Impact of closed-loop power control to received signal statistics is studied. Results in this paper are based on single-user link level simulations with a fixed-step power control. Main interest is on the Rayleigh fading channel correlation, amplitude and phase changes in the system due to the closed-loop power control. Power control dependent changes in the complex channel coefficient correlation are needed, e.g., in the Kalman or Wiener filter based channel estimation. Key adjustable parameters in the simulations are mobile speed, power control step size and power control command error rate. Simulation results indicate that power control can compensate channel variations at low velocities. When the fading is fast enough compared to the power control rate power control can increase fluctuation in the received signal. Well-working power control reduces channel correlation slightly.

I. INTRODUCTION

Power control is an important component of direct-sequence CDMA systems. Main tasks of power control (PC) are to combat the near-far problem and to reduce the transmitted power levels [1, 2, 3]. The near-far effect is an inherent CDMA property where the near base station users overwhelm more distant simultaneous users due to the non-orthogonality of these transmissions. Savings in transmitted powers decrease mutual interference and extend battery life, which is crucial for the light mobile units. As far as the power control is close to perfect the system capacity can be high [4, 5]. However, it is also well known that CDMA capacity is very sensitive to imperfections in power control [1, 6, 7, 8]. These errors are usually modelled by a lognormal distribution.

The conventional fixed-step PC algorithm is very simple. It requires measurement of the received signal power (S-based PC) and/or interference level (SIR-based PC). Measured values are compared to the targets and a hard decision on the power control command of one step up or down is sent over a feedback channel and executed in the mobile unit. Fixed-step algorithms cannot fully react to fast changes in the signal level (deep fades) at reasonable update rates. Therefore adaptive step-size and predictive approaches have also been proposed, e.g., [1, 9]. Impact of power control becomes a complicated issue when multiple users’ contribution in one or multiple cells is to be studied. The reason for this complexity is that every user’s power control commands change interference statistics observed in other links. This leads to a challenging SIR target optimisation problem where SIR targets should be adaptive depending on the network load and transmitted data rates [5, 10].

In this paper the focus is on the conventional fixed-step closed-loop power control. Only a single-user uplink with a feedback power control loop is modelled. Data, modulation, coding, interleaving, etc. link details have been omitted in the system model. Interest lies in the received signal magnitude and phase plus mean value, variance and correlation of the received signal power. These statistics are compared with and without power control. Additionally, sensitivity of these statistics to mobile speed, power control step size and error rate variations is investigated. Results of this study can be used in the research of advanced receiver structures for wireless CDMA systems.
II. SYSTEM MODEL

A. Preliminaries

Theoretical channel autocorrelation values have been calculated from the Clarke’s model [11] that can be represented as

$$\rho(\tau) = J_0(2\pi f_D \tau)$$  \hspace{1cm}(1)$$

where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind,

$$f_D = \frac{v}{c_l}$$  \hspace{1cm}(2)$$

is the maximum Doppler spread, $v$ is the speed of the mobile, $c_l$ is the speed of light, $f_c$ is the carrier frequency and $\tau$ is the delay (sampled at power control command rate, i.e., symbol rate).

In the frequency domain, the corresponding power spectrum density (classical Jake’s Doppler spectrum [11]) is of the form

$$S(f) = \begin{cases} \frac{1}{\pi f_D^2 \left(1 - \frac{f}{f_D}\right)} & \text{if } |f| \leq f_D \\ 0 & \text{if } |f| > f_D \end{cases}$$  \hspace{1cm}(3)$$

A. Simulation Model

Fig. 1. shows a block diagram of the simulation model used in this paper. Thick solid lines represent complex signals divided into in-phase (I) and quadrature (Q) branches in the model.

![Simulation model block diagram](image)

Fig. 1. Simulation model block diagram.

Signal source generates a constant, complex signal (equally strong normalised I and Q components). Data and modulation is neglected in the model. The amplification block adjusts the transmitted power up or down according to power control commands. The fading channel model is multiplicative complex noise whose magnitude depends on the desired distribution (Rayleigh in this case). Additionally, the signal waveform is filtered in order to include the Doppler spectrum characteristics, e.g., classical Jakes spectrum. Signal statistics (channel complex envelope and phase, correlation, PSD, received power mean and variance) are recorded at the output of the Rayleigh fading channel. Additive white Gaussian noise (AWGN) is summed according to the desired signal-to-noise ratio. Desired signal power is estimated by taking the square of the complex envelope magnitude.

Interference caused by other users is modelled as a Gaussian random variable. The complex channel coefficient is of the form

$$c(t) = |A(t)|e^{j\theta(t)} = A_I(t)\cos(\theta(t)) + jA_Q(t)\sin(\theta(t))$$  \hspace{1cm}(4)$$

where $|A(t)|$ is the magnitude of the complex coefficient that can be divided to in-phase and quadrature components $A_I(t)$ and $A_Q(t)$ and $\theta(t)$ is the phase of the coefficient.

The averaged and normalised channel sample autocorrelation function is calculated as

$$\rho(\tau) = \text{Re} \left\{ \frac{\sum_{k=0}^{n-1} c(k)c^{*}(k - \tau)}{\sum_{k=0}^{n-1} |c(k)|^2} \right\}$$  \hspace{1cm}(5)$$

where, in this paper, the delay index $k$ ranges from 0 to 9 and the averaging is made over $n \equiv 100000$ samples of channel coefficients in the simulations.

III. NUMERICAL RESULTS

Key simulation parameters and variables are presented in Table 1. Bold parameters are nominal values. Notice that the signal-to-noise ratio in the AWGN block is so high that the channel can be treated as noiseless. Hence, the
flat Rayleigh fading channel statistics purely causes the channel distortions.

### Table 1. Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>1920 MHz</td>
</tr>
<tr>
<td>Channel model</td>
<td>1-path Rayleigh</td>
</tr>
<tr>
<td></td>
<td>(Classical Doppler spectrum)</td>
</tr>
<tr>
<td>Mobile speed</td>
<td>3, 10, 30, 50, 100, 200 km/h</td>
</tr>
<tr>
<td>PC algorithm</td>
<td>S-based, S/R-based</td>
</tr>
<tr>
<td>PC command rate</td>
<td>1600 Hz</td>
</tr>
<tr>
<td>PC loop delay</td>
<td>1 symbol = 1/1600 s</td>
</tr>
<tr>
<td>PC step size (ΔS)</td>
<td>0.5, 1, 2 dB</td>
</tr>
<tr>
<td>PC command error rate (BER&lt;sub&gt;PC&lt;/sub&gt;)</td>
<td>0, 0.01, 0.02</td>
</tr>
<tr>
<td>PC dynamic range</td>
<td>± 40 dB</td>
</tr>
<tr>
<td>S target</td>
<td>0 dB</td>
</tr>
<tr>
<td>Signal-to-Noise Ratio</td>
<td>100 dB</td>
</tr>
</tbody>
</table>

Figs. 2-4 illustrate how well the power control algorithm can track the fading channel variations. At low speed (Fig. 2, \( v = 3 \) km/h) the fading is so slow that power control operates almost perfectly. Only the deepest fades cause some additional variation to the step-size dependent ripple. At slightly higher velocities (Fig. 3, \( v = 10 \) km/h) deep fades occur more often, and consequently, power control fails to track these notches. At the mobile speed \( v = 50 \) km/h the complex envelopes of the received signal with or without power control become very similar. Hence, the power control rate is too slow at high velocities.

Fig. 2. Received envelope (\( v = 3 \) km/h).

Fig. 3. Received envelope (\( v = 10 \) km/h).

Fig. 4. Received envelope (\( v = 50 \) km/h).

Channel autocorrelation and power spectral density (PSD) characteristics are illustrated in Figs. 5-7. Fig. 5 shows the channel autocorrelation function values for \( τ = 0, \ldots, 9 \) symbols (0 - 5.625 ms) at slow mobile speeds. Impact of power control is most significant at 10 km/h velocity. In majority of the cases the power control decreases correlation less than 1 %. Without power control the theoretical values and simulations agree well. Fig. 6 depicts autocorrelation properties at higher speeds. Here it is difficult to distinguish between the curves with or without PC.

Due to symmetry only one-sided channel power spectral density is plotted in Fig. 7. In PSD simulation the Bartlett method was used with the FFT length of 1024. Without PC the classical U-shaped spectrum is received. With PC the power levels are slightly higher. Additionally, peaks in PSD are observed at lowest simulated speeds. These smaller Doppler
peaks can be explained by the successful PC (- higher probability for lower Doppler frequencies).

Some statistics of the received signals are presented in the Appendix (Table 2). At the mobile speeds higher than 10 km/h the power control only causes extra variance to the signal. Table 2 also demonstrates how the correlation between two consecutive samples of complex channel coefficients, during one symbol interval of a \( \tau \), varies with and without power control. All simulation results have been averaged over 100000 samples.

Simulation results and theoretical correlation values agree perfectly at very low mobile speeds. Small deviations are seen for higher speeds (30 - 200 km/h). According to these simulation results the impact of PC at low velocities could be modelled by multiplying (1) with a constant \( \alpha = 0.9935 \). For high velocities (\( v > 50 \text{ km/h} \)) the impact of PC to autocorrelation seems to diverge from the trend at lower velocities.

In the Appendix the received mean power and variance are compared at variable PC step sizes (Table 3) and at variable PC command error rates (Table 4). According to Table 3 the 1 dB step size seems to be a good compromise at moderate velocities. PC command error rates up to 2 % cause only a minor degradation in the statistics.

IV. CONCLUSIONS

Impact of closed-loop uplink power control to WCDMA channel parameters was studied. Power control was noticed to be able to compensate relatively slow fading. However, in fast fading channels power control only introduced additional channel variations and the received mean signal power exceeded the target level. Power control decreased the correlation between consecutive channel samples at low mobile speeds (\( v < 50 \text{ km/h} \)). This reduction could be compensated in the Clarke’s model by multiplying the Bessel function with a correction constant. For high mobile speeds (\( v > 50 \text{ km/h} \)) the changes in correlation became more arbitrary. 1 dB PC step size showed best performance at \( v = 10 \text{ km/h} \) and was a good compromise at other speeds as well. Received signal statistics were barely affected by moderate PC command errors.
ACKNOWLEDGEMENT

The author would like to thank Prof. Savo Glisic for the valuable discussions and comments during the preparation of the manuscript.

REFERENCES


APPENDIX

Table 2. Mean value, variance and autocorrelation comparison with and without power control.

<table>
<thead>
<tr>
<th>Case</th>
<th>Mean E[S]</th>
<th>Variance E[S²]</th>
<th>Autocorrelation ρ(0,1) (sim.)</th>
<th>Autocorrelation ρ(0) (theor.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v = 3 km/h, PC off</td>
<td>0.9929</td>
<td>1.068</td>
<td>0.9999</td>
<td>0.9999</td>
</tr>
<tr>
<td>v = 3 km/h, PC on</td>
<td>1.040</td>
<td>0.09485</td>
<td>0.9934 (- 0.65 %)</td>
<td>-</td>
</tr>
<tr>
<td>v = 10 km/h, PC off</td>
<td>0.9940</td>
<td>0.9874</td>
<td>0.9988</td>
<td>0.9988</td>
</tr>
<tr>
<td>v = 10 km/h, PC on</td>
<td>1.142</td>
<td>0.4721</td>
<td>0.9922 (- 0.66 %)</td>
<td>-</td>
</tr>
<tr>
<td>v = 30 km/h, PC off</td>
<td>1.001</td>
<td>0.9975</td>
<td>0.9889</td>
<td>0.9891</td>
</tr>
<tr>
<td>v = 30 km/h, PC on</td>
<td>1.525</td>
<td>3.003</td>
<td>0.9825 (- 0.65 %)</td>
<td>-</td>
</tr>
<tr>
<td>v = 50 km/h, PC off</td>
<td>1.003</td>
<td>1.004</td>
<td>0.9685</td>
<td>0.9698</td>
</tr>
<tr>
<td>v = 50 km/h, PC on</td>
<td>1.592</td>
<td>3.647</td>
<td>0.9627 (- 0.60 %)</td>
<td>-</td>
</tr>
<tr>
<td>v = 100 km/h, PC off</td>
<td>1.003</td>
<td>1.013</td>
<td>0.8770</td>
<td>0.8818</td>
</tr>
<tr>
<td>v = 100 km/h, PC on</td>
<td>1.691</td>
<td>4.658</td>
<td>0.8758 (- 0.14 %)</td>
<td>-</td>
</tr>
<tr>
<td>v = 200 km/h, PC off</td>
<td>1.000</td>
<td>1.005</td>
<td>0.5548</td>
<td>0.5689</td>
</tr>
<tr>
<td>v = 200 km/h, PC on</td>
<td>1.651</td>
<td>4.061</td>
<td>0.5706 (+ 2.8 %)</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3. Impact of PC step size to received signal statistics ($BER_{PC} = 0$).

<table>
<thead>
<tr>
<th>Case</th>
<th>$E[S]$, $\Delta S = 0.5 \text{ dB}$</th>
<th>$E[S]$, $\Delta S = 1 \text{ dB}$</th>
<th>$E[S]$, $\Delta S = 2 \text{ dB}$</th>
<th>$E[S^2]$, $\Delta S = 0.5 \text{ dB}$</th>
<th>$E[S^2]$, $\Delta S = 1 \text{ dB}$</th>
<th>$E[S^2]$, $\Delta S = 2 \text{ dB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v = 3 \text{ km/h}$</td>
<td>1.034</td>
<td><strong>1.040</strong></td>
<td>1.123</td>
<td>0.08204</td>
<td><strong>0.09485</strong></td>
<td>0.3207</td>
</tr>
<tr>
<td>$v = 10 \text{ km/h}$</td>
<td>1.236</td>
<td><strong>1.142</strong></td>
<td>1.1898</td>
<td>0.847</td>
<td><strong>0.4721</strong></td>
<td>0.7327</td>
</tr>
<tr>
<td>$v = 50 \text{ km/h}$</td>
<td>1.455</td>
<td><strong>1.525</strong></td>
<td>1.653</td>
<td>2.535</td>
<td><strong>3.003</strong></td>
<td>4.024</td>
</tr>
<tr>
<td>$v = 100 \text{ km/h}$</td>
<td>1.492</td>
<td><strong>1.592</strong></td>
<td>1.879</td>
<td>2.740</td>
<td><strong>3.647</strong></td>
<td>6.670</td>
</tr>
<tr>
<td>$v = 200 \text{ km/h}$</td>
<td>1.543</td>
<td><strong>1.691</strong></td>
<td>2.043</td>
<td>2.975</td>
<td><strong>4.658</strong></td>
<td>10.57</td>
</tr>
</tbody>
</table>

Table 4. Impact of PC command errors to received signal statistics ($\Delta S = 1 \text{ dB}$).

<table>
<thead>
<tr>
<th>Case</th>
<th>$E[S]$, BER$_{PC} = 0$</th>
<th>$E[S]$, BER$_{PC} = 1 %$</th>
<th>$E[S]$, BER$_{PC} = 2 %$</th>
<th>$E[S^2]$, BER$_{PC} = 0$</th>
<th>$E[S^2]$, BER$_{PC} = 1 %$</th>
<th>$E[S^2]$, BER$_{PC} = 2 %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v = 3 \text{ km/h}$</td>
<td><strong>1.040</strong></td>
<td>1.041</td>
<td>1.042</td>
<td><strong>0.09485</strong></td>
<td>0.09739</td>
<td>0.1026</td>
</tr>
<tr>
<td>$v = 10 \text{ km/h}$</td>
<td><strong>1.142</strong></td>
<td>1.144</td>
<td>1.148</td>
<td><strong>0.4721</strong></td>
<td>0.4935</td>
<td>0.5152</td>
</tr>
<tr>
<td>$v = 50 \text{ km/h}$</td>
<td><strong>1.525</strong></td>
<td>1.529</td>
<td>1.536</td>
<td><strong>3.003</strong></td>
<td>2.907</td>
<td>2.9074</td>
</tr>
<tr>
<td>$v = 100 \text{ km/h}$</td>
<td><strong>1.592</strong></td>
<td>1.596</td>
<td>1.605</td>
<td><strong>3.647</strong></td>
<td>3.831</td>
<td>3.913</td>
</tr>
<tr>
<td>$v = 200 \text{ km/h}$</td>
<td><strong>1.691</strong></td>
<td>1.696</td>
<td>1.701</td>
<td><strong>4.658</strong></td>
<td>4.730</td>
<td>4.799</td>
</tr>
<tr>
<td></td>
<td><strong>1.651</strong></td>
<td>1.656</td>
<td>1.658</td>
<td><strong>4.061</strong></td>
<td>4.099</td>
<td>4.122</td>
</tr>
</tbody>
</table>