Band Based Power Control (BBPC) for MC-CDMA Radio Interface

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Abstract— This paper highlights, limitations of ECPC (Each Carrier Power Control) concept [1] - originally proposed for OFDM-DS-CDMA - when extended to MC-CDMA (Multi-Carrier Code Division Multiple Access) systems. First, its impractical signaling overhead of 80% secondly; its inability to be used as an uplink power control mechanism. Then we propose BBPC (Band Based Power Control) as a practical alternative to ECPC for MC-CDMA systems. Unlike, ECPC that controls power on each carrier basis, BBPC assigns same power level to a band of carriers (lying within coherence bandwidth of channel). It has been shown that with a nominal performance loss, BBPC reduces the signaling overheads to 2.5% and by employing the control index estimator after de-spreading, it can be used as an uplink power control mechanism for MC-CDMA. We have used SIR (Signal to Interference Ratio) as a power control index, BER and standard deviation of power control error as performance metrics.

Keywords; *power control; uplink; MC-CDMA; coherence bandwidth.*

I. INTRODUCTION

Recently, MC-CDMA (Multi-Carrier Code Division Multiple Access) has gained significant interest as a multiple access method and has emerged as a potential candidate for 4G cellular systems [2-3]. This is mainly due to its capability of simultaneously exploiting the advantages of OFDM (Orthogonal Frequency Division Multiplexing) and CDMA (Code Division Multiple Access) to cope with frequency selective fading encountered in large bandwidths and thereby ensuring very high data rates required for 4G systems. Being CDMA based system; MC-CDMA is susceptible to MAI (Multiple Access Interference) [6]. Apart from MAI, near far effect [6] and fast fading experienced by the signal, causes deterioration in received power, resulting in performance loss. To compensate these effects while maintaining reasonable Quality of Service (QoS), a fast and accurate mechanism of controlling the power of transmitted signal is required for MC-CDMA [4-5].

Opposed to single carrier CDMA systems, a more comprehensive power control scheme is required for MC-CDMA, because data is transmitted over several orthogonal sub-carriers in this system. Furthermore, depending upon the coherence bandwidth of channel the received power level on different sub-carrier may results in appreciably different

values. Hence, for a precise control over transmitter power, ideally, power assignment must be done on carrier-to-carrier basis that pose many problems (i.g. feedback bandwidth requirement for transmission of control bits) not encountered in single carrier systems.

Although, there has been a significant amount of work [6] reported into the investigation of TPC (Transmit Power Control) techniques for single carrier systems like W-CDMA, however very few attempts [1, 4, 5, 7] have been reported for multi-carrier systems so far. Works reported in [1] and [4] target OFDM-DS-CDMA systems only and don't encompass MC-CDMA, whereas [5] and [7] only establish a requirement for power control in MC-CDMA systems rather than proposing any practicable TPC technique for it. ECPC (Each Carrier Power Control) has been shown [1] to outperform ACPC (All Carrier Power Control), but concept of ECPC can't be extended to the system under consideration (i.e. MC-CDMA) mainly due to its following limitations:

- ECPC is meant to control power on per sub-carrier basis, so control index (power or SIR) needs to be estimated prior to combining operation [Fig. 2]. Since, in MC-CDMA, spreading is done in frequency domain using user specific codes [Fig. 1], therefore desired user data can't be segregated prior to de-spreading. Hence idea of ECPC can't be extended to MC-CDMA environment.
- Being uplink power control mechanism, ECPC needs to be implemented in closed loop [6], hence, requires a certain feedback bandwidth on downlink. With reference to simulation parameters [Table II], a signaling overhead analysis of ECPC has been carried out [Table I], which resulted in an unfeasibly high feedback overhead of 80%, so ECPC is not even a suitable TPC mechanism for MC-CDMA systems.

Therefore keeping in mind the limitations of ECPC, this paper proposes a Band Based Power Control (BBPC) mechanism that exploits the coherence bandwidth information B_c of channel, and controls the power of a band of sub-carriers (lying within B_c , hence undergoing a highly correlated fading process) with single power control command. We demonstrate through simulations that against a nominal performance loss of less than .5dB, BBPC remedies both of the above stated

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limitations of ECPC that makes it a suitable and practically realizable TPC mechanism for MC-CDMA radio interface.

Rest of this paper has been organized as follows; in section II we describe the system's conceptual model used in this study, section III elaborates the BBPC concept. Comparison of BBPC performance against ECPC and ACPC is given in section IV using simulation results. This section also validates the concept of BBPC using channels of different coherence bandwidths and also by varying the bandwidth occupied by one band of sub-carriers, whereas section V concludes the paper.

TABLE I. SIGNALLING OVERHEAD ANALYSIS OF ECPC

No	Parameter	Symbol	Value
1	Baseband modulation index	m	2(QPSK)
2	No. of parallel branches	P	23
3	Information bits per OFDM symbol	$I_b = m \cdot P$	46
4	Frame length [OFDM symbols]	N_s	20
5	No. of Information bits per frame	$I_b = I \cdot N_s$	920
6	Spreading factor	K_{MC}	32
7	Number of data sub-carriers	$N_{sc} = K_{MC} \cdot P$	736
8	Required control bits per frame	$C_b = N_{sc}$	736
9	Signalling overhead (fixed step mode)	C_b / I_b	80%

II. SYSTEM ARCHITECTURE

A. Transceiver Model

The transmitter part of MC-CDMA for j^{th} user is modeled as shown in Fig. 1. Random binary data stream is generated with bit duration of T_b , and passed through a QPSK modulator. This serial stream of modulated symbols is converted to P parallel streams $a_{j,p}[p=0,1,...,P-1]$ thereby increasing symbol duration to $T_s = T_b/P$. Each of these streams is then subjected to spreading in frequency domain. This is where CDMA feature has been incorporated; user specific codes (Walsh Hadamard) $d_{j,m}[m=0,1,...,K_{MC}-1]$ with spreading factor of K_{MC} have been used. This spreaded signal consists of $P \cdot K_{MC}$ chips each with duration of T_s . Prior to multi-carrier modulation, to avoid burst errors these chips are interleaved over different frequency carriers in Frequency Interleaving block. Finally all of these streams are applied to the multi-carrier modulation using IFFT to generate OFDM symbols. However, to avoid ISI (Inter Symbol Interference), prior to transmission a cyclically extended guard interval of duration τ_g (depending upon the channel delay spread) is inserted before every OFDM symbol.

On receiving end [Fig. 2], the received signal $r(t)$ is serial to parallel converted, cyclic prefix is removed and multi-carrier demodulation is performed using FFT. Prior to combining, frequency de-interleaving is done. Channel Estimator provides an estimation of channel response $Z_{j,p,m}$, which denotes the channel complex gain of the $(mP+p)^{th}$ sub-carrier of the j^{th} user. Based on combining technique, the combiner coefficients $G_{j,p,m}$

are calculated. Equation (1) gives these coefficients for Equal Gain Combining (EGC) [9].

$$G_{j,p,m} = \frac{d_{j,m} Z_{j,p,m}^*}{|Z_{j,p,m}|} \dots \dots \dots (1)$$

These coefficients are then supplied to the combiner that combines energy of the received signal scattered in frequency domain. The decision variable for j^{th} user and p^{th} parallel stream $D_{j,p}$, is obtained as given by (2).

$$D_{j,p}(i) = \sum_{m=0}^{K_{MC}-1} G_{j,p,m}(i) Y_{p,m}(i) \dots \dots \dots (2)$$

Where $Y_{p,m}(i)$ is received, demodulated and frequency de-interleaved signal on $(mP+p)^{th}$ sub-carrier as given by (3).

$$Y_{p,m}(i) = \sum_{j=0}^{J-1} Z_{j,p,m}(i) a_{j,p} d_{j,m} + n_{p,m}(i) \dots \dots (3)$$

Figure 1. MC-CDMA Transmitter Architecture

Figure 2. MC-CDMA Receiver Architecture

B. Multipath Channel Model

Multi-path Rayleigh channel is simulated using Jakes model of sum of sinusoids [8] and is characterized by its PDP (Power Delay Profile). We have employed PDP given by Table II. Parameter K_{MC} in this table is chosen so that the value $\Delta f * K_{MC}$ becomes smaller than the coherence bandwidth B_c of the frequency selective channel (the reason for this assumption will become clear in the sequel). Where Δf is inter-carrier spacing given by (4).

$$\Delta f = \frac{1}{T_s - \tau_g} \dots\dots\dots(4)$$

III. BAND BASED POWER CONTROL

As described in section II-A, data on each parallel stream is spread in frequency domain. Furthermore, in absence of frequency interleaving; it is transmitted on adjacent carriers. Therefore, in absence of any frequency interleaving and by subjecting the spreading factor K_{MC} and Δf to (5) we can ensure highly correlated fading on all K_{MC} number of sub-carrier being modulated by a single data stream $a_{j,p}$.

$$K_{MC} \Delta f \leq B_c \dots\dots\dots(5)$$

Therefore, one single power control command is theoretically justified for all of these K_{MC} adjacent sub-carriers lying within coherence bandwidth of channel. Thereby, reducing the feedback bandwidth by a factor of K_{MC} (as compared to ECPC) ideally without any loss of BER performance. Furthermore, by measuring the power control index after de-spreading, the second limitation of ECPC can also be eliminated, which is the main theme followed by BBPC. Fig.3 shows BBPC in MC-CDMA transmission loop. We have used it in adaptive step mode which uses multi-level power control commands $P_{cmd_{j,p}}$ for each user and each band of sub-carriers generated by Power Controller as given by (6)

$$P_{cmd_{j,p}}(k) = \left\lfloor \frac{SIR_{r,j,p}(k) - SIR_{tg,j,p}(k)}{stepres} \right\rfloor \dots\dots\dots(6)$$

Where $SIR_{r,j,p}$ [10] and $SIR_{tg,j,p}$ are received and target SIRs of j^{th} user on p^{th} band (stream). These TPC commands accordingly adjust the transmit power of $P_{T,j,p}(k)$ of j^{th} user and

p^{th} band in the k^{th} frame by an integral multiple of a minimum power excursion step size $stepres$ nearest to the actual difference of received and target value of control index as given by (7).

$$P_{T,j,p}(k) = P_{T,j,p}(k-1) 10^{\frac{P_{cmd_{j,p}} * stepres}{20}} \dots\dots\dots(7)$$

IV. SIMULATIONS AND RESULTS

The BBPC concept described in previous section is validated through numerous system level simulations targeting different aspects like its performance against ECPC and ACPC and its performance for different channel coherence bandwidths (i.e. delay spread). BER and standard deviation of PCE (Power Control Error) are chosen to be the performance metrics for this comparison. We assume one OFDM symbol delay ($\tau_d = 1$) in generation of power control commands by Power Controller and their implementation at Power Amplifier [Fig. 3]. All of the simulation parameters assume the values tabulated in Table-II unless specified differently.

First of all the BER performance of BBPC was investigated as function of target SIR [Fig. 4] at a constant channel fading rate characterized by mobile's normalized speed ($F_d T_p$) of 0.0598 that corresponds to an average mobile speed of 30 Km/hr and power control period of 0.43ms. Fig. 3 shows that there is hardly any performance difference between BBPC and ECPC, however, performance difference between ACPC and BBPC kept on increasing with increase in SIR target, which is attributed to the decreasing interference from AWGN at higher values of target SIR.

Since for a TPC validation, its channel tracking ability is a key metric, so it becomes essential to study its performance as function of channel fading rate as well. This feature of BBPC is investigated and compared against ECPC and ACPC in Fig. 5. The study reveals that although BER performance of ECPC and BBPC is nearly identical, but ECPC outperforms its other two alternatives as far as its channel tracking ability is concerned. It can also be seen from Fig. 5 that standard deviation of PCE for all three TPC techniques are appreciably different at low channel fading rates experienced by pedestrians ($F_d T_p = 0.00688$). However, this performance difference diminishes with increase in fading rates and

Figure 3. BBPC in MC-CDMA transmission loop

ultimately all three curves converge to a single asymptotic value of 4.5dB at $F_d T_p = 0.2$. However, BBPC competes ECPC well with a nominal performance loss of 0.27dB at $F_d T_p = 0.0598$.

TABLE II. SIMULATION PARAMETERS

No	Parameter	Symbol	Value
1.	RF carrier frequency	F_c	5 GHz
2.	Baseband modulation index	m	2(QPSK)
3.	No. of parallel branches	P	23
4.	Spreading Codes	Hadamard Walsh	
5.	Spreading factor	K_{MC}	32
6.	FFT size	N_{FFT}	1024
7.	Useful symbol duration	T_b	17.75 μ s
8.	Guard Interval	τ_g	3.75 μ s
9.	Symbole total duration	T_s	21.506 μ s
10.	Sampling frequency	f_s	57.6 MHz
11.	Combining technique	EGC	
12.	Multiple Access Interf.	MAI	0
13.	Dynamic range	P_{DR}	80 dBm
14.	Min. power excursion step	stepres	.5 dBm
15.	Power excursion mode	Adaptive step mode	
16.	SIR estimation window size	T_p	20 OFDM Symbols
17.	Number of multi-paths	4	
18.	Relative delays [ns]	[0, 230, 400, 500]	
19.	Relative Powers [dB]	[0, -9.7, -19.2, -22.8]

Figure 4. Performance of BBPC, ECPC and ACPC vs SIRtg at $F_d T_p = 0.0598$

Furthermore, to have an insight into the behavior of BBPC as function of bandwidth occupied by one band of sub-carriers

($\Delta f * K_{MC}$); BER performance was studied while changing the number of sub-carriers per control band while keeping the channel fading rate, coherence bandwidth and SIR target at constant values of .0598, 1.8882 MHz and 10 dB respectively. The results [Fig. 6] show that as we increase the band size from one carrier per band (ECPC) to thirty-two carriers per band (BBPC), there is a negligible loss in BER performance. However, this loss increases abruptly when $\Delta f * K_{MC}$ is increased beyond the coherence bandwidth of the channel (1.8022 MHz) that reinforces the very concept of BBPC.

Figure 5. Performance of BBPC, ECPC and ACPC vs $F_d T_p$ at $SIR_{tg} = 10$ dB.

Figure 6. BER vs carriers per band at $F_d T_p = 0.0598$, $SIR_{tg} = 10$ dB

Since BBPC expected to perform well subjected to (5), therefore we have conducted a series of simulations to study the behavior of BBPC under channels with different delay spreads. The channels [Table III] for this experimentation are chosen to cover whole range of coherence bandwidths ranging from $[B_c > K_{MC} \Delta f]$ to $[B_c < K_{MC} \Delta f]$. In this study, BER

performance of the system with and without BBPC in the absence of any frequency interleaving as a function of channel coherence bandwidth was studied and corresponding gains in performance are plotted in Fig.7. The performance gains is in terms of SNR, in the sense that with the same BER performance power control scheme requires that amount of less SNR. The results shows considerable BBPC performance improvement in terms of the achieved performance gains when the channel bandwidth is above 1.8022 MHz. However a performance gain of 4.15 dB can be seen even at .5418 MHz, which is considerably below the bandwidth occupied by one band of sub-carriers (1.8022 MHz). This gain is actually associated with decreased (as compared to case without BBPC) level of correlation of the fading envelop on different sub-carriers within the one band due to inefficient power control where BBPC starts acting as a means of frequency inter-leaver (indirectly) rather than a true TPC mechanism.

TABLE III. SIGNALLING OVERHEAD ANALYSIS OF BBPC

No	Channel Designator	Channel delay profile [ns]	Coherence Bandwidth [MHz]
1	Ch1	[0, 100, 150, 200]	4.5295
2	Ch2	[0, 110, 190, 410]	3.4603
3	Ch3	[0, 230, 400, 500]	1.8882
4	Ch4	[0, 400, 700, 1000]	1.0581
5	Ch5	[0, 700, 1000, 1500]	0.6456
6	Ch6	[0, 805, 1400, 1700]	0.5418

* Channel power profile used is [0, -9.7, -19.2, -22.8] dB

Figure 7. Performance gain in terms of required average received SNR using BBPC compared with no power control and frequency interleaving scenario

Lastly, the feedback bandwidth required by BBPC for transmission of TPC commands on downlink has been analyzed in Table IV. It is revealed that BBPC causes only 17.5% of signaling overhead when used in adaptive step mode with a TPC command resolution of seven bits per command which reduces to only 2.5% when used in fixed step mode i.e. one bit per TPC command.

TABLE IV. SIGNALLING OVERHEAD ANALYSIS OF BBPC

No	Parameter	Symbol	Value
1	Power dynamic range	P_{DR}	60 dB
2	Min. power excursion step	stepres	.5 dB
3	TPC command resolution [bits/comd]	η	7
4	Signaling overhead [adaptive step mode]	$\eta * P / I_b$	17.5 %
5	Signaling Overhead [fixed step mode]	P / I_b	2.5%

V. CONCLUSIONS

In this paper we have proposed and investigated Band Based Power Control as an uplink power control technique for MC-CDMA radio interface. It has been demonstrated through simulations that with no considerable performance loss in terms of BER and a nominal performance loss of .27dB in terms of Power Control Error, BBPC can reduce the signaling overhead to just 17.5% and 2.5 % with seven bit and one bit TPC command resolution respectively when compared with ECPC which poses impractically high overheads of 80% even in fixed step mode. Secondly by employing the power control index (SIR) estimator after de-spreading and Combining, BBPC successfully overcomes the inability of ECPC to be used as an uplink power control for MC-CDMA radio interface. A gain of at least 4.6 dB in terms of required average SNR is achieved with BBPC compared with no power control technique.

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