Noncoherent RAKE-Receiver with Optimum Weighted Combining and Improved Closed-Loop Power Control

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Abstract[2]: In this paper, we present two methods to improve the performance of a mobile communication system compatible to the standard IS-95. The first approach reduces the bit error rates by modifications of the closed-loop power control scheme. In order to overcome the detrimental effects of delayed control information, linear prediction is used. This is especially helpful at higher velocities of the mobile user. Secondly, we apply weighted combining of correlation components in the demodulation process within the RAKE receiver.

1 Introduction

DIRECT sequence code division multiple access (DS-CDMA) is an attractive candidate to be considered for future mobile communication applications. It is regarded as a promising technique to increase the capacity of cellular mobile radio systems. In 1993 the standard IS-95, also called QUALCOMM-CDMA, was adopted in the USA [1]. Here, we use this standard as a basis to improve system performance in the uplink by means of optimized components.

To reach the same level of transmission quality for each user in the uplink of a given cell, the corresponding powers from these units must be made nearly equal at the cellular base station. Large disparities are caused by differing distances between the users and the common base station and by shadowing. These can be adjusted by each mobile station by measuring the received power in the downlink and controlling the transmit power accordingly (open-loop power control). However, the fading due to Doppler spread strongly depends on the carrier frequency which differs between the two links. For this reason, this sort of propagation loss is not symmetric in both directions. To overcome the independent fading effects in the uplink and the downlink, additional closed-loop power control has to be used [2].

For this purpose the base station determines the received power of each mobile transmitter. The conventional approach uses the average of S successive power estimates to decide whether to send to the mobile unit a command to raise or lower the transmit power. Together with the necessary transmission of power control information from the base station back to the mobile station this strategy causes a considerable time lag. Especially at high vehicle speeds the current channel condition may deviate remarkably from the one valid at the instant of the energy estimation.

The improved behaviour of the closed-loop power control presented here is achieved by a linear prediction of the channel energy at the base station. This approach allows to compensate for the delay in the control loop. In section 4, the performance of this method is shown by simulation results.

Another component considered in this paper is the well known RAKE receiver. Although a pilot channel can be employed in point-to-multiuser connections, its usage is impossible in the uplink of the treated communication system. For this reason, it is convenient to use a noncoherent detection method. A drawback of conventional square-law combining is the equally weighted addition of correlation components of the distinct diversity links. This scheme offers quite a good performance if all propagation paths have the same power. However, this is not the case if the powers differ much. RAKE fingers assigned to paths in deep fading do not contribute a significant signal energy to the sum of correlation results. Nevertheless, they do deliver the entire noise power. To avoid this disadvantage it is helpful to weight the correlation results of the

[1]Compressed postscript files of our publications are readily available over Internet at 'http://www.comm.uni-bremen.de'.

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distinct RAKE fingers prior to their addition. Under specific assumptions, the bit error rate can be decreased considerably in this way.

Since the demodulation schemes described above require some sort of information about the current channel condition, they may be looked upon as "semicoherent". Results of computer simulations presented at the end of the paper emphasize the importance of using "realistic" assumptions to assess the performance of the proposed configurations. This is to say that, on the one hand, we use a channel model in accordance with COST 231 and on the other hand that in absence of the known channel parameters one has to rely on estimates. Especially the second restriction leads to a performance poorer than expected.

2 Improvement of Closed-Loop Power Control

We examine the influence of power control in a single isolated cell. We assume that the considered user is already tracking a pilot signal and is transmitting and receiving at full data rate. An open-loop power control mechanism is assumed to compensate for propagation loss due to range and to shadowing in an ideal manner, i.e. the mean received energy at the base station is constant.

As noted above, the propagation loss is not equal in the two directions. The induced Doppler shifts due to mobile movement depend on the carrier frequency. For example, the standard IS-95 fixes the difference in center frequencies between forward and reverse link at 45 MHz. Thus, a closed-loop power control scheme is necessary to compensate for the direction–dependent effects of fading due to Doppler spread.

For this purpose, the base station continuously measures the received powers of all mobile units. The calculation of the current received power is done by averaging the energy estimates of the last six received symbols. Depending on whether the measured value is above or below a desired level, the base station transmits commands *"raise transmit power"* and *"lower transmit power"* to the mobile user, respectively. The change in transmission power at the mobile station is done by a fixed amount of e.g. 0.5 dB.

For the sake of reduced capacity in transmitting of power control information in the forward link, the adjustment of power is done in intervals of 1.25 ms corresponding to the duration of 6 Walsh symbols[3]. The power control information is represented by two equal bits. To avoid an additional decoding delay, these bits are transmitted in the downlink without further coding.

The strategies described above already cause an effective delay of six symbols – without the consideration of an additional delay due to transmission and calculation time. In the simulation results presented here, an additional delay of six symbols is taken into account. The whole effective delay therefore grows to an interval of 12 symbols.

Figure 1 illustrates the influence of the power control scheme described above on the channel energy probability density. The vehicle speed of the mobile subscriber varies in the range of 8 km/h and 180 km/h. The underlying mobile channel is a Rayleigh channel with mean equal energy on four independent paths. The total mean energy m_E

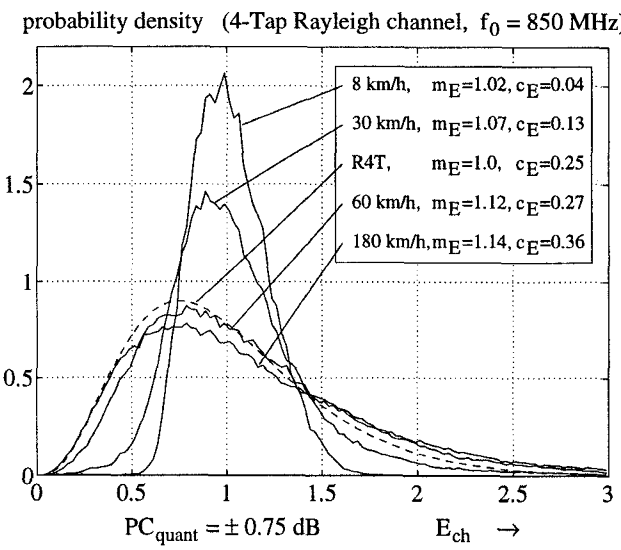

Figure 1: Energy probabilities

in the case that no closed-loop control scheme is used equals one, the normalized variance c_E therefore equals 0.25. The dashed line in Figure 1 represents the corresponding chi-square distribution. This theoretical result can be compared with the simulation results indicated as solid lines.

Obviously, the power control policy allows to combat the effects of moderately slow fading. In case of 8 km/h the energy is strongly concentrated around one as the desired value. At vehicle speeds above 60 km/h, the control scheme is no longer able to cope with the fading. In addition, the closed-loop mechanism decreases system performance compared with the case when using the assumed ideal open-loop control by itself. This is due to the control delay which affects the loop especially at high speeds. A fast varying channel may have

[3]One Walsh symbol represents a 64-ary signal of duration $4 \cdot 64$ chips $= 208\,\mu s$. Six of these are combined into one power control group (PCG).

changed its condition from the moment of estimation to the moment of action considerably. The attempt to control can therefore be seen as an additional disturbance.

At time instant i, QUALCOMM proposes an averaging over the six latest estimates $(i-6)\dots(i-1)$ (symbol period). The current control instruction comes into effect from $(i+6)$ to $(i+11)$. The task is to overcome the detrimental effects of the transmission delay. For this purpose, linear prediction is used. It is implemented following the RLS-algorithm (e.g. [3]) and uses a longer interval of length n of estimated channel energies to determine the control instruction. From these values, the energy at instant $(i+8)$ is predicted (this is in the middle of the PCG when the information will become valid). Furthermore, it was already determined at instant $(i-6)$ what will happen during $(i)\dots(i+6)$. This control operation will influence the following intervalls, too. Therefore, it can be taken into account when predicting the channel energy. The performance achieved with these modifications in comparison with the QUALCOMM proposal is presented in section 4.

3 RAKE Receiver with Channel dependent Path Weights

The demodulation scheme of the IS-95–uplink contains the well known RAKE receiver. In order to demodulate the received multipath signals, a separate correlator is provided for each echo delay considered. In each of those L_R "fingers" the receiver has to correlate the incoming signal with all hypotheses of transmitted symbols h_j, $j\in\{0,\dots,63\}$. The results form the correlation components $U_{j,\lambda}$, $\lambda\in\{0,\dots,L_R-1\}$.

The optimal detection method is given by coherent reception. The maximum ratio combiner detects the value with maximum magnitude of the decision components V_j according to

$$V_j^{coh} = \sum_{\lambda=0}^{L_R-1} \mathrm{Re}\{c_\lambda^* \cdot U_{j,\lambda}\} \quad , \qquad (1)$$

where c_λ denotes the channel coefficients of the corresponding propagation path. The index of $\max_{\{j\}}(V_j)$ indicates the most likely transmitted symbol [3]. The lack of a pilot in the uplink leads to the necessity of noncoherent reception. The simplest method is square-law combining (SLC):

$$V_j^{SLC} = \sum_{\lambda=0}^{L_R-1} |U_{j,\lambda}|^2 \quad . \qquad (2)$$

This scheme is efficient as long as the propagation paths have equal average relative powers. However, the performance degrades if the multipath components differ in power. To mitigate this degradation, it is useful to weight the correlation results before summing them up.

Under the assumption of known path strengths and equally distributed phases, the weighted combining has to be carried out according to [4]

$$V_j^{AWC} = \sum_{\lambda=0}^{L_R-1} \ln \mathrm{I}_0\left(\frac{2\,E_S}{N_0}\,|c_\lambda|\cdot|U_{j,\lambda}|\right) \quad , \qquad (3)$$

where the superscript AWC stands for ***A**mplitude **W**eighted **C**ombining*. $\mathrm{I}_0(\cdot)$ denotes the 0th-order modified Bessel function of the first kind. This function increases approximately exponentially for large arguments. For that, in this application the term $\ln(\mathrm{I}_0(\cdot))$ can be approximated by the linear function and (3) simplifies to

$$V_j^{AWC} \approx \sum_{\lambda=0}^{L_R-1} |c_\lambda|\cdot|U_{j,\lambda}| \quad . \qquad (4)$$

If the path strengths are assumed to be Rayleigh distributed and mutually independent, an alternative combining law can be exploited. With the mean-square strength $\bar{c}_\lambda^2 = E\{|c_\lambda|^2\}$ of propagation paths this is [5]

$$V_j^{PWC} = \sum_{\lambda=0}^{L_R-1} \frac{\bar{c}_\lambda^2}{N_0 + \bar{c}_\lambda^2\,E_S}\,|U_{j,\lambda}|^2 \quad , \qquad (5)$$

where E_S is the common energy of the symbols h_j. In contrast to AWC in (4), PWC (***P**ower **W**eighted **C**ombining*) emphasizes the use of the mean powers in the combining procedure.

In a practical receiver design we obtain an estimate for the channel weights by evaluating the correlation components $U_{j,\lambda}$. Without any disturbance in the ideal case, the results in each RAKE finger contain at one position the channel coefficient and all other components are zero. Unfortunately, in practical systems the existing noise heavily disrupts the situation. A way out is short time averaging which suppresses the noise.

The estimation of the mean-square strengths required in (5) can be performed by means of averaging with exponential weighting into the past. The running sums are recursively calculated for each finger

$$\hat{\bar{c}}_\lambda^2(i) \;=\; w\cdot\hat{\bar{c}}_\lambda^2(i-1) \;+\; (1-w)\cdot|\hat{c}_\lambda(i)|^2 \quad ,$$

where w represents a "forgetting" factor $0 < w < 1$.

4 Simulation Results

4.1 Closed-Loop Power Control

We present some simulation results for a noncoherent RAKE receiver in an asynchronous CDMA uplink connection. To achieve moderate simulation times, the investigations were done without channel coding. The fixed amount by which the mobile unit raises or lowers its transmit power is chosen to be $PC_{quant} = 0.75$ dB. The probability of erroneous transmission of control bits in the downlink is fixed at 5%. A mobile radio channel with four independent diversity paths and equal mean-square strength is assumed.

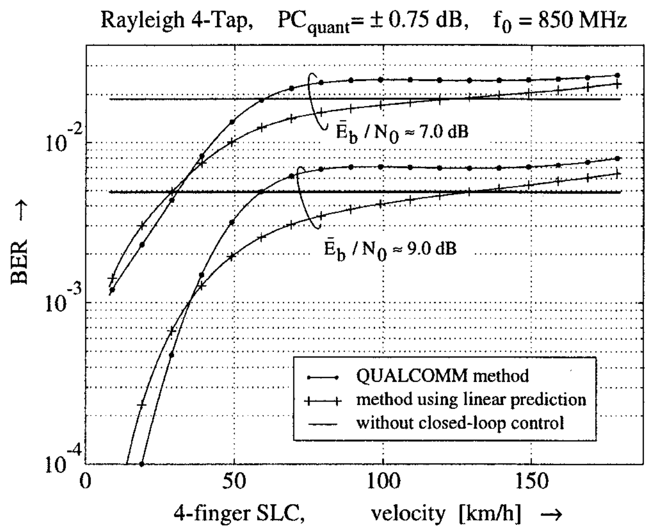

Figure 2: Bit error rates

Figure 2 illustrates the gain in bit error performance which can be achieved by the use of linear prediction in the control scheme. The horizontal lines represent the error rates when no closed-loop control is used. The dotted lines represent the conventional approach. As already deduced from Figure 1, the QUALCOMM method gets worse above 60 km/h compared with pure (ideal) open-loop control. The modified power control policy presented here obviously reduces the bit error probability in the important range of higher velocities corresponding to high error rates. Furthermore, this method provides a lower bit error rate up to 120 km/h compared with the case without closed-loop control instead of only 60 km/h obtained by using the QUALCOMM method. Being sufficiently low anyway, the slightly increased bit error rates at low speeds can be accepted.

4.2 Semicoherent Detection using Path Weighting

Figure 3 summarizes the bit error rates for the different combining methods. In all cases, the receiver combines the signal components of four RAKE fingers. If needed, the requested parameters of the propagation channel are ideally supplied. The results visualized in the upper group of curves were obtained by transmitting over a single path channel with Rayleigh distributed amplitude. The remaining curves stem from a four path Rayleigh channel with equal mean-square strength. As expected, the lower bound for the bit error rates is given by the coherent detection method (c.f. (1), dotted line) and the upper bound by the incoherent method according to (2).

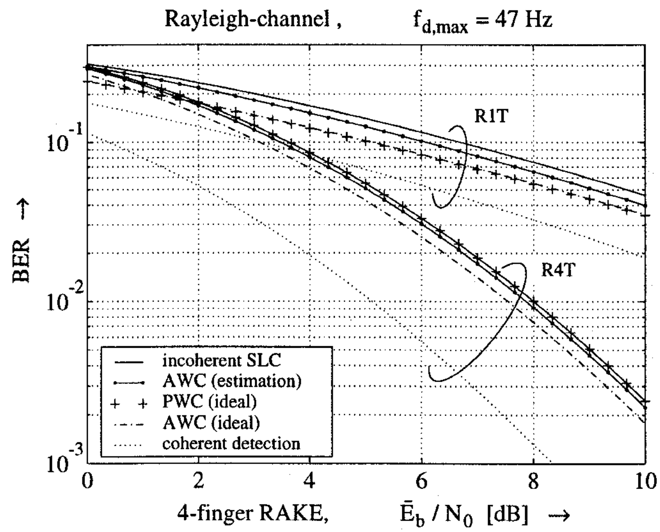

Figure 3: Bit error rates for transmission over Rayleigh channels

Considering the upper group, it can be seen that both combining methods *AWC* and *PWC* lead to nearly the same improvement of 1.6 dB compared with the square law combining. If only one path is present, the use of a 4-finger RAKE receiver represents the worst case for square law combining. For that, the loss in signal to noise ratio should be less than 1.6 dB under more realistic circumstances.

The other extreme is given by the "R4T" group. We first notice that the improvements are smaller compared with the "R1T" group. Second, the *AWC* and *PWC* methods offer different performance. The bit error rates of the *PWC* method are nearly the same as those for square law combining due to identical path strengths. The advantage of the *AWC* method arises from the fact that the actual fading situation on the individual paths may differ much from the mean-square strength and from each other. When using a 4-finger RAKE receiver, the reachable gain decreases from 1.6 dB for the 1-tap to 0.5 dB for the 4-tap Rayleigh channel. In [6], a performance of the same order has been found under similar conditions.

For the *AWC* combining method, the inevitable estimation of the actual path strengths in realistic implementations decreases its advantage considerably. In contrast, the estimate of the mean-square strength for the *PWC* method is sufficiently accurate so that the curves for estimated and ideal known parameters would be congruent.

To further investigate the performance of the different methods, we considered a channel with a realistic power delay spectrum. We made use of a hilly terrain (HT) channel profile, assuming a velocity of 60 km/h (maximum Doppler shift 47 Hz). Due to the shape of the HT power delay spectrum, one might expect results comparable to those obtained for the 1-tap Rayleigh channnel. In fact this is true, as illustrated in **Figure 4**.

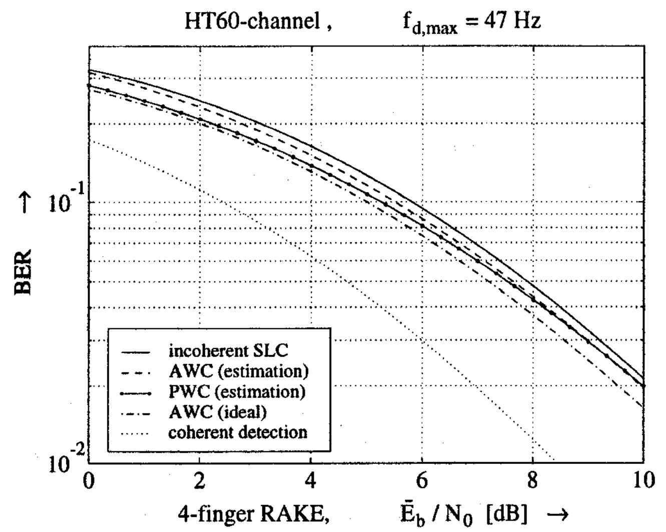

Figure 4: Bit error rates for transmission over HT channel

The bit error rates increase if estimated parameters are used rather than ideal known ones. It is surprising that under these conditions the *PWC* method is superior to the *AWC* method. The reason for this behaviour are the accurate estimates of the mean-square strengths for the *PWC* method whereas the estimation performance for the actual path strengths for the *AWC* method is quite poor.

The curve for the *PWC* method with ideal known parameters is left out in Figure 4 because it would cover the *PWC* curve for the case of estimation. It should be noticed, that even the HT channel profile used is advantageous for the proposed combining methods, as the mean-square strength is mainly concentrated on one tap. Transmitting over channels with larger delay spreads produces results more similar to those obtained for the R4T channel profile. Thus, the potential gain in E_b/N_0 is reduced.

5 Summary

Two improvements have been introduced which reduce the bit error rate in the uplink of a CDMA system. The modified closed-loop power control mechanism offers better BER performance for fast fading channels than the conventional scheme. The second approach introduced weighted combining of correlator output signals within the RAKE receiver. In our example, the advantage in SNR performance is in the order of 1.6 dB under idealized conditions. Simulations in a realistic propagation environment show that the estimation of the required channel parameters make this gain unduly optimistic.

References

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