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Source: Telia AB, Anders Henriksson, Christian Bergljung.

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1. INTRODUCTION

In this note, we consider the channel impulse response models used in the evaluation of the WCDMA concepts and the distribution of the power received by a RAKE receiver. It is proposed that the tap weights in the impulse-response model is characterised by a Rician or a log-normal distribution (Section 2); the Rayleigh distribution is just a special case then (a Rician distribution without a specular component). Furthermore, the Doppler spectrum should not always be the classical "Jakes" spectrum. In Section 3, we give closed form expressions for the power received by a RAKE receiver given certain distributions of the tap variations. Finally, in Section 4, we give an upper bound of the number of resolvable paths in a RAKE receiver, which then represents the maximum frequency diversity gain.

2. CHANNEL IMPULSE RESPONSE MODELS

In this section, it is proposed that the channel tap variations be modelled by a Rician or a log-normal distribution; the Rayleigh distribution is just a special case then. The point is that each tap may not always represent an "infinite" number of field constituents. The shape of the Doppler spectrum is also considered.

Suppose that the channel impulse response is given by

(2.1) $$h(t,t) = \sum_n a_n(t)\, d(t - t_n)\,,$$

where a_n denotes the tap weights and t_n is the delay. For simplicity, we assume that the tap weights are statistically independent.

In the evaluation of the WCDMA concept, it is assumed that the tap weights a_n are complex Gaussian processes with zero mean. The tap envelopes are then Rayleigh distributed. The correlation properties of the taps are characterised by the classical Doppler spectrum. One then assumes that each tap represents a large number of rays that arrive uniformly distributed in azimuth and elevation. This so-called isotropic scattering model is often relevant for narrowband systems in which the bandwidth W is smaller than the coherence bandwidth B_c of the channel. If, however, W increases relative to B_c, we can resolve more propagation paths, and the isotropic scattering model assumed for each tap becomes less valid.

A large number of taps can be resolved when the delay spread is large compared to the chip duration. Then the spreading bandwidth B_{ss} is larger than B_c. The point is that the resolved taps may not represent a large number of equally distributed rays, but rather a single or a few specular reflections (from large surfaces, for example) superposed by a number of weaker randomised ray contributions. The tap variation is then more properly described by a Rician distribution. Furthermore, the Doppler spectrum will not be the classical one.

Generally speaking, the isotropic scattering assumption will be less valid for any channel impulse response model when the tap spacing decreases. The Rician distribution is probably more appropriate then, since a tap may represent a particular scattered field constituent. The log-normal distribution sometimes appears. This is more difficult to explain from a physical standpoint. To this end, suppose that a tap represents a single ray, the amplitude of which can be written as a product of a number of factors such as antenna gains and reflection coefficients. Taking the logarithm, we obtain a sum. One could then hope that the terms are Gaussian distributed, in which case we may end up with a log normal distribution (if the number of terms is sufficiently large). Moreover, the isotropic scattering model is doubtful when directive antennas are employed.

The Doppler spectrum for a tap will contain sharp peaks when dominant specular components are present. If the resolution is high enough, one may assume that the Doppler spectrum contains a single peak. In this case, a Gaussian shaped profile may be more appropriate. The angle of incidence of the dominant contribution then determines the position of the peak, and the Doppler spread is characterised by the standard deviation. The correlation function will also be Gaussian.

For indoor channels, the time-delay spread is not sufficiently large in comparison to the spreading bandwidth of the WCDMA system. The indoor channel will therefore behave just like a narrowband channel. Hence there is virtually no multi-path diversity effect (cf. the RAKE receiver)

The number of taps captured by the RAKE receiver will have an impact on the fast (wideband) fading characteristics. This will be considered in the next section.

3. WIDEBAND FADING DISTRIBUTIONS

In this section, we give closed form expressions for the power received by a RAKE receiver.

If we normalise the received signal to the local mean and drop the time dependence of the taps in (2.1), the received power can be written as

(3.1) $$C = \int_{B_{ss}} |H(f)|^2 S(f)\, df$$

with $H(f)$ the Fourier transform of the channel impulse response, $S(f)$ the spectral density of the received signal and B_{ss} spreading bandwidth. Suppose that $S(f) = S_0$ for $|f| < B_{ss}/2$ and $S(f) = 0$ otherwise. Substituting (2.1) into (3.1) we obtain the inequality

(3.2) $$C = S_0 \int_{B_{ss}} |H(f)|^2 df \le S_0 B_{ss} \sum_n |a_n|^2 .$$

The right-hand side is simply the power obtained by a RAKE receiver that can resolve all the paths. Recall that we have assumed that the tap weights a_n are *uncorrelated*. Hence, in this case, we have $B_c << B_{ss}$. If the converse is true, we have flat fading, and (3.1) may be approximated by

(3.3) $$C \approx |H(0)|^2 \int_{-\infty}^{\infty} S(f)\, df = |H(0)|^2 S_0 B_{ss} .$$

Note that the ”narrowband power” is lower than that obtained by the RAKE receiver:

(3.4) $$|H(0)|^2 = \left|\sum_n a_n\right|^2 \le \sum_n |a_n|^2 .$$

If the tap weights are complex Gaussian distributed with zero mean, then it is easy to obtain the distribution of the power obtained by a RAKE receiver. Let

(3.5) $$U = S_0 B_{ss} \sum_{n=1}^{l} |a_n|^2$$

denote the received power by a RAKE receiver with l taps. It is then well known (from the theory of maximum-ratio combining) that

(3.6) $$p(U) = \sum_{n=1}^{l} \frac{p_n}{\overline{\mathrm{A}}_n} \exp\left(-\frac{U}{\overline{\mathrm{A}}_n}\right),$$

where

(3.7) $$p_n = \prod_{i=1, i \neq n}^{l} \frac{\overline{\mathrm{A}}_n}{\overline{\mathrm{A}}_n - \overline{\mathrm{A}}_i},$$

and $\overline{\mathrm{A}}_n = E\left(|a_n|^2\right)$. The mean value of U is

(3.8) $$E(U) = \sum_{n=1}^{l} p_n \overline{\mathrm{A}}_n .$$

If the taps are Rician distributed, the situation is more complicated. We then assume that $|a_n|$ are characterised by the specular parameter $m_n > 0$, which describes the steady component, and a random fading variation with a mean-square value $2s_n^2$. However, a closed form expression for the power can only be obtained when $s_n = s$. In this case, all the taps have the same fading variation. The distribution is then given by

(3.9) $$p(U) = \frac{1}{2s^2}\left(\frac{U}{m_T^2}\right)^{(l-1)/2} \exp\left\{-(U + m_T^2)/2s^2\right\} I_{l-1}\left(\frac{m_T\sqrt{U}}{s^2}\right),$$

where I_{l-1} denotes a modified Bessel function of the $(l-1)$th order and $m_T^2 = \sum_l m_l^2$.

Here we have assumed that the RAKE receiver can resolve l paths. In the next section, we shall obtain an upper bound for the largest number of resolvable paths given a certain delay spread and a spreading bandwidth.

4. MAXIMUM NUMBER OF TAPS

Suppose that the channel is characterised by a coherence bandwidth $B_c = B_r$, within which the signal components are correlated. The coherence bandwidth is associated with a coherence level r; usually one picks $r = 0.5$. If $B_{ss} >> B_r$, we may obtain a frequency diversity of the order $L \approx B_{ss} / B_c$ using a RAKE receiver. Essentially, this means that the chip time must be sufficiently short in relation to the length of the channel impulse response. This will rarely be the case in smaller cells if we use the 4.096 MHz chip rate as a starting point.

A common approximation is

(4.1) $$B_r \approx (4t_{rms})^{-1},$$

where t_{rms} denotes the time-delay spread. Hence the number of taps of the RAKE receiver is $L \approx 4t_{rms}/T_c$. For WSSUS (Wide Sense Stationary Uncorrelated Scattering) we may obtain an upper bound on the number of taps. For, it can be shown that [1]

(4.2) $$B_r \geq \arccos(r)(pt_{rms})^{-1},$$

and equality is obtained if and only if the power-delay profile can be described by two discrete components (delta functions) of equal magnitude. Hence, if the number of taps is $L = \lfloor B_{ss}/B_r \rfloor + 1$, it follows that

(4.3) $$L \leq \lfloor pt_{rms}(T_c \arccos(r))^{-1} \rfloor + 1,$$

where T_c is the chip time.

To get an idea of the number of taps dictated by (4.3), let us consider the following measured data obtained at a square, which may represent a small outdoor micro cell. The carrier frequency was 5.8 GHz. However, the results would not have been significantly different at 2 GHz. The measurements were made in a square with the transmitter and receiver antennas located 3 m and 1.2 m above ground, respectively. Six different transmitter locations were chosen; three each in LOS (line-of-sight) and OLOS (obstructed LOS, where the direct path is just about obstructed). The square is approximately 150 times 135 m, and the transmitter-receiver locations ranged from 66 to 106 m. The surrounding buildings have a height of 15-20 m.

The cumulative density function (CDF) of the *instantaneous* delay spread in LOS and OLOS is shown in Figure 1 [2]. Note that the delay-spread value in (4.3) is obtained from a mean power delay profile (a local mean) rather than a single profile. However, the CDFs in Figure 1 will be adequate to get an overall estimate of the number of taps. Thus, we observe from Figure 1 that the median value of the instantaneous delay spreads was 124 ns in LOS and 146 ns in OLOS. Using these values in (4.3) with $T_c = 244$ ns and $r = 0.5$, we obtain $L \leq 2$. Note that this value is an *upper bound*.

Finally, we see that (4.3) implies that the delay spread must be larger than 80 ns, essentially, in order to get more than one finger when the chip rate is 4.096 MHz. Hence, for most indoor channels, there is no diversity effect unless the chip rate is increased.

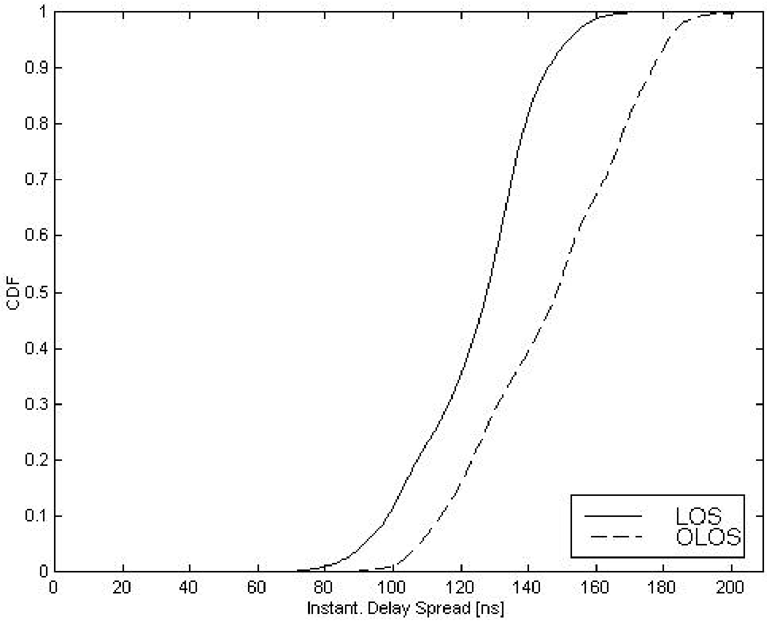

Figure 1. CDF of the instantaneous delay spread obtained at a square.

5. REFERENCES

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[2] C. Bergljung and P. Karlsson, "Propagation characteristics for broadband radio access networks in the 5 GHz band." In the proceedings of the Nordic Radio Symposium 1998 (NRS98).