Optimal Power Allocation Scheme under FSA Constraint for OFDM Based Cognitive Radio Systems

Ahmed Sohail, Pei Xiao, Barry G. Evans
Centre for Communication Systems Research
University of Surrey
Guildford, GU2 7XH, United Kingdom
Email: a.sohail@surrey.ac.uk

Abstract—**In the literature, researchers have evaluated optimal power loading algorithms under the Zero Mean Circularly Symmetric Complex Gaussian (ZMCSCG) constraint in OFDM based CR systems. The capacity of the Secondary User (SU) is maximized while keeping the interference introduced to the Primary User (PU) band remains within tolerable range. However the drawback of such an approach is that channel capacity increases with increasing Signal to Noise Ratio (SNR), which is not applicable to a practical scenario. Therefore, we propose an optimal power loading scheme under the Finite Symbol Alphabet (FSA) constraint, (i.e., QPSK, 8-PSK, 16-QAM and 64-QAM, etc.) to achieve realistic system performance especially under the high SNR region. Subsequently, Mutual Information (MI) is derived and compared against channel capacity which reveals that in the low SNR region, they are closely related. Conversely, MI saturates in the high SNR region which indicates maximum achievable data rates for practical systems. We further evaluate channel capacity and MI by varying the interference threshold and our observation is that the saturation value of the achievable SU data rate indicated by MI changes accordingly, but total achievable data rate remains constant. On the other hand, capacity increases with increasing interference threshold.**

Keywords: Cognitive radio, OFDM, ZMCSCG, FSA

I. Introduction

Radio spectrum is a scarce resource, the use of which is managed by government bodies such as Ofcom in UK, FCC in USA. Spectrum management involves spectrum assignment to operators in order to provide services on a long term basis over large geographical regions. Todays wireless networks are based on a fixed spectrum assignment policy providing interference-free exclusive use of the spectrum, however this yields inefficient use of the radio spectrum. The UK & USA frequency allocation charts [1], [2] indicate that the spectrum is overcrowded especially below 3 GHz. This is due to intense competition for use of spectrum which means that no more opportunities are left for emerging wireless devices and services. While on the other hand, spectrum occupancy measurements conducted by QinetiQ on behalf of Ofcom in different areas of the UK (e.g., Central London, Heathrow Airport, and Rural Areas) show underutilization of spectrum for significant periods of time [3]. Similarly, according to FCC in New York City & downtown Washington DC, only 13.1% & 35% of spectrum utilization has been reported respectively below 3 GHz [4]. These studies clearly suggest that instead of physical spectrum shortage, scarcity is mainly due to the inflexible spectrum licensing scheme. On the other hand, the access to a spectrum block is also expensive. It can be concluded that spectrum scarcity and efficiency are becoming challenging tasks for regulators as well as for service providers. The major factors include increased developments of bandwidth hungry wireless communication systems and underutilization of fixed allocated spectrum to different wireless services due to inefficient licensing schemes.

To overcome the spectrum underutilization problem, the Dynamic Spectrum Management (DSM) scheme is proposed which is the opportunistic access of the licensed frequency band by the Secondary User (SU) under the condition of acceptable interference to the Primary User (PU) [5]. In 1999, Joseph Mitola III proposed CR systems which enable the designer to adopt the DSM techniques [6]. Although there is no unique definition of CR, however according to FCC document [7], cognitive radio is: "*a radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets*".

There are several methods of spectrum sharing in CR system to enhance the spectrum efficiency and maximize the data rate, i.e., Underlay Spectrum Sharing (USS), Overlay Spectrum Sharing (OSS) and Interweave (opportunistic) Spectrum Sharing (ISS) schemes [8]. In the USS scheme, there is no need of sensing and SU can always access the PU spectrum simultaneously under the condition that the interference introduced by the SU is below the acceptable noise floor of the PUs of the spectrum. In this scheme, the data rate is independent of PU activity whereas SU transmit power is low. Therefore, it guarantees low data rate and is suitable for short range applications. On the contrary, sensing is required in ISS scheme and the spectrum is only accessible by the SU once the PU is idle. Therefore, the data rate is dependent on the PU activity. This scheme provides high data rate but without any guarantee compared to the underlay scheme. The OSS scheme also allows simultaneous transmission of primary and secondary users, however, the SU can use part of its power for secondary transmission and the remaining power for primary transmission in order to compensate the PU's SNR degradation. The drawback of the OSS scheme is that it requires a priori knowledge of the PU's transmission and it works well when primary and secondary transmitters are in close proximity.

Orthogonal Frequency Division Multiplexing (OFDM) is widely used in current wireless communication standards and services due to its mitigation of multipath [9] but it is also very suitable for CR systems via use of its sub-carriers for PU and SU operation.

In opportunistic spectrum access where PU and SU co-exist side by side, mutual interference is the limiting factor for performance of both networks. The amount of interference introduced by the SU subcarriers into the PU's band depends on (i) power allocated in that subcarrier (ii) spectral distance between that particular subcarrier and the PU's band. In the literature, different power allocation schemes in OFDM based CR systems have been introduced in order to maximize the SU data rate while keeping the interference introduced to the PU band within limits. However, authors have assumed ZMCSCG constraint to evaluate optimal power allocation algorithms in OFDM based CR systems which maximize the channel capacity of the SU. The derived capacity is always too optimistic for practical systems especially for high SNR and interference threshold values. It remains of interest and of practical importance to evaluate optimal power loading schemes under the FSA constraint, e.g., QPSK, 8-PSK, 16-QAM & 64-QAM. This loading scheme saturates the achievable data rate of the SU at high SNR and values. To address the problem, in this paper we propose an optimal power loading scheme under the FSA constraint using Lagrange formulation in SISO-OFDM based CR systems.

The remainder of the paper is organized as follows. In the next section we review the related work for the allocation of optimal power in OFDM based cognitive radio systems.Section II describes the system model. Sections III & IV present optimal power allocation with FSA and ZMCSCG constraints, respectively. We compare the results under both constraints in Section V. Finally, conclusions are drawn in Section VI.

II. Related Work

In conventional OFDM systems, power allocation depends mainly on the channel gain of the subcarriers. If the channel condition is good, more power is allocated to that subcarrier and vice versa. However, the same power allocation scheme cannot be applied in OFDM based CR systems due to mutual interference. The amount of interference introduced to the PU's band not only depends on the power allocated in that subcarrier, but also on the spectral distance between that particular subcarrier and the PU's band. Therefore, in the interference limited scenario, allocation of power is based on the location of the subcarrier with respect to the PU's spectrum, i.e., more power should be allocated to distant subcarriers and vice versa. Therefore in the OFDM based CR system, a judicious power loading scheme is required which should take into consideration the fading gain of the subcarrier as well as spectral distance between the subcarrier and the PU's band. An optimal and ladder based suboptimal power profile is proposed in [10], [11] based on the position of the SU with respect to PU.

Another important aspect of power allocation in OFDM based CR networks is the reliability of the subcarriers, i.e., subcarriers that are more frequently available for SU transmission as compared to those which are always busy due to PU activity. Previously, it was assumed that after sensing spectrum holes are available to secondary usage up to a certain time until the SU completes its task. However, in the real time scenario, the PU being the spectrum owner may return at any time and retrieve its spectrum which is currently available for secondary access. Therefore, power allocated by the SU is wasted due to the unaccomplished task by the SU. In view of this fact, more power should be allocated to more reliable subcarriers in order to guarantee the SU's QoS requirements [12] and [13]. In [14] & [15], optimal power allocation scheme has been analyzed for multiuser scenario where more subcarriers are given to those SUs which not only increase the capacity but also introduce low interference to the PU. For a given subcarrier allocation, optimal power allocation has been proposed to maximize the capacity of the SU. In [16], authors considered fairness constraint among multiple SUs and proposed algorithms which first ensure fairness that each user has received and then use a greedy approach for power allocation.

In [17], author has investigated MI of wireless systems under the FSA constraint whereas an expression has been derived for the achievable data rate between the input and the output of the system. In this paper, we propose to analyze an MI based optimal power loading scheme under the FSA constraint for SISO-OFDM based CR system and compare it with channel capacity. Our simulation results reveal that the capacity of the OFDM based CR system is unachievable especially in the high SNR region. This motivates us to analyze MI, resulting in an achievable data rate over the entire SNR region. It also holds true especially in the case of the high SNR region where it achieves a saturation level and remains constant with increasing SNR value in contrast to channel capacity.

III. System Model

A one-cell wireless system is assumed, where the PU and SU transceivers coexist in the same geographical location as shown in Fig. 1. The scenario is investigated for one SU in the downlink path. There are three instantaneous fading gains: (i) g_{ss}, between the SU transmitter and SU receiver; (ii) g_{sp}, between the SU transmitter and PU receiver; and (iii) g_{ps}, between PU transmitter and SU receiver. We assume these instantaneous fading gains are perfectly known at the SU transmitter. The SU network has an individual base-station that

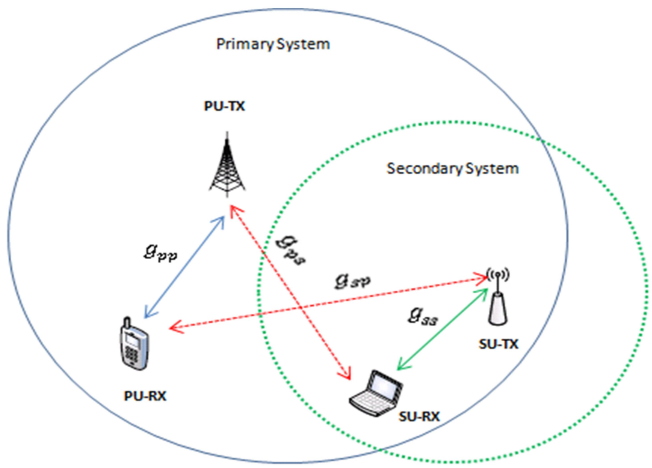

Fig. 1. Distribution of PU & SU

identifies the spectrum holes on the basis of the information collected about the spectrum; then deactivates the PUs' sub-carriers and transmits its users information via the remaining sub-carriers as shown in Fig. 2.

We consider adjacent co-existence of primary and secondary users in a frequency localised way, i.e., the Discrete Fourier Transform (DFT) outputs are mapped to consecutive sub-carriers as shown in Fig. 2. The OFDM modulation scheme is employed for SUs and the available bandwidth for SU transmission is divided into N subcarriers each having a bandwidth of Δf. This implies that the bandwidth of the transmitted signal is very small and can be assumed frequency flat. It is assumed that subcarriers are orthogonal to each other, therefore no Inter-Symbol Interference (ISI) occurs. The transmit power is adaptively loaded in each secondary user's subcarrier.

In the OFDM based CR system, the interference limited scenario limits the transmit power and accordingly achievable data rate of the SU. Therefore, we propose to calculate an optimal power under the FSA constraint based on Lagrange formulation. This optimal power will be allocated to each OFDM subcarrier for a given channel fading gain such that the total transmission rate of the SU is maximized while keeping the interference introduced into the PU band within threshold level. The mutual information is given by [17]

$$I_i(s_i;(y,H_i)) = \\ -E\left\{E\left\{\sum_{i=1}^{N}\log_2\left\{X\sum_{s\in\mathcal{S}} exp\left[-\frac{\|y-H_iP_is_i\|^2}{2\sigma_N^2}\right]\right\}\right\}\right\}-B \tag{1}$$

s.t

$$X=\frac{1}{2^{M_c n_T}(2\pi e\sigma_N^2)^{n_R}}, \qquad B=\log_2(e)n_R\ln(2\pi e\sigma_N^2)$$

The unit for Eq. (1) is rate in bits per channel use. In Eq. (1) n_T & n_R are the number of transmit and receive antennas, M_c is the number of bits per symbol, P_i & H_i are the transmit power and channel response of the i^{th} subcarrier, σ_N^2 denotes AWGN noise variance, y is received signal and s_i is the transmitted symbols of the i^{th} subcarrier. $s\in F^{n_T}$ and $y\in F^{n_T}$ are finite symbols alphabet input and output respectively, where $\mathbb{F}$ denotes the symbol alphabet (like QAM or PSK [17]). In Eq. (1) expectations are taken over variables P_i & H_i. The total MI is the sum of the MI of N number of available subcarriers is as follows.

$$I_{Total}=\max_{P_i}\sum_{i=1}^{N}I_i \tag{2}$$

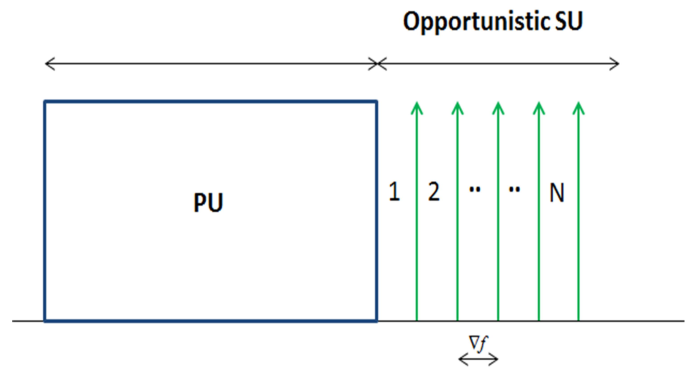

Fig. 2. Co-existence of PU & SU in Opportunistic Scheme

Due to adjacent co-existence of PU & SU, there are two types of interference in the system (i) interference introduced from the PU into the SU band (ii) interference introduced from the SU into the PU band. Our objective is to protect the PU from an unacceptable interference, therefore, in this paper we will consider interference introduced by the SU into PU band.

A. Interference introduced by the seconday user's signal

The power density spectrum of the i^{th} subcarrier in the SU user band can be written as [11]

$$\phi_i(f)=P_iT_s\left(\frac{\sin\pi fT_s}{\pi fT_s}\right)^2, \tag{3}$$

where P_i is the total transmit power emitted by the i^{th} subcarrier in the secondary user's band and T_s is the symbol duration. The interference introduced by the i^{th} subcarrier to the PU band is the integration of the power density spectrum of the i^{th} subcarrier across the PU band and can be written as

$$J_i(d_i,P_i)=P_iT_s\int_{d_n-\frac{B}{2}}^{d_i+\frac{B}{2}}\left(\frac{\sin\pi fT_s}{\pi fT_s}\right)^2 d_f \tag{4}$$

where B is the bandwidth in Hz occupied by the PU, d_i represents the spectral distance between the i^{th} subcarrier of SU and the PU band. $J_i(d_i,P_i)$ represents the interference introduced by the i^{th} subcarrier of SU into the PU band. The interference Eq. (4) should also take into account channel gain from the SU base station to the PU receiver. We use a normalized channel gain of 1.

IV. OPTIMAL POWER ALLOCATION UNDER THE FSA CONSTRAINT

Our purpose is to analyze an optimal power allocation scheme that maximizes the achievable data rate of the SU provided that the interference introduced into the PUs' bands does not exceed to a certain level. This problem can be dened as an optimization problem as follows

$$I_{Total} = \max_{P_i} \sum_{i=1}^{N} I_i, \tag{5}$$

subject to

$$\sum_{i=1}^{N} J_i(d_i, P_i) \leq \tau_{th} \tag{6}$$

$$P_i \geq 0 \qquad \forall_i = 1, 2, ...N \tag{7}$$

where I_i denotes the mutual information, N denotes the total number of available subcarriers and τ_{th} denotes the interference threshold prescribed by the PU. Using Lagrange formulation we can write

$$L(P_i, \lambda) = \left[-E\left\{E\left\{\sum_{i=1}^{N} \log_2\left\{X \sum_{s\in\mathcal{S}} exp\left[-\frac{\|y - H_i P_i s_i\|^2}{2\sigma_N^2}\right]\right\}\right\}\right\} - B\right] - \lambda(\sum_{i=1}^{N} J_i(d_i, P_i) - \tau_{th}) \tag{8}$$

where λ is the Lagrange constraint. Differentiating Eq. (8) with respect to P_i yields

$$\frac{\partial L}{\partial P_i} = \frac{\partial}{\partial P_i} \left[-E\left\{E\left\{\sum_{i=1}^{N} \log_2\left\{X \sum_{s\in\mathcal{S}} exp\left[-\frac{\|y - H_i P_i s_i\|^2}{2\sigma_N^2}\right]\right\}\right\}\right\} - B\right] - \lambda \underbrace{\frac{\partial J_i}{\partial P_i}}_{K_i}, \tag{9}$$

where K_i is given by [10]

$$K_i = \frac{\partial J_i}{\partial P_i} = T_s \int_{d_n - \frac{B}{2}}^{d_i + \frac{B}{2}} \left(\frac{\sin \pi f T_s}{\pi f T_s}\right)^2 d_f. \tag{10}$$

Setting Eq. (10) to zero and after some mathematical manipulations, optimal transmit power in i^{th} subcarrier can be written as

$$P_i^{\star} = \frac{y}{H_i s_i} + \frac{\lambda K_i \sigma_N^2}{H_i^2 s_i^2}. \tag{11}$$

Now the value of λ can be calculated by differentiating Eq. (8) with respect to λ

$$\frac{\partial L}{\partial \lambda} = \frac{\partial}{\partial \lambda} \left[-E\left\{E\left\{\sum_{i=1}^{N} \log_2\left\{X \sum_{s\in\mathcal{S}} exp\left[-\frac{\|y - H_i P_i s_i\|^2}{2\sigma_N^2}\right]\right\}\right\}\right\} - B\right] - \frac{\partial \lambda}{\partial \lambda}(\sum_{i=1}^{N} J_i(d_i, P_i) - \tau_{th}). \tag{12}$$

Setting Eq. (12) to zero, we can derive λ as

$$\lambda = \frac{\tau_{th}}{\sigma_N^2 \sum_{i=1}^{N} \frac{K_i^2}{H_i^2 s_i^2}} - \frac{y}{\sigma_N^2 \sum_{i=1}^{N} \frac{K_i}{H_i s_i}}. \tag{13}$$

Hence an optimal power can be calculated under the FSA constraint that maximizes the SU achievable data rate while keeping the interference introduced to the PU below the specific threshold.

V. OPTIMAL POWER ALLOCATION UNDER THE ZMCSCG CONSTRAINT

The objective is to maximize the sum capacity by keeping the interference introduced to the PU band below a tolerable range [11].

$$C = \max_{P_i} \left\{\sum_{i=1}^{N} \log_2\left(1 + \frac{P_i |H_i|^2}{\sigma_N^2}\right)\right\}. \tag{14}$$

The unit for Eq. (14) is rate in bits per channel use, In Eq. (14) expectation is taken over the variables P_i & H_i . In an adaptive structure, to achieve maximum capacity, power of the transmitted symbol on each subcarrier is optimally allocated. Therefore, we can formulate the following constraint optimization problem.

$$C = \max_{P_i} \left\{\sum_{i=1}^{N} \log_2\left(1 + \frac{P_i |H_i|^2}{\sigma_N^2}\right)\right\}. \tag{15}$$

subject to

$$\sum_{i=1}^{N} J_i(d_i, P_i) \leq \tau_{th} \tag{16}$$

$$P_i \geq 0 \qquad \forall_i = 1, 2, ...N \tag{17}$$

where C denotes the SU transmission capacity, N denotes the total number of available subcarriers and τ_{th} denotes the interference threshold prescribed by the PU. The optimization parameter of Eq. (15) is P_i. Using Lagrange formulation we can write

$$L(P_i, \lambda) = \left\{\sum_{i=1}^{N} \log_2\left(1 + \frac{P_i |H_i|^2}{\sigma_N^2}\right)\right\} - \lambda\left(\sum_{i=1}^{N} J_i(d_i, P_i) - \tau_{th}\right), \tag{18}$$

where λ is the Lagrange constraint. Differentiating Eq. (18) with respect to P_i yields

$$\frac{\partial L}{\partial P_i} = \frac{\partial}{\partial P_i}\left\{\sum_{i=1}^{N} \log_2\left(1 + \frac{P_i |H_i|^2}{\sigma_N^2}\right)\right\} - \lambda \underbrace{\frac{\partial J_i}{\partial P_i}}_{K_i}, \tag{19}$$

where K_i is given by [10]

$$K_i = \frac{\partial J_i}{\partial P_i} = T_s \int_{d_n - \frac{B}{2}}^{d_i + \frac{B}{2}} \left(\frac{\sin \pi f T_s}{\pi f T_s}\right)^2 d_f. \tag{20}$$

Setting Eq. (19) to zero and after some mathematical manipulations, optimal transmit power in i^{th} subcarrier can be written as

$$P_i^{\star} = \frac{1}{\lambda K_i} - \frac{\sigma_N^2}{|H_i|^2}. \tag{21}$$

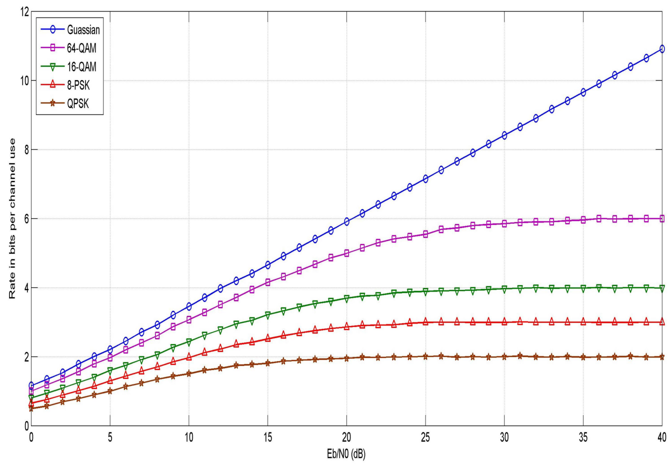

Fig. 3. Mutual information curves under FSA compared to channel capacity under ZMCSCG for 32 subcarriers at 1mW

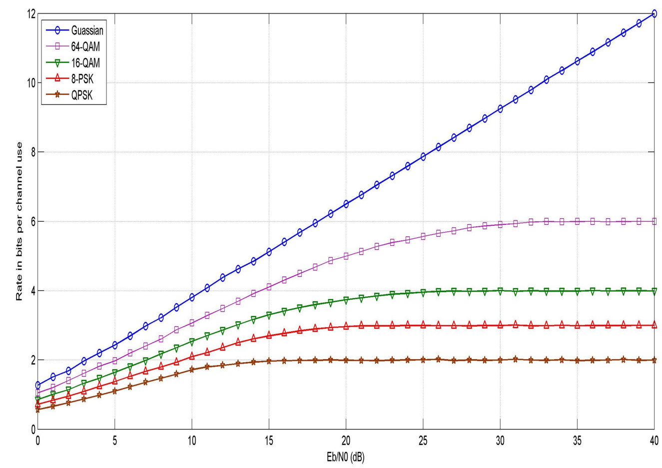

Fig. 4. Mutual information curves under FSA compared to channel capacity under ZMCSCG for 32 subcarriers at 10mW

Now the value of λ can be calculated by differentiating Eq. (18) with respect to λ

$$\frac{\partial L}{\partial \lambda} = \frac{\partial}{\partial \lambda} \left\{ \sum_{i=1}^{N} \log_2 \left(1 + \frac{P_i |H_i|^2}{\sigma_N^2} \right) \right\} - \frac{\partial \lambda}{\partial \lambda} \left(\sum_{i=1}^{N} J_i(d_i, P_i) - \tau_{th} \right). \tag{22}$$

Setting Eq. (22) to zero, we can derive λ as

$$\lambda = \frac{N}{\tau_{th} + \sum_{i=1}^{N} \frac{K_i \sigma_N^2}{|H_i|^2}} \tag{23}$$

Hence an optimal power can be calculated under the ZMCSCG constraint to maximize the SU capacity while keeping the interference introduced to the PU below the specific threshold.

VI. EVALUATION OF OFDM BASED CR SYSTEM

In this section, we compute optimal power for ZMCSCG and FSA constraints in CR networks and accordingly calculate and compare capacity and MI in both cases. The simulations are performed for a SISO-OFDM based CR network in an opportunistic scheme as given in Fig. 2. It is assumed that the SU base station has the information about PU active subcarriers and accordingly disables them. Consider that there are 64 subcarriers of which 32 subcarriers are used by the PU and the remaining are used by the SU in frequency localized transmission. The values of T_s, B & τ_{th} are $4\mu s$, $1MHz$ and $1mW$, respectively. We further assume the IEEE 802.11 multipath channel model with RMS delay spread of 50ns. The results are averaged over 1000 MATLAB simulations.

In Fig. 3, we plot achievable data rate indicated by MI (bits per channel use) and channel capacity for an un-coded CR system versus $\frac{E_b}{N_0}$. From this figure we observe that the achievable data rate indicated by MI (Eq. 1) closely follow the channel capacity (Eq. 14) under low SNR region, oppositely MI saturates in the high SNR region. The reason for this saturation is that in the high SNR region, the achievable data rate is limited by the signal constellation. Thus after saturation, the data rate remains constant no matter how high the SNR value is. It is clearly evident from the Fig. 3 that the saturation value for QPSK, 8-PSK, 16-QAM & 64-QAM are 20dB, 25dB, 30dB & 35dB and the maximum achievable data rate is 2, 3, 4 & 6 bits per channel use respectively. In contrast to that, channel capacity increases with increasing SNR value.

TABLE I
SATURATION VALUE AND ACHIEVABLE DATA RATE OF SU UNDER THE FSA CONSTRAINT

Finite Symbol Alpha-bets	$\tau_{th} = 1mW$ & N=32		$\tau_{th} = 10mW$ & N=32	
	Saturation Value (dB)	Achievable data rate for FSA input (bits PCU)	Saturation Value (dB)	Achievable data rate for FSA input (bits PCU)
QPSK	20	2	15	2
8-PSK	25	3	20	3
16-QAM	30	4	24	4
64-QAM	35	6	32	6

Fig. 3 clearly indicates that the channel capacity as derived in Section V is unrealistic for the practical systems. On the other hand analysis of MI calculated in Section IV provides a realistic prediction of achievable data rate in real systems as shown in Table 1.

In the opportunistic scheme, the achievable data rate of the SU is dependent on the available bandwidth and interference threshold level of the PU. In Fig. 4, we vary interference threshold from 1mW to 10mW for 32 available subcarriers. The capacity changes from 11 to 12 bits per channel use, however, MI remains unchanged except that it achieves a saturation value earlier for the 1mW case, i.e., 15dB instead of 20dB for QPSK as shown in Table 1. So we can conclude that, varying the interference threshold value only affects the saturation value but the maximum achievable data rate remains the same for FSA constraint. Table 1 presents the overall summary of obtained results.

VII. Conclusion

In this paper, we have evaluated an optimal power loading schemes under both FSA and ZMCSCG constraints for SISO-OFDM based CR networks. Results have revealed that the derived power loading scheme under ZMCSCG constraint maximizes the capacity by keeping the interference introduced to the PU band within a given limit. The capacity increases with increasing SNR and cannot be achieved in practical systems. On the contrary, the proposed power loading scheme under the FSA constraint results in a saturated MI at high SNR value and provides a realistic prediction of achievable data rate in real systems, e.g., saturation values for QPSK, 8-PSK, 16-QAM & 64-QAM are 20dB, 25dB, 30dB & 35dB and maximum achievable data rate is 2, 3, 4 & 6 bits per channel use respectively. We have further investigated channel capacity and MI by varying the interference threshold i.e., from 1mW to 10mW and observed that the saturation value of MI changes accordingly e.g., 15dB instead of 20dB for QPSK but total achievable data rate remains the same. On the other hand, the capacity increases with increasing interference threshold i.e., 11 to 12 bits per channel use. In future work we will evaluate optimal power allocation algorithm under the FSA constraint in MIMO-OFDM based CR system.

Acknowledgment

This work has been supported by the India UK Advance Technology Center of Excellence in Next Generation Networks, Systems and Services (www.iu-atc.com).

References

[1] http://www.roke.co.uk/resources/datasheets/UK-Frequency-Allocations.pdf. Accessed April 2012.

[2] http://www.ntia.doc.gov/osmhome/allochrt.pdf. Accessed April 2012.

[3] A. Shukla. "cognitive radio technology-a study for ofcom,". *Tech.Rep. 830000143, QinetiQ Ltd, Hampshire, UK*, 2006.

[4] Federal communications commission: Spectrum policy task force report. http://fjallfoss.fcc.gov. November 2002.

[5] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity. part I. system description. *IEEE Transactions on Communications*, 51(11):1927 – 1938, nov. 2003.

[6] J. I. Mitola and G.Q. J. Maguire. Cognitive radio: making software radios more personal. *IEEE Personal Communications*, 6(4):13 –18, aug 1999.

[7] F. c. commission, "notice of proposed rule making and order: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies,". ET Docket Feb2005.

[8] S. Srinivasa and S.A. Jafar. "COGNITIVE RADIOS FOR DYNAMIC SPECTRUM ACCESS - the throughput potential of cognitive radio: A theoretical perspective". *IEEE Communications Magazine*, 45(5):73 – 79, may 2007.

[9] H. Mahmoud, T. Yucek, and H. Arslan. OFDM for cognitive radio: merits and challenges. *IEEE Wireless Communications*, 16(2):6 –15, april 2009.

[10] G. Bansal, M.J. Hossain, and V.K. Bhargava. Adaptive power loading for OFDM-based cognitive radio systems. In *In Proc. of IEEE International Conference on Communications (ICC 07)*, pages 5137 –5142, june 2007.

[11] G. Bansal, M.J. Hossain, and V.K. Bhargava. Optimal and suboptimal power allocation schemes for OFDM-based cognitive radio systems. *IEEE Transactions on Wireless Communications*, 7(11):4710 –4718, november 2008.

[12] Z. Hasan, E. Hossain, C. Despins, and V.K. Bhargava. Power allocation for cognitive radios based on primary user activity in an OFDM system. In *IEEE Global Telecommunications Conference, 2008.*, pages 1 –6, 30 2008-dec. 4 2008.

[13] Z. Hasan, G. Bansal, E. Hossain, and V. Bhargava. Energy-efficient power allocation in OFDM-based cognitive radio systems: A risk-return model. *IEEE Transactions on Wireless Communications*, 8(12):6078 –6088, december 2009.

[14] G. Bansal, Z. Hasan, M.J. Hossain, and V.K. Bhargava. Subcarrier and power adaptation for multiuser ofdm-based cognitive radio systems. In *In Proc. of National Conference on Communications (NCC 2010),*, pages 1 –5, jan. 2010.

[15] Chen Chiuan-Hsu and Wang Chin-Liang. Power allocation for ofdm-based cognitive radio systems under primary user activity. In *IEEE 71st Vehicular Technology Conference (VTC 2010-Spring)*, pages 1 –5, may 2010.

[16] Tao Qin and C. Cyril Leung. Fair adaptive resource allocation for multiuser ofdm cognitive radio systems. In *Second International Conference on Communications and Networking in China, 2007. CHINACOM '07.*, pages 115 –119, aug. 2007.

[17] M. Wrulich. *"Capacity Analysis of MIMO Systems",Vienna University of Technology*. PhD thesis, Jan. 2006.