REGULAR PAPER SECTION

A NEW WCDMA TRANSMIT POWER CONTROL TECHNIQUE

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Abstract: In this paper a new Transmit Power Control (TPC) scheme is proposed for SINR-based fast PC algorithms using frequency-mutiplexed pilot symbols on the uplink of a WCDMA Rayleigh fading mobile radio channel with multi-path. The performance of various PC techniques is evaluated by means of Monte Carlo computer simulation. The WCDMA modem considered includes different coding schemes and a matched filter RAKE combining receiver. The objective is to investigate the effects of the number of resolvable propagation paths, the antenna diversity reception scheme employed and the coding scheme used on the performance of the fast power controlled WCDMA receiver in a Rayleigh fading single-cell environment. The results obtained indicate that the unbalanced PC algorithms outperform the conventional balanced PC algorithms. It is also theoretically proved that the unbalanced PC algorithms have better tracking ability than the conventional PC algorithms.

Keywords: *Fast Power Control (FPC), Transmit PC (TPC), SINR-based PC, pilot symbols, WCDMA, Monte Carlo simulation, frequency-selective multi-path Rayleigh fading*

1. INTRODUCTION

Over the past several years, Direct Sequence Code Division Multiple Access (DS-CDMA) has proven itself to be a viable alternative to both Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) [1], [2]. The advantage that CDMA has over TDMA can be attributed to the number of CDMA spreading codes or users that can be accommodated within a given spreading bandwidth, compared to the number of time slots or users within an expanded (with respect to a single user system) on-the-air bandwidth. Whereas TDMA only allows a limited number of slots (users) for a given channel bandwidth, CDMA can accommodate as many users as the quality of service would allow, with a gradual degradation in performance as the number of users increases beyond a predetermined quality of service (QoS) level. The degradation is primarily determined by the correlation characteristics of the *spreading sequences* and *sharing resources* that give the advantage of providing higher capacity and greater flexibility than TDMA. Spread-Spectrum (SS) techniques are broadband in the sense that the entire transmission bandwidth is shared between all users at all times. It implies that the system capacity is very much dependent on Multiple-Access Interference (MAI). Therefore, the design of wideband CDMA (WCDMA) systems are considered as a design of power management wireless network architecture with power control being the central mechanism for resource allocation and interference management amongst users.

The paper by Bambos [3] proposed the Multi-Target PC (MTPC) algorithm and investigated the power management in multi-media environments in various layers of operation. However, it is a challenge to design a system that can dynamically adapt to the time-varying channel and traffic, and, at the same time, deliver the services according to the user required QoS. This paper focuses on the tracking ability and Bit-Error-Rate (BER) performance at physical layer of fast power control techniques, which are aimed to overcome the power variations due to distance dependent path loss, shadowing and multi-path fading. The ultimate goal is to evaluate the effects of the number of resolvable propagation paths, antenna diversity reception and multi-finger RAKE receiver on the fast power control (FPC)-algorithms considered in a single-cell WCDMA fading channel environment.

The outline of the paper is as follows: Section 2. describes the system model used in the Monte Carlo Simulation package. The proposed new W-CDMA PC technique and its stability is presented in Section 3. Section 4. is devoted to the simulation results on the tracking ability and BER performance of various PC algorithms under various settings. A brief conclusion in drawn in Section 5. and acknowledgements are presented in Section 6.

2. SYSTEM MODEL

The uplink transmission structure considered in this paper is shown in Fig. 1. It is assumed here that the in-phase and quadrature components of the transmitted signal are multiplied by a random segment of a pre-generated fading channel complex envelope and then channel encoded and

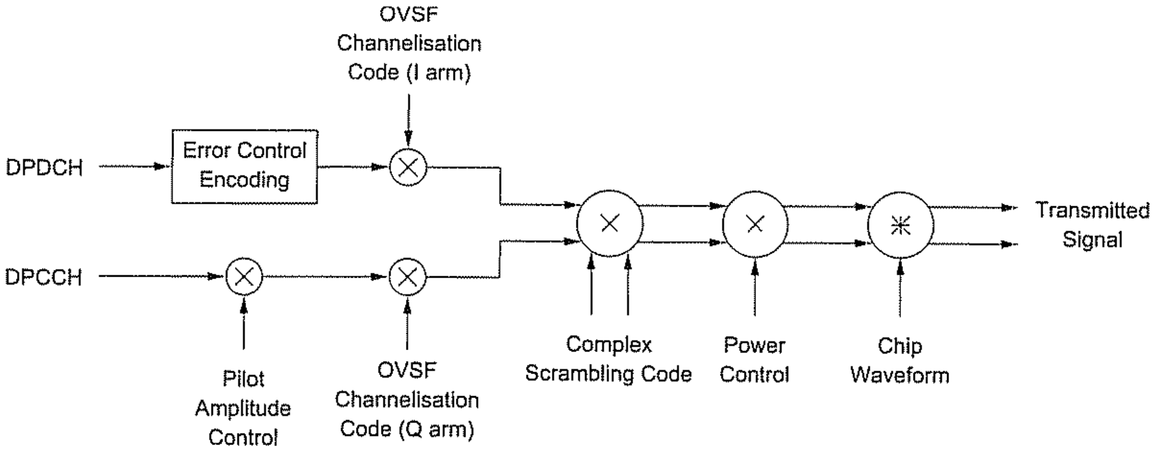

Figure 1: Transmitter Processing for Single User

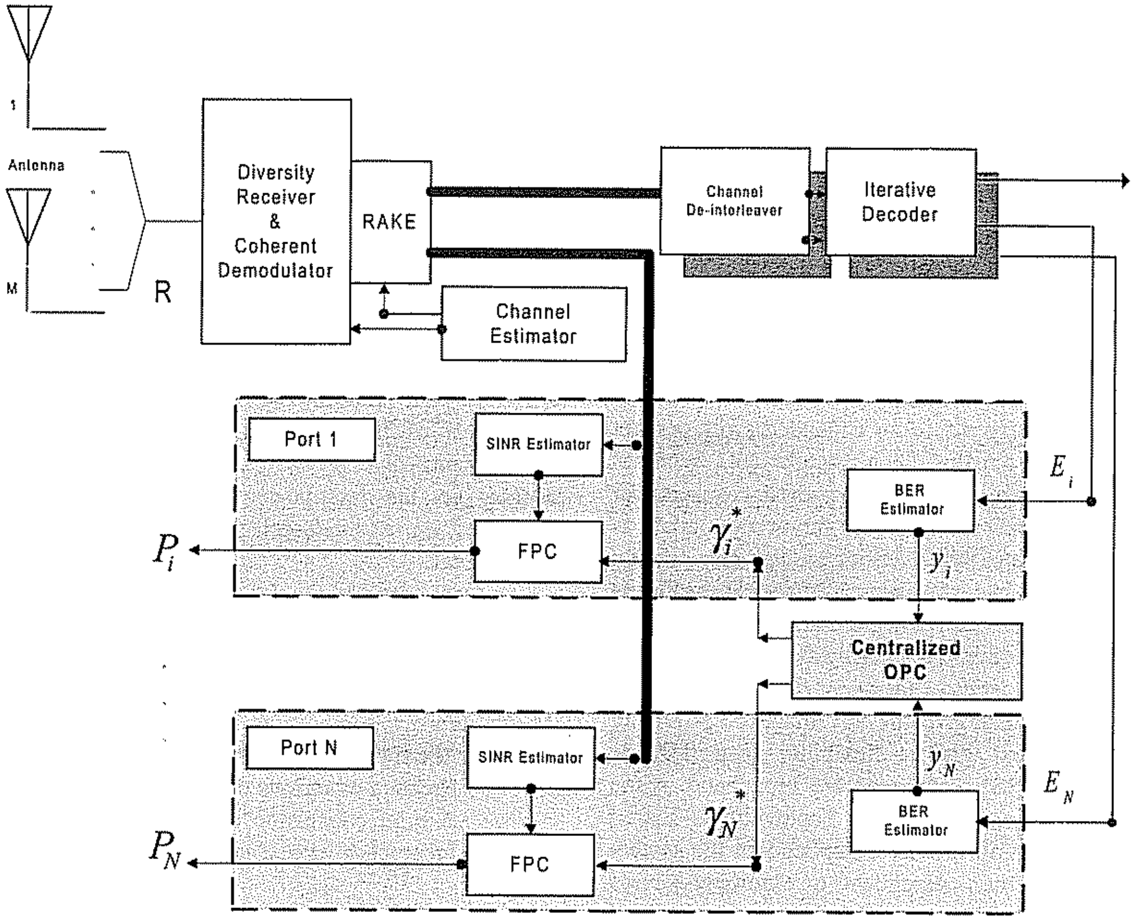

Figure 2: A multi-target APC with N distributed Outer-loop Power Control.

block interleaved. The QPSK symbol sequence is spread by the spreading sequence to a bandwidth wider than the inverse of the symbol period. Finally the spreaded signal is power amplified, according to the PC command received from the cell site, and transmitted over a fading multi-path channel.

With reference to Fig. 2, when the multi-path spread-slot signals are despread by the matched filter and resolved into L QPSK signals that have propagated via different propagation paths with different time delays, the fast power control command is computed for the next transmit slot using pilot symbols. Only when the entire de-interleaver buffer is filled, can the receiver frame-based processing commence. For data reception, the RAKE combiner output is QPSK demodulated and decomposed into a soft decision sample sequence, whereafter the Turbo decoder recovers the transmitted data.

The Outer-loop Power Control (OPC) mechanism will generate N sets of desired signal-to-interference-noise ratio (SINR) for the next transmit frame, i.e. a power vector $(\gamma_1^*, \ldots, \gamma_N^*)$. This power vector representing N different QoS (BER) requirements is used to control the transmitted signal in different iterative decoding ports. In Figure 2, $y_1(n), \ldots, y_N(n)$ are the outputs of ports $1, \ldots, N$ at the nth iteration, representing the estimated BER, $(\gamma_1, \ldots, \gamma_N)$ denotes the power vector and $p_1, \ldots, p_N$ the power control commands of N users.

3. A NEW WCDMA TRANSMIT POWER CONTROL TECHNIQUE

Depicted in Fig. 3 is a block diagram of a general closed-loop PC system, which could be signal-strength based or SINR-based, depending on the threshold-method used. Channel variation in Fig. 3 is used to describe how a transmitted signal is affected by conditions such as fading, interference or noise while the signal is transmitted through the channel. The conventional SINR-based Fast Power Control (FPC) can be viewed as [3]:

$$\gamma_i^* = \frac{P(n)}{P(n-\iota)}\gamma_i = \frac{P(n)}{P(n-\iota)}\frac{P(n)\mu_{ik}(P(n))W}{R} \qquad (1)$$

where γ_i^* is the desired SINR level for user i, γ_i is the measured SINR level at the n^{th} iteration, $P(n)$ is the power command calculated for the next slot and $P(n-\iota)$ is the current transmitted power level. $\mu_{ik}(P)$ is the total interference received at base station k with respect to mobile user i, and R is the required data rate for user i. W is the CDMA spreading bandwidth.

The increase or decrease of the power level of a mobile user are often done in a balanced manner [4, 5], i.e., the power is incremented in similar fractional amounts for both increasing and decreasing power levels due to fading. But in practice, the signal power level fades more often below the nominal signal level than above. This phenomenon can also be easily verified by observing the Rayleigh fading pdf describing the fading distribution of the signal envelope. Because of the unbalanced nature by which the signal envelope fades, four FPC-algorithms will be considered and compared to compensate for signal power fluctuations, namely: Delta Modulation (DM) FPC, Pulse Coded Modulation (PCM) FPC, Unbalanced Delta Modulation (unDM) FPC and Unbalanced Pulse Coded Modulation (unPCM) FPC.

Refer to [3] for a detailed description of the first two algorithms. A brief description of the last two are given below.

3.1 Unbalanced DM TPC

The unbalanced DM (unDM) transmit power control (TPC) is a modification of the DM TPC: when the received SINR value is smaller than the desired value γ_i^*, the transmitted power is increased by a step-size Δ_1, and when the received SINR value is greater than the desired valued γ_i^*, the transmitted power is decreased by a different step-size Δ_{-1}. It is called an unbalanced DM TPC, because the up step-size and the down step-size are chosen to be distinctly different.

A mathematical description of the SINR-based unbalanced DM TPC is:

$$\begin{aligned} &P(n) = P(n-\iota)\Delta\text{sgn}(\tfrac{\gamma_{in}^*}{\gamma_{in}}) \\ &or \\ &P(n) = \begin{cases} P(n-\iota) * \Delta_1, & if \qquad \Delta_1 < \frac{\gamma_{in}^*}{\gamma_{in}} \\ P(n-\iota)/\Delta_{-1}, & if \qquad \Delta_1 > \frac{\gamma_{in}^*}{\gamma_{in}} \end{cases} \end{aligned} \qquad (2)$$

where Δ is the power increment amount, normally called the power step-size, 'sgn' is the sign function and ι is the transmitting loop delay. The other parameters are as defined previously (refer equation (1) and [7]).

A stability proof, outlined in Section 3.3, will show that the power control performance of the unbalanced DM TPC is considerably better than that provided by the original DM TPC.

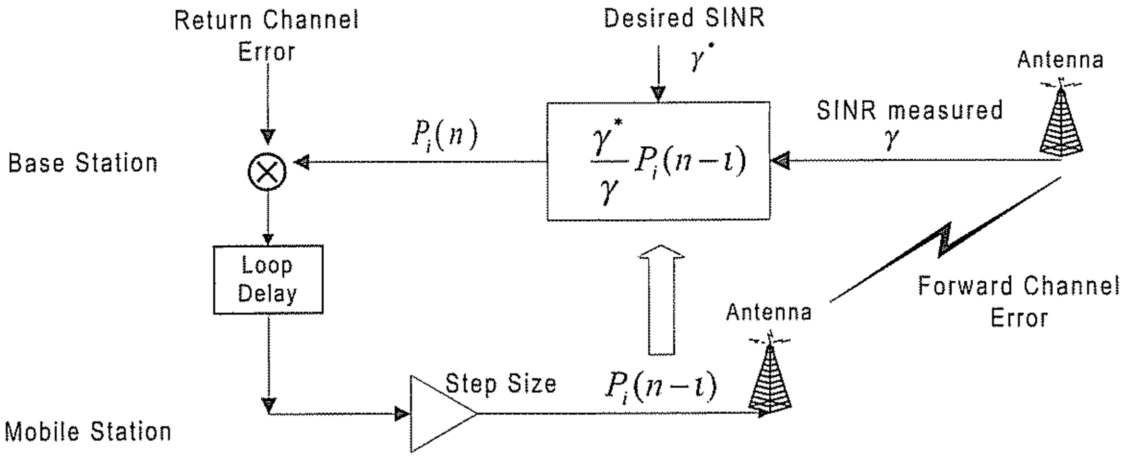

Figure 3: Traditional Power Control configuration

3.2 *Unbalanced PCM FPC*

A two bit TPC for the third generation (3G) UMTS wireless cellular standard is proposed as follows:

$$P(n) = P(n-\iota)\Delta cmd_{n-\iota}(\tfrac{\gamma^*_{in}}{\gamma_{in}})$$

or

$$P(n) = \begin{cases} P(n-\iota) * \Delta_1, & if \quad \Delta_1 < \frac{\gamma^*_{in}}{\gamma_{in}} \\ P(n-\iota) * \Delta_2, & if \quad \Delta_2 < \frac{\gamma^*_{in}}{\gamma_{in}} \le \Delta_1 \\ P(n-\iota) & if \quad \Delta_3 < \frac{\gamma^*_{in}}{\gamma_{in}} \le \Delta_2 \\ P(n-\iota) * \Delta_3, & if \quad \Delta_3 > \frac{\gamma^*_{in}}{\gamma_{in}} \end{cases} \tag{3}$$

This is a modification of the 2-mode PCM TPC. It is also unbalanced: there are two up levels and one down level Note that there are altogether 4 power levels, so that two bits are needed in the downlink to implement this scheme.

3.3 *Stability Analysis for Power Control Algorithms*

Let $e_n = \gamma^*_{in}/\gamma_{in}$. If γ^*_{in} and γ_{in} are expressed in dB units, with values at discrete time instant n denoted by $\gamma^*_{in}(dB)$ and $\gamma_{in}(dB)$ respectively, then

$$e_n(dB) = \gamma^*_{in}(dB) - \gamma_{in}(dB) \tag{4}$$

Define

$$\Delta e_n(dB) = e_n(dB) - e_{n-\iota}(dB) \tag{5}$$

Therefore, it can be derived [6] that

$$\begin{aligned} e_n = \; & e_{n-\iota} - \Delta\text{sgn} * e_{n-\iota} - \\ & \left[(\textstyle\sum P_j)_n - (\textstyle\sum P_j)_{n-\iota}\right] + (i_n - i_{n-\iota}) + \delta_n^2 \end{aligned} \tag{6}$$

where $\sum P_{j_n}$ is the total interference to user i at the nth iteration, and $\sum P_{j_{n-\iota}}$ is the total interference at the previous iteration $n-\iota$. δ_n^2 denotes the variance or power of a Gauss noise sample.

It is reasonable to assume that

- $[(\sum P_j)_n - (\sum P_j)_{n-\iota}] + \delta_n^2$ is ultimately bounded by an upper bound ε_1 * and a lower bound $-\varepsilon_{-1}$, that is, there exists an iteration $N > 0$, such that when $n > N$

$$-\varepsilon_{-1} \le [(\sum P_j)_n - (\sum P_j)_{n-\iota}] + \sigma_n^2 \le \varepsilon_1 \tag{7}$$

- $(i_n - i_{n-\iota})$ is ultimately bounded by a upper bound χ_1 ** and a lower bound $-\chi_{-1}$, i.e, there exists an iteration $N > 0$, such that when $n > N$

$$-\chi_{-1} \le (i_n - i_{n-\iota}) \le \chi_1 \tag{8}$$

- The step size Δ_1 is larger than $\varepsilon_1 + \chi_1$ and Δ_{-1} is larger than $\varepsilon_{-1} + \chi_{-1}$.

A smaller increment of the power level may not be able to offset the fast fading and Multiple Access Interference (MAI). Under the above assumptions, one can prove [6] that the unbalanced FPC ensures that there exists a $N' > 0$, such that when $n > N'$

$$-\ell(\Delta_1 + \varepsilon_{-1} + \chi_{-1}) \le e_n \le \ell(\Delta_{-1} + \varepsilon_1 + \chi_1) \tag{9}$$

It can be seen from (9) that the steady state error of the difference between the received SINR-level and the desired SINR-level is upper bounded by $\ell(\Delta_{-1} + \varepsilon_1 + \chi_1)$ and lower bounded by $-\ell(\Delta_1 + \varepsilon_{-1} + \chi_{-1})$, which is determined by four factors:

1. the loop delay ℓ: the longer the loop delay, the larger the steady state error;
2. the step size Δ: the larger the step size, the larger the steady state error;

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* The rate of fading and disturbance

** The rate of the change of inter-cell interference

3. the rate of fading and disturbance ϵ: the quicker the rate, the larger the steady state error. A major quantity affecting the rate of fading is the speed of the mobile unit, i.e., the Doppler effect contributes to ϵ;
4. the rate of change of the inter-cell interference χ: the quicker the change, the larger the steady state error. A major variable affecting the rate of change is the sudden increase or decrease in the number of mobile users.

4. SIMULATION RESULTS AND DISCUSSION

4.1 Uplink Parameters

To facilitate the above theoretical analysis, simulations were carried out to demonstrate the performance of the various PC- schemes under various mobile radio channel conditions. The link parameters assumed in the simulation are listed in Table 1.

Table 1: FDD W-CDMA Radio Link Parameters

The definition of the notations	
Parameter	**Description**
Chip rate	41472/frame
User data rate	48 kbps/256 kbps/1024 kbps.
Spreading factor	32/16/4.
Interleaver length	10 ms.
Modulation	QPSK.
Oversampling factor	4.
Number of slots/frame	16.
Number of fingers/Antenna	3.
Initial Power	0.5 W.
Diversity (Receive Antenna)	2
FEC	Uncode
	Convolutional decoder
	Turbo coder

The link parameters given above represent that of an uplink DS-WCDMA system, and is based on the specification for the UMTS FDD system [2]. The modulation scheme used is QPSK and the chip rate, f_{chip} = 4.096 Mchips/s. The base station uses a six-finger RAKE combiner (3 fingers/antenna) The FPC command is relayed to the mobile every 0.625 ms to raise or lower the mobile transmitted power level by x dB, depending on the FPC-algorithm used.

4.2 Fading Channel Model

The UMTS radio channel models are described in terms of four channel types, namely the AWGN channel (used as a benchmark), together with three typical frequency-selective Rayleigh fading scenarios, viz. *Indoor-Office* (UMTS Channel Model 1), *Vehicular* (UMTS Channel Model 3) and *Outdoor* (UMTS Channel Model 2) communication environments. The complex lowpass equivalent representation of the channel for the link between any transmit-receive antenna pair of the ith user can be modelled as

$$h_i(t) = a_k \sum_{\ell=1}^{L_i} Ray_i(\tau)\sigma(t-\tau_{\ell,i})e^{j\Phi_{\ell,i}} \tag{10}$$

where $Ray_i(\tau)$, $\tau_{\ell,i}$, and $\Phi_{\ell,i}$ are the path gain due to Rayleigh fading, the time delay, and the phase shift of the ℓth multi-path component from the ith user's transmit-receive antenna path, respectively. Therefore, L_i is the number of paths received from the transmit antenna for user i. The variable a_k models the effects of path loss and log-normal shadowing. The phase term $\tau_{\ell,i}$ is assumed to be uniformly distributed over $[0, 2\pi]$. In the simulation, the MAI is approximated by complex Gaussian noise and is combined with the background noise characterized by AWGN. The multi-path delay spread is assumed to be much shorter than the data-symbol duration, so that inter-symbol interference (ISI) may be neglected at the receiver. It is furthermore assumed that the multi-path channel parameters vary slowly compared to the chip duration, so that they are approximately constant (stationary) over several chip periods.

Table 2: Summary of Fast Power Control (FPC) algorithms considered; PCM = Pulse-Code-Modulation

FPC-algorithm	**Definition**
DM1	Balanced DM FPC with 1dB step-size
DM2	Balanced DM FPC with 2dB step-size
DM3	Balanced DM FPC with 3dB step size
PC5	Balanced PCM with 5 steps
PC7	Balanced PCM with 7 steps
unDM	Unbalanced DM FPC
unPC4	Unbalanced PCM with 2 pos, 0 and 1 neg step
unPC6	Unbalanced PCM with 3 pos, 0 and 2 neg steps
Perfect PC	Perfect Power Control

4.3 Bit-Error-Rate (BER) performance

The performance comparison between eight different balanced and unbalanced PC algorithms is given in this section using the AWGN, Vehicular and Outdoor channel models outlined above. The eight PC-algorithms are denoted by the abbreviations DM1, DM2, DM3, PC5, PC7, unDM, unPC4 and unPC6, compared to Perfect PC, tabulated in Table 2. A detailed description of each of these FPC-algorithms can be found in [7].

To generate the BER curves for the eight FPC-algorithms, the same power levels are transmitted initially and the same desired SINR values are set for each user. At the receiver, RAKE combining and coherent demodulation is performed to dissolve the received multi-path components and to extract the desired signals from the resultant (multi-user) corrupted received signal using a matched filter technique The output of the matched filter is then fed into the SINR estimator (refer Figures 2 and 3) to determine the received SINR value. This estimated value is then compared with the pre-determined SINR value and a power command is calculated for each FPC-algorithm used. The BER value of each user is calculated using hard decisions of desired signals, and the average BER values are then determined and used in the BER performance plots. Since no coding schemes are used in the simulation tests presented here, we can evaluate the influence of the number and severity of multi-path components on the FPC algorithms. The BER graphs and FPC error signal probability density function (pdf) and moments (mean and standard deviation, reflecting the degree of channel variation), are presented in this section using Monte Carlo simulation.

The BER-performances versus SINR of the eight PC-algorithms in channels with varying degrees of multi-path and with no coding, are shown in Fig 4.

In the case where there are no multi-path components and only AWGN, the uncertainty of estimating time-varying wireless channels is negligible in a consideration of performance. This is primarily due to the fact that the received waveform is well preserved, and that only a constant background noise power affects the transmitted signals. The BER results for the AWGN channel therefore reveal that, with the exception of the perfect FPC-algorithm, most of the algorithms exhibit similar performance. However, when the BER results of the eight FPC-algorithms are compared at 16 dB, there is little improvement with unbalanced FPC-algorithms in AWGN channel conditions. Generally, unbalanced PCM algorithms outperform unbalanced DM algorithms and unbalanced FPC-algorithms outperform balanced FPC algorithms. Focusing on the actual SINR versus the target SINR, it is clear that the main characteristic of the ideal FPC-algorithm is that actual and target SINR values are the same, irrespective of the channel-variations. Thus, it follows that the pdf of the FPC error signals will be close to an impulse at 0dB.

For the vehicular channel the presence of both (three) multi-path components and a fast-fading Rayleigh fading envelope is assumed. The fast fading can primarily be attributed to a maximum vehicle speed of 200 km/h. The frequency-selective fast-fading implies that the rate of change in amplitude, phase and time-delay of any of the multi-path components may vary faster than the transmitted signal [8], thereby decreasing the effectiveness and efficiency of the FPC-algorithms. This can be observed by comparing the BER performance graphs for AWGN and Vehicular channels in Fig. 4, at a target BER of 4×10^{-4}. It is immediately clear that the effect of a frequency-selective fast-fading channel on WCDMA performance and capacity is substantial. There is a decrease in power efficiency of approximately 8 dB at the target BER obtainable with a balanced DM FPC-algorithm in a Vehicular channel compared to an AWGN channel. The results show that there is a substantial improvement with unbalanced FPC-algorithms compared to balanced FPC-algorithms, especially at high SINR values. This is primarily due to the fact that the power signals fade more quickly than they are increasing in a typical Rayleigh and Rician frequency-selective fading channel. Thus, unbalanced FPC-algorithms outperform balanced ones on a Rayleigh fading channel.

Simulation results have indicated that the smaller the FPC error-signal pdf, the shorter the error-free run-length experienced in the receiver. In other words, burst errors will occur less frequently. Since unbalanced FPC-algorithms improve SINR outage probability by increasing average transmitted power, burst errors can be better controlled and eliminated by the new unbalanced FPC-algorithms proposed, especially at high SINR levels.

Table 3 summarises the BER-performance attainable with the eight FPC-algorithms in a Vehicular channel at a SINR of $E_b/N_0 = 20$. Generally there is a 4 dB improvement with the unbalanced DM algorithms over the balanced DM algorithms. This is because DM algorithms cannot cope with fast channel variations. This deficiency can be overcome by introducing PCM algorithms where more FPC control bits are available. A slight improvement can be observed when employing unbalanced PCM algorithms compared to unbalanced DM algorithms: an approximate 5 dB improvement is experienced with unPCM6 compared to unDM, with diminishing improvement as the SINR value decreases.

Finally, the introduction of additional multi-path components (more than three) in the time-dispersive channel model results in a so-called Outdoor channel model. The influence of such a power profile on system performance is evaluated in the presence of FPC. The BER results for the Outdoor channel is depicted in Fig. 4. The result show that subscribers are in this experiencing unacceptable QoS and BER performance. Apart from an irreducible BER value of approximately 2×10^{-3} for all SINR values, Fig. 4 shows a staggering Outdoor channel power deficiency of approximately 13 dB at a BER of 3×10^{-3}, compared to the Vehicular channel for practically all FPC-algorithms considered. This can be attributed to the fact that when the number of multi-path components exceeds the number of receive antenna elements as well as RAKE fingers, other multi-path components become a source of interference to the desired signals, and the noise power level increases drastically. Consequently, received signal envelope and power levels commence to fluctuate more rapidly and stochastically than the signal variations. This can be improved by incorporating antenna space-diversity and

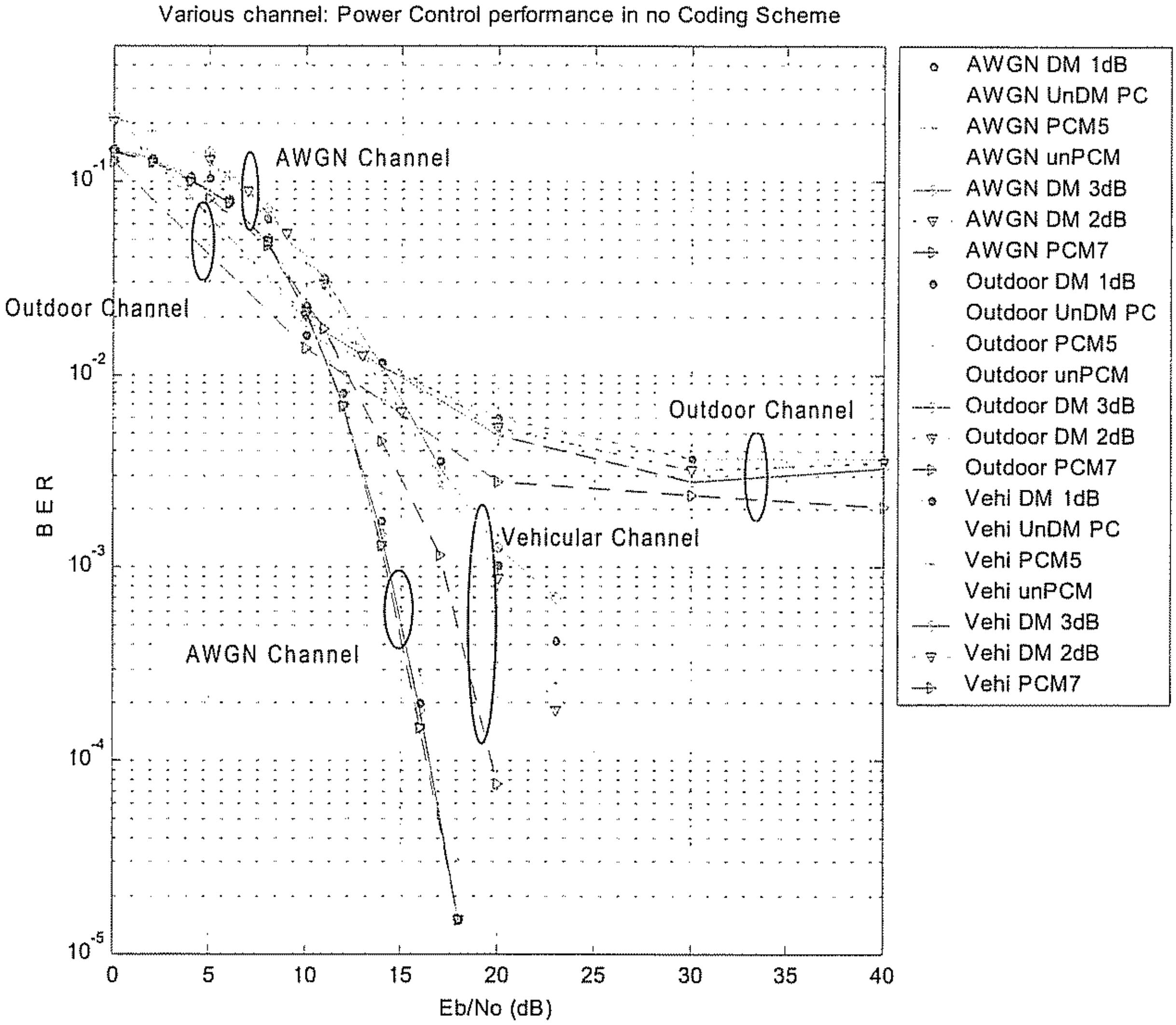

Figure 4: Comparison of the performance of various fast power control (FPC) algorithms in AWGN, Vehicular and Outdoor Channel conditions (no coding) with various degrees of multi-path.

coding schemes to combat the induced ISI distortion and MAI, but will not be considered here, as it falls outside the scope of this paper.

Table 3: Vehicular Channel at 20 dB SINR

$E_b/I_0 = 20$ dB	**BER**
Unbalanced DM PC	0.000633
balanced PCM with 5 step size	0.001065
unbalanced PCM 4 step size	0.000471
balanced DM with 3dB	0.001265
balanced DM with 2dB	0.001120
unPCM6 step size	0.000077

In summary, in general, it can be observed that the unbalanced PC algorithms improved system performance significantly. It also performs better than the balanced DM and balanced PCM algorithms under all channel conditions.

From the results it may also be concluded that if a too small PC step size value Δ is used, the PC error increases as the PC-algorithm loses its ability to track the channel fading. To prevent this from happening, a larger SINR is required, resulting in a reduction in system capacity. Also, the more quantization levels (or bits) used in PC algorithms, the better the BER performance. Due to loop delay, overshoot and rise time, the desired signal level and SINR is not tracked perfectly. In the next subsection, the focus is turned to the problem of SINR stability.

Signal-to-Interference and Noise Ratio (SINR) Stability: Two aspects of the pdf of the error signals of the FPC-algorithm considered are of utmost important in the analysis that follows, namely their mean value and spread (width). The width of the pdf is a measure of the ability of the FPC algorithm to cope with fast changes in the channel. If the algorithm has a limited dynamic range or responds slowly to changes in channel variations, the error signal at a specific instant in time will range from small values to large ones. Secondly, the mean value of the error signal provides a measure of the power efficiency of the FPC-algorithm under consideration. Therefore, FPC-algorithms can be compared by considering the mean and variance of the error signals generated in each case. The lower the mean value, the better the power efficiency of the algorithm; the lower the variance of the error signal, the better the algorithm can cope with short-term channel variations

Accurate FPC may compensate for bad radio-channel conditions by keeping the received SINR above the target level. However, under adverse radio channel conditions, the source may have to transmit at higher power levels, causing extensive interference to other active users. Consequently, the PC-error is one of the most important system parameters affecting system capacity. To achieve capacity during bad channel conditions, fast power control (FPC) techniques, such as those listed in Table 2, are required to keep the SINR stable within acceptable limits.

In the remainder of this section the tracking ability of the eight PC-control schemes considered will be investigated. The distribution of the received SINR levels is plotted in Fig. 5 for the AWGN channel, in Fig. 6 for the Vehicular channel and in Fig. 7 for the Outdoor channel.

A summary of the FPC error mean variation, variance and range comparisons for each of the eight FPC-algorithms considered is depicted in Fig. 5 for the AWGN channel, with two receive antenna elements (Rx=2) and a matched-filter WCDMA RAKE receiver with 3 fingers per antenna element. There are $N = 32$ users and $i = 1$ denotes the reference user. It is observed that the balanced FPC-algorithms have lower mean and variance and therefore yield better power efficiency than the unbalanced FPC-algorithms. Comparing DM and PCM algorithms, it is found that the variance of both balanced DM and unbalanced PCM algorithms is less than the balanced and unbalanced PCM techniques, respectively. It is therefore important to note that the more quantization levels used in FPC-algorithms, the better the BER performance, but the more the overshoot and steady state error exhibited by the SINR outage probability test. The smaller the step-size, the smaller the overshoot and steady state error and the lower the BER performance

These observations can be attributed to the fact that, firstly, the unbalanced FPC-algorithms increase the average transmitted power more than balanced FPC-algorithms do. Thus, improved BER performance will result in better power efficiency with unbalanced FPC-algorithms. Secondly, since there is no time-dispersion and rapid time-variation of the received signal envelope in the AWGN channel, all FPC-algorithms, and therefore also the unbalanced ones, can control the transmitted power more effectively. Thirdly, since the rate of change in amplitude, phase and time-delay of the transmitted signals are slower than the transmitted signals in fast-fading channels with Doppler spread, unbalanced FPC-algorithms are able to control the transmitted power more efficiently. It is expected that as the number of resolvable multi-path components and the Doppler spread increase, so will the effectiveness and efficiency of these FPC-algorithms decrease. This has in fact already been observed with the Outdoor channel BER performance in Fig. 4.

A summary of the the mean FPC error-signal (and thus channel) variation, variance and range comparisons for the Vehicular channel is depicted in Fig. 6, with two receive antenna elements (Rx=2) and a matched-filter WCDMA RAKE receiver with 3 fingers per antenna element. There are $N = 32$ users and again $i = 1$ denotes the reference user. The introduction of a frequency-selective fading channel significantly changes (broadens) the FPC error-distribution pdf. The balanced FPC-algorithms still yield lower mean variation values than the unbalanced ones; however, the increase in mean value is generally about five times more than in an AWGN channel. Therefore, the balanced FPC-algorithms improve power efficiency considerably more than unbalanced FPCs do. Also, both the balanced and unbalanced DM algorithms yield lower aggregate values. Thus, DM FPC-algorithms yield better tracking ability and robustness under different channel conditions.

Validation of the Gaussian approximation of the FPC error distribution in frequency-selective fading channel conditions is also investigated in the simulation study, and it is found that this assumption is not valid in a conventional RAKE receiver structure, as can be deduced from the pdf-results.

Fig. 7 summarises the mean variation, variance and ranges of different FPC-algorithms in the Outdoor channel, with two receive antenna elements (Rx=2) and a matched-filter WCDMA RAKE receiver with 3 fingers per antenna element. There are, as before, $N = 32$ users and $i = 1$ denotes the reference user. The balanced FPC-algorithms still yield better power efficiency and the balanced DM algorithms also yield better tracking ability. Although the FPC-algorithms still attempt to narrow (stabilise) the SINR levels at the receiver, there is no significant improvement in the BER performance graphs. The BER performance is completely characterised by the pdf of the FPC error signal, and more specifically its mean and variance, and its absolute effect on the overall system performance is a function of the underlying receiver structure (i.e., coding mechanism(s), antenna space

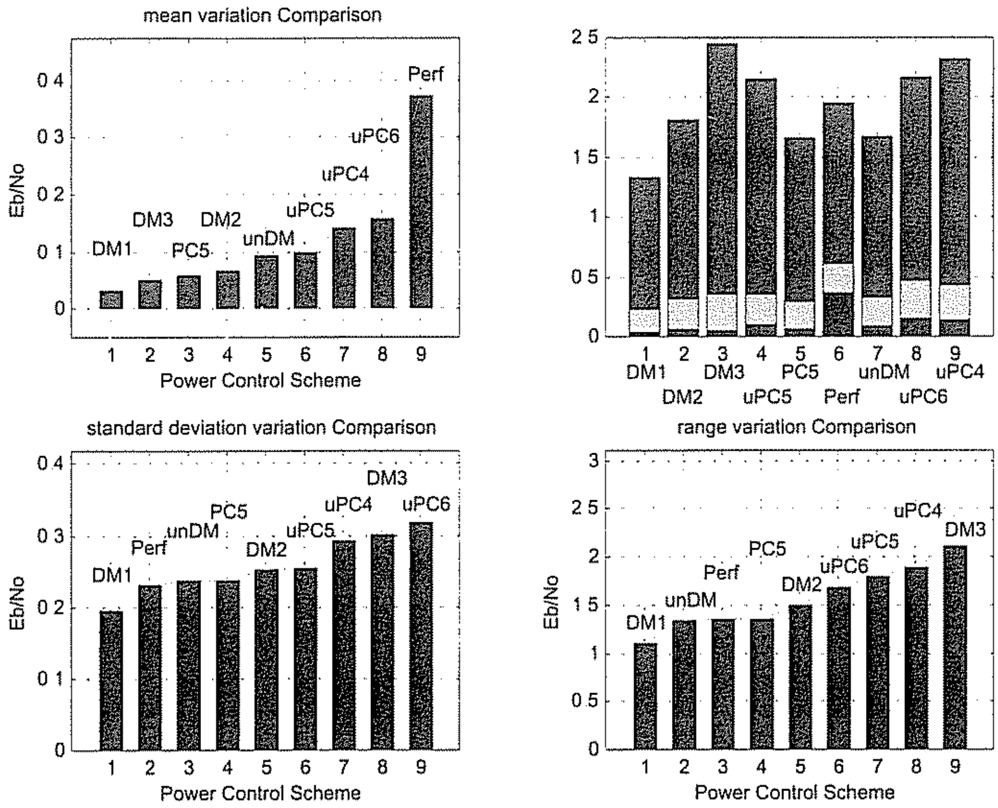

Figure 5: Effect of the number of resolvable paths: Mean, standard deviation and range comparisons for different FPC algorithms in an AWGN channel with Rx=2 receiver antennae, i=1 (reference user), RAKE fingers = 3, N=32 total users and matched-filter WCDMA receiver with no coding

diversity method and interference cancelling algorithms used). A perfect FPC-algorithm would mean that the receiver structure always operates at the some (optimal) operating point. In reality, power cannot be perfectly controlled due to overshoot, rising time and loop delay. Also, the capacity of a WCDMA system would be maximised if FPC-algorithms could be *jointly* controlled with other supplementarily essential supporting receiver mechanisms, such as coding, synchronisation, MAI-cancellation and RAKE combining. This approach therefore calls for a combined approach, integrating all system resources in an optimal way.

5. CONCLUDING REMARKS

This paper studied the performance of eight fast closed-loop power control schemes in the uplink of a Rayleigh fading WCDMA environment by means of computer simulation. The basic channel models considered were AWGN (used as benchmark), Vehicular Rayleigh fading and Outdoor multi-path channels.

It can be seen from the BER-performance results from Fig. 4 that, in general, the unbalanced PC-algorithms outperform the conventional balanced PC-algorithms in various channel environments. Also, all PC-techniques perform considerably better on the Vehicular channel than on the Outdoor channel. This observation can be attributed to the fact that although there are more multi-path components in the Outdoor channel, their time-delayed replicas are relatively small compared to that of the Vehicular channel model used. Thus, the received resultant channel effects at the base station, after diversity schemes have been applied, appear to be more consistent in the case of the Vehicular channel. Therefore, PC-schemes perform better in the Vehicular channel, as can be clearly noted from the BER graphs depicted in Fig. 4.

It has been observed from the BER-results of Fig. 4 that unbalanced FPC-algorithms do not improve the system BER-performance in AWGN channels significantly, as this channel does not exploit the presence of multi-path components and Doppler spread. When a frequency-selective Rayleigh fast-fading channel is introduced in the WCDMA up-link, there is significant improvement in BER-performance compared to balanced FPC-algorithms. This can be primarily attributed to the fact that the power signals fade more often and by larger amounts than they grow in such channels. The performance of the FPC-algorithms has been found to

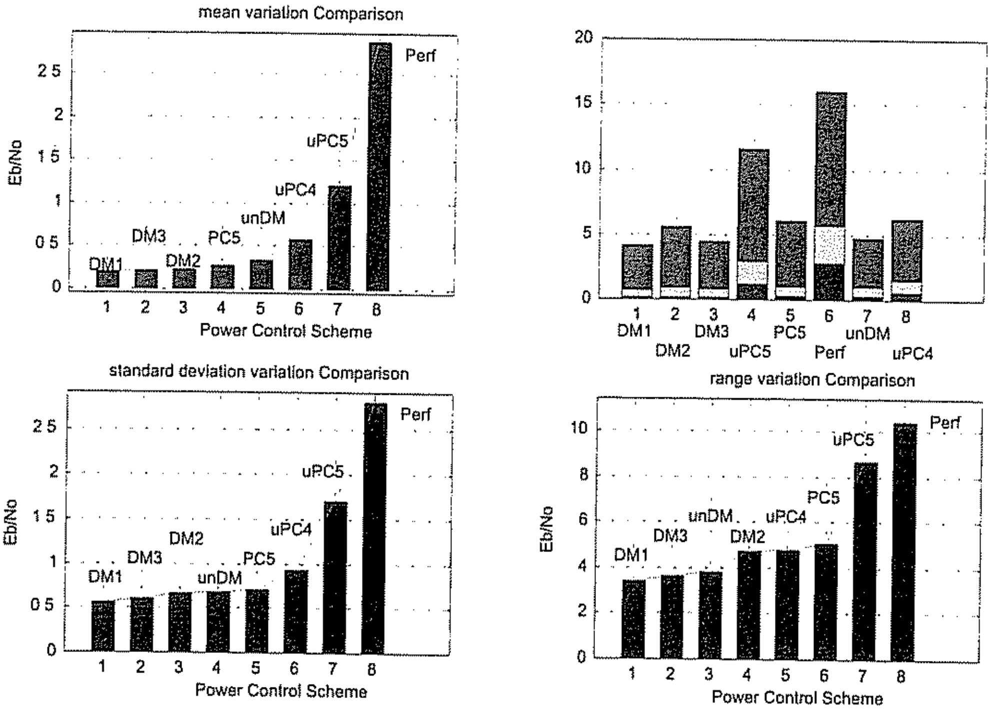

Figure 6: Effect of the Number of resolvable paths: Mean, standard deviation and range comparisons for different FPC algorithms in a Vehicular Channel model with Rx=2 receiver antennae, i=1 (reference user), RAKE fingers = 3, N=32 total users and matched-filter WCDMA receiver with no coding

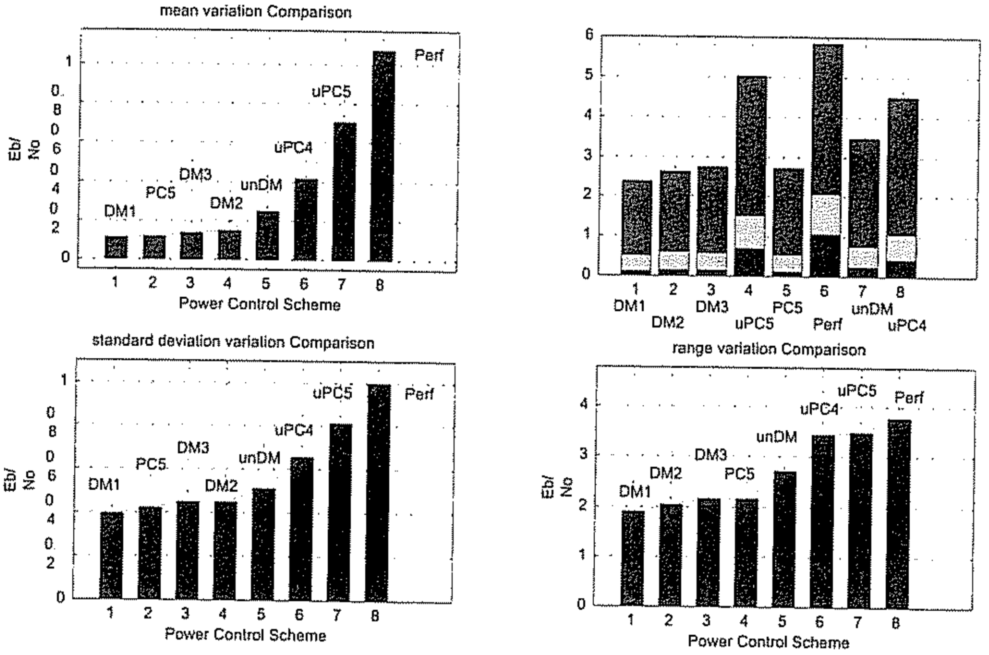

Figure 7: Effect of the number of resolved paths: Mean, standard deviation and range comparisons for different FPC algorithms in an Outdoor Channel model with Rx=2 receiver antennae, i=1 (reference user), RAKE fingers = 3, N=32 total users and matched-filter WCDMA receiver with no coding

be completely characterised by the pdf of the PC error signal, and more specifically, by its mean and variance, and its absolute effect on the overall system performance has been observed to be a function of the specific receiver structure (i.e., coding technique employed, antenna space diversity and interference cancellation algorithm used).

In conclusion: It was found that the unbalanced PC-algorithms in general outperform the conventional balanced PC- algorithms. It has also been theoretically proved that the unbalanced PC-algorithms have better tracking ability than the conventional PC-algorithms in frequency-selective Rayleigh fast-fading multi-path channels

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