Keynote Paper

Discovery of Uniform Multi-Carrier Frameworks for Multiple Access Technologies

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ABSTRACT

Multi-carrier technologies are emerging as a considerable force in the wireless world. OFDM charges ahead, with MC-CDMA close behind. However, as this tutorial demonstrates, multi-carrier technologies are not limited to OFDM and MC-CDMA. By application of Carrier Interferometry (CI) principles, we create CI/TDMA and CI/DS-CDMA, multi-carrier implementations of existing TDMA and DS-CDMA technologies. These implementations enable significant improvements in both performance and network capacity. Specifically, we double the network capacity of existing TDMA and DS-CDMA system and simultaneously outperform their traditional implementations. Of course, the benefits of Carrier Interferometry are not limited to TDMA and DS-CDMA: It also significantly improves the existing MC-CDMA and OFDM multi-carrier systems. What emerges is a very powerful technology that creates a common multi-carrier architecture for DS-CDMA, TDMA, OFDM, and MC-CDMA, bridging the hardware gap between the world's most promising technology, all the while enhancing network capacity and probability of error performance.

Keywords: OFDM, MC-CDMA, TDMA, DS-CDMA, multi-carrier, carrier interferometry, software radio, network capacity

1. INTRODUCTION

In the rapidly growing world of wireless telecommunications, a number of trends are gaining widespread popularity. Among these is the explosion of interest in multi-carrier communications, and its application to wireless multiple-access techniques. In particular, there has been a great deal of research and development of late in areas of OFDM (orthogonal frequency division multiplexing) and MC-CDMA (multi-carrier code division multiple access).

In addition to the interest in multi-carrier communications, there is also a growing interest in creating a single architecture for wireless devices: engineers envision a simple piece of software capable of switching mobiles from TDMA (time division multiple access) to DS-CDMA (direct sequence code division multiple access) to MC-CDMA to OFDM, while maintaining a common hardware platform.

In this brief tutorial, we outline how to advance existing multi-carrier technologies to bring the vision of a common hardware platform to immediate reality, bringing the future to life today. In the opening section, we review the popular multi-carrier technologies of OFDM and MC-CDMA, explaining the reasons that underlay their growing importance. In the sections that follow, we explain how a common multi-carrier platform can be designed for TDMA, DS-CDMA, MC-CDMA and OFDM. We demonstrate how, in each and every scenario, the proposed multi-carrier platform is able to reduce complexity and outperform existing receiver structures in multipath fading channels, due to better exploitation of the channel diversity and a minimization of the MAI (multi-access interference). Furthermore, we demonstrate how to use multi-carrier technologies to increase network capacities (measured by numbers of user). The mathematical justification and detailed "how-to" is not presented in this brief tutorial, but rather is the stuff that fills references [1-12].

2. REVIEW OF MULTICARRIER TECHNOLOGIES

2.1. OFDM and COFDM

OFDM, short for orthogonal frequency division multiplexing, was first proposed in the 50's, and only now, with substantial advancements in DSP (digital signal processing) technology, becoming an important part of the telecommunications landscape. Some examples of the rapidly growing use of OFDM include its adoption as a standard for the European wireless data link known as HYPERLAN, as well as its adoption in the US for by the well-known IEEE 802.11. Perhaps of even greater importance is the emergence of this technology as a competitor for future 4G wireless systems. These systems, expected to emerge by the year 2010, promise to at last deliver on the wireless Nirvana of anywhere, anytime, anything communications. Should OFDM gain

Enabling Technologies for 3G and Beyond, Vijay K. Garg, Carl R. Nassar, Steve J. Shattil, Editors, Proceedings of SPIE Vol. 4529 (2001) © 2001 SPIE · 0277-786X/01/$15.00

prominence in this arena, and companies such as Motorola are banking on just this scenario, then OFDM technology will become the technology of choice in most wireless links worldwide.

The beauty of OFDM lies in its simplicity. In OFDM, an incoming data stream, most likely with a high data rate, enters at the transmitter side. This incoming data enters a serial to parallel converter, mapping the high rate data stream into N lower rate (parallel) data streams. Each data stream is then placed on its own carrier, and carrier spacing is carefully selected to ensure orthogonality, i.e., to ensure that carriers can be perfectly separable one from another at the receiver side. The N carriers are next added together, modulated up to the transmit frequency, and finally sent out across the channel. One trick-of-the-trade that makes these transmitters low cost is the ability to implement the mapping of bits to unique carriers via the use of an inverse FFT (fast Fourier transform).

In OFDM, each of the N low-rate data streams demonstrate a narrow bandwidth. As a result, when sent over the channel, each low-rate data stream experiences a flat fade, i.e., the gain is constant over all the frequencies that make up the low-rate data stream. As a result, no equalizer structure will be required at the receiver.

At the receiver side in OFDM, the incoming data stream is first returned to baseband by use of an appropriate mixer. Next, the incoming data stream is separated into its N low-rate data streams by: to extract the i^{th} low-rate data stream, apply the i^{th} carrier's frequency followed by a low pass filter (implemented using an integrator). Once the data streams have been separated one from another, a simple decision device is applied.

Unfortunately, OFDM, when implemented as described above, comes with a severe drawback that limits its applicability. In short, the performance of OFDM, measured in terms of probability of error, is very poor. This results because: In times of deep fade, the data on a narrowband carrier is effectively lost.

To improve OFDM such that it achieves the desired performance benchmarks, coded OFDM, or COFDM for short, was introduced. The idea underlying coded OFDM follows. The incoming data stream first enters a convolutional coder, typically of rate ½ and constraint length 7. This maps every incoming bit into two outgoing bits, with the extra bit added to enable the receiver to detect and correct bit errors. Following the convolutional coder is an interleaver, which reorders the incoming bits. (Specifically, the interleaver spaces bits such that the 2 bits output from the convolutional coder (for each input bit) are NOT sent on adjacent carriers, but will be sent out on carriers that are far apart from one another.) Next, the usual OFDM transmitter is employed, following the description outlined above.

The benefits that COFDM offers (over OFDM), in terms of performance improvement, are two-fold. First, and most apparent, is the benefit that the convolutional channel coding brings. This channel coding allows the receiver to detect and correct for errors in transmission. The second performance benefit comes in the form of the interleaver. The interleaver ensures that the 2 bits output by the channel coder (for each incoming bit) are sent on carriers that are far apart from one another. This leads to a frequency diversity benefit.

2.2 MC-CDMA

MC-CDMA, first proposed in 1993, refers to a technique for the transmission of multiple users' data over a set of N narrowband carriers. Specifically, the problem that MC-CDMA poses then answers is simply this: If I have N orthogonal carriers available for use, and N users who want to send their information simultaneously over these carriers, how do I go about allowing these users to send their information over these carriers?

There are many answers to this question. The classic answer is to allow each of the N users to occupy one of the N carriers, and there we have the classic technology known as FDMA (frequency division multiple access). MC-CDMA presents a more elegant answer, one that enables significant performance improvement relative to FDMA.

In MC-CDMA, each user sends his data on all N carriers. That is, user j sends the exact same data (his own data) on all N carriers simultaneously. Another user, user k, sends his own data at the same time over the same N carriers. The problem, of course, is that the data from user j and the data from user k "collide". We must provide some way to make the data from user j and the data from user k separable from one another at the receiver side.

To make this possible, user j applies a unique code to the N carriers (typically a series of +1 and –1 values), and user k applies a different code to all N carriers. These codes are carefully selected to make the users separable at the receiver. Typically, these codes correspond to well-known spreading codes such as Hadamard-Walsh codes.

Typically, the channel effects a transmitted MC-CDMA signal as follows. Each of the N carriers is usually narrow in its bandwidth, and, as a result, when sent over the wireless link, each experiences a flat fade. However, over this entire frequency bandwidth, the channel is frequency selective, meaning different carriers will experience different fades.

The MC-CDMA receiver built to detect user k's data first divides up the MC-CDMA signal into its carrier components. With the data separated into its carrier components, the carriers are next "despread": The spreading code applied to user k is removed by application of the appropriate "despreading code". Next, the received signals are applied to a combiner. The combiner combines the carriers in such a way that it: (1) minimizes (or completely eliminates) the presence of the other users' signals; (2) maximizes the frequency diversity benefit, i.e., the performance benefit achievable by sending the information simultaneously over all the N carriers; and/or (3) minimizes the presence of the noise. Possible combining techniques include the EGC (equal gain combiner), ORC (orthogonality restoring combiner), or the MMSEC (minimum mean squared error combiner).

MC-CDMA demonstrates a number of benefits when compared to the widely adopted DS-CDMA systems. The primary benefit is an improvement in terms of probability of error performance, which arises for two primary reasons: (1) MC-CDMA systems are capable of better exploiting the energy spread introduced by the channel; and (2) each diversity branch in the MC-CDMA receiver experiences a much higher SIR (lower interference) than the corresponding diversity branches in the DS-CDMA RAKE receiver.

3. THE CARRIER INTERFEROMETRY (CI) APPROACH

We now propose a powerful method known as Carrier Interferometry (CI) to broaden the scope of multi-carrier technologies. Specifically, using the proposed CI method, existing multiple-access techniques, from TDMA to DS-CDMA, can be implemented as a multi-carrier technology. By combining the multi-carrier implementations at the transmitter side with simple changes in the receiver technology, the performance (measured in terms of probability of error) *and* network capacity (measured in terms of numbers of users sharing the system) are significantly enhanced.

3.1 The CI Signal

At the heart of our technology lies the signal referred to as the Carrier Interferometry (CI) signal. The CI signal demonstrates both excellent frequency resolution and excellent time resolution. That is, the CI signal is composed of multiple narrowband carriers that allow it to be resolved into its frequency components. Additionally, when observed in the time domain, the CI signal is very narrow, enabling it (1) to be easily separated from other CI signals, and (2) to resolve the channel's multipath profiles.

The CI signal, denoted $c(t)$, is, conceptually, very simple. The CI signal is the addition of N carriers, each equally spaced by frequency separation Δf. All carriers are in-phase, with a zero phase offset. This is illustrated in the frequency domain in Figure 1(a). The linear combining of these carriers leads to the time domain signal shown in Figure 1(b). Here, we see a mainlobe of duration $2/(N\Delta f)$ followed by times of sidelobe activity, each of duration $1/(N\Delta f)$.

Placing this in the context of traditional communication signals, the CI signal appears to be a frequency sampled version of the *sinc()* waveform. That is, the CI signal is an approximation to the *sinc()* waveform, generated by frequency sampling the *sinc()* waveform using N equally spaced samples. Of course, frequency sampling leads to time repetition, which explains the periodic nature of the CI signal.

3.2 Orthogonality Properties of the CI Signal

A CI signal positioned with a mainlobe centered at time 0 is orthogonal to a CI signal with its mainlobe positioned at time τ, whenever τ is a value in the set $\{k/(N\Delta f),\ k=1,2,\ldots,N-1\}$. This property assures us that CI waveforms can be applied to represent information symbols located sequentially in time, without creating inter-symbol interference.

There exists an important alternative representation to the statement: a CI signal positioned with a mainlobe centered at time 0 is orthogonal to a CI signal with a mainlobe positioned at time $\tau \in \{k/(N\Delta f),\ k=1,2,3,\ldots,N-1\}$. This alternative is explained in the next paragraph.

An offset in the time domain corresponds to a linearly increasing phase offset in the frequency domain. With that in mind, we note the following equivalence. A CI signal with a mainlobe positioned at time 0 is equivalent to a CI signal with carrier 1 to carrier N demonstrating phase offsets $\{\theta_1, \theta_2, \ldots, \theta_N\} = \{0, 0, \ldots, 0\}$. Correspondingly, a CI signal with time offset $\tau = k/(N\Delta f)$ is equivalent to a CI signal with carrier 1 to carrier N demonstrating phase offsets $\{\theta_1, \theta_2, \ldots, \theta_N\} = \{0, 2\pi k/N, 2 \cdot 2\pi k/N, \ldots, (N-1) \cdot 2\pi k/N\}$. This is illustrated in Figure 2. Hence, the orthogonality between CI signals can be understood as either: (1) CI signals with an appropriate time separation $\tau \in \{k/(N\Delta f), k=1,2,3,\ldots,N-1\}$ are orthogonal to one another, or (2) CI signals, with carriers coded with an appropriate "complex spreading sequence", namely $\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N}, e^{j2 \cdot 2\pi k/N}, \ldots, e^{j(N-1) \cdot 2\pi k N}\}$, $k=0,1,2,\ldots,N-1$ are orthogonal to one another.

3.3 Pseudo-Orthogonality Properties of CI Signals

Consider two sets of CI signals:

Set 1:
$c(t), c(t-t_1), c(t-t_2), \ldots, c(t-t_{N-1})$ where $\{t_1, t_2, \ldots, t_{N-1}\} = \{1/(N\Delta f), 2/(N\Delta f), \ldots, (N-1)/(N/\Delta f)\}$

Set 2:
$c(t-\Delta t), c(t-t_1-\Delta t), c(t-t_2-\Delta t), \ldots, c(t-t_{N-1}-\Delta t)$ where $\{t_1, t_2, \ldots, t_{N-1}\} = \{1/(N\Delta f), 2/(N\Delta f), \ldots, (N-1)/(N\Delta f)\}$

These sets of CI signals are illustrated in Figure 3. Referring to the discussion of the previous subsection, the CI signals in set 1 are orthogonal to one another, and the CI signals in set 2 are orthogonal to one another. However, the CI signals in set 1 are not orthogonal to the CI signals in set 2. We seek the value of Δt that minimizes the mean squared value of the interference between the signals of set 1 and set 2. A mathematical derivation confirms the intuitively pleasing result: select $\Delta t = 1/(2N\Delta f)$; pictorially, this is shown in Figure 3, and conceptually, this corresponds to the rather simple notion of placing the second set of signals in the middle of the first set of signals.

Of particular interest is the following result: with $\Delta t = 1/(2N\Delta f)$, the interference between the signals of set 1 and the signals of set 2 is small.

Expressing this result in terms of phase offsets, we can state the following (by simply recognizing the equivalence between shifts in the time domain and phase offsets in the frequency domain). Consider two sets of CI signals:

Set 1:

$c_0(t), c_1(t), \ldots, c_{N-1}(t)$
where
$c_k(t)$=*the CI signal with carriers 1 to N demonstrating phase offsets (complex spreading codes)* $\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N}, e^{j2 \cdot 2\pi k N}, \ldots, e^{j(N-1) \cdot 2\pi k N}\}$

Set 2:

$c_0(t), c_1(t), \ldots, c_{N-1}(t)$
where
$c_k(t)$=*the CI signal with carriers 1 to N demonstrating phase offsets (complex spreading codes)* $\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j(0+\Delta\theta)}, e^{j(2\pi k/N+\Delta\theta)}, e^{j(2 \cdot 2\pi k/N+\Delta\theta)}, \ldots, e^{j((N-1) \cdot 2\pi k/N+\Delta\theta)}\}$

The CI signals in set 1 are orthogonal to one another, as are the CI signals in set 2. The CI signals in set 1 and set 2 are not orthogonal to one another, but demonstrate a minimal amount of interference when $\Delta\theta = \pi/N$. This is equivalent to the earlier statement, with shifts in the time domain replaced by offsets in the frequency domain.

4. APPLICATION OF THE CI APPROACH: MULTI-CARRIER IMPLEMENATION OF MULTIPLE ACCESS TECHNIQUES

4.1 CI/MC-CDMA: The application of the CI signal in MC-CDMA

In the MC-CDMA, the input signal is first split into N branches, and the signal on each branch is modulated onto one of N carriers. Each carrier is then coded with user k's spreading code, a combining and modulation to the passband occurs, and the signal is sent out over the channel. Of particular relevance to this section is: typically, the spreading code applied to user k corresponds to well-known codes, where each value is either +1 or –1, such as the Hadamard-Walsh spreading codes or Gold codes.

To apply the CI concept to MC-CDMA, we simply replace the usual spreading codes with the "complex spreading codes" that make up the CI signal. That is, the spreading codes for user k are now selected as the set $\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N}, e^{j2\cdot 2\pi k/N}, \ldots, e^{j(N-1)\cdot 2\pi k/N}\}$. By application of these spreading codes, each user's code now corresponds to one of the CI signals shown in the solid line of Figure 3.

With this selection of CI codes, N users $(k=1,2,\ldots,N)$ can be supported orthogonally, with each user receiving one of the CI signals shown in the solid line of Figure 3. If, however, additional users wish to be supported by the MC-CDMA system, these users can be introduced (in a pseudo-orthogonal manner) by assigning user $N+k$ the spreading code $\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j(0+\Delta\theta)}, e^{j(2\pi k/N+\Delta\theta)}, e^{j(2\cdot 2\pi k/N+\Delta\theta)}, \ldots, e^{j((N-1)\cdot 2\pi k/N+\Delta\theta)}\}$ where $\Delta\theta=\pi/N$. In this way, an additional N pseudo-orthogonal users (users $N+1$, $N+2$, ..., $2N-1$) are supported, by assigning, to these users, codes corresponding to CI signals pseudo-orthogonal to the original N user's CI signals. This is seen in Figure 3, where the dotted CI signals represents the new users' codes in accordance with minimizing the mean squared MAI (multi-access interference)).

This CI/MC-CDMA system demonstrates "flexibility with elegance": when N users or less are to be supported, the CI/MC-CDMA system supports these users orthogonally; when additional users request service, these users are supported in a pseudo-orthogonal manner.

Most impressive of all is the performance curve demonstrated by the use of CI signals as multi-carrier codes. When applying the complex spreading codes associated with CI signals, performance curves typified by Figure 4 result. From this curve, it is evident that with 2N=64 users occupying an MC-CDMA system with CI codes, the performance is effectively identical to that of an MC-CDMA system supporting only N=32 users with Hadamard-Walsh spreading codes. In MC-CDMA, CI codes are capable of supporting twice as many users, doubling network capacity, *without* performance degradation.

4.2 CI/TDMA: Multicarrier Implementations of TDMA & the Demise of the Equalizer

Carrier Interferometry in general, and the CI signal, *c(t)*, shown in Figure 1, are easily applied to TDMA systems with impressive results in terms of both performance and complexity.

Consider the modulator used in TDMA. With near exclusivity, the pulse shape *p(t)* used to modulate the data is either the *sinc( )* pulse shape or the root raised cosine pulse shape. Since the CI signal *c(t)* represents a sampled version of the *sinc( )* pulse shape, and satisfies the same Nyquist criteria for zero ISI, we apply Carrier Interferometry to TDMA by setting the pulse shape *p(t)* to the CI signal *c(t)*. While this appears to be a minor revision, it creates a dramatic improvement in terms of both performance and capacity, as outlined next.

First, we demonstrate the performance improvement, based on a redesigning of the receiver. Typically in TDMA, upon transmission over a wireless link, the channel introduces a multipath effect, representing a major roadblock to successful data detection. In order to overcome this roadblock, TDMA receivers are built with equalizers, which (in essence) is an attempt to undo the multipath effect of the channel by building a filter which approximates the inverse of the channel effect. The equalizer effectively aligns (in time) the multiple paths, and linearly recombines them, allowing the receiver to benefit from the energy spread among the many paths. Although many equalizer structures are available, the most popular among these is the DFE (differential feedback equalizer).

In CI/TDMA, i.e., TDMA where the pulse shaping filter is matched to the CI signal *c(t)*, the equalizer is abandoned, replaced by a frequency recombining receiver structure. Recall that the CI signal *c(t)* is decomposable into its N frequency components. The first task implemented by the receiver is the breakdown of the CI signal into its N frequency components. While frequency selective fading arises over the entire channel, the N narrowband frequency components allow the signal, in the frequency domain, to be resolved into N bands each experiencing a flat fade. A combiner is then applied which, much like the CI/MC-CDMA case, serves to (1) maximize the frequency diversity benefit available across the frequency selective channel, (2) minimize any inter-bit interference introduced by the channel, and/or (3) minimize the additive noise.

The recombining in the frequency domain easily outperforms the equalizer processing in the time domain as shown in Figure 5, where probability of error performance versus SNR is demonstrated over a Hilly Terrain fading channel. Over 10dB performance gain is available at probability of errors of 10^{-3}.

Next, we demonstrate a significant throughput benefit, trading in a small percentage of our performance gain for dramatic increases in TDMA throughputs. TDMA increase its throughput via the use of pseudo-orthogonal pulse shapes.

Returning to the presentation of CI signals and their properties, it was shown that, given N orthogonal carriers frequency separated by Δf, N orthogonal CI signals can be located at positions $\{\tau=k/(N\Delta f),\ k=0,1,2,\ldots,N-1\}$. Additionally, an extra set of N CI signals can be introduced pseudo-orthogonally at times $\{\tau=k/(N\Delta f)+1/(2\ N\Delta f),\ k=0,1,2,\ldots,N-1\}$. This was shown pictorially in Figure 3. In terms of the current TDMA discussion, this corresponds to: In a length N TDMA burst, locate N information bearing pulses at the usual times $0, Ts,\ 2Ts, \ldots, (N-1)Ts$, and place an additional set of N information bearing pulses at times $Ts/2,\ Ts+Ts/2,\ 2Ts+Ts/2, \ldots, (N-1)Ts+Ts/2$. This leads to a total of 2N information bearing pulses in a length-N burst, which doubles throughput. The cost, of course, is a degradation in probability of error performance because we are introducing a carefully-controlled amount of ISI at the transmitter side.

The probability of error performance is evaluated for a transmitter sending 2N information symbols in a packet that would typically hold N orthogonal symbols, and with a receiver designed based on frequency recombining principles. The performance is plotted in Figure 6, where we see that doubling the throughput leads to a degradation in performance relative to the CI/TDMA system operating with only N symbols per burst. *However, CI/TDMA with 2N symbols per burst still outperforms tradition TDMA (with the usual N symbols per burst and using a DFE equalizer) by up to 7 dB at a probability of error of* 10^{-3}.

4.3 CI/DS-CDMA: A Multi-Carrier Implementation of DS-CDMA and the Demise of the RAKE Receiver

The Carrier Interferometry principle in general, and the CI signal in particular, can be applied to DS-CDMA, offering significant benefits in terms of performance and network capacity.

The application of the CI signal to DS-CDMA is very similar to its applicability in TDMA. Specifically, in TDMA, the first and most significant update took place at the transmitter side, where the usual *sinc( )* and raised cosine pulse shapes were replaced by the CI signal $c(t)$, i.e., the pulse shape $p(t)=c(t)$. This same principle will apply to chip shaping in DS-CDMA.

Specifically, in DS-CDMA, each user's code consists of a spreading sequence (a sequence of values typically +1 or –1 each) applied to N chip shapes, each separated in time by chip duration T_c. Now, much like the pulse shaping that transformed TDMA into CI/TDMA, we can update the chip shaping in DS-CDMA to create CI/DS-CDMA. Specifically, we replace the usual chip shaping filter at the code generator with a chip shaping filter matched to the CI signal $c(t)$. This enables improvements in performance and network capacity as outlined next.

Typically, when a DS-CDMA signal is transmitted over a wireless link, the major channel impairment is the multipath effect. The DS-CDMA receiver attempts to turn this impairment to its advantage by use of a RAKE receiver, which, to the best of its ability, separates the multiple paths, realigns them, then recombines them in a way to optimizes receiver performance. However, the RAKE receiver's performance is limited by its inability to effectively separate paths from one another.

When DS-CDMA is used with CI chip shapes, i.e., in CI/DS-CDMA, the RAKE receiver is abandoned, and in its place a receiver based on frequency decomposition and recombining is applied. Specifically, at the receiver side, each chip is separated into its N frequency components and recombined in a manner that enables (1) optimal frequency diversity benefits, (2) minimal inter-chip interference, and (3) a reduction in additive noise power. Upon recombining of the chips, the DS-CDMA spreading codes are applied to separate users one from another.

Impressive performance benefits are available via the new frequency-based receiver, which replaces the traditional RAKE receiver when CI chips shapes are used at the transmitter side. Figure 7 plots a typical performance comparison, showing probability of error versus SNR for a fully loaded DS-CDMA system with a processing gain of 32. Here, the performance of typical DS-CDMA with a RAKE receiver levels off at a poor probability of error due to the damaging effects of a large inter-path interference. The CI/DS-CDMA system, on the other hand, demonstrates a probability of error performance that continues to improve as SNR increases. At probability of errors of 10^{-2}, a 14 dB performance improvement is evident. This results from the frequency processing benefit discussed when comparing MC-CDMA with DS-CDMA.

Some of the performance improvement of CI/DS-CDMA can be traded in for an increase in capacity, much like in the CI/TDMA case. Specifically, in CI/DS-CDMA, rather than place N CI-shaped chips in a system with processing gain N, we place 2N CI-shaped chips in the same time duration and bandwidth. The result is inter-chip interference introduced at the transmitter side, which leads to a performance degradation at the receiver. The benefit, of course, is the ability to locate twice as many users on 2N chips as were possible when only N chips were available.

Specifically, much like the CI/TDMA case, in CI/DS-CDMA N chips are located at the usual positions, i.e., N chips correspond to $c(t), c(t-T_c), c(t-2T_c), \ldots, c(t-(N-1)T_c)$, and the other N chips are located at the mid-positions between these chips, i.e., the other N chips correspond to $c(t+T_c/2), c(t-T_c+T_c/2), c(t-2T_c+T_c/2), \ldots, c(t-(N-1)T_c+T_c/2)$. This concept is illustrated in Figure 3, with the first set of chips represented by the solid line, and the second set of chips corresponding to the dotted line. The 2N CI-based chips demonstrate the same occupancy in the time domain and frequency domain (i.e., the same total time duration and frequency bandwidth), while supporting twice as many users as an N-chip system. The cost is performance degradation due to the introduction of interchip interference at the transmitter side.

The performance of the CI/DS-CDMA system with 2N CI-based chips per bit, i.e., capable of supporting 2N users, is shown in Figure 8. This is compared with the performance a typical DS-CDMA system with N chips per bit and a RAKE receiver. All systems demonstrate an identical bandwidth occupancy. It is apparent that by application of CI principles to DS-CDMA, we can double the capacity of DS-CDMA while maintaining performance improvements.

4.4 CI/OFDM: Increasing Performance & Throughput and *Eliminating* the PAPR Problem

Another system of prominence in the wireless world is OFDM. Here, Carrier Interferometry principles enable performance and network capacity gains in OFDM, as well as the elimination of the PAPR problem. Specifically, to apply the principle of CI in OFDM, we make a simple decision: we will not send each bit over its own carrier. Instead, we will send each bit over all N carriers *simultaneously*. That is, the N bits are sent out at the same time, and each of these N bits occupies the same set of N carriers.

To enable bits to be separated from one another at the receiver side, we code each bit with a CI spreading code: that is, the N carriers for the kth bit experience the respective phase offsets $\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N}, e^{j2\cdot 2\pi k/N}, \ldots, e^{j(N-1)\cdot 2\pi k/N}\}$.

At the receiver side, bit k is extracted as follows. First, the N orthogonal carriers are separated from one another; next the phase offsets applied to the carriers for bit k are removed; and finally, a combiner is applied which combines the signal across carriers to exploit the available frequency diversity, minimize inter-bit interference, and reduce the additive noise power. In this way, each bit benefits from the full frequency diversity benefit available over the frequency selective channel, dramatically improving performance.

A typical performance benefit of the proposed CI/OFDM relative to OFDM is illustrated in Figure 9. Here, we see a 10 dB performance benefit over OFDM at a probability of error of 10^{-3}. Additionally, CI/OFDM, which offers the same throughput as OFDM, can be compared to coded OFDM (COFDM), where a reduction in throughput by a factor of 2 has been introduced by a convolutional coding. CI/OFDM demonstrates only a 4dB degradation relative to COFDM while demonstrating twice the throughput. (Of course, coded CI/OFDM can be constructed which notably outperforms coded OFDM.)

CI/OFDM can trade off some of its performance benefit for significant gains in the throughput of OFDM systems. This is achieved by allowing 2N bits to simultaneously occupy the N orthogonal OFDM carriers. Specifically, we allow 2N bits to be sent over all N carriers simultaneously. We ensure bits are separable from one another (as best as possible) at the receiver side by applying a unique CI spreading sequence to each of the 2N bits. Specifically, for bit k, we assign the following phase offsets to bit k's carriers:

$$\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N}, e^{j2\cdot 2\pi k/N}, \ldots, e^{j(N-1)\cdot 2\pi k/N}\} \text{ if } k=0,1,2,\ldots,N-1$$

$$\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j\pi/N}, e^{j2\pi(k-N)/N+\pi/N}, e^{j2\bullet 2\pi(k-N)/N+\pi/N}, \ldots, e^{j(N-1)\cdot 2\pi(k-N)/N+\pi/N}\} \text{ if } k=N,N+1,\ldots, 2N-1$$

This corresponds to what was referred to as set 1 and set 2 in the original discussion of Carrier Interferometry signals and their properties.

Figure 10 represents a typical probability of error performance curve for CI/OFDM with 2N bits on its N carriers. It is evident from this curve that CI/OFDM with twice as many bits on its N carriers, can still significantly outperform OFDM. If we introduce a coded CI/OFDM, where the coding reduces the bit rate to that of the original OFDM system, *we see that coded CI/OFDM offers* *the same throughput as original OFDM with the performance of coded OFDM.* In other words, with Carrier Interferometry, we get the best of both worlds.

In the case of OFDM, yet another powerful benefit emerges: the *elimination* of the PAPR (peak to average power) problem. The peak to average power ratio problem, described next, limits the practicability of OFDM. In OFDM, the N independently modulated carriers combine in-phase at times, resulting in sudden peaks in transmit power, and at other times combine out-of-phase, leading to times of low transmit power. This creates problems for linear amplifiers, which are now required to demonstrate large ranges of linear operation. In CI/OFDM, on the other hand, where each bit is carefully phase coded onto all the carriers, it is easily shown that when one bit's energy is at a maxima, the other bits' energies are at minima. This eliminates peaks in transmit power, which in turn eliminates the PAPR problem.

5. CONCLUSIONS

In summary, multi-carrier technologies are emerging as a considerable force in the wireless world. OFDM charges ahead, with MC-CDMA close behind. However, as this chapter demonstrates, multi-carrier technologies are not limited to OFDM and MC-CDMA. By application of Carrier Interferometry (CI) principles, we have demonstrated that we can create CI/TDMA and CI/DS-CDMA, i.e., multi-carrier implementations of existing TDMA and DS-CDMA technologies. These implementations enable significant improvements in both performance (measured in terms of probability of error) and network capacity (measured in terms of numbers of users or throughput per user). Specifically, we double the network capacity of existing TDMA and DS-CDMA system and simultaneously outperform these systems in their current implementations. Of course, the benefits of Carrier Interferometry are not limited to TDMA and DS-CDMA: It also significantly improves the existing MC-CDMA and OFDM multi-carrier systems.

What emerges is a very powerful technology indeed! Through the application of Carrier Interferometry, we create a common multi-carrier architecture for DS-CDMA, TDMA, OFDM, and MC-CDMA, bridging the hardware gap between the world's most promising technology. But that is only the tip of the iceberg. The technology that bridges the gap also improves all the systems it comes into contact with, enhancing network capacity and probability of error performance of DS-CDMA, TDMA, OFDM and MC-CDMA.

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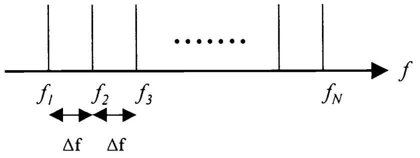
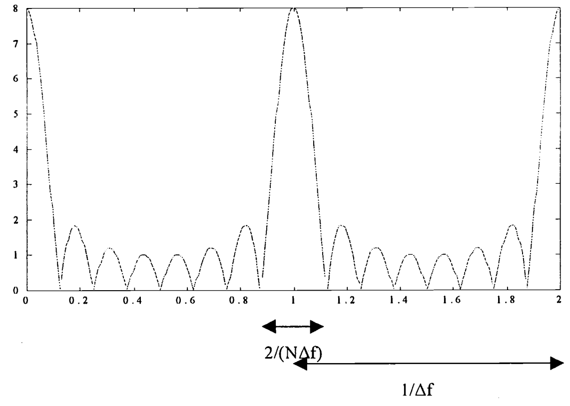
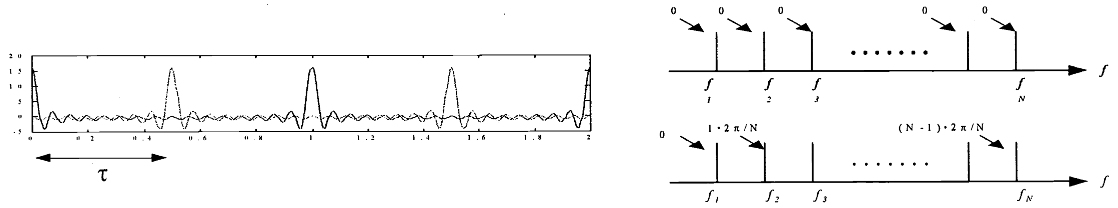


(a) CI signal in the frequency domain



(b) CI signal in the time domain

Figure 1. CI signal



(a)

(b)

Figure 2: Orthogonality in Time and Frequency

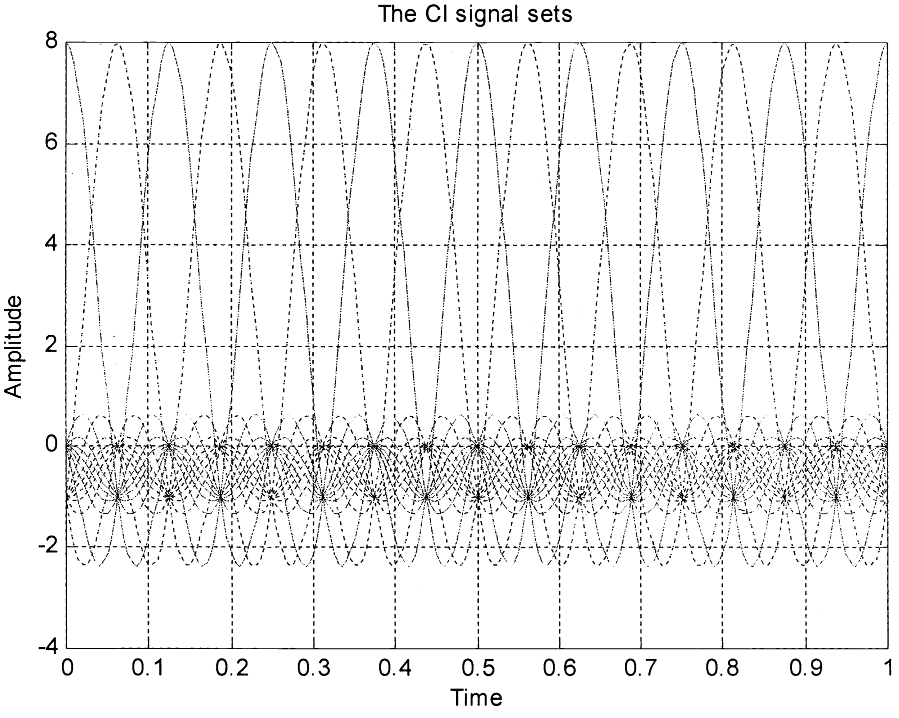


Figure 3: Set 1 - solid line; set 2 - dotted line

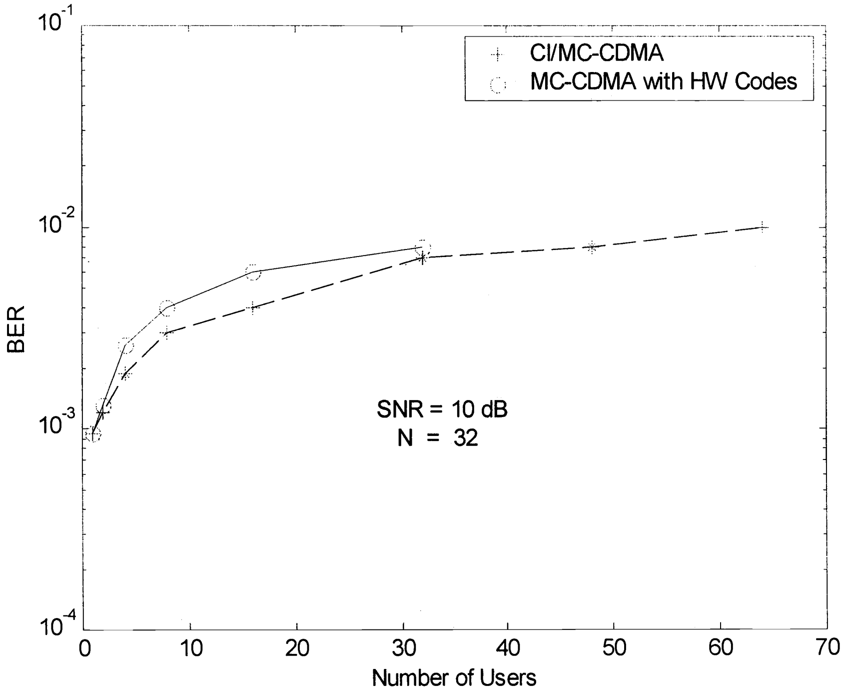


Figure 4. Performance of MC-CDMA and CI/MC-CDMA

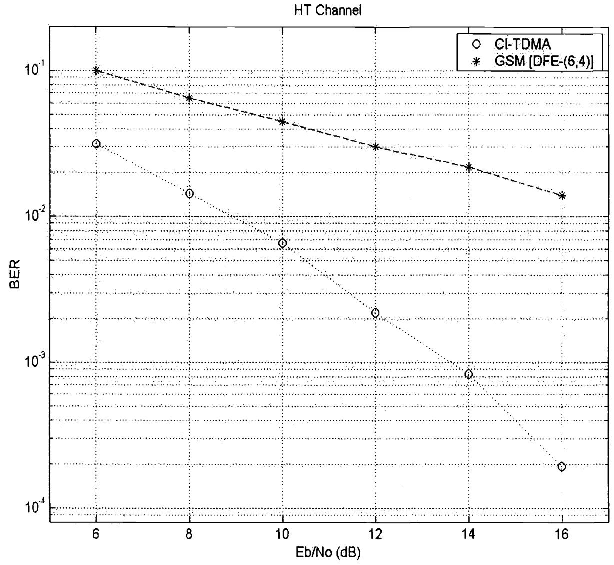


Figure 5: Performance Benefit of CI pulse shape introduced in TDMA

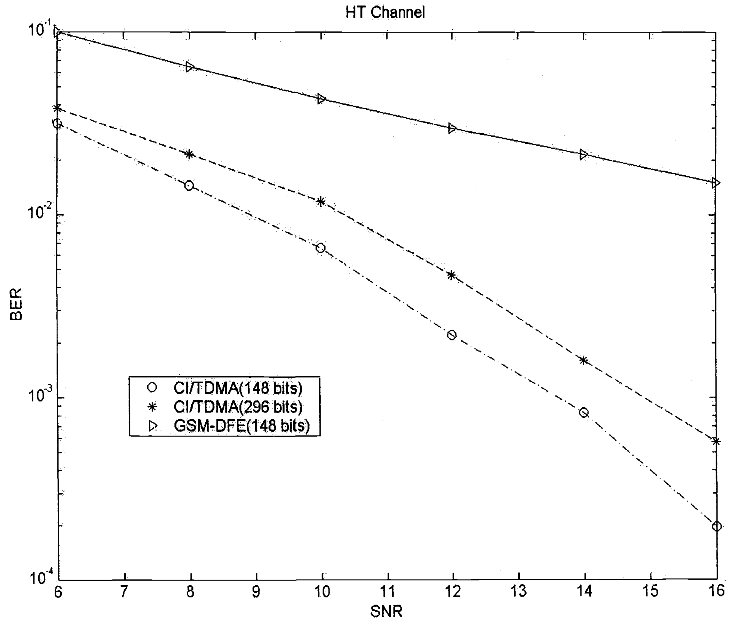


Figure 6. Performance and Throughput Benefit of CI in TDMA

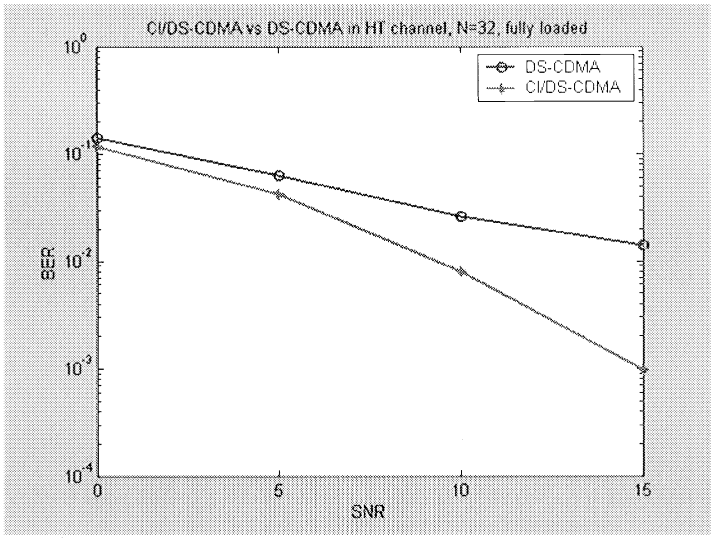


Figure 7. Performance benefit of CI in DS-CDMA

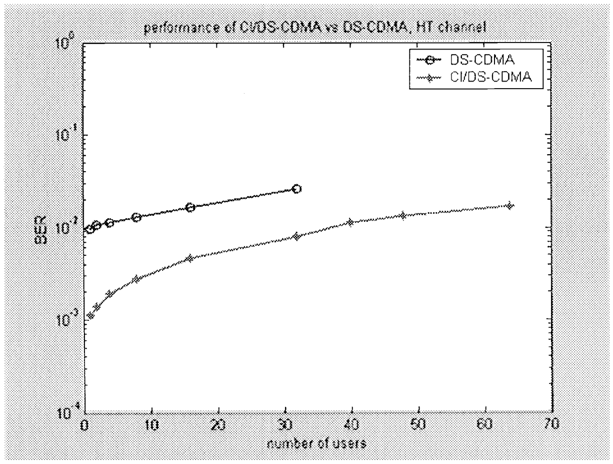


Figure 8. Performance and Throughput benefit of CI in DS-CDMA

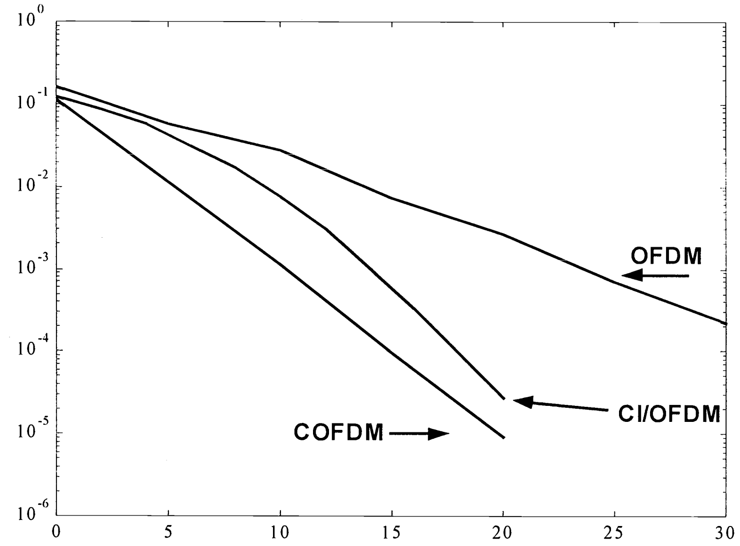


Figure 9. Performance of OFDM and COFDM vs. CI/OFDM

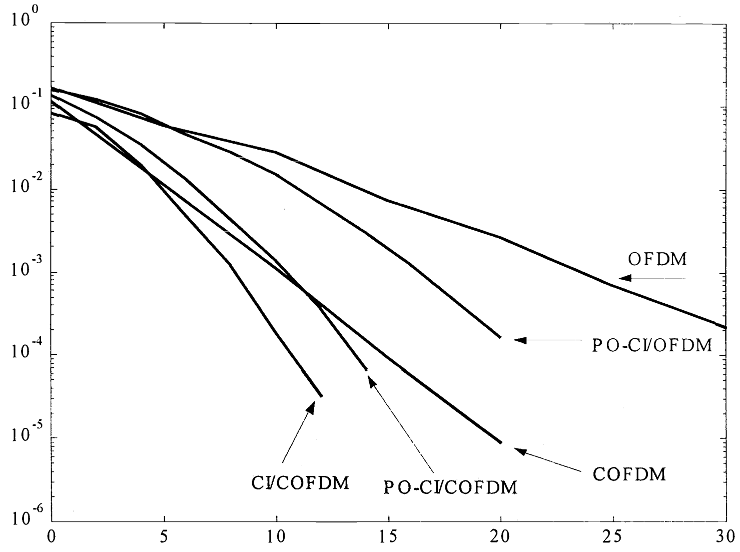


Figure 10. Performance of OFDM vs. PO-CI/OFDM