Enabling FCC's Proposed Spectral Policy via Carrier Interferometry

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***Abstract-* In this work, we propose a new multi-carrier platform to optimize the efficiency of wireless operators' licensed bands *and* to enable flexible sharing of licensed and unlicensed bands (in different spectral regions). This research supports a recent FCC proposal which suggests innovative spectrum management regulations to improve spectral efficiency. Specifically, this work presents a multi-carrier platform capable of (1) achieving high spectral efficiency by application of "narrow" orthogonal carriers; *and* (2) enables flexible spectral sharing across different licensed and unlicensed bands via operator borrowing/ lending.**

I INTRODUCTION

In a recent proposal [1], the FCC (Federal Communications Commission) strongly suggests that a number of innovative regulations may soon be applied to manage the electromagnetic spectrum. These regulations will radically redefine the spectral landscape, allowing each operator far more freedom to operate in their own licensed bands, and requiring cooperation between operators (e.g., in adjacent bands) [1]. The aim of these future regulations is to improve spectral efficiency by removing rigid requirements on spectral allocation, ushering in a new era of "spectral freedom". The intention is that of increased cooperation among companies to (1) reduce resource wastage e.g., elimination of "white spaces" (unused or highly underused bands), and (2) to allow for faster and far more flexible spectral assignment.

It is the contention of the FCC itself that the current spectrum management structure is cumbersome and creates excessive delays in frequency allocation and re-assignment of bands to new operators. In short, the current regulations lead to high inefficiency. The FCC has focused on two main sources of the problems that it seeks to eliminate; the lack of freedom in employing licensed bands (e.g., the ability to introduce new and efficient techniques) and the rigid structure of spectral allocations which restrict both usage and time-sharing.

In this paper, the authors introduce a multi-carrier platform based on our early research of [2]-[10], which can serve as an important physical layer "enabler" to future FCC policy. Our multi-carrier platform is intended to: (1) provide high spectral efficiency (i.e., large bit/s/Hz) in each spectral band; (2) enable efficient sharing of wireless spectrum across different channels in the same band and/or across different bands; and (3) maintain low interference among adjacent systems.

Specifically, we propose a multi-carrier implementation of TDMA and DS-CDMA (similar to OFDM and MC-CDMA) using carrier interferometry (CI) pulse shape and chip shape, respectively ([2]-[10]). We demonstrate that the CI approach not only enhances system's performance and capacity/throughput, but also provides the capability to operate over non-contiguous spectral bands. This in turn enables the implementation of different spectral sharing strategies presented in Section 5. Furthermore, we also illustrate the ability of CI-based systems to support transmissions with different power levels in different sub bands within the total transmission bandwidth. This enables CI-based systems to maintain low interference while coexisting with other wireless systems in the same spectral band.

II THE FCC SPECTRUM POLICY REPORT

In November 2002, the FCC released a report generated by the Spectrum Policy Task Force [1] in response to the growing demand for more up-to-date regulation – regulation that reshapes traditional models of spectral allocation and control. Operators were complaining about the ever-increasing time gap between filing and actual assignment of bandwidth. Moreover, engineers were pushing for technology upgrades that ensured increased resistance against RF (Radio Frequency) interference, while the FCC was assessing interference using out-dated techniques. Finally, measures of spectrum usage revealed the presence of various "white spaces", i.e. spectral regions that are underused or not used at all for long periods of time. All these factors motivated the creation of an FCC proposal that remodels spectral regulations.

Some key points of the new policy, at the physical layer, include:

A. *Flexibility*: Allow for maximum feasible flexibility of spectrum use by both licensed and unlicensed users;
B. *Metric:* Adopt a new quantitative metric that may be used to manage interference and set interference floors for distinct bands, geographical areas and services;

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C. *Dimensionality:* Account for all potential dimensions of spectrum usage (frequency, power, space, and time);
D. *Grouping*: Encourage grouping of spectrum neighbors with technically compatible characteristics.

Regarding item (A) (*flexibility*), the proposed FCC approach will allow operators to:

1. Choose the services that will be provided on their own spectrum (e.g., commercial private use);
2. Choose the technology that is most appropriate for the desired spectrum environment (e.g., techniques that use low power in highly congested areas and higher power in rural areas);
3. Have the right to transfer, lease or subdivide spectrum (e.g., for narrow band services with short (in time) requests such as public safety, the excess capacity should be leased to other users via time sharing of the spectrum).

Concerning item (B) (*metric*), the FCC introduced the Interference Temperature [1], which refers to the RF power at the receive antenna per unit bandwidth. The Interference Temperature will be used to provide the following:

1. Licensed users will receive guarantees regarding the maximum permissible level of aggregate noise (interference) in their band;
2. Unlicensed users will be provided with a threshold, indicating the highest interference they are allowed to create in their environment (e.g., the interference temperature cannot exceed XdB in the Y_1 to Y_2 Hz band, as this would otherwise create harmful interference to other operators; if the X dB threshold is exceeded, unlicensed user communication is terminated).

Regarding item (C) (*dimensionality*), the FCC will begin to request multiple dimensions of efficiency, summarized as follows:

1. Spectral Efficiency*,* i.e., a measure of the amount of information transmitted within the bandwidth, to ensure maximum data rate in minimum bandwidth;
2. Technical Efficiency*,* i.e., a measure of the operator equipment cost and operator financial investments, to ensure the highest output for the least cost to the operator;
3. Economic Efficiency*,* i.e., user's equipment cost, and user's financial investments, to generate the best consumer value.

Regarding item (D) (*grouping*), the FCC has proposed the following. First, the FCC has categorized spectral usage into three main groups or categories:

1. Command-and-control *group*: FCC assigned frequencies for specific government-defined uses.
2. Exclusive use group: FCC licensed bands where the operator (who purchases the license) has exclusive and *transferable* rights to the band with *flexible use rights*.
3. Commons or open access group: A virtually unlimited number of unlicensed users to share FCC designated frequencies, with usage rights governed by technical standards or "etiquette," but with no guarantee of protection from interference.

With regard to the spectral bands for these three groups, the FCC proposes the following:

(a) The command and control group be located at low frequencies, and that groups be allocated as little bandwidth as possible for the shortest time possible, or this group does not permit spectral efficiency.
(b) The exclusive model group is best suited for bands below 5GHz, where congestion of services is the highest, and efficiency is ensured by the high level of competition among operators.
(c) The commons group is strongly encouraged in regions where spectral scarcity is low and transactions cost may be high, i.e., bands over 50GHz (regions where narrowband services with low levels of mutual interference can be implemented).

In the remainder of this paper, we present a spectral allocation and a physical layer technology that can meet the FCC spectral allocation goals mentioned above.

III PROPOSED SPECTRUM ALLOCATION

We begin by suggesting a subdivision of the radio spectrum in four broad regions, namely:
(1) *Very Low Band*, frequencies below 1 GHz; (2) *Low Band,* frequencies in the range 1-3.5 GHz; (3) *Medium Band,* frequencies in the range 3.5-25 GHz; and (4) *High Band*, frequencies over 25 GHz. We propose this regionalization of spectrum for a number of reasons, both regulatory and technical.

First, from a regulatory stand point, we use this spectral allocation to accommodate unique groups as in the requirement of the FCC proposed spectral policy. Specifically, the Very Low Band region will be reserved to accommodate the command-and-control group. This is a likely choice because most public services (e.g., radio broadcasting, police and other emergency response communication) already exist at low frequencies; as such, we minimize any change to services that usually require lengthy governmental approval processes and large amounts of funding to accommodate equipment updates [1].

The Low Band region (1-3.5 GHz) is reserved for the exclusive use group. This band is currently occupied by a variety of commercial services (e.g., 2G and 3G cellular systems) and the competition to acquire licensure in this bandwidth is already strong. It seems natural to allow this region, already controlled by market demands, to fulfill the goals of the exclusive use policy.

The Medium and High Band regions are reserved for the commons use group. Specifically, in most of this broad range of frequencies, competition is already limited (due in part to high costs of RF devices) and transactions costs are high.

The four-region band is also selected based on technical considerations. First, at very high carrier frequencies, a LOS (Line-of-Sight) path is of utmost importance. A threshold between applications that require LOS and applications that can rely on N-LOS (Non LOS) may be set at a carrier frequency of approximately 3.5 GHz, although it is possible that technological improvement will enable the 3.5 GHz threshold to be moved to higher frequencies in the future [11]. Because commercial services such as wireless mobile cellular systems must be able to operate without the assurance of LOS, we locate the exclusive use group in frequencies below 3.5 GHz. Additionally, the above four region characterization is well suited to the multi-carrier framework discussed next.

IV THE CI PLATFORM: A NOVEL PHYSICAL LAYER

Recently, the authors have proposed multi-carrier implementations of TDMA ([4],[10]) and DS-CDMA [9] systems based on a multi-carrier chip shape (in DS-CDMA) and pulse shape (in TDMA). The starting point for both these implementations is the multi-carrier waveform:

$$h_{CI}(t) = \mathrm{Re}\left\{ \sum_{n=0}^{N-1} e^{j2\pi n f_n t} \right\} \quad (1)$$

This multi-carrier signal corresponds to a linear combination of *N* "in-phase" carriers and results in the well known interferometery pattern referred to as the Carrier Interferometery (CI) signal [3]-[10].

The multi-carrier CI signal of (1) can be employed both as a chip shape at the DS-CDMA transmitter and a pulse shape at the TDMA transmitter. To demonstrate this concept, consider a DS-CDMA system. Here, the sent signal corresponding to, user k's jth bit (in complex baseband notation) is

$$s^{(k)}(t) = b_j^{(k)} c^{(k)}(t - jT_s) \quad (2)$$

where $b_j^{(k)} \in \{-1,+1\}$ represents k^{th} user j^{th} modulated BPSK symbol, and $c^{(k)}(t)$ is user k's spreading code:

$$c^{(k)}(t) = \sum_{l=0}^{N-1} \beta_l^{(k)} h_{CI}(t - lT_c) \quad (3)$$

In (3), $\beta_l^{(k)}$ refers to l^{th} element of the k^{th} user spreading sequence; T_c is chip duration, and $h_{CI}(t)$ is the chip shape implemented using the CI signal of Eq.(1). In CI/DS-CDMA, HW codes are employed as the spreading sequence [14]. Alternately, the CI codes introduced in [3]-[10], may be employed as the spreading sequence in DS-CDMA. This modified CI/DS-CDMA scheme is referred to as CI-CDMA (see [15]).

We can rewrite the transmit signal as

$$s^{(k)}(t) = \sum_{i=0}^{N-1} \left(b_j^{(k)} \sum_{l=0}^{N-1} e^{-j2\pi(i)(j)\Delta f T_s} \beta_i^{(k)} e^{-j2\pi(i)(l)\Delta f T_c} \right) \cdot e^{j2\pi i \Delta f t} \quad (4)$$

From (4), much like OFDM and MC-CDMA, the CI-based DS-CDMA (and similarly TDMA) transmitter can be constructed using weighted IFFT's with the weights determined by the term in the parenthesis of Eq.(4).

CI signaling concepts may also be incorporated into traditional MC-CDMA architecture (referred to as CI/MC-CDMA) in the form of novel CI spreading codes [2],[3]. Furthermore, coupling OFDM with CI spreading codes (referred to as CI-OFDM), enhances the robustness of OFDM against frequency selective fading and reduce the PAPR of OFDM transmissions [3]-[5].

The CI based DS-CDMA, TDMA, OFDM and MC-CDMA systems offer not only a common multi-carrier hardware platform for software radio application, but also enhance the performance and capacity/throughput of these systems in hostile propagation environments (see [2]-[10]). Most importantly, the CI multi-carrier physical layer provides an ideal framework to implement spectral sharing and meet the FCC spectral policy regulations. This is detailed next.

V THE CI PLATFORM: MATCHING THE FCC REQUIREMENTS

Traditionally, frequency division has been adopted to divide the electromagnetic spectrum between different wireless operators. In frequency division, portions of the spectrum are statically assigned to operators to support their customers' transmissions. This assignment has some inherent disadvantages with respect to spectral efficiency. For example, consider two Companies operating on their licensed bands (i.e., exclusive use model). It is possible that the first Company be fully loaded, while the second Company may have unused resources (or vice-versa). It would be profitable for both Companies if these unused resources are shared to allow more capacity for the fully loaded Company. In this section we demonstrate how the CI multi-carrier platform enables the new FCC spectral policy regulation regarding "*dimensionality*."

We propose two strategies for dynamically allocating spectrum (i.e., "sharing" strategies) to allow spectral sharing with the CI multi-carrier platform: (1) contiguous allocation and (2) non-contiguous allocation. Consider the case of two Companies employ the proposed multi-carrier CI-CDMA system, with N_1 and N_2 carriers respectively. In the contiguous approach, Company 1 borrows a contiguous block of carriers from Company 2 (or vice-versa), while in the non-contiguous case the borrowed carriers (by Company 1) are evenly distributed over Company 2's entire spectrum. The contiguous approach is easier to implement, whereas the non-contiguous approach may result in improved system performance (for both systems) via increased frequency diversity. Further details on the sharing strategies can be found in [14].

V.1 ***Harmonizing Spectral Sharing among Operators and across Spectral Regions***

In order to allow operators to borrow/lend spectral bands from/to operators residing in the same or different spectral region, we develop a strategy for selecting Δf (the frequency separation among carriers that constitute the CI chip-shape). Specifically, we have chosen different values of Δf for different spectral regions based on the following practical considerations:

1. Δf is selected much smaller than the coherence bandwidth of the channel (to ensure that each carrier undergoes a flat fade).

2. Δf is selected big enough to prevent the use of large number of carriers (to allow practical implementation of the system via FFT/IFFT).

Therefore, we suggest the following sub-carrier spacing: (1) $\Delta f = 25\,kHz$ for the Low Band region; (2) $\Delta f = 100\,kHz$ for the Medium Band region; and (3) $\Delta f = 200\,kHz$ for the High Band region. These choices were made based on coherence bandwidth measurements for a typical indoor small office channel operating in the three different spectral bands (*65 kHz*, *232 kHz* and *678 kHz* are the measured coherence bandwidths for the low, mid and high band regions, respectively [16]). In this paper, whenever we refer to CI-based systems operating in Region 1, 2 or 3, we implicitly assume an indoor small office channel and the corresponding Δf values suggested above.

The major drawback of utilizing different carrier spacings is that operators using different values of Δf will be unable to implement an "orthogonal spectral sharing" (i.e., sharing orthogonal carriers among the CI platforms). Consequently, for cross region spectral sharing, the only alternative is to implement "frequency separable sharing", an FDM technique that separates the borrowed band from the remaining portion of the lender's band. Figure 1 shows the orthogonal and the frequency separable sharing strategies. Figure 1(a) and (b) show the contiguous and non-contiguous orthogonal approach. Figure 1(c) and (d), on the other hand, show frequency separable sharing with the contiguous and noncontiguous approach.

V.2 System Model for Spectral Sharing via the CI Platform

When we integrate spectral sharing into CI-CDMA system model, the transmit signal corresponds to:

$$s(t)=\mathrm{Re}\left\{\sum_{k=0}^{K-1} A^{(k)} b^{(k)} \sum_{i=0}^{N_1+N^{'}-1} \beta_i^{(k)} \left[\sum_{n=0}^{N_1-1} e^{j\left(2\pi n\Delta f t+\frac{2\pi i}{N_1+N^{'}} n\right)} e^{j2\pi f_c t} + \sum_{m=0}^{N^{'}-1} e^{j\left(2\pi m\Delta f^{'} P(m) t+\frac{2\pi i}{N_1+N^{'}}(N_1+m)\right)} e^{j2\pi f_c^{'} t}\right] g(t)\right\} \quad (5)$$

where N_1 is the number of carriers in the borrowing system (i.e., Company 1); $N^{'}$ is the number of borrowed carriers from the lending system (i.e. Company 2); Δf is the carrier frequency separation in the borrowing system's bandwidth; $\Delta f'$ is the carrier frequency separation in the lending system's bandwidth ($\Delta f^{'} = \Delta f$ in the case of orthogonal sharing); f_c is the carrier frequency in the borrowing system; $f_c^{'}$ denotes the transmit frequency of the lending system, and *P()* is a vector that characterizes the location of borrowed carriers in the lending company spectrum. Specifically, in the contiguous sharing strategy,

$$P(m) = m \quad (6a)$$

and, for the non-contiguous allocation strategy:

$$P(m) = \frac{m}{\lfloor N_2 / N^{'} \rfloor} \quad (6b)$$

In (6b), N_2 denotes the total number of carriers in the lending system (i.e., Company 2), and $\lfloor x \rfloor$ refers to the closest integer less than or equal to *x*.

Similarly, the transmit signal in the lending system (i.e., Company 2 in our example) is modified according to:

$$s(t)=\mathrm{Re}\left\{\sum_{k=0}^{K-1} A^{(k)} b^{(k)} \sum_{i=0}^{N_2-N^{'}-1} w(k,i) \sum_{n=0}^{N_2-N^{'}-1} e^{j\left(2\pi n\Delta f^{'} \overline{P}(n) t+\frac{2\pi i}{N_2-N^{'}} n\right)} e^{j2\pi f_c^{'} t} g(t)\right\} \quad (7)$$

In (7), $\overline{P}(\ )$ is a vector characterizing the location of the lending system carriers (the carriers that remain allocated to Company 2 upon lending $N^{'}$ carriers to Company 1).

The flexibility in designing CI codes translates into the following benefit: (1) the sharing strategy provides flexible system capacity over noncontiguous bandwidth, (2) it is possible to dynamically update quantities of borrowed spectrum and borrowing duration, and (3) spectral efficiency as well revenues of both lender and borrower are optimized.

V.3 Accounting for "Interference Temperature" in Spectral Sharing

The interference temperature *metric* in the new FCC proposal mandates wireless operators to be able to operate under different power constraints on different parts of the spectrum [1]. For example, if a company utilizes several spectral regions, it should be able to transmit with different powers in different bands. The required power levels may be continuously updated through the MAC protocol that monitors signal transmissions within a spectral band.

Since CI based systems involve multi-carrier transmission, selective power control can be accomplished by controlling the amplitude of the individual carriers. Modulating the transmitted carriers with different powers at the transceiver end forces the MMSEC receiver to update the combining weights. With this minor modification to the transmitter structure, CI-based systems can operate under different power constraints over the electromagnetic spectrum.

VI NUMERICAL RESULTS

In order to illustrate the ability of CI multi-carrier platform to improve spectral efficiency, we consider two companies (Company 1 and Company 2) that have an agreement on sharing their spectrum. Company 1 possesses 16 orthogonal carriers (i.e., it can accommodate 16 orthogonal users simultaneously), and is overwhelmed with users. Company 2 has a large number of carriers, and can lend part of its spectrum if required.

Figure 2 shows CI-CDMA BER vs. SNR performance curves when Company 1 borrows 9 carriers from Company 2 using different sharing strategies.

At first, we consider the case of two companies utilize the same Δf (the bottom-most curve). Here, we assumes that

Company 2's band is large enough to distribute the 9 borrowed carriers across its bandwidth. This assures independent fade among the 9 carriers, and guarantees maximum channel diversity gain.

The second set of simulations (the top three curves) present the "Frequency Separable Sharing," where Company 1 and Company 2 have different Δf values. Here, the borrowed spectrum consists of one contiguous band. Two examples are considered:

1) Company 1 and 2 are in the same region (Region 2 in our simulation) but operate with different Δf (the top-most curve)--Company 1's $\Delta f = 10\ kHz$ and Company 2's $\Delta f = 25\ kHz$. This is a legitimate assumption, because companies in the exclusive region are free to select their system parameters. For this scenario, we observe a 3dB degradation in performance relative to the orthogonal sharing case (the bottom-most curve). However, it is important to note that this non-orthogonal sharing strategy provides better performance as well as capacity relative to the CI-CDMA system with no sharing.
2) Company 1 is in Region 2 with Δf = 25 kHz, while Company 2 is in Region 3. Two frequency separable sharing (FSS) procedures are considered:
   i) The 9 borrowed carriers are allocated contiguously (the second curve from the top).
   ii) The 9 borrowed carriers are allocated in 3 independent groups each consisting of 3 carriers (the third curve from the top).

   It is evident from Figure 2 that noncontiguous FSS outperform contiguous FSS due to increased diversity gain.

The four examples discussed above, illustrate the various sharing strategies and Figure 2 presents a comparative performance analysis of these schemes.

Figure 3 presents four CI-CDMA BER performance curves for the case of Company 1 (that is operating in Region 2) borrowing increasing numbers of contiguous carriers to support increasing numbers of users. These curves demonstrate the relationship between the numbers of borrowed carriers and system performance. It is evident from Figure 3 that the BER performance of the CI-CDMA system improves with the increase in the number of borrowed carriers. The top-most curve, represents Company 1's performance utilizing it own 16 carriers, i.e., no spectral sharing is considered. The curves from top to bottom in Figure 3 represent BER performance with increasing numbers (5, 10, 16 and 32) of borrowed carriers. At BER of 10^{-3}, a 2dB improvement (relative to no sharing case) is observed when Company 1 borrows 32 carriers. This improvement in performance (due to increased diversity gain) is obtained alongside an increase in capacity. It is important to note that even though the bandwidth of Company 1 increases with the number of borrowed carriers, the total bandwidth of Company 1 and Company 2 is still the same. In short, the sharing strategy provides a smarter way to utilize the total bandwidth in order to optimize capacity, performance and revenues.

Figure 4 demonstrates the potential of CI-based systems to transmit at different power levels in different spectral bands. Here, we consider a CI-CDMA system in Region 2 employing 25 carriers. The 25 carriers are divided into two groups: 16 carriers without any power constraint and 9 borrowed carriers with specific power restrictions. The performance for the following three cases are simulated in Figure 4: (1) All 25 carriers transmit at the same power; (2) the power/carrier in the 9 borrowed carriers is 50% of the power/carrier in the 16-carrier set, and (3) power/carrier in the 9-carrier set is 25% of the power/carrier in the 16-carrier set. From Figure 4 we observe that imposing power constraints degrades system performance. The authors are currently exploring advanced reception techniques that can help reduce this degradation in performance.

VII CONCLUSION

With the rapid growth of wireless systems and services, there is a tremendous pressure to optimize spectral usage. The FCC has identified the main focus areas for better spectrum management in its latest spectral policy task force report. In this work, we suggest a CI-based multi-carrier platform to meet the new spectral policy requirements. To summarize, it is believed that the CI approach will pave the roadway for a wireless future where growth is not limited by spectral scarcity.

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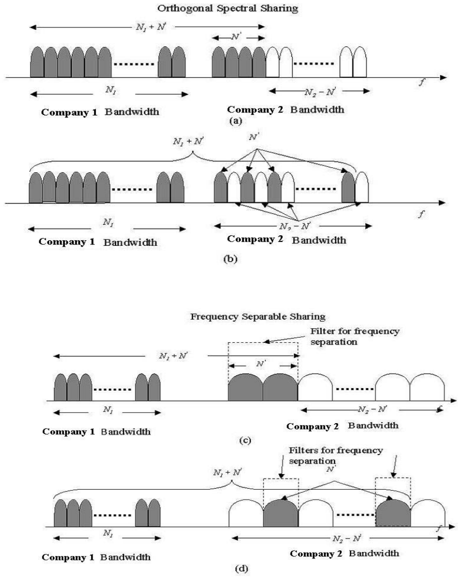

Figure 1 Sharing strategies (a) Contiguous Orthogonal. (b) Non-contiguous Orthogonal. (c) Frequency Separable Contiguous (d) Frequency Separable Non-Contiguous.

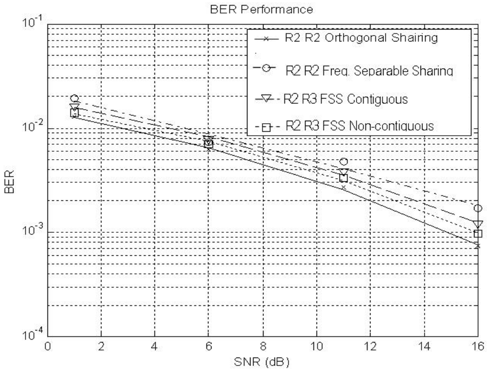

Figure 2 CI -CDMA BER performance curves for different sharing schemes.

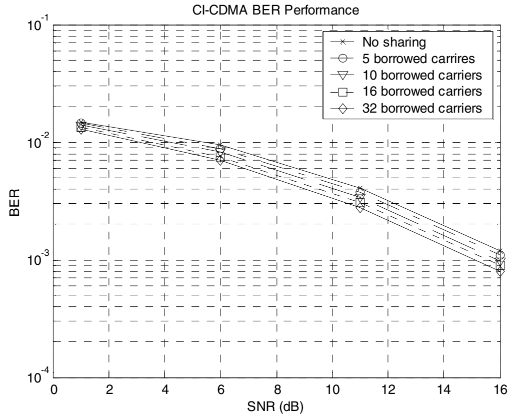

Figure 3 BER Performance as a function of borrowed carrier number in CI-CDMA system.

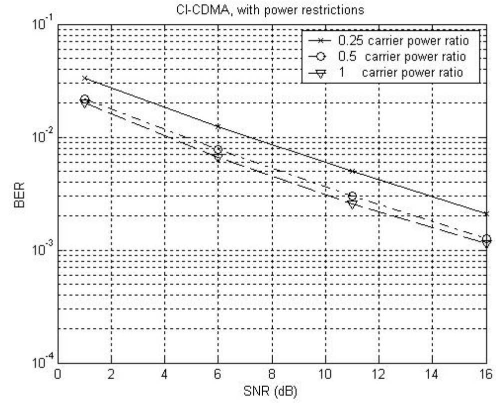

Figure 4 of CI-CDMA system with power constraints.