Effects of Bit Allocation on Non-contiguous Multicarrier-based Cognitive Radio Transceivers

Alexander M. Wyglinski
Information and Telecommunication Technology Center
The University of Kansas
Lawrence, Kansas 66045–7612
Email: alexw@ittc.ku.edu

***Abstract*— In this paper, we evaluate a cognitive radio transceiver employing both non-contiguous multicarrier modulation (NC-MCM) and adaptive bit allocation. Although NC-MCM and bit allocation have potential benefits with respect to enabling dynamic spectrum access (DSA) and increasing throughput, they also require the transmission of overhead information between the transmitter and the receiver. To reduce this overhead information, operating parameters can be assigned to a block of subcarriers, at the cost of some throughput. The trade-offs between subcarrier block size and two different bit allocation approaches for several DSA scenarios are assessed in this work. The results show that as percentage of available spectrum decreases, the throughput loss of systems employing larger subcarrier block sizes rapidly increases. Nevertheless, larger block sizes also yield greater reductions in transmission overhead.**

I. Introduction

With the demand for additional bandwidth increasing due to existing and new services, both spectrum policy makers and communication technologists are seeking solutions for this apparent spectrum scarcity. Meanwhile, measurement studies have shown that much of the licensed spectrum is relatively unused across time and frequency [1]. Nevertheless, current regulatory requirements prohibit unlicensed transmissions in these bands, constraining them instead to several heavily populated, interference-prone frequency bands. To provide the necessary bandwidth required by current and future wireless services and applications, the Federal Communications Commission (FCC) has commenced work on the concept of unlicensed users "borrowing" spectrum from spectrum licensees [2, 3]. This approach to spectral usage is known as *dynamic spectrum access* (DSA).

Simultaneously, with the rapid evolution of microelectronics, wireless transceivers are becoming more versatile, powerful, and portable. This has enabled the development of *software-defined radio* (SDR) technology, where the radio transceivers perform the baseband processing entirely in software, e.g., modulation/demodulation. The ease and speed of programming baseband operations in an SDR makes this technology a prime candidate for DSA networks. SDR transceivers that can rapidly reconfigure operating parameters due to changing requirements and conditions are known as *cognitive radios* [4]. With recent developments in cognitive radio technology, it is now possible for these systems to simultaneously respect the rights of incumbent license holders while providing additional flexibility and access to spectrum.

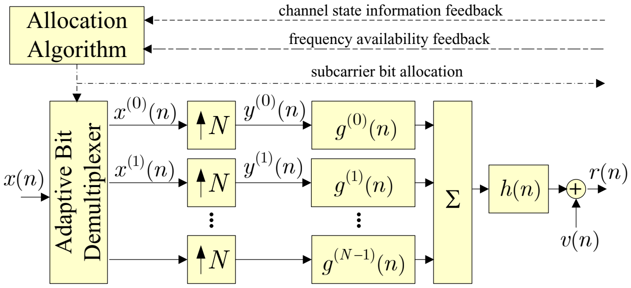
To exploit the advantages of cognitive radio transceivers and enable unlicensed users to transmit in the presence of incumbents license holders, several researchers have proposed a flexible modulation technique based on multicarrier modulation that turns off subcarriers which would otherwise interfere with incumbent transmissions. This technique is known as *non-contiguous multicarrier modulation*, or NC-MCM [5–7][1]. To further exploit the flexibility offered by cognitive radio transceivers and NC-MCM, bit allocation[2] and other transmission parameter adaptations can be employed to enhance system performance, such as throughput [9]. However, the design trade-offs involved with employing these techniques have never really been assessed with respect to computational and implementation complexity, as well as the overhead information required for the transmission parameter adaptations. Given the restrictions on hardware resources and computational power of portable, self-contained cognitive radio implementations, such trade-offs need to be determined before implementation.

In this paper, we examine the design trade-offs associated with a cognitive radio transceiver employing NC-MCM transmission and bit allocation in a single user scenario. Specifically, we will focus on implementations that fully exploit the flexibility offered by NC-MCM using non-uniform bit allocation and compare them with implementations that attempt to reduce the computational complexity and transmission overhead[3]. This paper is organized as follows: Section II presents an overview of a multicarrier-based cognitive radio transceiver and NC-MCM. Section III describes the process of bit allocation. Simulation results and comparisons are presented in Section IV, and several concluding remarks are

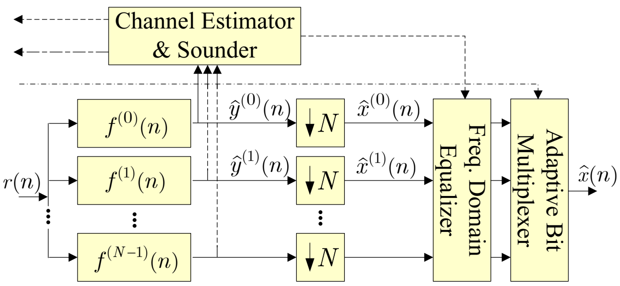
[1] In the literature, most researchers employ an efficient form of multicarrier modulation called *orthogonal frequency division multiplexing* (OFDM) as the basis for NC-MCM transmission. For these implementations, NC-MCM is usually referred to as either non-contiguous OFDM (NC-OFDM) or discontiguous OFDM (D-OFDM).

[2] The subcarrier signal constellations are adjusted to the prevailing channel conditions in order to achieve some performance goal, such as throughput optimization [8].

[3] Several techniques to achieve this include using uniform bit allocation instead of non-uniform bit allocation, and assigning a signal constellation to a block of subcarriers rather than per subcarrier.

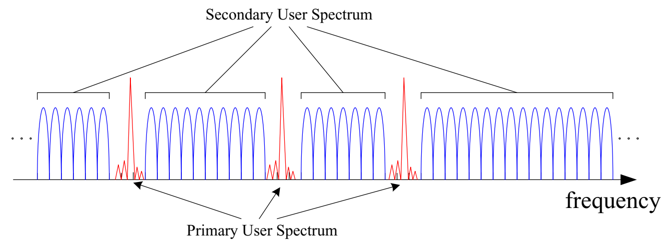


(a) Transmitter with bit allocation algorithm and the channel.

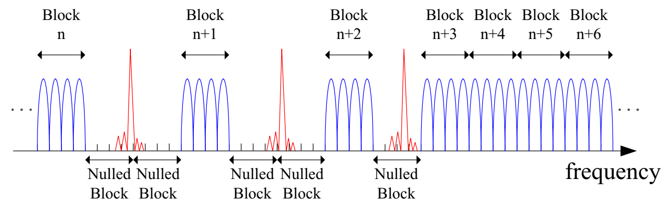


(b) Receiver with channel estimator and sounder.

Fig. 1. Schematic of a single user multicarrier-based cognitive radio transceiver operating in the downlink direction, employing bit allocation, and using feedback from the channel estimator and sounder.



(a) Individual subcarriers (i.e., $B = 1$).



(b) Subcarrier blocks of size $B = 4$.

Fig. 2. Schematic of unlicensed (secondary) users operating in the frequency domain when employing non-contiguous multicarrier modulation in the presence of transmissions from incumbent (primary) users.

made in Section V.

II. System Framework

The general setup for a multicarrier-based cognitive radio transceiver is shown in Fig. 1. The high speed input symbol stream, $x(n)$, is demultiplexed into N streams, with stream i having b_i bits per symbol epoch. The value of b_i is determined by the allocation algorithm, which uses the subcarrier SNR values γ_i, $i = 0, \ldots, N-1$, to compute the subcarrier BER [8]. The subcarrier SNR values are computed from the channel state information (CSI) provided by the data-aided channel estimator at the receiver. We only consider the downlink in this paper, with bit allocation decisions performed solely at the transmitter. Furthermore, information regarding the spectral availability across the transmission bandwidth, obtained through channel sounding and spectrum analysis [10, 11], is also used by the transceiver to deactivate subcarriers, i.e., $b_i = 0$, that can potentially interfere with incumbent transmissions.

Once the bit streams are modulated onto one of several signal constellations consisting of $M_i = 2^{b_i}$ points, the outputs, $x^{(i)}(n)$, $i = 0, \ldots, N-1$, are upsampled by a factor N to produce $y^{(i)}(n)$, $i = 0, \ldots, N-1$, and filtered by synthesis filters $g^{(i)}(n)$, $i = 0, \ldots, N-1$, before being summed together, yielding the composite transmit signal, $s(n)$. This signal is transmitted across the channel, where the multipath propagation and additive noise are modelled with channel impulse response $h(n)$ and noise $v(n)$. The received signal, $r(n)$, is separated into the N subchannels using the analysis filters $f^{(i)}(n)$, $i = 0, \ldots, N-1$, downsampled by a factor N, equalized using frequency-domain equalizers, demodulated, and then multiplexed together to form the estimate of $x(n)$, $\hat{x}(n)$. Moreover, the receiver uses the subcarrier information $\hat{y}^{(i)}(n)$, $i = 0, \ldots, N-1$, to generate a channel estimate, as well as to locate and identify non-negligible transmissions within the transmission bandwidth as either spurious interference/noise or an incumbent user. The identification process is performed using one of several spectral analysis techniques (refer to [10, 11] and references therein). Once the locations of incumbent transmissions have been obtained, the transceiver then configures itself for NC-MCM, as described in the next subsection.

A. Non-contiguous Multicarrier Modulation

Given the locations in frequency of spectrum occupied by incumbent users, the goal of the cognitive radio transceiver employing NC-MCM is to deactivate subcarriers that could potentially interfere with these users and transmit over the remaining active subcarriers. Referring to Fig. 2(a), we observe the spectral usage of the incumbent (primary) and unlicensed (secondary) users. Notice how the subcarriers of the unlicensed user are evenly spaced through frequency. Moreover, observe how the subcarriers located in the same vicinity as the incumbent spectrum are deactivated, i.e., nulled, resulting in the non-contiguous characteristic of the multicarrier signal.

Although very flexible, the amount of overhead information required to indicate whether a subcarrier should be activated or not is large, especially if this information is frequently updated[4]. One solution is to activate or deactivate blocks of

[4]Given that the spectral occupancy and location of an incumbent transmission are both random, the unlicensed transceiver must be monitoring the spectrum frequently to avoid interference.

subcarriers[5], as shown in Fig. 2(b). In this case, we choose a subcarrier block size of $B = 4$ subcarriers across the entire transmission bandwidth of operation. As a result, the amount of overhead information is reduced by a factor of B.

Nevertheless, with the reduction in overhead comes the trade-off that the transceiver loses flexibility, resulting in a decrease in throughput. This is due to the fact that instead of nulling a single subcarrier, one must deactivate the entire block containing that interfering subcarrier. Moreover, the larger the block size B, the greater the chance of having a subcarrier interfering with an incumbent user, resulting in having all the subcarriers in that block nulled. On the other hand, the amount of overhead is substantially reduced.

Once the NC-MCM transceiver has decided on which subcarriers to activate, bit allocation can be performed, as will be discussed in the next section.

III. Adaptive Bit Allocation

One of the primary advantages of multicarrier modulation is its ability to transform a frequency-selective fading channel into a collection of approximately-flat subchannels. As a result, distortion compensation of the transceiver becomes simpler to perform. Furthermore, the agility of the transceiver to tailor its operating parameters to the channel conditions is enhanced due to the resolution of the subcarriers.

The subcarrier signal constellation is one operating parameter that can be tailored to the channel conditions. To illustrate, suppose we have a frequency-selective fading channel, a constant transmit power level across all subcarriers, and additive white Gaussian noise. The resulting subcarrier signal-to-noise ratios (SNR) and bit error rates (BER) will probably not be equal for all subcarriers. Moreover, those subcarriers with low SNR values/high BER values will dominate the average BER of the overall transceiver. By changing the subcarrier signal constellations, the subcarrier BER values can be changed in order to yield a better average BER for the system. The process of changing the subcarrier signal constellations is known as *bit allocation*.

Mathematically, the process of performing bit allocation in order to increase the overall throughput of the system while ensuring the mean BER, $\bar{P}$, is below a specified mean BER limit, P_T, can be defined by the following optimization problem:

$$\max_{b_i} \sum_{i=0}^{N-1} b_i \tag{1}$$

$$\text{subject to}:$$

$$\bar{P} = \left(\sum_{i=0}^{N-1} b_i P_i \right) \Big/ \left(\sum_{i=0}^{N-1} b_i \right) \leq P_T, \tag{2}$$

where b_i is the number of bits per symbol for subcarrier i, P_i is the BER for subcarrier i, which is computed from the subcarrier signal-to-noise ratio (SNR), γ_i, via closed form expressions [12][6].

As discussed in Section II-A, one of the disadvantages of exploiting the flexibility of multicarrier modulation is the amount of overhead information generated. One solution is to perform *uniform bit allocation*. As oppose to *non-uniform bit allocation*, where the subcarrier signal constellations can vary [8], uniform bit allocation imposes the additional constraint of

$$b_0 = b_1 = \ldots = b_{N-1} \tag{3}$$

when trying to solve for the objective function of Eq. (1). Another solution that employs some of the flexibility offered by multicarrier modulation is to assign a signal constellation to a block of B subcarriers[7]. The bit allocation process would assess the average SNR of each block of subcarriers, and then select an appropriate signal constellation for each block, insuring that the BER constraint of Eq. (2) is satisfied while attempting to increase the system throughput in Eq. (1).

In the next section, the design trade-offs discussed in this paper, e.g., subcarrier block size, uniform versus non-uniform bit allocation, are evaluated for an NC-MCM cognitive radio transceiver.

IV. Simulation Results

A. Simulation Parameters

In this work, several of the operating parameters from the IEEE Std. 802.11a [13] have been employed in these computer simulations[8]. For instance, although the cognitive radio transceiver consists of $N = 512$ subcarriers within a bandwidth of 128 MHz, this is approximately equivalent to transmitting eight IEEE Std. 802.11a transmissions in adjacent frequency bands. The BER limit of the transceiver was set to be $P_T = 10^{-5}$. Moreover, for the purpose of straightforward comparison, no channel coding was employed by the system.

With respect to subcarrier block size, values of $B = 1, 8, 16, 32$ were used by the transceiver. Furthermore, the unlicensed transceiver was evaluated for different percentages of available spectrum. Regarding the different bit allocation algorithms studied in this work, two types were considered. The non-uniform bit allocation algorithm proposed by Wyglinski, Labeau, and Kabal [8] was employed, where the allocation was applied to the blocks of B subcarriers. The other type was a simple uniform bit allocation approach applied to all subcarriers, such that largest signal constellation obeying Eq. (2) was chosen.

The statistical indoor propagation modeling technique of Saleh and Valenzuela [14], which employs a Rayleigh fading statistic, was used in this work. We used a mean cluster arrival time of 100 μs, a mean ray arrival time of 1 μs, a

[5]Although multiband OFDM (MB-OFDM) also groups subcarriers together [5], this is done to reduce the hardware cost of the implementation, instead of the overhead information. As a result, this allows for ultra-wideband (UWB) bandwidths in excess of 500 MHz to be supported by the transceiver.

[6]In a practical implementation, the BER values would be stored in a look-up table.

[7]This approach is similar to the block technique employing in Section II-A for the reduction of transmission overhead.

[8]The operating frequency of the transceiver is 5 GHz, and each subcarrier can employ $M = 5$ signal constellations: BPSK, QPSK, square 16-QAM, square 64-QAM, and null (turned off).

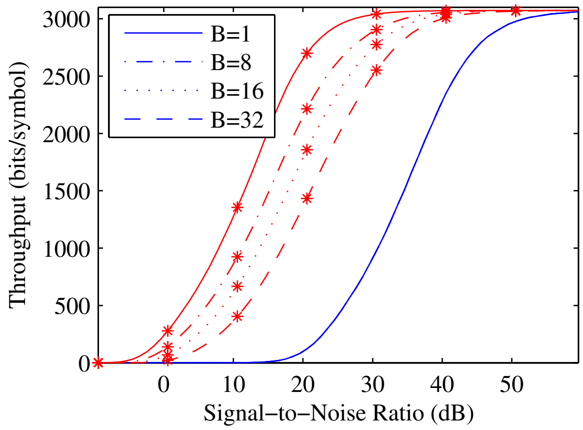


Fig. 3. Throughput results of a cognitive radio transceiver employing NC-MCM when 100% of the spectrum is available for unlicensed transmission, given block sizes of B subcarriers. Note that uniform bit allocation (no stars) and non-uniform bit allocation (with stars) were employed.

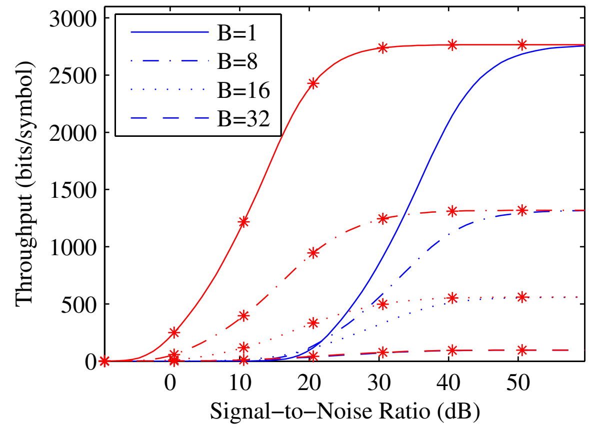


Fig. 4. Throughput results of a cognitive radio transceiver employing NC-MCM when 90% of the spectrum is available for unlicensed transmission, given block sizes of B subcarriers. Note that uniform bit allocation (no stars) and non-uniform bit allocation (with stars) were employed.

cluster power-decay time constant of 20 μs, and a ray power-decay time constant of 6 μs. For each time-invariant channel realization, the physical separation between the transmitter and receiver was varied between 1 m and 60 m[9]. The system was evaluated at 70 different average SNR values, and the trials were repeated for 10000 different channel realizations[10], with the results averaged.

B. Throughput Results

In Fig. 3, throughput results of a cognitive radio transceiver employing NC-MCM when 100% of the spectrum is available for unlicensed transmission is presented for four different subcarrier block sizes, when either uniform or non-uniform bit allocation is performed. We observe that when the system employs uniform bit allocation, the throughput given the four different block sizes are all equivalent. This is due to the fact that when 100% of the spectrum is available, all the subcarriers are active and employ the same signal constellation. As a result, block sizes are irrelevant with respect to throughput. Nevertheless, block size will make an impact with respect to overhead reduction. When non-uniform bit allocation is performed, there are significant throughput gains. Although all the curves reach the maximum of 3072 bits per symbol[11], the curves for non-uniform bit allocation achieve greater throughput sooner due to the flexibility of the allocation. Moreover, as the block size decreases in size, increasing the flexibility, the throughput increases rapidly.

When 10% of the spectrum is occupied by incumbent transmissions, as shown in Fig. 4, there are some noticeable differences between the throughput curves here and those in Fig. 3. First, the maximum attainable throughout of 2766 bits per symbol is only achieved by transceivers using the smallest block size, i.e., $B = 1$ subcarrier. Moreover, the more flexible non-uniform bit allocation implementation reaches that maximum throughput significantly faster relative to the uniform bit allocation implementation. Second, as the block sizes get larger, maximum attainable throughput declines substantially. This is due to the fact that if one subcarrier is interfering with an incumbent user, the whole block of subcarriers is nulled, resulting in a significant throughput penalty. Hence, the larger the block, the greater the penalty. Third, the block-wise non-uniform bit allocation outperforms the transceiver employing the uniform bit allocation, especially in the mid-range SNR values.

C. Overhead Reduction and Trade-offs

Regarding the amount of overhead required for each bit allocation technique, the non-uniform bit allocation takes 3 bits to represent 5 possible signal constellations. Since each block has the same signal constellation, this translates into $3 \times N/B$ bits to represent a bit allocation and a subcarrier activity level. On the other hand, for uniform bit allocation, only 1 bit is required to indicate the subcarrier activity level per block, and 3 bits for the entire transmission to represent the 5 possible signal constellations. This translates into $1 \times N/B + 3$ bits to represent an allocation and subcarrier activity. Note that to obtain a straightforward comparison, we assume that no source coding is performed on the overhead information.

Thus, the amount of overhead information required by the NC-MCM cognitive radio transceiver, employing either uniform or non-uniform bit allocation with block sizes of B subcarriers, is given in Fig. 5. It can be observed that a system employing non-uniform bit allocation generates as much as three times the amount of overhead relative to a system employing uniform bit allocation. When the transceiver employs non-uniform (uniform) bit allocation, an overhead reduction of 87.5% (87.0%), 93.8% (93.2%), and 96.9%

[9] The change in transmitter/receiver separation distance corresponds to an SNR change ranging from 59 dB to -11 dB.

[10] For each channel realization, the locations of incumbent users in the frequency domain is different, although the percentage of the occupied bandwidth is the same.

[11] This is equal to 512 subcarriers multiplied by 6 bits per subcarrier for 64-QAM modulation.

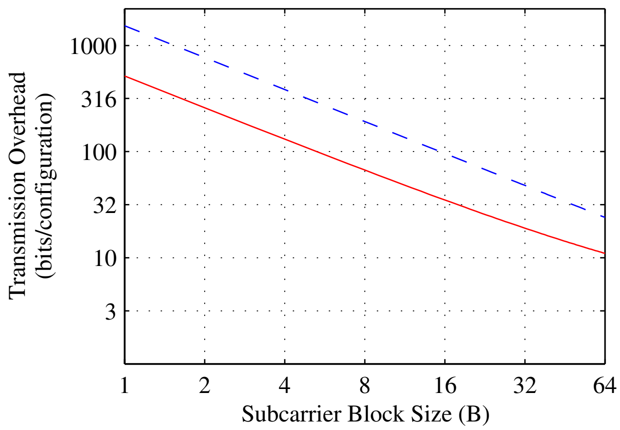


Fig. 5. Amount of overhead transmission per configuration for the NC-MCM cognitive radio transceiver employing either uniform or non-uniform bit allocation with block sizes of B subcarriers.

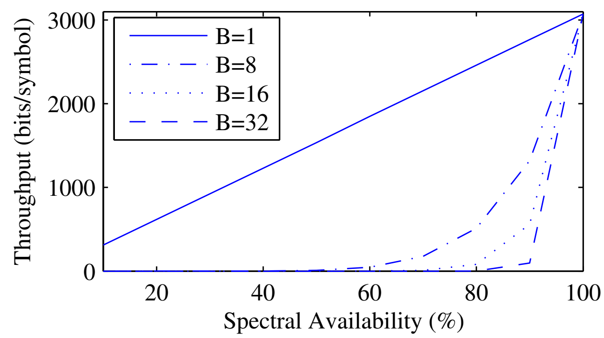


Fig. 6. Maximum-attainable throughput results of a cognitive radio transceiver employing NC-MCM for different percentages of spectrum availability, given block sizes of $B = 1$, 8, 16, and 32 subcarriers. Note that results were obtained for an SNR of 59 dB.

(96.3%) is achieved when using block sizes of $B = 8$, 16, and 32 subcarriers, relative to an implementation using $B = 1$.

With respect to the maximum-attainable throughput of the cognitive radio transceiver, we observe in Fig. 6 that smaller subcarrier block sizes achieve higher throughput values relative to systems employing larger block sizes. Note that both bit allocation algorithms will converge to the same maximum-attainable throughput, as shown in Figs. 3 and 4 for high SNR values, i.e., an SNR of 59 dB. However, as the percentage of available spectrum decreases, there is an overall decrease in the maximum-attainable throughput. The decrease is greater for larger subcarrier block sizes. For instance, the throughput loss of a transceiver employing either bit allocation technique, when the spectral availability is 95% (85%), is 29.8% (67.9%), 53.4% (91.3%), and 78.9% (99.4%) for block sizes of $B = 8$, 16, and 32 subcarriers, relative to a system with $B = 1$.

Thus, when we compare the percentage decrease in overhead to the percentage throughput loss due to decreased flexibility, we can conclude that for spectrum sparsely occupied by incumbent users, the percent gain in reduced overhead is significantly greater than the throughput loss due to subcarrier block size. However, as the spectrum fills up with incumbent transmissions, the advantages of establishing blocks of subcarriers quickly diminishes, especially for large block sizes.

V. Conclusion

We have examined the throughput performance of a cognitive radio transceiver employing NC-MCM that uses either uniform or non-uniform bit allocation. To reduce overhead information and bit allocation algorithm complexity, the transceiver was implemented to assign the same signal constellation and activity level to blocks of subcarriers. The results show that for low spectral occupancy by the incumbent users, the cost of using blocks of subcarriers to reduce overhead was worth it relative to the throughput penalty incurred by using blocks. However, as the incumbent spectral occupancy increases, the benefits in reduced overhead relative to the throughput penalty diminished very quickly. Therefore, it is recommended that one adaptable parameter to be included in the cognitive radio transceiver employing NC-MCM is an algorithm that decides on a value for the subcarrier block size, which is a function of the incumbent spectral occupancy.

References

[1] Federal Communications Commission, "Spectrum policy task force report," ET Docket No. 02-135, 2002.

[2] M. J. Marcus, "Unlicensed cognitive sharing of TV spectrum: The controversy at the federal communications commission," *IEEE Commun. Mag.*, vol. 43, no. 5, pp. 24–25, May 2005.

[3] Federal Communications Commission, "Unlicensed operation in the TV broadcast bands," ET Docket No. 04-186, 2004.

[4] J. Mitola, III, "Cognitive radio for flexible multimedia communications," in *Proc. IEEE Int. Wksp. Mobile Multimedia Commun.*, San Diego, CA, Nov. 1999, vol. 1, pp. 3–10.

[5] M. P. Wylie-Green, "Dynamic spectrum sensing by multiband OFDM radio for interference mitigation," in *Proc. IEEE Int. Symp. New Frontiers Dynamic Spectr. Access Networks*, Baltimore, MD, Nov. 2005, vol. 1, pp. 619–625.

[6] J. D. Poston and W. D. Horne, "Discontiguous OFDM considerations for dynamic spectrum access in idle TV channels," in *Proc. IEEE Int. Symp. New Frontiers Dynamic Spectr. Access Networks*, Baltimore, MD, Nov. 2005, vol. 1, pp. 607–610.

[7] H. Tang, "Some physical layer issues of wide-band cognitive radio systems," in *Proc. IEEE Int. Symp. New Frontiers Dynamic Spectr. Access Networks*, Baltimore, MD, Nov. 2005, vol. 1, pp. 151–159.

[8] A. M. Wyglinski, F. Labeau, and P. Kabal, "Bit loading with ber-constraint for multicarrier systems," *IEEE Trans. Wireless Commun.*, vol. 4, no. 4, pp. 1383–1387, July 2005.

[9] M. B. Pursley, T.C. Royster, IV, and J. S. Skinner, "Protocols for the selection, adjustment, and adaptation of transmission parameters in dynamic spectrum access networks," in *Proc. IEEE Int. Symp. New Frontiers Dynamic Spectr. Access Networks*, Baltimore, MD, Nov. 2005, vol. 1, pp. 649–657.

[10] F. Weidling, D. Datla, V. Petty, P. Krishnan, and G. J. Minden, "A framework for RF spectrum measurements and analysis," in *Proc. IEEE Int. Symp. New Frontiers Dynamic Spectr. Access Networks*, Baltimore, MD, Nov. 2005, vol. 1, pp. 573–576.

[11] S. Shankar, C. Cordeiro, and K. Challapali, "Spectrum agile radios: Utilization and sensing architectures," in *Proc. IEEE Int. Symp. New Frontiers Dynamic Spectr. Access Networks*, Baltimore, MD, Nov. 2005, vol. 1, pp. 160–169.

[12] J. G. Proakis, *Digital Communications*, McGraw-Hill, New York, NY, USA, 3rd edition, 1995.

[13] Institute of Electronics and Electrical Engineers, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: High-speed physical layer in the 5 GHz band," IEEE Standard 802.11a, Nov. 1999.

[14] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Select. Areas Commun.*, vol. 5, no. 2, pp. 128–137, Feb. 1987.