecting the noise). A RAKE receiver using maximum ratio combining will give a power on the output which is the power sum of the N strongest paths, where N is the number of correlator branches or "fingers". With N sufficiently large, the output of the RAKE receiver will be approximately equal to the total channel power.

In the following section we will concentrate on the signal fluctuations for the total channel, or equivalently, for a RAKE

receiver employing a sufficient number of "fingers". In section B the result of using a finite number of RAKE "fingers" will be investigated. In section C, the effect of power control is studied.

A. Channel fading

A parameter which can be used to characterize the amount of fading of the channel is the fading width, defined as the difference in dB between the 99% level and the 1% level in the CDF for the received signal power [4]. Using the approach in [4], we plot the fading width vs. the product of the signal bandwidth and the rms delay spread in Fig. 2. The solid line is an empirical curve which gives a very good representation of the fading gains obtained in simulations using the exponential channel model.

Denoting the above defined fading width as FW the curve in Fig. 2 is then given by the following equation:

$$FW = A(1 - \gamma \tanh(\alpha \ln(\beta W \tau_{sp})))\qquad(6)$$

where $\alpha=0.4$, $\beta=1.49$, $\gamma=0.83$ and $A=14.54$ dB. The fading width approaches 26.6 dB as the system bandwidth-delay spread product becomes smaller, which is the fading width that corresponds to the Rayleigh CDF.

As can be seen, this curve is also a good fit to the experimental data, though the spread is much larger than for the simulated data (not shown). Some deviations are evident, as there are some data points with low fading width and low signal bandwidth-delay spread product, i.e. the two groups of four points located to the lower left in the figure. These are identified as being measurements in or close to LOS, which provides an explanation for the low fading widths. LOS channels tend to be Rician rather than Rayleigh fading, resulting in much lower fading variations.
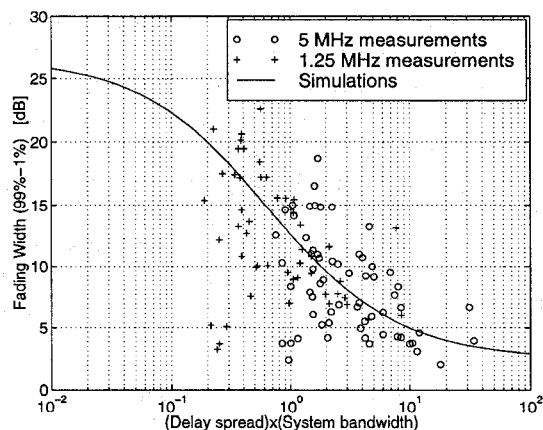

Fig. 2   Fading width vs. the product of delay spread and system bandwidth. Measurement results are marked with o (5 MHz) and + (1.25 MHz). The solid line is an empirical fit to the simulations results.

From Fig. 2 we find that increasing the bandwidth for a fixed delay spread reduces the fading variations of the channel, a result which is well-known from experience. This reduction

is largest when the signal bandwidth-delay spread product is near unity, where the slope of the curve in Fig. 2 is most steep.

Alternately, the reduction in fading can be investigated by looking at the reduction in fading margin, or the increase of the value of the CDF for the received signal power at a specific probability level. To get a good ground for comparison, all measurements in each of the environments were normalized to the same average power, and then the total CDF for the signal power was calculated for the whole ensemble of measurements. Fig. 3 shows the total CDFs for the bandwidths of 1.25 MHz and 5 MHz for the urban/suburban environment (left) and the urban (right). The reduction in signal fading when increasing the bandwidth is clearly evident when comparing the two curves. We can look at the gain at a specific probability level, such as the 1% level. For the two curves, a gain of 3.5-4.0 dB is achieved.
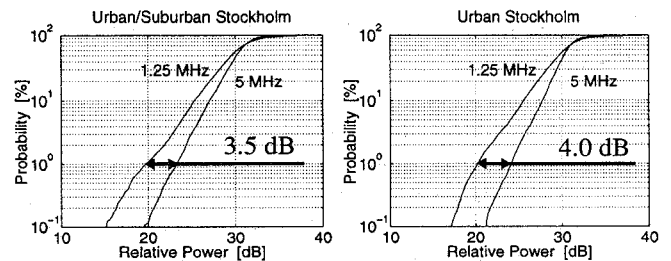

Fig. 3   Distributions of fading variations (normalized) for each of the environments at 1.25 MHz and 5 MHz bandwidth. Also shown are the fading gains at the 1% probability level.

Fig. 4 shows the fading gain obtained when simulating the channel using the exponential model for the average power delay profile and Rayleigh fading taps. The fading gain with the 5 MHz system relative to the 1.25 MHz system is presented at different CDF levels using 1, 2, 4, 8 and all possible taps in the profile. At the 1% probability level, the fading gain is 3.5 dB, which is in conformity with the value obtained from the measurements.
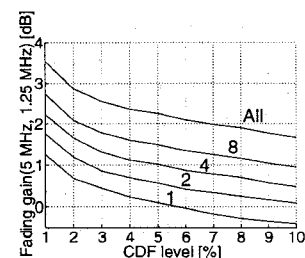

Fig. 4   Fading gains vs. CDF probability level for 1, 2, 4, 8, and all taps in the power delay profile.

B. Fading in ideal RAKE receivers

A practical communications system can utilize the signal energy in different manners. In CDMA systems using RAKE receivers, correlator branches or RAKE "fingers" are used to

capture part of the signal energy. These fingers are assigned to different delays in the time domain description of the radio channel, and utilizes the signal energy present at those delays. To evaluate the signals at the output of RAKE receivers, we make the following simplifying assumptions:

- The RAKE receiver has no time window, and can consequently have fingers at large delay separations.

- Correct decisions are always made regarding which delays the fingers are to be used at, and the delays can be changed instantly.

- The noise level is assumed to be the threshold level of the measurements, so that for measurements with good dynamic range even very weak peaks may be used.

These assumptions distinguish our "ideal" RAKE receiver from a practical one, but are useful for investigating the performance limits of this type of receivers. Furthermore, to facilitate detection of peaks, our "ideal" RAKE receiver will operate on a channel impulse response which has been oversampled to exactly two times the system bandwidth. The minimum distance between two RAKE fingers must then be two samples, or 1/B where B is the system bandwidth.
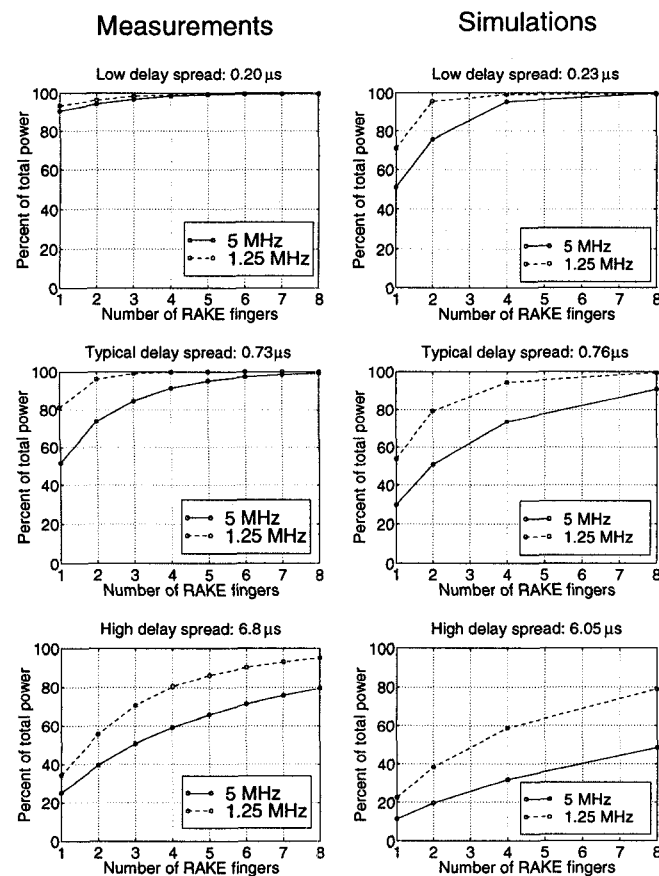
The first question we look at is how much of the total signal power is captured in a RAKE receiver with a limited number of fingers. In Fig. 5, we present three special cases, a low-delay spread channel, a typical delay spread channel and a high-delay spread channel. Corresponding results from simulations are also shown. The measurements are taken from the urban environment.

Not surprisingly, higher delay spread means a larger number of fingers is necessary to capture a given percentage of the total signal power. Interesting to note is the general trend of the simulations predicting a larger number of fingers than the measurements do. For a given percentage of the total power, the number of RAKE fingers predicted by the simulations is approximately twice the number indicated by the measurements. This indicates that the exponentially shaped channel may be more difficult from a power capture point of view than a typical measured channel. Probably the signal energy is more concentrated to a few peaks than what is the case in an exponential channel.

Apart from not capturing the total received power, the result of only using a limited number of RAKE fingers is that fading variations will increase (path diversity will be less when less paths are combined). Fig. 6 shows the captured power CDFs for the urban and the urban/suburban environments for different number of RAKE fingers.

Fig. 5   Percent of total power captured as a function of RAKE fingers for measurements (left) and simulations (right).
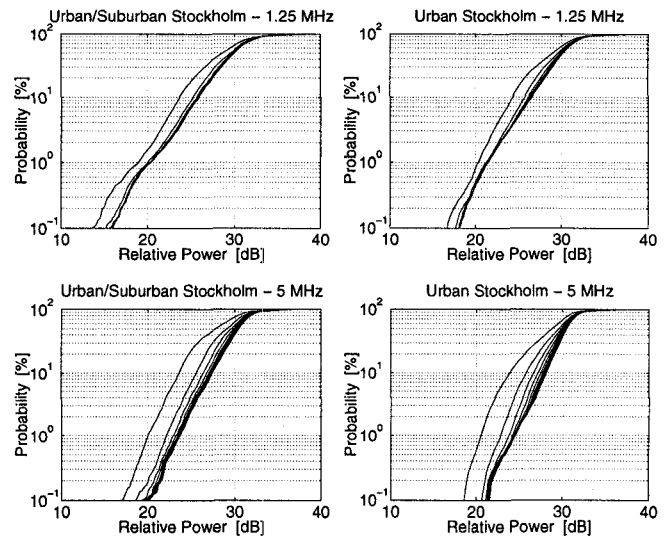

Fig. 6   Distributions of fading variations at the RAKE receiver output using different number of RAKE fingers. The curves in each diagram represents an increasing number of RAKE fingers from left to right, starting at one and increasing up to ten.

After a certain number of fingers, asymptotic curves are reached which correspond to the curves in Fig. 3. As can be seen, the CDF curves approach these asymptotic curve with different speeds, the 1.25 MHz system will be very close to this after 3 fingers, while the 5 MHz system will need more fingers to reach the asymptote. As an example, we can look at the 1%

fading gain when both systems are using 4 RAKE fingers. This will be 2.8 dB in the urban and 2.9 dB in the urban/suburban. For comparison, the simulations predict a fading gain of 2.2 dB, as can be seen in Fig. 4.

C. RAKE receivers in CDMA systems with power control

Fast power control is a way of mitigating the effects of fading. If fast power control is used, one may ask what the point of investigating the fading in a RAKE receiver is when the received signal will be constant if the power control is perfect. But there is a price to pay for achieving constant received power, and that is that the average transmitted power is increased in comparison with a less fading channel. In essence, the transmitted power will be the inverse of the received power shown in Fig. 6, and the more severe the fading, the higher the average transmitted power need to be to achieve *equal* constant received power level. Defining the Excess transmitted power as the average increase in transmitted power relative to a non-fading channel, we can plot a figure such as Fig. 7.
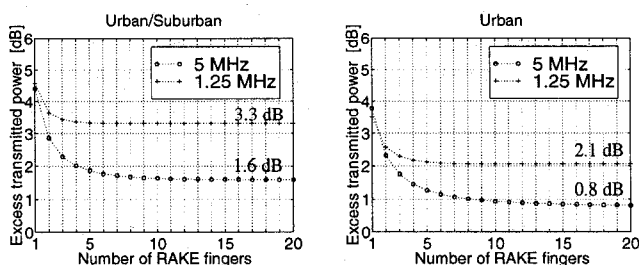

Fig. 7   Excess transmitted power as a function of the number of RAKE fingers. The asymptotic values which the curves tend to for a large number of RAKE fingers are also shown.

For the urban/suburban environment and a large number of RAKE fingers, more or less equivalent with the total channel, a 5 MHz system is transmitting at 1.6 dB higher power than would be required on a non-fading channel, while a 1.25 MHz system is 3.3 dB higher. The behaviour in the urban environment is similar but with lower excess transmitted power levels, 0.8 dB and 2.1 dB respectively. The increase in excess transmitted power when reducing the number of RAKE fingers is also seen. The reason for the lower excess transmitted power levels in the urban environment is the higher time dispersion.

Fig. 7 summarizes the trade-off between fading reduction and complexity in a good way, as the 5 MHz system will need more fingers to achieve optimum performance, but will gain more by doing so. The gain is that the 5 MHz system will be able to transmit on average 1.7 dB lower power in the urban/suburban environment, and 1.3 dB lower in the urban environment.

V. CONCLUSIONS

The reduction of fading variations when increasing the bandwidth has been demonstrated, both in measurements and simulations. The empirical curve for the fading width as a function of the bandwidth-delay spread-product presented in Fig. 2 shows good agreement both with measurement and simulation results.

Specifically, when increasing the bandwidth from 1.25 MHz to 5 MHz the fading gain at the 1% probability level is in the order of 3.5-4.0 dB in the measured urban and suburban environments. A fading gain of 3.5 dB is also obtained from the simulations.

To capture a given fraction of the signal power in a RAKE receiver, more RAKE fingers are necessary at 5 MHz than at 1.25 MHz. For a typical urban measurement, a 5 MHz system needs four fingers to capture 90% of the received power while a 1.25 MHz system only needs two. Here the channel model gives pessimistic predictions which are probably due to the assumed exponential power delay profile.

When using fast power control to compensate for signal fading, the average transmitted power will increase with increasing fading variations. The results presented indicate that an increase of bandwidth from 1.25 MHz to 5 MHz will reduce the average transmitted power with 1.3-1.7 dB.

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