Pilot Pollution Interference Reduction Using Multi-Carrier Interferometry

Mostafa M. El-Said, Anup Kumar and Adel S.Elmaghraby
123 J B Speed Building, CECS Department, University of Louisville, Louisville, KY 4029
{mostafa, ak, adel}@louisville.edu

Abstract

Mobile stations, in CDMA systems, have the capability to communicate with multiple base stations whenever it is located in the fringe areas covered by overlapping base stations. However, it is not desirable for an overlap area to contain pilot signals from a large number of base stations. As this would create pilot pollution interference and overload the mobile station's RAKE receiver. Therefore, the mobile station's RAKE receiver attempts to separate paths from three or more dominant pilot signals in the time domain to utilize path diversity. In each diversity (path/branch/finger), a large interference component exists due to the finger's own signal and others' signals. We demonstrated the power of using a novel multi-carrier chip shaping in CDMA transmitters to reduce the effect of pilot pollution interference. Simulation studies have been carried out to verify the appropriateness of the proposed approach and we have obtained very promising results.

Keywords *CDMA, pilot pollution interference, Carrier Interferometry*

1. Introduction

The channel organization in the second-generation systems such as GSM differs remarkably from the next generation systems (3G and 4G). In the new generations, the channel architecture is classified into three different categories: *logical*, *transport* and *physical* channels. Different wireless system organizes these channels differently from downlink to uplink path. In the WCDMA system, there are four types of logical channel categories: *traffic, synchronization, paging and common pilot* channels. The base station (BS) sends a short code (Walsh code 0) on the common pilot channel. The mobile station keeps listening to the pilot signals while searching for the strongest power level. The base station's pilot signal is vital for the system operation such as handover measurements, load balancing. Also, it acts as a demodulation reference for the mobile stations [5,13].

The *RAKE receiver* technology of the mobile station handset plays a vital role in creating the pilot pollution interference (*PPI*) problem in wireless environment. The shortcomings of the *RAKE* receiver technology are (i) orthogonality loss among different users in a multipath diversity environment which in turn reduces the Signal to Interference Ratio (SIR), and (ii) the limited number of available fingers (three fingers per receiver) [2,3,4,10]. In addition, the RAKE receiver of the mobile station's handset is designed to effectively demodulate up to three different pilot signals from three different base stations or three multi-path components of the same base station pilot [2]. Existence of more than three pilot signals with significant power level contributes to the *PPI*.

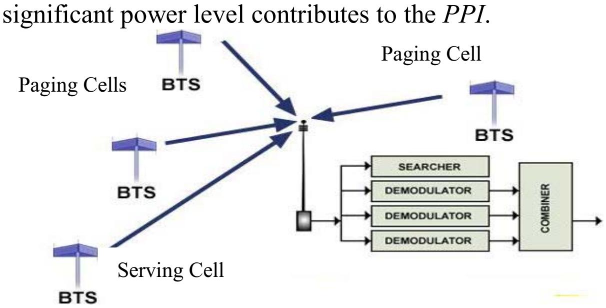

Figure 1. Pilot Pollution Interference Scene

Figure 1 illustrates the pilot pollution interference scenario due to the presence of the serving base station, and other three paging cells at the same time. Consequently, the serving base station increases its power level to reach the mobile station at the overlap fringe area (soft handoff region). This leads to create a non-orthogonality among different pilot signals in the overlapped fringe area and, consequently, the mobile station's RAKE receiver suffers from the existence of the PPI effect. It is also worth mentioning that this problem will be more complicated in the 4G systems operated at the 60 GHZ frequency range where system heterogeneity and small coordinated close cells are expected [1,2,5,6].

Due to the PPI problem, the system suffers from dropping of ongoing calls, blocking of originating fresh calls, and decreasing the system capacity. In addition, WCDMA signals are sent over multipath channels, which result in severe channel dispersions. As a result, the pilot signal orthogonality erodes dramatically faster than other CDMA systems such as MS-CDMA or DS-CDMA [10].

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Another aspect, which might influence the PPI problem to a great extent, is the WCDMA coding scheme.

It has been suggested in the literature that reducing the height of the undesirable antennas, introducing down tilting or change-outs, reducing the BS transmitted power and introducing advanced smart antenna systems may help ameliorate the impact of the pilot pollution interference problem [8]. Unfortunately, most of these solutions have the influence of reducing the coverage footprint within the radio network boundaries, not just where the pilot pollution exists but also over the entire system, which eventually creates additional intolerant coverage gaps. In addition, the IS-95 *repeaters* have been investigated by [13] as a possible solution for the PPI problem. The repeaters are equipped with donor and service antennas. The donor antenna is used to capture a specific signal from the base station; whereas the service antenna transmits the signal to the desired user after amplification. This solution is expensive and undependable because it requires installation of another expensive hardware component and in case of the repeater went done the mobile stations will suffer from the threat of the PPI. In [2], we introduced an innovative early sensory approach to detect and monitor any excess of the pilot pollution interference beyond a pre-specified certain threshold limits. The proposed approach was designed based on the signal to interference ratio measurements. We proved that the proposed algorithm would be able to save up to 50% of the required time to perform conventional pilot drive scanning test within the coverage area to ensure coverage.

This paper introduces a novel solution approach for minimizing the impact of the pilot pollution interference. The solution stems from the integration of *the multi carrier technology* and *the Interferometry phenomena*. We extend the work presented in [11,12,14] to provide a feasible and efficient solution for the PPI problem. The solution aims to replace the WCDMA chip-shaping filter with another Multi-Carrier Interferometry (CI) chip shaping at the base station. The CI signals maintain a perfect orthogonality property among themselves in the frequency domain. Each CI signal has a mainlobe at certain time τ and multiple sidelobes elsewhere. Therefore, the pilot signal of each base station can be clearly identified and detected by its unique mainlobe position at the mobile station. At the mobile station side, the detection strategy illustrated in [10] will be used. It depends on decomposing each chip into its N frequency components to establish a frequency diversity benefits. By using the CI chip shaping, the BER and the SIR of the WCDMA systems can be improved significantly.

This paper is organized as follows. Section 2 provides a problem definition overview. Section 3 describes the proposed solution approach. Section 4 summarizes the simulation results. Section 5 concludes the paper .

2. Problem Definition

Specifically, the pilot pollution interference problem can be viewed as a direct result of the drawbacks of two main technology partners employed in the 3G generation systems. These partners are: (i) the generation of pilot signal at the base station side and (ii) the multi-path diversity property at the RAKE receiver of the mobile station. These issues will be illustrated in the following sections.

2.1. Pilot Signal Generation

Generally, the generation process of the pilot code starts by multiplying the output of the chip shaping filter ($P_{Tc}(t)$) with *nine* pilot code values [1,-1] to construct a unique pilot code ($c^{(k)}(t)$) for that base station. Consequently, this code signal is sent using a single carrier frequency $\mathrm{Cos}(2\pi f_c t)$ over the communication channel. This code is given by the following equation [10]:

$$c^{(k)}(t) = \sum_{i=0}^{i=N-1} B_i^{(k)} P_{Tc}(t - iT_c) \qquad (1)$$

Where

$B_i^{(k)} \in$ [1, -1] is the i^{th} values of the pilot code belonging to the base station k^{th}.

T_c : Chip duration.

P_{Tc} : Chip shaping filter's characteristics function.

N : Number of bits in the short pilot code.

2.2. Computing the Pilot PPI Component

When a mobile station (u^{th}) has an on going call and is located at the fringe area between more than two base stations (Pilot pollution scenario). The mobile station receives more than pilot code signal ($c^{(k)}(t)$) in addition to the real time voice data information. For better understanding the whole process, let us trace all the *inter-cell, intra-cell* incoming signals to the mobile station from the serving base station [7].

Let $S_u(t)$ is the u^{th} user's voice signal after spreading but before scrambling:

$$S_u(t) = \sum_{i=-\infty}^{\infty} b_u(i) m_u(t - iNT_c) \qquad (2)$$

Where

$b_u(i)$: The i^{th} data symbol for the u^{th} user.

$m_u(t)$: The spreading code for the u^{th} user.

T_c : The chip duration.

The base station combines all users' signals including our particular interest mobile user u^{th} and scrambling them by

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its unique scrambling code a(t). Thus, the combined and scrambled signal can be written such as follows:

$$x(t) = a(t)\sum_{u=1}^{U} S_u(t)\sqrt{Pu} \quad (3)$$

Where

U: The total number of users.

P_u: The transmitted power for the u^{th} user.

Assume that the communication physical channel is the same for all users and is given by the impulse response:

$$h_c(t) = \sum_{f=1}^{F} \alpha._f \delta(t - \tau._f) \quad (4)$$

Where

F : Total number of paths/fingers.

α_f: The f^{th} complex path gain.

τ_f: The f^{th} complex delay.

$\delta(t-\tau._f)$: Low pass impulse characteristics function.

Thus, the received signal at the mobile station r(t) can be given with following expression:

$$r(t) = \sum_{f=1}^{F} \alpha.f.x(t - \tau.f) + n(t) \quad (5)$$

Where

n(t): Additive White Gaussian Noise (AWGN)

Now, the output of the (f^{th}) finger ($f=1, \ldots ,F=3$) can be given by the following equation assuming that the receiver is demodulating the data $b_1(0)$, (the bit number 0 of the u^{th} user signal):

$$O_u^f = \int_{\tau_f}^{\tau f + NT_c} r(t).a*(t-\tau_f).c_u^*(t-\tau_f).dt \quad (6)$$

Where:

r(t): The received signal at the (f^{th}) finger.

a(t): The base station scrambling code.

$C_u(t-\tau_f)$: The spreading waveform of the u^{th} user .

N: The spreading factor.

T_c: Chip duration.

Equation (6) can be rearranged as follows:

$$O_u^f = d_u^f + s_u^f + i_u^f + \eta_u^f \quad (7)$$

Where

d_u^f : The u^{th} user's desired signal output developed by the f^{th} finger's correlator.

s_u^f : The inter-symbol interference (ISI) component.

i_u^f : The output of multi-user interference component.

η_u^f The output signal noise, including AWGN

Since the mobile station is located in the soft handoff region, equation (7) should be modified to reflect the impact of the PPI component. Thus, equation (7) can be rewritten such as follows:

$$O_u^f = d_u^f + s_u^f + i_u^f + \eta_u^f + \sum_{z=1}^{Z} P_z^f \quad (8)$$

Where

$\sum_{z=1}^{Z} P_z^f$: The output pilot pollution interference component originated from strong power level pilot signals corresponding to the base station z^{th}, $(z=1 \ldots Z)$, $z \neq k$, (k: the serving BS).

One way to represent the power spectrum of the pilot pollution interference component (P_o) is to utilize the number of chips in the pilot signal (N_{pc}) and its phase offset α_{pc}. In [6], the power spectrum of the pilot pollution interference is found to have a direct relationship with the N_{pc}.

$$(P^f_o)_u = K.\ ((1/N_{pc}) - (1/N_{pc})^2))\angle\ \alpha_{pc} \quad (9)$$

Consequently, the pilot pollution component can be mathematically formulated by the following equation:

$$\sum_{z=1}^{Z} P_z^f = K.\{(1/\text{Npc}) - (1/\text{Npc})^2)\angle\alpha._{pc1} +, \ldots, + (1/\text{Npc}) - (1/\text{Npc})^2)\angle\alpha._{pcz}\}, z \neq k \quad (10)$$

Where

k: is the serving base station.

We seek the value of $(\angle\ \alpha_{pcz})$ that *minimize* the power spectrum value of the PPI component.

3. System Paradigm and Solution Approach

The idea behind the proposed solution is to replace the existent chip shaping filter unit with another integrated unit composed of *the multi carrier technology* and the principle of *Carrier Interferometry* (CI) signal analysis at the base station side. Implementation of the CI principles along with the multi carrier technology at the base station side requires simple changes at the mobile station side; the problem of PPI can be alleviated significantly. The subsequent sections describe the principles of the CI technology and the proposed solution.

3.1. Carrier Interferometry (CI) Technology

The term *Carrier Interferometry* is composed of two parts. Starting with the second part, namely, *Interferometry* which is a standard approach used in the physics experiments to study the interference patterns resulting from the superpositioning of electromagnetic waves. The Interferometry technology generates a special characteristics signal called Carrier Interferometry (CI) signal using N carriers. The main important properties of this signal are [10]:

- In the time domain, the pattern of the CI signal is composed of multiple narrowband carriers

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(sidelobes) and only *one strong carrier (mainlobe)* such as shown in figure 2.

- In the frequency domain, it is constructed by the super-positioning of *N* carriers, each equally spaced by Δf.
- Observing the CI signal in the time domain such as shown in figure 2, the linear combining of the N carriers leads to forming a periodic pulse shape signal with a period of $1/\Delta f$. Each period composed of only *one mainlobe* of duration $2/(N\Delta f)$ and an array of sidelobes around the main lobes with period of $1/(N\Delta f)$.
- The most important property of the CI signals is the ***orthogonality*** property.

Each CI signal is uniquely identified with the position of its mainlobe. Therefore, a CI_1 signal possesses mainlobe positioned at time 0 is *orthogonal* to another one CI_2 with its mainlobe is positioned at time τ having the values of ($\tau=k/(N\Delta f)$, k=1,2, … ,N-1). An offset in the time domain can be mapped into a linearly increasing phase offset in the frequency domain.

Example

Figure 2 demonstrates the two CI orthogonal sets CI_1 and CI_2. They can be represented as follows:

- *CI_1* can be represented with N carriers possessing a phase offsets of $(\Theta_1, \Theta_2, \Theta_3, \dots, \Theta_N)=(0,0,0, \dots ,0)$.

- *CI_2* can be represented with N carriers possessing a phase offsets of $(\Theta_1, \Theta_2, \Theta_3, \dots, \Theta_N)=(0, 1.2\pi k/N, 2.2\pi k/N, 3.2\pi k/N, \dots, (N-1).2\pi k/N)$.

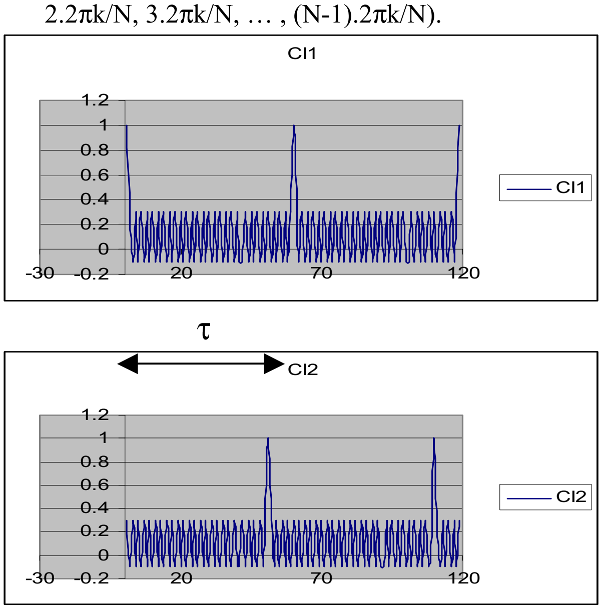

Figure 2. Orthogonality in Time Domain

Thus, the orthogonality between the CI signals can be pictured as CI signals with carriers having an adjustable phase separation ($e^{j\theta 1}$, $e^{j\theta 2}$, $e^{j\theta 3}$, ….,$e^{j\theta N}$), which is corresponding to (e^{j0}, $e^{j2\pi k/N}$, $e^{j2.\ 2\pi k/N}$, $e^{j3.\ 2\pi k/N}$,……., $e^{j(N-1).2\pi k/N'}$). The perfect orthogonality property of the CI signals make them possible to be applied to represent any sequential information symbols in the time domain with significant capability of frequency diversity selectivity rather than path diversity. Therefore, the CI technology is suitable to be applied to represent the WCDMA chip shaping mechanism, which allows us to control the phase offsets among the chips to reach a minimum phase offset value ($\angle\ \alpha_{pcz}$). Accordingly, the minimization condition in equation (10) will be met and satisfied.

3.2. Detailed Solution Approach

In the proposed solution, the existing chip shaping pilot code filter is replaced with another intelligent CI-chip shaping filter based on the principles of *multi-carrier Interferometry*. In the downlink path, the base station generates a short code using *nine* orthogonal CI signals instead of just one signal.

In the frequency domain, each bit is decoded with a certain frequency shift from the other bits. Likewise in the time domain, the phase shift offset between different CI signals will be adjusted carefully and combined to represent a unique base station pilot code. The new CI-chip shaping signal ensures signal orthogonality property among the combined carriers representing different base stations.

Observing the modified new pilot signal (CI-chip shaping signal) in the time domain indicates that the CI-chip shaping signal is composed of a single periodic mainlobe at ($t=0\dots t=\tau$) and multiple sidelobes elsewhere. Therefore, the mobile's RAKE receiver would be able to resolve the received composite carrier frequency components (from more than one base stations) and detect only one stronger mainlobe while the other pilots, which are related to other base stations are at the times of sidelobes position.

The CI-WCDMA's receiver is similar to the one presented in [10]. Since the mobile station is located in the soft handoff region, the receiver will perform *two demodulation* simultaneous tasks. One task is regarding the demodulation process of the *real time voice data* information. The other task is to *detect the strongest pilot signal* and reject the interfere ones. The receiver is divided into multiple chip receivers. In respect to the first task, each received chip will be multiplied by the user's spreading code and linearly combine all chips' output. This leads to get the user's desired voice information. For the second task, each received chip will be multiplied by

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the scrambling codes for those base stations, which their codes are stored in the mobile user's active list, and linearly combine all chips' output. Therefore, only one pilot signal will yield a peak (mainlobe) at the combiner's output, whereas, other pilots contribute to the sidelobes.

In summery, the proposed solution relies on replacing the existing chip shape filter with a CI chip shape filter employing (N) equally spaced frequency carriers. The CI chip shape filter characteristics function is given by:

$$h(t) = \sum_{n=0}^{N-1} A \quad \cos(\ 2n\pi\Delta f\ ) \qquad (11)$$

Where

A: the chip energy value (1/N).

As a result, the transmitted CI pilot code can be defined such as follows:

$$c_k(t) = \sum_{i=0}^{N-1} B_i^{(k)} h(t - iT_c) \qquad (12)$$

$$c_k(t) = \sum_{i=0}^{i=8} B_i^{(k)} \cos(2\pi n f_c t + 2\pi n\Delta f(t - iT_c)) \quad (13)$$

Where

Δf : Frequency offset used to make sure that the carrier frequencies are orthogonal to each other

$\Delta f = 1/T$ where T is the bit duration

f_c : The system carrier frequency.

4. Performance Analysis

The goal is to simulate the downlink of the new design of the mobile radio system in the presence of the pilot pollution interference scenario; and measure how significant is the proposed solution. From the simulation, the bit error rate (BER) of the system under evaluation will be determined. The BER depends upon a number of factors such as the signal-to-interference ratio (SIR), and the frequency offset between the desired signal, and the interferers. The MATLAB system simulation tool package (Simulink) was used to investigate the implementation of the transmitter/receiver model shown in figure 3. The channel is modeled by a Rayleigh fading hilly terrain model as given in [10].

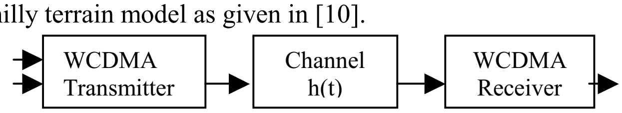

Figure 3. WCDMA Downlink Transmission Model

4.1. Performance Metrics

4.1.1. Signal to Interference Ratio (SIR)

No mater how strong is the carrier signal; the SIR is a remarkable measure to assess the level of the pilot pollution interference.

Let $SIR = \frac{E_c}{I_o}$ (14)

Where:

E_c : signal energy in one chip duration of the pilot signal

I_o : Power spectrum of the interference and noise

E_c is proportional to the mean value of the demodulated pilot chips = K. $(1/N_{pc})^2$

I_o is proportional to the interference and noise measured value = K. $((1/N_{pc}) - (1/N_{pc})^2)$

N_{pc} is the number of chips in the pilot signal.

$$SIR = \frac{E_c}{I_o} = \frac{1/N_{pc}}{(1 - 1/N_{pc})} \qquad (15)$$

4.1.2. Bit Error Rate (BER)

Assuming QPSK modulation, the BER is given by equation (16), where E_b is the energy per bit.

$$BER = Q(\text{sqrt}(E_b/N_0))$$

Where

E_b/N_0: bit energy-to-noise density and is given by

$$\frac{E_b}{N_0} = \frac{W/R}{(U-1) + (\frac{\eta}{S})} \qquad (16)$$

W: The total system bandwidth

R: Information bit rate

U: Total number of users

η: Background noise

S: Signal power

4.2. Simulation Results

Table 1 lists the values of the main system parameters employed for this study.

Table 1: Simulation Parameters

Carrier frequency f_c	5 GHZ
Spreading Code	Walsh Hadamard
Modulation	BPSK
No. of mobile stations	1
No. of Base stations	[1-6]
CI frequency spacing Δf	313 KHZ
Channel model	Hilly terrain (HT) model
Guard period	800 ns
Mobility Pattern	Pedestrian

Figure 4 demonstrates the power of using the CI-chip shaping signal. It is clearly shows the significant performance improvement in the WCDMA. Comparing the two curves representing the pure WCDMA system and the CI-WCDMA system, it is evident that both systems perform well until the mobile station is getting engaged in communication with more than *two* base station. A dramatic increase of the BER belongs to the

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WCDMA system is occurred while the CI-WCDMA system expresses a stale BER value around 0.01. Specifically, the performance of the WCDMA system degrades to a great extent when the mobile station is overloaded with more than three communication links from different base stations or multipath links. In addition, the CI-WCDMA outperforms the WCDMA system by keeping the BER in safe margin (~ (0.0325-0.01=0.0225)). As the mobile station is communicating with more than *two* base stations, we had observed that the system simulation took very lengthy BER computations (direct relationship). It indicates the presences of high interference level than the usual.

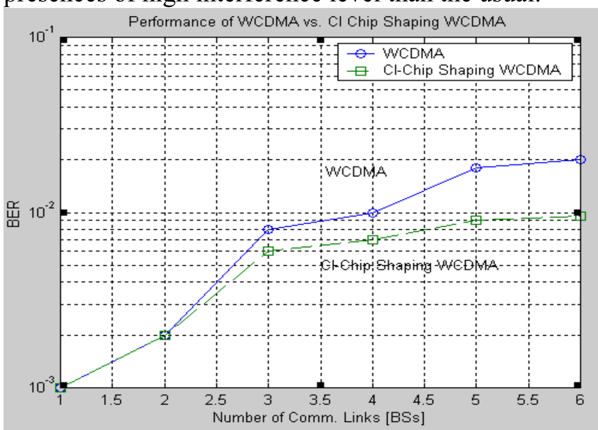

Figure 4 BER Performance of WCDMA vs. CI Chip Shaping WCDMA

On the other hand, figure 5 explains a typical WCDMA BER performance versus SIR. In WCDMA system, when the interference level dominates the signal level, the mobile station suffers from increasing the interference level and the BER goes up. Therefore, the serving base station should increase its power level to reach the mobile station. Eventually, this may lead to increase the system interference level. However, CI-CDMA is able to discriminate against the increasing level of interference and keep the BER value in acceptable margin (0.01-0.001).

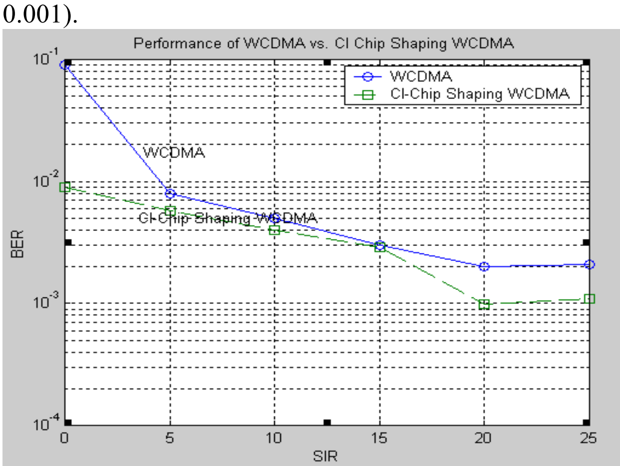

Figure 5 (BER-SIR) Performance of WCDMA vs. CI Chip Shaping WCDMA

5. Conclusions

This paper proposes and discusses a multi *Carrier Interferometry* approach for reducing the impact of the pilot pollution interference in wireless mobile communications systems. The integration of the Multi-*Carrier Interferometry* with the WCDMA system requires minor changes at the downlink of the mobile radio system partners (base station and mobile station). These changes are including the usage of the orthogonal multi carrier inteferometry at the base station side and a frequency diversity detection receiver at the mobile station side.

Simulation performance analysis demonstrated that there is a significant improvement in the BER and SIR values by employing the CI-chip shaping technology. Some illustrative output results were presented such as the CI-WCDMA outperforms the WCDMA system by keeping the BER in safe margin (~ (0.0325-0.01=0.0225)).

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