MAINTAINING USER DEFINED QOS IN PROPOSED MB OFDM COGNITIVE RADIO SYSTEM USING POWER CONTROL AND CHANNEL CAPACITY ANALYSIS AS DESIGN TOOLS FOR SUBCARRIER SELECTION

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ABSTRACT
The objective of this paper is to study various methods of maintaining user defined Quality of Service (QoS) in a wireless Cognitive Radio (CR) System. The agility of CRs can be used to make adjustments to Bit Error Rate (BER), Bit Rate (BR) and transmit Power Spectral Density (PSD). We present a modified channel capacity analytic formula, methods for a power control algorithm, and methods for decision making on spectrum allocation. We show how parameters such as BER, Signal to Interference Noise Ratio (SINR) thresholds, and analysis and design based on our modified channel capacity formula can be subtly manipulated to affect QoS. The power control algorithm is part of a system that maintains user defined BER and BR in the presence of external user interference. This system is a design tool with which to achieve predictable and consistent QoS.

Keywords: Power Control, Cognitive Radio, QoS, MB-OFDM.

1. INTRODUCTION
A Personal Area Network (PAN) is a human centered network that connects personal communication devices within a very limited distance (usually less than 20 metres) [1][2]. PANs may consist of devices in an office environment, such as printers, computers, mobile and non-mobile phones. PANs may also form in the home environment and comprise mobile phones, TVs, speakers, DVD players, game consoles, routers, and cable or satellite set top boxes [3]. PANs may also form transitorily in mobile situations such as between five mobile phones and a laptop. Our vision is of tetherless home and office environments. The wireless devices in these environments form PANs which are controlled by a leader or manager. The leader is responsive to the ingress and egress of devices and to time varying channel conditions. The leader also promotes efficient communication by controlling the medium access of member devices. This paper addresses a leader-less environment in which devices are responsible for medium access. This is important because in the absence of a leader, devices must perform efficiently and independently. In addition, the concepts presented in this paper is the foundation upon which our PAN is built. The individual devices can be referred to as Personal Area Devices (PADs) and they each have different requirements in terms of Bit Rate (BR) and acceptable Bit Error Rate (BER). We will henceforth refer to those requirements as user defined Quality of Service (QoS).

We introduce a system (see Figure 4) which is used by each device to maintain its user defined QoS, regardless of channel conditions and without external management. This system consists of the combined operation of algorithms and methods which control transmit power, selective bit allocation, the use of underlay and overlay techniques, variable modulation and channel ranking. The channels are ranked using a new approach to calculating channel capacity.

In order for this system to be viable, each device needs to be able to sense channel conditions and respond accordingly. The radios in the PAN therefore need to be Cognitive Radios (CRs). We define CRs as wireless devices that have hardware and software that can be reconfigured to respond to changing channel conditions [4]. CRs can perform functions such as those listed below [5]:
- Spectrum sensing: find used and unused spectrum and give feedback on channel condition.
- Dynamic spectrum management: make use of the best available spectrum in order to meet QoS needs.
- Spectrum sharing: Spectrum should be allocated in order to meet the QoS needs of all applications and devices. As we seek to optimize spectrum usage by leveraging the abilities of the CR, we need to be able to guarantee QoS in the presence of incumbent users of the spectrum. It is important that the devices operate efficiently in environments where medium access is competitive.
- In section 2 we present basic concepts and related work.
In section 3 we present the system architecture.
In section 4 we present the Modified Group Channel Capacity (MGCC) analytic formula for MB-OFDM UWB and the concept of a minimum constraint on the number of consecutive subcarriers used to transmit an underlay signal.
In section 5 we present methods for allocating PSD to symbols transmitted using underlay.
In section 6 we present the power control algorithm and its components.
In section 7 we detail the simulation parameters.
In section 8 we present results and analysis.

2. PREVIOUS AND RELATED WORK

2.1. MB OFDM UWB

There are different implementations of UWB, one of which is defined by the Multiband Orthogonal Frequency Division Multiplexing Ultra-wideband (MB OFDM UWB) standard. MB-OFDM UWB defines a system of 14 bands, each 528 Mhz in size. There are four groups of three bands and one group of two for a total of five channels. Each band is sub-divided into 128 OFDM Subcarriers (SCs) with designated pilot, guard and null subcarriers. Each subcarrier has a bandwidth of 4.125 MHz.

The inclusion of OFDM brings its legacy of positives to the table. One example is the ability to turn subcarriers on or off by notch insertion [6]. Other advantages include lower maximum transmission power for lower data rate multiuser systems [7] and resistance to multipath. A very important aspect of OFDM is the built in division of spectrum [8]. To facilitate ease of implementation of the CR aspect of our system we require spectrum segmentation. User noise and signal power spectral density can be calculated over fixed, finite bandwidth intervals.

2.2. Underlay and Overlay

To achieve Interference Avoidance (IA) we make use of underlay and overlay techniques. The spectrum is scanned, Power Spectral Density (PSD) measured and subcarriers are determined to have been used or unused. SCs 1 and 3 in Figure 1 are examples of unused spectrum. Unused spectrum describes some predefined bandwidth, in our case, an OFDM subcarrier, without incumbent user PSD. In this paper we refer to incumbent user PSD as interference. Overlay describes transmission in unused spectrum by opportunistic users (see Figure 2) [9]. In underlay, the signal is spread over a wide bandwidth with low PSD and thus causes minimum interference (see Figure 1) to Incumbent Users (ICU). For pertinent FCC regulations, see [10].

![Figure 1. Underlay Subcarrier Allocation](image1.png)

![Figure 2. Overlay Subcarrier Allocation](image2.png)
Figure 3 illustrates the concepts of incumbent users, unused and underused spectrum. Underlay makes use of underused spectrum. Underused spectrum is spectrum in which the PSD of the incumbent user is less than the PSD Limit for the subcarrier. The PSD Limit is the maximum PSD allowed for a given spectral region. In this example we assume each subcarrier has the same PSD Limit. A device sensing an incumbent user with PSD \( x \), can transmit at maximum PSD \( y \), where \( y = \text{PSD Limit} - x \). This case applies to underlay signals. Overlay signals can transmit at, or, below the PSD Limit.

2.3. Channel Capacity Analytic Formula

Table 1. Symbols and Definitions for Channel Capacity Analytic Formula.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_i )</td>
<td>Interference tolerance level in the ( i )th used subcarrier.</td>
</tr>
<tr>
<td>( n_0 )</td>
<td>AWGN.</td>
</tr>
<tr>
<td>( N )</td>
<td>Total number of unused subcarriers in a bandwidth ( W ).</td>
</tr>
<tr>
<td>( M )</td>
<td>Total number of incumbent users in bandwidth ( W ).</td>
</tr>
<tr>
<td>( \Phi_{\text{max}} )</td>
<td>Maximum total transmit power permitted for cognitive users in ( W ).</td>
</tr>
<tr>
<td>( \phi_k )</td>
<td>Maximum transmitted PSD allowed in ( k )th unused subcarrier.</td>
</tr>
<tr>
<td>( \Phi_{\text{CR}1} )</td>
<td>CR transmitted PSD in ( k )th unused subcarrier.</td>
</tr>
<tr>
<td>( \Phi_{\text{CR}2} )</td>
<td>CR transmitted PSD in ( i )th underused subcarrier.</td>
</tr>
<tr>
<td>( \Phi_{p_i} )</td>
<td>PSD of ( i )th incumbent user.</td>
</tr>
<tr>
<td>( W )</td>
<td>Total bandwidth.</td>
</tr>
<tr>
<td>( W_{u_k} )</td>
<td>Bandwidth of the ( k )th unused subcarrier.</td>
</tr>
<tr>
<td>( W_{p_i} )</td>
<td>Bandwidth of ( i )th incumbent user.</td>
</tr>
</tbody>
</table>

Table 1 contains some of the symbols and definitions used in this section. Shannon’s capacity formula is used as the basis for Wu et al’s MB OFDM capacity formula in which the transmitted power spectral density in the region is determined by the spectrum usage [9]. Their channel capacity formula is stated in (1). The transmit PSD in an overlay subcarrier is represented by \( \Phi_{\text{CR1}} W_{u_k} \) while underlay is represented by \( \Phi_{\text{CR}2} W_{p_i} \).

\[
C_{\text{SDCR}} = W \log \left( 1 + \frac{\sum_{k=1}^{N} \Phi_{\text{CR}1} W_{u_k} + \sum_{i=1}^{M} \Phi_{\text{CR}2} W_{p_i}}{n_0 W + \sum_{i=1}^{M} \Phi_{p_i} W_{p_i}} \right)
\]  

(1)

The system proposers also imposed the constraints in (2) to maximize overall channel capacity while minimizing mutual interference between CR and other users.
\[ \Phi_{CR_2} \leq I_i, \forall_i \]
\[ \Phi_{CR_1} \leq \Phi_k, \forall_k \]
\[ \sum_{k=1}^{N} \Phi_{CR_1} W_{u_k} + \sum_{i=1}^{M} \Phi_{CR_2} W_{p_i} \leq \Phi_{max} \]  

(2)

3. SYSTEM ARCHITECTURE

Figure 4 is the flowchart for our system. The curved arrows are indicative of sequential flow and data forwarding. The straight arrows are used to indicate that the output from one block is used as input for another. In the setup phase, the CR’s BER, BR, and Band Pool (bands available for transmission) are specified. The procedures in the Time Varying Phase and OFDM process blocks are performed on every transmission. The CR senses the channel, and obtains the AWGN and incumbent user PSD.
profile for the bands in the Band Pool. BER feedback measured from previous transmissions is compared to the maximum allowable BER. The result of the comparison, BER, and the Band Pool are used as input to decide whether to use overlay only, or to include underlay. If underlay is used, underlay group size and power application methods are chosen and used as input to the channel capacity analysis module. Other input to this module are the maximum acceptable BER (BER threshold), and the Band Pool. BER threshold is used to calculate minimum acceptable Signal to Interference Noise Ratio (SINR). SINR includes the interference provided by incumbent users in addition to AWGN. Channel capacity analysis is then performed on each band individually. The bands are ranked and selected using this analysis. Power is then allocated to the symbols and the power control module is then applied. This module makes critical adjustments to maintain balance between acceptable BER, desired BR and minimum transmit PSD.

After the operations above are performed, regular OFDM process is resumed. Each subcarrier is independently modulated using Quadrature Phase Shift Keying (QPSK). Information bits are taken two at a time and the symbols are represented using basis functions \( \Psi_1 = \sqrt{E} \cos(2\pi f_c t) \) and \( \Psi_2 = \sqrt{E} \sin(2\pi f_c t) \cdot f_c \) is the centre frequency of the subcarrier. There are four symbols which are represented by \( \Xi_m t \) (3).

\[
\Xi_m t = \left( \sqrt{E} \cos \left( \frac{2\pi m}{M} \right) \Psi_1 + \sqrt{E} \sin \left( \frac{2\pi m}{M} \right) \Psi_2 \right)
\]

In (3) \( m \in \{1, 4\} \). \( E \) is the energy of the waveform in a subcarrier while \( M \) is the total number of symbols in the modulation scheme. \( \alpha \) is a variable we use to increase or decrease the amplitude of a symbol in a subcarrier relative to the amplitude of the last transmission. \( \alpha \) is equal to 1 on the first transmission. In subsequent transmissions, \( 0 < \alpha < 2 \). An IFFT is performed separately on each band, a cyclic prefix is added, and the band symbols are then transmitted individually. At this point channel sensing occurs and the information is fed to the relevant module in preparation for the next transmission. On the receiving side of operations, cyclic prefix removal, FFT, and demodulation are then performed on each band. Bit detection of each symbol is performed, BER is calculated then fed to the module used for feedback collection.

In communications systems, there are tradeoffs between BER, BR, and transmit PSD. Our system utilizes these tradeoffs to maintain user defined QoS. System performance is used to cue the selection of the various methods. Each method offers different benefits. For example, one method might increase BR while increasing BER, another might reduce BER while increasing PSD. In the following section we introduce and explain the MGCC channel capacity analytic formula.

4. MODIFIED GROUP CHANNEL CAPACITY ANALYTIC FORMULA (MGCC)

4.1. Introduction to MGCC

In this section, the symbols and definitions from Section 2.3 are used. New symbols are listed in Table 2. In (1) there are \( M \) underused subcarriers. Every underused subcarrier, even the ones with high incumbent user PSD, is included in Wu et al’s channel capacity analysis. The MGCC analytic formula, (3), is more selective. For example, in Figure 5, subcarrier 3 has relatively high incumbent user PSD and is neighbored by two overlay subcarriers (SCs 2 & 4). If an underlay symbol is transmitted in subcarrier 3, it has little chance of being correctly detected. In order to increase SINR, we attempt to reduce noise (and interference) relative to signal power by spreading the symbol over contiguous underused subcarriers.

![Figure 5. Overlay PSD, underlay PSD and subcarrier allocation - initial stage.](image-url)
Table 2. Additional Symbols and Definitions for MGCC.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b$</td>
<td>Bit energy.</td>
</tr>
<tr>
<td>$E_s$</td>
<td>Symbol energy.</td>
</tr>
<tr>
<td>$G_v$</td>
<td>The $v^{th}$ underlay group in bandwidth $W$.</td>
</tr>
<tr>
<td>$Q_x$</td>
<td>$Q_x$ is the upper limit on the subcarriers in group $G_v$.</td>
</tr>
<tr>
<td>$L$</td>
<td>Number of subcarriers with incumbent user PSD that have not been used for</td>
</tr>
<tr>
<td></td>
<td>underlay transmission.</td>
</tr>
<tr>
<td>$\min_{\text{sinr}}$</td>
<td>Minimum acceptable SINR for a symbol.</td>
</tr>
<tr>
<td>$\Phi_{\text{CR2},i}$</td>
<td>CR transmitted PSD in $i^{th}$ underlay subcarrier within a group $G_i$.</td>
</tr>
<tr>
<td>$\Phi_{\text{CR3},i}$</td>
<td>PSD in $i^{th}$ underlay subcarrier not used by CR</td>
</tr>
<tr>
<td>$\Phi_{p,i}$</td>
<td>PSD of incumbent user in $i^{th}$ subcarrier not used by CR.</td>
</tr>
<tr>
<td>$P_b$</td>
<td>Probability of bit error.</td>
</tr>
<tr>
<td>$P_s$</td>
<td>Probability of symbol error.</td>
</tr>
<tr>
<td>$P_r$</td>
<td>Received symbol power.</td>
</tr>
<tr>
<td>$Q(x)$</td>
<td>Q-function.</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Time taken to transmit a bit.</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Time taken to transmit a symbol.</td>
</tr>
<tr>
<td>$W_p$</td>
<td>Bandwidth of $p^{th}$ incumbent user.</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Bandwidth used to transmit a symbol.</td>
</tr>
</tbody>
</table>

Figure 5—Figure 7 depict the subcarrier PSD allocation process. Figure 5 is a snapshot of a channel sensed by a CR. Incumbent users and AWGN are represented. AWGN is present in all subcarriers, and, for the purpose of this example, is uniform across the channel.

![PSD Allocation Process](image)

Figure 6. Overlay PSD, underlay PSD and subcarrier allocation - intermediary stage.

Figure 6 shows an intermediary stage in the process in which the PSD of subcarriers with overlay and underlay transmission are depicted. The overlay subcarriers (1, 2, 4, 8, 9, 13, etc.) are the subcarriers without incumbent user PSD. In the intermediary stage, PSD in all transmitting subcarriers is assigned as the Temporary Threshold. This threshold is calculated by dividing $\Phi_{\text{max}}$ by the number of subcarriers in the channel. It enforces a limit on the
cumulative PSD (AWGN, incumbent user, and CR underlay PSD) in any particular subcarrier. It also ensures that $\Phi_{\text{max}}$ is not exceeded.

In Figure 6, the minimum group size for underlay subcarriers is three. This means that underlay groups can only be formed when there are at least three contiguous subcarriers occupied by incumbent users. However, three contiguous underlay subcarriers do not automatically form a group. Subcarriers 17-19 cannot form an underlay group because subcarrier 19 exceeds the Temporary Threshold (indicated by the dotted line).

![Figure 6](image)

Figure 6. Minimum group size for underlay subcarriers is three.

Figure 7 depicts the final stage. The Temporary Threshold is not used in this stage but is left in for comparative purposes. For example, let 2 be the minimum acceptable SINR. The overlay subcarriers need to transmit at only twice the PSD of AWGN. The PSD that has been ‘saved’ can now be allocated to the underlay groups according to the selected power allocation method (see Section 4). The transmit PSD of each symbol is now twice that of its respective noise (explained in the following subsection).

$$C_{\text{MGCC}} = W \log \left( 1 + \frac{\sum_{k=1}^{N} \Phi_{CR1_k} W_{u_k} + \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \Phi_{CR2_j} W_{p_j}}{n_0 W + \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \Phi_{P1_j} W_{p_j} + \sum_{r=1}^{L} \Phi_{P2_r} W_{p_r}} \right)$$  \hspace{1cm} (4)

In (4), the total PSD for the band is the sum of the PSD of all the overlay subcarriers $\left( \sum_{k=1}^{N} \Phi_{CR1_k} W_{u_k} \right)$, plus the sum of the PSD of the symbols transmitted in the underlay subcarriers $\left( \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \Phi_{CR2_j} W_{p_j} \right)$. The noise PSD for the band, is the sum of the thermal noise $\left( n_0 W \right)$, the incumbent user PSD in the subcarriers used to transmit underlay symbols $\left( \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \Phi_{P1_j} W_{p_j} \right)$, and the incumbent user PSD in the underused subcarriers that have not been used to transmit symbols $\left( \sum_{r=1}^{L} \Phi_{P2_r} W_{p_r} \right)$. This SINR is added to 1, the log is taken of the result and multiplied by the bandwidth of the entire band ($W$). The MGCC analytic formula, (4), does not yield as large a capacity as the analytic formulae in [9] and [11], but we have a more accurate assessment of achievable channel capacity.

### 4.2. MGCC analytic formula and system design

In this subsection, we describe how the MGCC analytic formula is used for system design. BER is lowest when only overlay subcarriers are used. The use of underlay subcarriers raises capacity at the risk of greatly increasing BER. In
a system with multiple bands, accurate assessment of band capacity can be used to improve band and subcarrier selection process. Selective band and subcarrier allocation are important system design tools that CRs possess. We use the MGCC formula to perform analysis, and also as a tool with which to control BR and BER through band selection, subcarrier selection and symbol PSD allocation.

In our system, we note that we are given the maximum acceptable BER or Symbol Error Rate (SER) for the CR (5 expresses the relationship between BER and SER). The maximum acceptable BER is used to calculate the minimum acceptable SINR for each symbol. The PSD necessary for each symbol can then be estimated. This is achieved by using the formula for calculating received SINR, (8), with the formulae used to calculate error probability of symbols at the receiver [12]. We note that this formula does not budget for channel coding. In this example the Quadrature Phase Shift Keying’s (QPSK’s) formula for symbol error probability, (6), is used.

\[ P_b \approx \frac{P_s}{\log_2 M} \]  
\[ P_s \approx 2Q\left(\frac{E_s}{N_0 + \Phi_{p_s}}\right) \]  
\[ Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-\frac{t^2}{2}} dt \]  
\[ \text{min}_{\text{sinr}} = \frac{P_s}{W} = \frac{E_s}{N_0 + \Phi_{p_s}} = \frac{E_s}{W_s N_0 + \Phi_{p_s} W_s} \]  

\( \Phi_{p_s} \) represents the PSD of the incumbent users in the subcarriers that are used to transmit a symbol. (7) is the expression for the Q function which is used to calculate error probability in digital systems with Gaussian noise. Though the noise is not Gaussian, the Q function is used because we only need to estimate the SINR needed. The system will correct for over or under-estimations. For overlay, one subcarrier is used, while multiple subcarriers can be used for underlay.

\[ \sum_{k=1}^{N} \Phi_{CR1_k} W_{u_k} + \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \Phi_{CR2_{v,j}} W_{p_{j,v}} \leq \Phi_{\text{max}} \]  
\[ \sum_{k=1}^{N} \Phi_{CR1_k} W_{u_k} \geq \text{min}_{\text{sinr}} \]  
\[ \frac{1}{n_u} \sum_{k=1}^{N} W_{u_k} \geq \text{min}_{\text{sinr}} \]  
\[ \frac{1}{n_u} \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \Phi_{CR2_{v,j}} W_{p_{j,v}} \geq \text{min}_{\text{sinr}} \]  

(9) expresses the constraint that the combined transmit PSD (both overlay and underlay) of the subcarriers in \( W \) must not exceed a specified maximum PSD, \( \Phi_{\text{max}} \). Now that we have \( \text{min}_{\text{sinr}} \), we note that since overlay subcarriers only have thermal noise to overcome, they can achieve a low BER with relatively low transmit PSD. To maximize capacity, we can then minimize the power utilized by the overlay subcarriers, while satisfying the constraint in (10) by transmitting with minimum PSD necessary. The PSD saved is applied to the symbols transmitted using underlay. The number of underlay groups is maximized, by transmitting with the minimum acceptable PSD (see (11)) per underlay symbol.
\[ \max \{ C \} = W \log \left( 1 + \frac{\sum_{k=1}^{N} n_k W_k \min_{\text{sinr}} + \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \left( \Phi_{v_j} W_{v_j} + n_v W_v \right) \min_{\text{sinr}}}{n_b W + \sum_{v=1}^{G} \sum_{j=1}^{Q_v} \Phi_{v_j} W_{v_j} + \sum_{r=1}^{L} \Phi_{r} W_{r}} \right) \]  

(12)

In (12) we obtain the minimum transmit PSD for underlay by multiplying the AWGN PSD in overlay subcarriers by \( \min_{\text{sinr}} \), and then subtracting total overlay PSD from \( \Phi_{\max} \). We apply the remaining PSD to the symbols transmitted using the underlay groups. We multiply the AWGN PSD plus the incumbent users PSD for each underlay symbol by \( \min_{\text{sinr}} \). Thus, the symbols transmitted using underlay are allocated as little transmit PSD as possible. In the following section, we introduce methods used to allocate transmit PSD to symbols transmitted using underlay.

5. UNDERLAY POWER ALLOCATION METHOD

Section 4.2 explains the relationship between BER and SINR. Generally stated, BER decreases as SINR rises. We cannot change the incumbent user and AWGN (noise) PSD in a subcarrier, but we have control over the transmit PSD of symbols. We explain two methods used to make this choice using Figure 8, and the algorithms in Methods 1 & 2. For this example, we assume that the minimum SINR (\( \min_{\text{sinr}} \)) is 2.

Table 3. Symbols and Definitions for Underlay Group Decision Methods.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>Storage bin for underlay groups that meet criteria.</td>
</tr>
<tr>
<td>( h )</td>
<td>Potential underlay group.</td>
</tr>
<tr>
<td>( n_k )</td>
<td>ICU Interference in the ( i^{th} ) subcarrier in group.</td>
</tr>
<tr>
<td>( n' )</td>
<td>PSD of Incumbent User in reference subcarrier.</td>
</tr>
<tr>
<td>( N_G )</td>
<td>Total interference of a group in Method 2.</td>
</tr>
<tr>
<td>( AN_G )</td>
<td>Average Incumbent User PSD in a group (Method 2).</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Temporary PSD Threshold.</td>
</tr>
<tr>
<td>( x )</td>
<td>Number of subcarriers within a group.</td>
</tr>
</tbody>
</table>

Figure 8. PSD for subcarriers 1-6 using methods 1 and 2.
Table 3 contains the symbols and definitions relevant to section 5. In Method 1, for each potential underlay group \( h \), the subcarrier with the highest incumbent user PSD is referred to as the reference subcarrier. The incumbent user PSD in the reference subcarrier is represented by \( n_r \). If \( n_r \) exceeds \( \tau \), we do not transmit a symbol in that group. If \( n_r \) is less than or equal to the temporary threshold \( \tau \), we multiply \( n_r \) by the min\_snr, and use the result as the CR PSD for each subcarrier in the group. In other words, the CR PSD allocated to each subcarrier in group \( \eta \) is the PSD necessary for the subcarrier with the most noise (\( n_r \)) to meet min\_snr. This group is included in \( \beta \).

In Method 2, if the reference subcarrier PSD (\( n_r \)) of a group \( \eta \) is greater than or equal to \( \tau \), we move on to the next group. If not, we take the average incumbent user PSD (\( AN_G \)) of the group and calculate the per-subcarrier PSD by multiplying \( AN_G \) by min\_snr. This group is included in \( \beta \). Reference to Figure 8 shows that in some cases, the methods result in different PSD profiles. Comparison of Methods 1 and 2 show that the transmit PSD is much higher in Method 1 than 2. Intuitively, BER is lower if Method 1 is used. The tradeoff is that overall PSD is greater. It also means that \( \Phi_{max} \) might be exceeded before transmit PSD is applied to all the symbols that are transmitted using underlay. If sufficient bands are not assigned to the CR, some symbols will not be transmitted, so BR is reduced. While the tradeoff may seem like a negative, it actually enables the system to maintain stability by temporarily increasing or decreasing transmit PSD and BR as needed. In Section 8 we examine the effect of each method on system performance. In the following section we describe the concepts upon which the power control process is based.

**Method 1 – Max SNR method**

For a potential group \( \eta \) of \( x \) subcarriers:

- \( \eta' = \max PSD(h) \)
- IF \( \eta' \leq \tau \)
  - For \( i = 1 \) to \( x \)
    - \( PSD(h_i) = \min\_\text{snr} \cdot \eta' \)
  - \( \beta = h \)
  - Move on to next \( h \)
- ELSE
  - Move on to next \( h \)

**Method 2 – Averaged SNR method**

For a potential group \( \eta \) of \( x \) subcarriers:

- \( \eta' = \max PSD(h) \)
- IF \( \eta' \leq \tau \)
  - For \( i = 1 \) to \( x \)
    - \( N_c = N_c + n_i \)
  - \( AN_G = N_c / x \)
  - For \( i = 1 \) to \( x \)
    - \( PSD(h_i) = \min\_\text{snr} \cdot AN_G \)
  - \( \beta = h \)
  - Move on to next \( h \)
- ELSE
  - Move on to next \( h \)

6. **POWER CONTROL ALGORITHMS FOR MGCC**

In this section, we describe two power control methods. In response to system performance, we increase or decrease the transmit PSD of symbols. We know that underlay subcarriers have higher BER than overlay because underlay has interference from incumbent users while overlay only has to contend with AWGN. It is difficult, however, to determine the extent to which BER is influenced by overlay and underlay respectively.

To study the problem, we have developed a sophisticated approach, Method 2, to manage the different effects on BER due to underlay and overlay transmission. We compare this approach with another method that uses Squared
Error (SE) as a design tool. Squared error has often been used in many adaptive systems, including power control systems, to adjust tap weights [13-15] etc. In this paper we use SE in Method 1 and refer to it as the ideal. SE is calculated by squaring the difference between the minimum acceptable BER ($\varepsilon$) and feedback BER. However, one problem with SE is that the precision of BER feedback becomes too important. In less than ideal channel conditions even the pilot signals that are used to calculate BER will become corrupted and return inaccurate figures. Simply stated BER is difficult to measure, and measuring it exactly is almost impossible [16]. Also with Method 1, there is no attempt made to differentiate between underlay and overlay transmission. We attempt to solve both problems with Method 2. In Method 2 we use BER feedback, but eliminate the need for exactitude of the BER feedback. In both methods we manipulate transmit PSD by changing the value of $\alpha$ (see (3)). One of the stated objectives of this paper is to achieve user defined QoS without external management. Thus we designed our algorithm to self correct, and avoid drastic fluctuations by self dampening. The power control methods are explained below.

6.1. Method 1
In this method we calculate $\alpha$ using (12).

$$\alpha_{i+1} = \alpha_i \pm \text{min}_\text{sinr}(\hat{e})$$

(12)

$\alpha_{i+1}$ is the alpha being calculated for the next transmission, $\alpha_i$ is the alpha used in the previous transmission, $\text{min}_\text{sinr}$ is the minimum SINR used for symbol transmission (see Section 4.2), while $\hat{e}$ is SE calculated using the last BER feedback. In the initialization stage, $\alpha = 1$.

```plaintext
1  CASE 1: BER < $\varepsilon$
2      Case 1a: Underlay is off
3          Turn underlay on
4          $\alpha_{i+1} = \alpha_i \cdot \text{min}_\text{sinr}(\hat{e})$
5          $\text{amp} = \text{amp}^{\alpha_{i+1}}$
6          End Case 1a
7      Case 1b: Underlay is on
8          $\alpha_{i+1} = \alpha_i \cdot \text{min}_\text{sinr}(\hat{e})$
9          $\text{amp} = \text{amp}^{\alpha_{i+1}}$
10     End Case 1b
11  END CASE 1

12  CASE 2: BER $\geq$ $\varepsilon$
13      Case 2a: Underlay is off
14          $\alpha_{i+1} = \alpha_i \cdot \text{min}_\text{sinr}(\hat{e})$
15      End Case 2a
16      Case 2b: Underlay is on
17          If ($\varepsilon + \text{BER}_\text{buffer} \leq \text{BER}$)
18              Turn underlay off
19          Endif
20          $\alpha_{i+1} = \alpha_i \cdot \text{min}_\text{sinr}(\hat{e})$
21          If ($\alpha_{i+1} \geq \text{psd}_\text{inc}_\text{max}$)
22              Turn underlay off
23          $\alpha_{i+1} = 1$
24      Endif
25      End Case 2b
26  END CASE 2
```

35
In Case 1a, if the BER is acceptable $\alpha$ is reduced using a proportion $(\min\_\text{sinr})$ of the distance $(SE)$ between the feedback BER and the BER threshold ($\epsilon$). If underlay is off (Case 1b), it is turned on.

$$\text{psd\_inc\_max} = 1 + \left( \frac{\Phi_{\text{max}} - \left( \sum_{k=1}^{N} \Phi_{\text{CR}_k} W_{u_k} + \sum_{i=1}^{G} \sum_{j=1}^{Q_i} (\Phi_{p_i} W_{p_j}) \min\_\text{sinr} \right)}{\sum_{i=1}^{G} \sum_{j=1}^{Q_i} (\Phi_{p_i} W_{p_j}) \min\_\text{sinr}} \right)$$

(13)

In (13), $\sum_{k=1}^{N} \Phi_{\text{CR}_k} W_{u_k}$ is the total overlay PSD which has already been adjusted using the power control algorithm.

$\sum_{i=1}^{G} \sum_{j=1}^{Q_i} (\Phi_{p_i} W_{p_j}) \min\_\text{sinr}$ represents the total underlay PSD that has been allocated by applying the minimum transmit power necessary to meet SINR requirement (see Section 3 for meaning of individual symbols). The adjusted overlay is added to the pre-adjusted underlay transmit PSD, and subtract the result from $\Phi_{\text{max}}$ (maximum band PSD). The result is divided by the total overlay transmit PSD and added to 1. Thus, $\text{psd\_inc\_max}$ sets the upper limit on $\alpha_u$, and ensures that transmit PSD does not exceed $\Phi_{\text{max}}$.

In Case 2a, BER is less than $\epsilon$, and underlay is off, so $\alpha$ is increased. $\text{BER\_buffer} = \epsilon/5$ (line 17) and is used to facilitate a quick response if BER is too high. If underlay is on (Case 2b), the system checks to see if the BER is unacceptably high, and underlay is turned off, if it is being used(line 17 - 19). Underlay transmission also gets turned off if the increase in alpha will cause $\Phi_{\text{max}}$ to be exceeded. This is done by ensuring $\alpha_{i+1} < \text{psd\_inc\_max}$, which is calculated using (13).

### 6.2. Method 2

In this method, underlay is decoupled from overlay using buffers and counters (described later in this section). The step size of the increments or decrements in transmit power is also responsive to the length of time the systems has been performing well or poorly. The algorithm is explained in the following paragraphs. First, we explain the operation and effect of the counters and buffers that are set during the initialization phase. Then, we detail the rest of the method that is used during transmission.

#### Initialization

<table>
<thead>
<tr>
<th>CounterBuffer, $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon =$ Minimum acceptable BER</td>
</tr>
<tr>
<td>$\lambda =$ $1/\epsilon$</td>
</tr>
<tr>
<td>underlayCounter = $\lambda$</td>
</tr>
<tr>
<td>overlayCounter = $\lambda$</td>
</tr>
<tr>
<td>gammaCounter = 0</td>
</tr>
<tr>
<td>PC_buffer = 0.5 secs</td>
</tr>
<tr>
<td>BER = 0</td>
</tr>
<tr>
<td>BER_buffer = $\epsilon/5$</td>
</tr>
<tr>
<td>psd_inc_max = 1.5</td>
</tr>
</tbody>
</table>

**Initialization**

**counterBuffer:**
It is used to ensure that underlay and overlay PSD are not simultaneously increased or decreased. It is also part of the mechanism that is used to decouple the effects, on BER, of overlay and underlay transmission.

$\epsilon$:

$\epsilon$ is the minimum acceptable BER, and is the standard with which the feedback BER is compared. $\epsilon$ is obtained at initialization and is the maximum acceptable BER for the CR. The value of $\epsilon$ is very important because it has a direct effect on the overall transmit PSD and BER. The threshold is used to make an assessment of system
performance. This assessment is used to make important decisions such as whether underlay is used, or transmit power is increased or decreased. Manipulation of transmit PSD affects BER and BR, as does the use (or non use) of underlay transmission. If \( \varepsilon \) is too high, the system does not correct itself quickly enough, and continues transmitting at unsuitably low power. This results in unacceptable BER for prolonged periods. Also, the system keeps transmitting for a long time in underlay groups with poor SNR. When \( \varepsilon \) is too low, the underlay system almost never gets turned on, and available capacity is not used. Results are displayed in Section 8.4.

\[ \lambda : \]
\[ \alpha_u = 1 + \frac{1}{\lambda} \frac{\text{underlayCounter}}{\lambda^2} \]  
\[ \alpha_o = 1 + \frac{1}{\lambda} \frac{\text{overlayCounter}}{\lambda^2} \]  

(14a) & (14b) were derived as follows. In order to affect transmit PSD based on the relationship between \( \varepsilon \) and BER feedback, two counters called the underlayCounter and overlayCounter are used. These counters are incremented and decremented according to the relationship between each received BER feedback and \( \varepsilon \). Thus, the value of the counters at any specific instant hold the memory of all prior BER feedback. Memory is important because it helps dampen the CRs response to aberrant occurrences in the channel.

\[ \lambda = \frac{\lambda + \text{underlayCounter}}{\lambda} \]

(15)

As an aid to comprehension, (14a) can be rewritten as (15). For the rest of this explanation, (14a) is used as an example because the same procedures and conditions are applicable to (14b). (3) shows that transmit power is calculated by applying \( \alpha_u \) as an exponent to the amplitude of underlay symbols. When a CR starts transmitting, \( \alpha_u = 1 \). In subsequent transmissions, amplitude is varied by changing \( \alpha_u \). Eq. 15 acts as a control mechanism with which \( \alpha_u \) is incrementally adjusted, using \( \alpha_u = 1 \) as the starting reference. It is important \( \alpha_u \neq 0 \), because the amplitude of any symbol cannot be 1.

In order to accomplish the goals above, the variable \( \lambda \) is introduced, and underlayCounter = \( \lambda \). Thus, for the first transmission, \( \alpha_u = 1 \). For subsequent transmissions, underlayCounter is incremented or decremented based on comparison with \( \varepsilon \), and \( \alpha_u \) is calculated using the new value of underlayCounter.

\[ \lambda = \frac{\lambda - \text{underlayCounter}}{\lambda} \]  

(16)

As in any control system, stability is ensured by the avoidance of zeros and poles. Zeros occur if the condition in (16) is met. If (16) is rewritten into the form of the characteristic equation, we obtain (17).

\[ \lambda^2 - \lambda + \text{underlayCounter} = 0 \]  

(17)

The solutions to (17) are (18a) and (18b), thus , \( \lambda \) cannot be equal to \( \lambda_1 \) or \( \lambda_2 \).

\[ \lambda_1 = \frac{1 + \sqrt{1 - 4 \text{underlayCounter}}}{2} \]  
\[ \lambda_2 = \frac{1 - \sqrt{1 - 4 \text{underlayCounter}}}{2} \]  

(18a) & (18b)

Observation of (14a) and/or (15) shows that the pole is at \( \lambda = 0 \). In order to avoid this, \( \lambda \) is made sufficiently large by initializing it as \( 1/\varepsilon \). Setting \( \lambda = 1/\varepsilon \) also tailors system response to each individual CR’s BER threshold. We have made mention of changing the step size of the increments or decrements of transmit PSD. This is accomplished by increasing or decreasing \( \lambda \) in sufficiently small increments, such as \( 0.02 \lambda \). Table 4 shows an example with \( \alpha_u = 1.017 \), underlayCounter = 8 and 4 different values of \( \lambda \). We can see that as the value of \( \lambda \) decreases, the step size...
of the $\alpha$ increment increases. $\lambda$ is one of the components that contributes to the Methods 2’s ability to self-adjust to channel conditions.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\alpha_u$</th>
<th>Underlay Counter</th>
<th>$\alpha_o$</th>
<th>Percentage Increase of $\alpha_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1.017</td>
<td>8</td>
<td>1.02</td>
<td>.31</td>
</tr>
<tr>
<td>35</td>
<td>1.017</td>
<td>8</td>
<td>1.022</td>
<td>.51</td>
</tr>
<tr>
<td>30</td>
<td>1.017</td>
<td>8</td>
<td>1.024</td>
<td>.75</td>
</tr>
<tr>
<td>20</td>
<td>1.017</td>
<td>8</td>
<td>1.027</td>
<td>1.02</td>
</tr>
</tbody>
</table>

**underlayCounter & overlayCounter:**
They are used to track the increase or decrease of BER during transmission. Upon initialization both counters are set to $\lambda$. Throughout transmission they are used to calculate the values of $\alpha_u$ and $\alpha_o$ ((14a) & (14b)). The counters are manipulated independently to reflect the respective effects, on BER, of underlay and overlay.

**gammaCounter & PC_buffer:**
They are used to track the duration of BER increase and/or decrease. gammaCounter works with $\lambda$ and PC_buffer to provide dampening. They prevent the CR from making drastic changes in response to temporary changes in channel conditions. The range of gammaCounter is from $-PC_buffer$ to $PC_buffer$. As an example, suppose BER has been decreasing, and is lower than the BER threshold, $\epsilon$. For every decrease in BER gammaCounter is incremented. gammaCounter increment step size is calculated using $(.02)\lambda$. When gammaCounter = $-PC_buffer$, $\lambda$ is then decreased, therefore, transmit PSD is decreased in greater increments.

**During transmission**
**Case 1a: BER < $\epsilon$, underlay is off**
When feedback BER is less than $\epsilon$, system performance is satisfactory, and the underlayCounter is set to the current value of $\lambda$. If system performance has been satisfactory for time $T_p$, then underlay is turned on, gammaCounter is reset to 0, and $\lambda$ is incremented. This slows the rate at which transmit PSD is decreased (lines 2-7). This is done because underlay has just been reintroduced, so BER will most likely increase. Therefore the decreases or increases in transmit PSD is minimized in order to encourage stabilization. $\alpha_u$ and $\alpha_o$ are calculated using (12), and then respectively applied to the amplitude of symbols transmitted using underlay and overlay (lines 8-9 & 29-30). If the system performance has not been satisfactory for long enough, then gammaCounter is increased and only $\alpha_o$ is calculated and applied to the amplitude of overlay symbols (lines 29-30).

**Case 1b: BER < $\epsilon$, underlay is on**
underlayCounter is compared to overlayCounter. This comparison controls the rate at which the transmit PSD of overlay subcarriers is reduced compared to the transmit PSD of overlay subcarriers. counterBuffer is used to facilitate this comparison. Lines 15-19 ensure that the PSD of more sensitive symbols transmitted using underlay (because of interference), is reduced at slower rates, and increased at faster rates than overlay. Lines 20-25 calculate whether $\lambda$ needs to be adjusted, then $\alpha_u$ and $\alpha_o$ are calculated and respectively applied to the amplitude of symbols transmitted by underlay and overlay (lines 26-27 & 29-30).

**Case 2a: BER $\geq \epsilon$, underlay is off**
If system performance is poor and underlay is off, overlayCounter and gammaCounter are decreased (lines 33 & 34). The decrease of gammaCounter contributes to tracking the length of time the system has been performing poorly. The decrease of gammaCounter increases the transmit PSD of symbols in overlay subcarriers so that BER is reduced. If the BER is unacceptably high, $\lambda$ is reduced in order to increase the rate at which transmit PSD is
During Transmission

<table>
<thead>
<tr>
<th>CASE 1: BER ≦ ε</th>
<th>CASE 2: BER &gt; ε</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CASE 1a:</strong> BER &lt; ε</td>
<td>Case 2a: Underlay is off</td>
</tr>
<tr>
<td>underlayCounter = $\lambda$;</td>
<td>overlayCounter = overlayCounter $(\cdot \delta \Lambda)$;</td>
</tr>
<tr>
<td>If (gammaCounter == PC_buffer)</td>
<td>gammaCounter = gammaCounter $(\cdot \delta \Lambda)$;</td>
</tr>
<tr>
<td>Turn underlay on;</td>
<td>If (BER $\leq$ BER)</td>
</tr>
<tr>
<td>gammaCounter = 0;</td>
<td>$\lambda = \lambda + 1.5\lambda$;</td>
</tr>
<tr>
<td>$\lambda = \lambda + 1.1\lambda$;</td>
<td>gammaCounter = gammaCounter $(\cdot \delta \Lambda)$;</td>
</tr>
<tr>
<td>$\alpha = 1 + \frac{1}{\lambda}$ underlayCounter;</td>
<td>Elseif (BER &gt; BER)</td>
</tr>
<tr>
<td>amp$_u$ = amp$_e$;</td>
<td>If (gammaCounter == PC_buffer)</td>
</tr>
<tr>
<td>END Case 1a</td>
<td>gammaCounter = 0;</td>
</tr>
<tr>
<td>Case 1b: Underlay is on</td>
<td>$\lambda = \lambda + 0.4\lambda$;</td>
</tr>
<tr>
<td>If (underlayCounter + counterBuffer $&lt;\overline{\text{overlayCounter}}$)</td>
<td>gammaCounter = gammaCounter $(\cdot \delta \Lambda)$;</td>
</tr>
<tr>
<td>underlayCounter = underlayCounter $(\cdot \delta \Lambda)$;</td>
<td>Else</td>
</tr>
<tr>
<td>Case 2a: Underlay is off</td>
<td>If (BER $\leq$ BER)</td>
</tr>
<tr>
<td>Turn underlay off</td>
<td>Turn underlay off</td>
</tr>
<tr>
<td>gammaCounter = gammaCounter $(\cdot \delta \Lambda)$;</td>
<td>$\lambda = \lambda - 1.1\lambda$;</td>
</tr>
<tr>
<td>overlayCounter $\triangleq$ overlayCounter $(\cdot \delta \Lambda)$;</td>
<td>Else</td>
</tr>
<tr>
<td>END Case 2a</td>
<td>gammaCounter = gammaCounter $(\cdot \delta \Lambda)$;</td>
</tr>
</tbody>
</table>

**Case 2b: BER $\geq$ ε, Underlay is on**

Firstly, if the BER is very poor (line 40), then underlay is turned off and the increment size of the transmit PSD increase is reduced (line 42). This is done because since underlay has been turned off, BER will decrease drastically, so the rate at which overlay PSD is increased has to be slowed. $\alpha_u$ is calculated and then applied to the amplitude of symbols transmitted using overlay (lines 64-65).

If BER is not unacceptably high (line 44), and the system has been performing poorly for time $T_p$, then the rate of PSD increase is accelerated (lines 45-50). The decision to increase the PSD of either underlay or overlay symbols is made (lines 51-55), and $\alpha_u$ is calculated. Lines 57-61 ensure that the transmit PSD of an entire band does not exceed $\Phi_{\text{max}}$. If this occurs, underlay subcarriers are not used for transmission. If the maximum PSD is not exceeded, then $\alpha_u$ is calculated, and applied to symbols in underlay subcarriers. In both instances, $\alpha_u$ is calculated and then applied...
to the amplitude of symbols transmitted using overlay subcarriers. In the following section we present the simulation parameters used to perform the research.

7. SIMULATION

Our system is based on the MB OFDM standard (see Figs. 1 & 2). We used 14 bands, 528 MHz in bandwidth, each with 128 subcarriers, 4.125 MHz each. Unless otherwise stated in individual sections, we use a BR of 200Mhz. To simulate the presence of incumbent users, we generate a fixed number of transmitting subcarriers in each band using a random Gaussian distribution. AWGN was uniform across all bands and subcarriers. For the subcarriers with incumbent users, we use a normal distribution, over the range of $[0 - \Phi_{\text{max}}/128]$ to generate incumbent user PSD. The denominator (128) is chosen because it is the number of subcarriers in each band. The average channel power gain is assumed to be one. For each simulation we transmit 6Gb of data. Unless explicitly stated, the max SINR PSD allocation method, and the power control Method 2 are used throughout simulation.

8. RESULTS AND ANALYSIS

In this section we studied the effects on QoS due to the following:

- Use of channel capacity as a design tool.
- Constraints on the number of bands available for transmission.
- PSD allocation methods for underlay groups.
- Underlay group size.
- Power control methods and choice of BER Threshold.

8.1. Channel capacity analytic formulas

![Figure 9. BER vs SINR. Wu et al’s channel capacity analysis vs MGCC channel capacity analysis. Comparison of formulae used as design tool.](image)

![Figure 10. PSD vs SINR. Wu et al’s channel capacity analysis vs MGCC channel capacity analysis. Comparison of formulae used as design tool.](image)
In Figure 9 and Figure 10, we compare Wu et al’s channel capacity formula to the MGCC formula in terms of BER and cumulative transmit PSD. The formulae are as design tools. After CRs sense the individual MB-OFDM bands, we use each formula to assess band capacity, rank them, and use the highest ranked bands. Observation shows that when the MGCC is used, BER is lower than when the Wu et al formula is used. When Figure 10 is taken into consideration, we see that the MGCC uses lower transmit PSD to achieve superior BER.

8.2. Effect of restricting maximum number of bands available

![Figure 11. BER vs SNR, Maximum number of bands available for use.]

Figure 11 shows the effect, on BER, due to limiting the number of bands available for transmission. BER increases as the number of bands available decreases. When few bands are available, in order to maintain device BER, either the transmission rate has to be increased, or transmission must occur in channels with low SINR. Either approach increases BER.

8.3. Comparison of PSD Allocation Methods

Figure 12 illustrates the comparative performances of the different underlay (PSD) allocation methods. The metric used is the number of bits transferred in 100 milliseconds, and the underlay group size is three. The average method outperforms the max SINR method because, with the average method, more underlay groups meet the minimum SINR requirements. This is understandable since assessed noise is typically higher in the max SINR method. As expected, underlay inclusive methods transfer more bits than the overlay-only method.

![Figure 12. Number of bits transmitted vs SINR. Overlay only compared with underlay inclusive PSD allocation methods.]

Overlay
Underlay Minimum
Underlay average
Figure 13 indicates that BER for almost all SINR values is lowest for overlay only, then the max SINR method, and lastly the average SINR method. This is because higher PSD per underlay group symbol is allocated with the max SINR method than with the average SINR method. Overlay-only BER is lowest because of lack of user interference in overlay subcarrier bandwidth. The results from Figure 12 & Figure 13 illustrate the tradeoff between BER and BR. The system can use the appropriate methods to improve BR or BER as necessary. For the remaining graphs in this paper, the max SINR method is used.

8.4. Comparison of Group Size for Underlay Groups
Table 5 shows that BER is lower when underlay symbols are spread over three subcarriers, than when only one subcarrier is used. The Wu et al (see (1)) analytical formula corresponds to $g_{min}=1$, $SNR = 0$ in Table 5. It is evident that the GMCC method provides significant improvement ($g_{min} = 3$, $SNR = 0$). These results support our assertion that in the presence of noise and user interference, spreading the symbol yields better BER performance.

<table>
<thead>
<tr>
<th>BER Threshold = 0.039</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group Size</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SINR</th>
<th>BER for $G_{min} = 1$</th>
<th>BER for $G_{min} = 3$</th>
<th>BER for Overlay Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.101534</td>
<td>0.068217</td>
<td>0.058723</td>
</tr>
<tr>
<td>0.3</td>
<td>0.083554</td>
<td>0.069525</td>
<td>0.058652</td>
</tr>
<tr>
<td>0.6</td>
<td>0.088255</td>
<td>0.071491</td>
<td>0.056804</td>
</tr>
<tr>
<td>1</td>
<td>0.080536</td>
<td>0.067862</td>
<td>0.061182</td>
</tr>
<tr>
<td>2</td>
<td>0.083202</td>
<td>0.056069</td>
<td>0.060637</td>
</tr>
<tr>
<td>4</td>
<td>0.070172</td>
<td>0.062047</td>
<td>0.060443</td>
</tr>
<tr>
<td>5</td>
<td>0.070485</td>
<td>0.060692</td>
<td>0.058748</td>
</tr>
<tr>
<td>6</td>
<td>0.073248</td>
<td>0.062420</td>
<td>0.058048</td>
</tr>
<tr>
<td>7</td>
<td>0.061907</td>
<td>0.054860</td>
<td>0.062198</td>
</tr>
<tr>
<td>8</td>
<td>0.066040</td>
<td>0.056941</td>
<td>0.058614</td>
</tr>
<tr>
<td>9</td>
<td>0.058432</td>
<td>0.054549</td>
<td>0.058508</td>
</tr>
<tr>
<td>10</td>
<td>0.058563</td>
<td>0.052208</td>
<td>0.062465</td>
</tr>
</tbody>
</table>
8.5. Power Control & BER Threshold

Figure 14. BER vs SINR. Comparison of power control methods.

Figure 14 and Figure 15 compare our power control method (Method 2) with the ideal (Method 1). Method 1 (SE) yields slightly higher BER, and higher transmit PSD than Method 2. The efficacy of the power control algorithm, when using Method 2, is evident, in that, as SINR rises and BER falls, transmit PSD initially increases, then levels off.

Figure 16 illustrates the relationship between BER and the value of BER threshold in the method 2 power control algorithm. Overlay only transmission, and underlay inclusive transmission, with group sizes = 1 and 3, are compared using variable and non variable transmit power. It is clear that BER is higher for group size 1 than for group size 3. In the case of variable transmit power, we observe that changes in the BER threshold effects BER more at some points than others.

Figure 15. PSD vs SINR Comparison of power control methods.

Figure 16. BER Threshold vs BER (with max SINR method).
Figure 17. BER Threshold vs required PSD (with max SINR method).

Figure 17 illustrates the PSD required to transmit 100Gb, for the corresponding BER shown in Figure 16. Figure 16 and Figure 17 examined together illustrate the effect of the BER threshold on the power control algorithm. Judicious manipulation of the threshold can be a tool used to influence transmit PSD or BER as the situation demands. As the BER threshold increases, transmit PSD decreases. Beyond a certain point, however, BER is not affected by the BER threshold.

9. CONCLUSION
In this paper we proposed concepts and methods with which user defined QoS can be maintained in a CR, without external management. We introduced a MB-OFDM UWB CR System with which we examined the effects of underlay group size, methods for underlay PSD allocation, BER threshold and power control. The proposed system uses band ranking based on using the Modified Group Channel Capacity (MGCC) analytic formula as a design tool. We introduced an adaptive power control algorithm which we demonstrated is effective in reducing transmit PSD and BER, and compares favorably with the ideal (SE). Very importantly, we were able to show how the CR’s capabilities can be used in myriad ways to influence QoS.

10. ACKNOWLEDGEMENT
The authors would like to acknowledge the support received from NSF Grant, CRI-0551501.

11. REFERENCES