

A Novel BER-feedback Power Control Algorithm for Personal Area Network Devices

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Abstract— Personal Area Network (PAN) Devices are often components of communication systems which opportunistically access the wireless spectrum. As such, they must operate without presenting interference to licensed users, while meeting their individual, varied Quality of Service (QoS) requirements. In this paper we use a novel Transmit Power Control (TPC) algorithm to reduce interference. In theory, over the life of a Secondary User's (SU's) transmission, there is an optimal power time curve reflective of the minimum amount of power necessary with which a device can transmit while maintaining acceptable BER, and practicing Interference Avoidance (IA). Using the response of the algorithm to instantaneous channel conditions as well as an iteratively updated QoS benchmark, we obtain a quadratic approximation of the desired power-time curve. Stability of the quadratic approximation is demonstrated through Matlab simulations using critical valued inputs to the approximator. From our results, we also show that our quadratic approximator outperforms others of different orders in terms of reduction in sensitivities to relatively small changes in inputs, and better tracking performance in following reference desired power curves used in the simulations. Our algorithm reduces transmit power (and thus interference) by approximately 3.5 dB compared to conventional methods while maintaining the required QoS.

Keywords— *Cognitive Radio; Power Control; Interference Avoidance; MB-OFDM UWB*

I. INTRODUCTION

Wireless Personal Area Network Devices (PADs) include printers, routers, wireless phones, MP3 players, computers, DVD and cable set top boxes, televisions and many other personal communication devices [1]. PADs differ however, from traditional ad hoc networks devices, in that PADs have different antenna power and sensitivities, processing power, memory, and BER and BR requirements. Because most wireless spectrum is licensed, PADs must operate opportunistically, and Interference Avoidance (IA) to licensed users is of paramount importance. Cognitive Radio (CR) technology allows devices to sense the spectrum, and adaptively bit load and allocate transmit power [2–4]. We stipulate that our PADs devices use CR technology and we use the WiMedia Alliance physical layer system, namely the

Multiband Orthogonal Frequency Division Multiplexing Ultra-wideband (MB-OFDM UWB) system [5].

In OFDM-based CR, underlay refers to transmission in the presence of PU transmission (interference to SU), whereas overlay is transmission in the absence of PU transmission [6]. Symbols transmitted using underlay have to overcome interference plus Additive White Gaussian Noise (AWGN), whereas overlay has to contend with only AWGN. It has been shown in [7] that CR and UWB technologies are two extreme cases of more general approach of Soft Decision Cognitive Radio (SDCR) where both underused (underlay) and unused (overlay) spectral regions are exploited for more efficient communication [8]. This paper accepts SDCR approach for applying proposed power adaptation technique.

In the literature different coexistence approaches between Secondary (SUs) and Primary (PUs) have been explored [9–11]. In [11] the authors consider dynamic spectrum access for SUs, when there are constraints on secondary user interference and QoS. Power control algorithms are essential for enabling dynamic Cognitive Radio (CR) operations. The Distributed Power Controller (DPC) is based on the well known Proportional Integral Derivative (PID) controller concept that has been shown to produce a stable system and is used to adaptively tune PID gains [9]. The controller input is the difference between actual received SNR and target SNR determined by Quality of Service (QoS) requirements. According to the authors of [4], one problem with the SNR based methods is that they are constrained by limits on SNR detectability. Our system eliminates this problem because we measure BER instead of estimating SNR.

The overall aim of the paper can be described as follows. In theory, over the life of a SUs transmission, there is an optimal power time curve reflective of the minimum amount of power necessary with which the device can transmit while maintaining acceptable BER, and practicing IA. Because of spatially-variable, time-variant channel conditions, and non-uniformity of the receiver sensitivity and transmit power of devices, modeling this curve is not trivial. Adding complexity, maximum acceptable BER varies by device. Therefore, in this paper we introduce a control algorithm that seeks to approximate this curve using BER as feedback.

The layout of this paper is as follows. In Section II we describe the system model and make the problem statement. In Section III we describe, analyze, and impose constraints upon

the power control mechanism. Finally, in Section IV we submit results, and close with conclusions.

II. SYSTEM MODEL AND PROBLEM STATEMENT

The system model is depicted in Figure 1, which includes several communication systems engaged in opportunistic, wireless, asymmetric bi-directional communication. In most cases one of the SUs (robots, wireless speaker) primarily transmits (SU_T), while the other primarily receives (SU_R). The figure depicts the systems as inter-operational. We propose that they share the spectrum of a MB-OFDM UWB band [5] and that the devices are CRs. Generalization of the illustration to include licensed Primary Users (PU e.g. mobile phone, TV) is straightforward. The system also follows environment specific restrictions imposed by FCC concerning emitted Power Spectral Density (PSD) [12]. For example, for indoors a PSD of -41.3dBm/Mhz is allowed between $3.1 - 10.6\text{ Ghz}$. Therefore, we use S_{\max} to represent the total power allowed in a band.

We use the term Channel Users (CUs) to describe the presence of both primary and secondary user transmissions in the channel which influence the transmission of the selected secondary user. We represent the PUs' transmission power is represented by P_1, P_2, P_3 . The respective channel gains between the PUs and SU_T in subcarrier j ($j = 1, 2, 3, \dots, 128$) are represented by $h_{i,j}$, where i is the CU index. The problem statement follows.

A. Pre-adjusted Power Vectors $P_o(k), P_u(k)$.

Here we introduce the vectors $P_o(k), P_u(k)$. In addition to S_{\max} we also cater for the possibility of limits on individual subcarriers within the MB-OFDM band. We refer to this limit as P_j^{sc} .

Then, we can define the maximum possible transmit power for SU_T in a subcarrier j as

$$P_j^{SU_T} \triangleq P_j^{sc} - \left(n_o w + \sum_{i=1}^M h_{i,j} P_i \right) \quad (1)$$

where n_o is the AWGN PSD, and w is the bandwidth of a subcarrier, $n_o w + \sum_{i=1}^M h_{i,j} P_i$ is the power sensed in subcarrier j , and M represents the number of CUs.

SU transmit powers in the subcarriers are represented by $P_1^{SU}, P_2^{SU}, P_3^{SU}, \dots, P_{128}^{SU}$.

$$[\bar{P}_o(k), \bar{P}_u(k)] = [P_{o1}^{SU} \dots P_{oN1}^{SU}, P_{u1}^{SU} \dots P_{uN2}^{SU}] \quad (2)$$

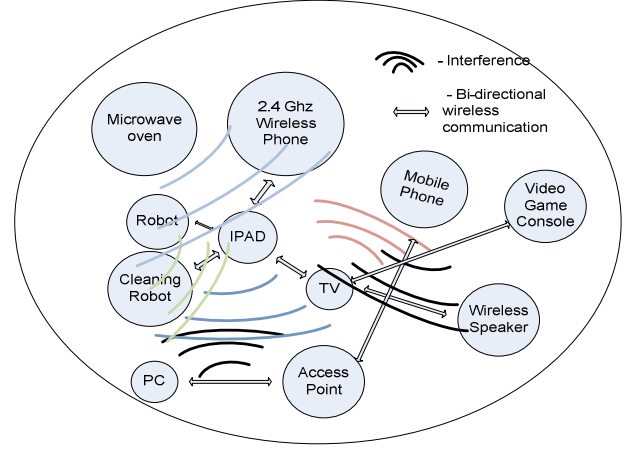


Figure 1. System model

In (2), $oN1$ is the number of overlay subcarriers, and $uN2$ is the number of underlay subcarriers $\bar{P}_o(k)$ is the vector representing the SU unadjusted transmit power in overlay subcarriers, which are subcarriers in which $\sum_{i=1}^M h_{i,j} P_i = 0$. The vector $\bar{P}_u(k)$ represents the SU unadjusted transmit power in the underlay subcarriers for which $\sum_{i=1}^M h_{i,j} P_i > 0$.

B. Control Parameters $\lambda(k), R_e^{F_s}(k), e_o(k)$

In OFDM-based systems, BER feedback can be assessed using fixed subcarriers that are known to both transmitting and receiving devices. We refer to these subcarriers as pilot subcarriers. The parameter $R_e^{F_s}(k)$ is called the *memory-based feedback index* and is a function of BER feedback. At initialization

$$R_e^{F_s}(0) = \lambda(0) = \frac{1}{1000 * R_e^M}, \quad (3)$$

where R_e^M is the maximum acceptable BER (usually manufacturer defined) for a SU. $R_e^{F_s}(k)$ is iteratively updated using

$$R_e^{F_s}(k) = \begin{cases} R_e^{F_s}(k-1) + 1, & \text{if } R_e^F(k) \leq R_e^M \\ R_e^{F_s}(k-1) - 1, & \text{if } R_e^F(k) > R_e^M \end{cases}, \quad (4)$$

where $R_e^F(k)$ is BER feedback, sent from the receiver to the transmitter. $R_e^F(k)$ is the mean of the BER in the MB-OFDM pilot subcarriers. The parameter $\lambda(k)$ is a dynamically adjusted benchmark that is a function of maximum acceptable

BER. It is initialized at $\lambda(0) = 1/(1000 * R_e^M)$ and defined in an iterative manner as

$$\lambda(\tau) = \begin{cases} \lambda(\tau-1) - 1, & \text{if } \lambda^c(k) > \lambda^T \\ \lambda(\tau-1) + 1, & \text{if } \lambda^c(k) < -\lambda^T \end{cases}, \quad (5)$$

where $\lambda^c(k)$ is a counter initialized and λ^T is a integer threshold that, when crossed triggers an adjustment in $\lambda(k)$. $\lambda^c(0) = 0$, and is reset to 0 when either of the cases described in (5) is satisfied. It is updated using

$$\lambda^c(k) = \begin{cases} \lambda^c(k-1) + 1, & \text{if } R_e^F(k) \geq R_e^M \\ \lambda^c(k-1) - 1, & \text{if } R_e^F(k) < R_e^M \end{cases}. \quad (6)$$

In the BER Feedback Power Control (BFPC) algorithm, the control error, $e_o(k)$ is defined by

$$e_o(k) = \lambda(k) - R_e^{F_s}(k) \quad (7)$$

The BFPC is effective using these two functions because $\lambda(k)$ is a dynamically adjustable benchmark that is responsive to slow changing time-varying channel conditions and eventually stabilizes. The other function $R_e^{F_s}(k)$ is also memory-based, but is more responsive to the instantaneous changes in channel conditions (fast fade). The parameter $e_o(k)$ therefore reflects the difference between the memory of the comparisons of BER feedback and maximum acceptable BER, and long term performance. In addition, because the estimates of $R_e^F(k)$ are obtained from pilot subcarriers and the SU CR operates by selecting data-carrying subcarriers with good SINR, the BER for those subcarriers will be at least less than $R_e^F(k)$. The difference between BERs in pilot and data-carrying subcarriers degrades the performance of power control algorithm. The approach described above eliminates that particular problem.

C. Control Functions $\alpha_o(k), \alpha_u(k) = f(R_e^{F_s}(k), \lambda(k), e_o(k), \nu)$

In this subsection we introduce the control parameters for overlay and underlay symbols, $\alpha_o(k), \alpha_u(k)$. First, $\alpha_o(k)$ is obtained using $e_o(k)$ which is tuned by normalizing using the dynamically adjusted benchmark, $\lambda(k)$. However, as mentioned in the introduction, if we think of the theoretically approachable time vs. power curve, then we can cite Taylor's theorem which states that if a function f is differentiable at point a , then it has a linear approximation at that point. To improve the approximation, we use a quadratic tuner and normalize $e_o(k)$ using $\lambda(k)^2$ as in (8).

$$\alpha_o(k) = 1 + \frac{e_o(k)}{\lambda(k)^2} = 1 + \frac{\lambda(k) - R_e^{F_s}(k)}{\lambda(k)^2} = 1 + \frac{1}{\lambda(k)} - \frac{R_e^{F_s}(k)}{\lambda(k)^2} \quad (8)$$

We present justification for the quadratic approximation in Section IV. The underlay control parameter is obtained using

$$\alpha_u(k) = \nu * \alpha_o(k) \quad (9)$$

where ν is used to scale $\alpha_o(k)$. If $R_e^F(k) \geq R_e^M$, underlay power is raised more quickly than overlay ($\alpha_u(k) = \nu * \alpha_o(k)$) to overcome user interference. When $R_e^F(k) < R_e^M$ underlay power is decreased less quickly than overlay ($\alpha_u(k) = \alpha_o(k) / \nu$).

D. Power control, BFPC and Comparative PID Algorithms

Transmit power is therefore adjusted using

$$P_T^{SU} = \bar{P}_o(k)^{\alpha_o(k)} + \bar{P}_u(k)^{\alpha_u(k)}, \quad (10)$$

where P_T^{SU} is the total power in a MB-OFDM band. The aim of the BFPC algorithm is to minimize P_T^{SU} through iterative adjustment of $\lambda(k), R_e^{F_s}(k)$, while satisfying the constraints

$$\begin{aligned} \sum_{i=1}^M \sum_{j=1}^{128} h_{i,j} P_i + P_T^{SU} &\leq S_{\max} \\ R_e^{SU} &\leq R_e^M, \end{aligned} \quad (11)$$

where R_e^{SU} is the SUs mean BER over the life of the transmission.

The BFPC minimization is heuristic. For comparative performance evaluation a conventional PID controller is used as a reference. The power update equation for the PID controller is given by

$$p(k) = \partial e(k) + \beta x(k) + \theta [e(k) - e(k-1)] \quad (12)$$

in which $p(k)$ is the power at time k in a subcarrier, ∂, β and θ are the control parameters.

$$e(k) = \left[1 - \frac{\gamma_{\min}}{\gamma_a(k-1)} \right] p(k-1), \quad (13)$$

is calculated as the $(k-1)$ power, by the normalized difference between the achieved SINR, γ_a , from the k -1 transmission and the device's target SINR, γ_{\min} . Finally,

$$x(k) = x(k-1) + e(k), \quad (14)$$

where $x(k)$ is the accumulated value for $e(k)$.

E. Contribution of power control algorithm(BFPC)

The contribution of the BFPC is that it is specific to the maximum acceptable BER (because of the initial values of $\lambda(k), R_e^{F_s}(k)$) of individual SU CRs. In addition, the desired power-time curve is closely approximated because of the quadratic tuning. Finally, the dynamically adjustable benchmark ensures that the BFPC is acutely responsive to time-varying channel conditions.

III. JUSTIFICATION FOR SECOND ORDER APPROXIMATION IN CALCULATION OF $\alpha(k)$

We further justify using the second order approximation in the calculation of $\alpha_o(k)$ as follows. We introduce $R_{e,\min}^{F_s}$ as the minimum acceptable value for $R_e^{F_s}(k)$. We also introduce $d_{\max, R_e^{F_s}(k), \lambda(k)}$, which we define as the maximum possible deviation (dependent upon the *dpi* value) between $R_e^{F_s}(k)$ and $\lambda(k)$. Let us define a dynamic range for $R_e^{F_s}(k)$ and place further restrictions on $R_e^{F_s}(k), R_{e,\min}^{F_s}$:

$$R_e^{F_s}(k) \in [\lambda(k) - d_{\max, R_e^{F_s}(k), \lambda(k)}, \lambda(k) + d_{\max, R_e^{F_s}(k), \lambda(k)}] \quad (15)$$

$$R_{e,\min}^{F_s} = -d_{\max, R_e^{F_s}(k), \lambda(k)} \quad (16)$$

$$R_e^{F_s}(k) \in (R_{e,\min}^{F_s}, \infty] \quad (17)$$

Because the lower bound for $\lambda(k)$ is 0, we can obtain a lower bound for (15) and (16). Stability of error exponent approximation is ensured provided by the design rules and assumptions (i-iv) which provide bounded inputs and outputs:

- i. Restriction in (15) provides acceptable oscillation magnitude in calculation of $\alpha_o(k)$ due to low sensitivity to $R_e^{F_s}(k)$.
- ii. Assumption: Equation (15) and (16) are always true due to channel diversity and optimal channel switching in OFDM. As BER on one channel decreases, another channel may be switched to depending on BER and other criteria.

- iii. Assumption: Given that $\lambda(k)$ tracks $R_e^{F_s}(k)$ by the dynamic range restrictions in (21), $\alpha_o(k) \cong 1$ as subject to the statement in (i). As $R_e^{F_s}(k)$ is approximately equal to the value of $\lambda(k)$ with maximum deviation $\pm d_{\max, R_e^{F_s}(k), \lambda(k)}$, the value $\alpha_o(k)$ is always approximately equal to 1.
- iv. Communication transceivers actual capabilities are limited by the receiver sensitivity and transmitter power; therefore, maximum and minimum values of $\alpha_o(k), \lambda(k)$ and $R_e^{F_s}(k)$ are already set by physical conditions and limits of the transceiver.

We introduce the *ideal conditions* of the approximator in (18), where the power output is equal to the required power output based on the BER feedback $R_e^F(k)$:

$$\alpha_o(k) = 1 \quad (18)$$

Where, with (15) and (16), criteria to meet the ideal condition is given in (19):

$$\lambda(k) = R_e^{F_s}(k) \neq 0 \quad (19)$$

Let us also define 1st and 3rd order approximations for $\alpha_o(k)$ in (24) and (25) respectively, for use in comparison with the 2nd order approximation:

$$\alpha_o(k)_1 = 1 + \frac{\lambda(k) - R_e^{F_s}(k)}{\lambda(k)} = 2 + \frac{R_e^{F_s}(k)}{\lambda^2(k)} \quad (20)$$

$$\alpha_o(k)_3 = 1 + \frac{\lambda(k) - R_e^{F_s}(k)}{\lambda^3(k)} = 1 + \frac{1}{\lambda^2(k)} - \frac{R_e^{F_s}(k)}{\lambda^3(k)} \quad (21)$$

Furthermore, behavior of the approximator's operation near critical points at poles of $\alpha_o(k)$ function is described by the following:

$$R_e^{F_s}(k) \approx R_{e,\min}^{F_s} :$$

- i. $\Delta\alpha_o(k)$ is large in the 1st order approximator due to $1/\lambda(k)$ term.
- ii. $\Delta\alpha_o(k)$ in second and third order approximators are reduced greatly as compared to 1st order approximator.

$$R_e^{F_s}(k) \gg R_{e,\min}^{F_s} :$$

- iii. $\Delta\alpha_o(k)$ is larger for the 1st order approximator than 2nd and 3rd order approximators, but smaller in scale than that in case (i).
- iv. $\Delta\alpha_o(k)$ is small for 2nd and 3rd order approximators.

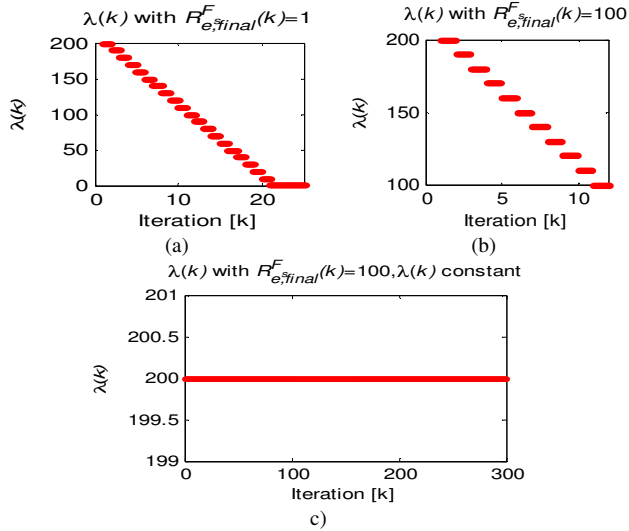


Figure 2. Approximator inputs to test critical points of $\lambda(k)$: (a) tracking $R_e^{F_s}(k)$ as it decrements from a value of 200 to 1, (b) tracking $R_e^{F_s}(k)$ from 200 to 100, (c) not tracking $R_e^{F_s}(k)$ ($\lambda(k)$ is constant).

In Figure 2, $R_{e,final}^{F_s}(k)$ refers to the desired value of $R_e^{F_s}(k)$ that would result in the ideal approximator value. We evaluate the approximator performance with conditions given in (15), (16) and (17) for 1st, 2nd and 3rd order versions of error exponent approximations for $\alpha_o(k)$ (equations (19), (8), and (20), respectively), in Figure 3. In the figure, a goal was set for the approximator to test the ideal criterion (24) under critical values of $\lambda(k)$ in (8). Figure 2a shows $\lambda(k)$ as it tracks $R_e^{F_s}(k)$ towards the critical value of 0 from $\lambda(0)=200$, stopping at a near-critical value of 1. Figure 2b shows when $\lambda(k)$ tracks a constant value of 100 from an initial $R_e^{F_s}(k)$ of 200. Figure 2c shows the case where $\lambda(k)$ remains constant while $R_e^{F_s}(k)$ decreases from 200 to 1.

Figure 3 shows the profile and enhanced detail of $\alpha_o(k)$ for 1st, 2nd and 3rd order approximators for the input in Figure 2.

We present the following conclusions on approximator performance based on the order of approximation. The first order approximator has larger overshoot tracking the “ideal” line with $\alpha_o(k)$ underdamped. The second order approximator has significantly reduced overshoot, $\alpha_o(k)$ is damped, and tracks the “ideal” line well with fast convergence. Third order tracks the “ideal” line with minimal overshoot with $\alpha_o(k)$ overdamped. Given the results stated above we decided that the second order approximation has ideal performance for our system.

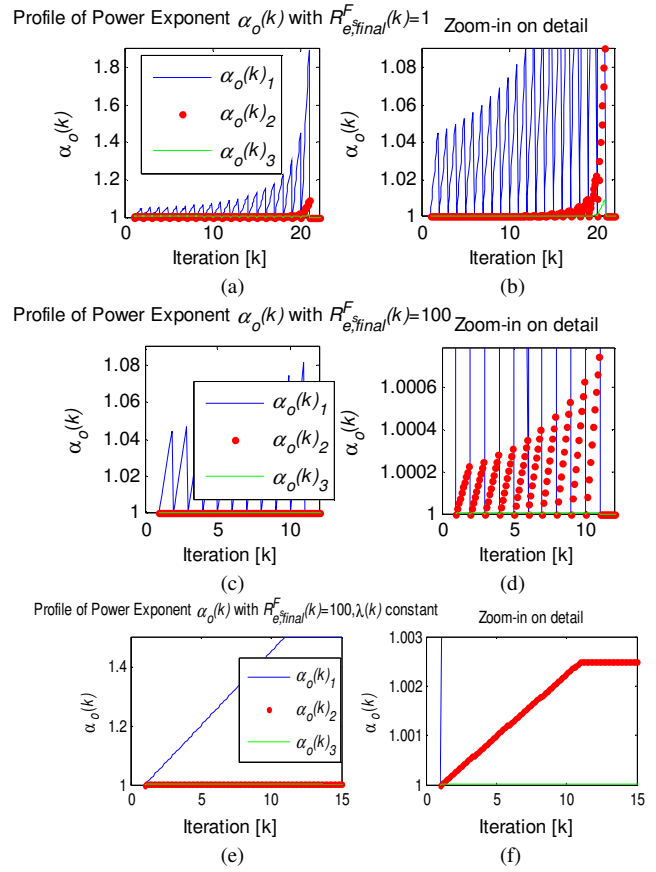


Figure 3. Error exponent $\alpha_o(k)$ performance (a) for $R_{e,final}^{F_s}=1$ for all values of t ; (b) is enhanced detail of (a) for 2nd and 3rd order approximations, (c) is performance for $R_{e,final}^{F_s}=100$ for all values of t ; (d) is enhanced detail of (c) for 2nd order approximator; (e) is performance for $R_{e,final}^{F_s}=200$ for all values of ‘ k ’ with $\lambda(k)$ constant value of 200; (f) is enhanced detail of (e) for the 3rd order approximator.

IV. RESULTS AND SIMULATIONS

The simulation parameters are as follows: modulation QPSK, line-of-sight (LOS) conditions, attenuation and path loss are assumed to be negligible, there are bands 14 with bandwidth of 528 Mhz, the bands are divided into 128 OFDM subcarriers with designated pilot, guard and null subcarriers, data rate 10Mbit/s, transmitted data 10Mb, subcarrier interference (PU) power is generated using a continuous uniform distribution over a range of -0dBm to 30.3dBm, S_{max} 47 dBm to 49 dBm, and BER reference value over the range $10e-3$ to $10e-6$. Typical OFDM transmission is used except the power control method is applied after band and subcarrier selection, and before modulation and bit loading. In all simulations, BER is the BER in the data carrying subcarriers.

Table 1 shows the performance of the DPC and SNR in comparison to the BER Feedback Power Controller (BFPC). The control parameters for the DPC controller, $C(DPC)$, are $\partial=0, \beta=-1, \theta=1$. The controller $C(SNR)$ represents Hoven and Sahai’s [10] SNR-constrained controller. In [10] the authors use detectable Signal to Noise Ratio (SNR) at the

receiver to control CR transmit power. Under the constraint of $S_{\max} = 48dBm$, in terms of BER, the BFPC outperforms the DPC by 12.8 dB, and the SNR controller by 11.7 dB. In terms of transmit power the SNR controller uses 2.6 dB less than the BFPC controller. However, the BFPC outperforms the DPC because it uses 3.5 dB less transmit power. It is evident that under constraints on radiated power for SUs, the BFPC exhibits superior overall performance.

Table 1. Comparison of PID and SNR controllers to the BFPC in terms of BER and transmit PSD (W/Hz)

	<i>C(DPC)</i>	<i>C(SNR)</i>
BER (dB)	+12.8	+11.7
PSD (dB)	+3.5	-2.6

Table 2 shows BER and PSD (W/Hz) (compared in terms of dB and percentages) for the power control algorithm with underlay signal power ($underlay_power=overlay_power*/\div v$) adjusted at different ratios ($v = 1.5, 2, 2.5$) to overlay power.

Table 2. Comparison of change in BER and PSD for underlay power adjusted at 3 difference rates, for SINR over the range [0:20]dB. The rates are compared to when underlay and overlay signal power is adapted at the same rate ($v=1$).

	$v=1.5$	$v=2$	$v=2.5$
BER (dB)	-.01	.18	+0.02
BER (%)	-.45%	-4%	+0.5%
PSD (dB)	+0.005	+0.05	-0.18
PSD (%)	+0.12	+1.21	-4.1

The increase or decrease in BER and PSD are compared to when $v=1$. For an instantaneous value of $\lambda(k)$, we know that $\hat{\epsilon}_o(k)$ determines the size of the increments of power adjustment for overlay signals. The parameter $\alpha_u(k)$ is calculated using $\hat{\epsilon}_u(k)$, while $\alpha_o(k)$ is calculated using $\hat{\epsilon}_o(k)$ and v (see Section III). If $R_e^f(k) > R_e^M$ underlay power is raised more quickly than overlay ($\hat{\epsilon}_u(k) = \hat{\epsilon}_u(k) * v$) to overcome user interference. When $R_e^f(k) \leq R_e^M$ underlay power is decreased less quickly than overlay ($\hat{\epsilon}_u(k) = \hat{\epsilon}_u(k) / v$). In the best scenario, when $v = 2$, the BER for $0 \leq SINR(dB) \leq 20$ is 4% lower than $v=1$. PSD is increased by 1.21% however. The $v = 2.5$ returns the best savings in PSD at 4.1% but with a 0.5% increase in BER. It is clear that the value of v is important, and can be used to obtain temporary improvement in BER and PSD and needed.

V. CONCLUSION

In this paper we proposed a power control algorithm which is suitable for secondary user cognitive radios using the MB-OFDM UWB system at the physical layer. The proposed

system allows secondary users to approximate the minimum transmit power needed while maintaining (QoS), observing IA to primary users, and observing spectral power emission limits. We established constraints upon the control, and showed that under restrictions on radiated power, power savings of approximately 3.5 dB can be realized by SUs in comparison to the standard PID controller. It is also a useful contribution because it is effected using two integer indexes. Therefore, it is not as memory intensive as comparative power control methods that require extensive data from previous transmissions. We also demonstrated that underlay signal power can be adjusted at a different ratio to overlay signal power to either conserve power or lower BER (as the situation demands), adding another known use to the litany of adaptabilities of the CR.

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