ADAPTIVE MODULATION AND POWER CONTROL FOR THROUGHPUT ENHANCEMENT IN COGNITIVE RADIOS[1]

Cheng Shilun Yang Zhen Zhang Hui*

(*Institute of Signal Processing and Transmission, Nanjing University of Posts and Telecommunications, Nanjing 210003, China*)

*(*Image and Image Communication Lab of Jiangsu Province, Nanjing 210003, China*)

Abstract To regulate the transmit-power and enhance the total throughput, a novel Transmit Power Control Game (TPCG) algorithm and an adaptive Modulation TPCG (M-TPCG) algorithm which combine bandwidth allocation, adaptive modulation and transmit-power control based on Space Time Block Coding (STBC) OFDM-CDMA system are designed and a cross-layer framework of database sharing is proposed. Simulation results show that the TPCG algorithm can regulate their transmitter powers and enhance the total throughput effectively, M-TPCG algorithm can achieve maximal system throughput. The performance of the cognitive radio system is improved obviously.

Key words Cognitive radio; Adaptive modulation; Cross-layer; Power control

CLC index TN929.5

DOI 10.1007/s11767-007-0013-4

I. Introduction

According to the frequency allocations of regulatory bodies around the world, few frequency resources are currently available for future wireless applications. In 2006, the IEEE 802.22 working group publicized a PHYsical layer (PHY) and Medium Access Control (MAC) proposal based on cognitive radio for IEEE 802.22 WRAN (Wireless Regional Area Network). Since cognitive radio systems using these spectra which are unlicensed and licensed but not being utilized, these radios would be designed to dynamically adapt their transmissions to their environment with two objectives, *i.e.*, highly reliable communication and efficient utilization of radio spectrum[1,2].

In wireless networks, a wireless channel is inherently a shared medium, where channel quality can vary dramatically in time and frequency, the efficient use of energy in mobile devices is of paramount concern. Efficient resource sharing mechanisms in this setting depend strongly on the selection of both PHY power control and modulation schemes. For cognitive radio environment, power control among unlicensed users is important to protect the licensed users and enhance the system performance. In Ref.[3], the Nash game algorithm obtained lower individual power, whereas the total throughput was not optimized at all. In Refs.[4–6], the power control algorithms were based on high Signal to Interference Ratio (SIR) constraint. In order to solve the problem of the above algorithms, we first design a novel Transmit Power Control Game (TPCG) algorithm based on Space Time Block Coding (STBC) OFDM-CDMA communication system, and an adaptive function of throughput per unit with the total interference to control the users' selfish in maximizing its utility. Secondly, we developed a novel adaptive Modulation and TPCG (M-TPCG) algorithm which combines bandwidth allocation, adaptive modulation and transmit-power control to maximize the spectral efficiency and the total throughput under the bandwidth constraint.

In the next section, we describe and analyze the system model. In Section III, the TPCG algorithm and M-TPCG algorithm is formulated. In Section IV, simulations are developed. In Section V, con-

[1] Manuscript received date: January 19, 2007; revised date: April 28, 2007.

Supported by National Natural Science Foundation of China (No.60772062), the Key Projects for Science and Technology of MOE (No.206055) and the Key Basic Research Projects for the Natural Science of Jiangsu Colleges (No.06KJA51001).

Communication author: Cheng Shilun, born in 1974, male, Ph.D. candidate. Institute of Signal Processing and Transmission, Nanjing University of Posts and Telecommunications, Nanjing 210003, China.

Email: ChengSL@njupt.edu.cn.

clusions are drawn.

II. System Model

The sensing ability of context aware is comprised of the power-based sensing, waveform-based sensing, spectral sensing, network sensing, user needs sensing and so on, so it is easy to design the shared database and get the information among the different layers through the technique of context aware. In this paper, we proposed a cross-layer framework to achieve information interaction based on a shared database in Fig.1.

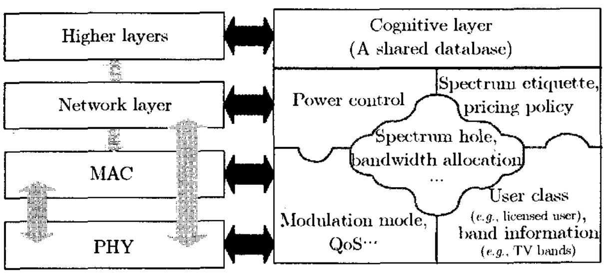


Fig.1 Cross-layer framework of cognitive database sharing

According to the bandwidth allocation of 802.22 users and cognitive communication needs, the STBC OFDM-CDMA system which combines the advantages of MIMO, CDMA and OFDM techniques can achieve highly reliable communication, allocate users' bandwidth easily and enhance the spectral efficiency. In frequency domain, we have designed an STBC OFDM-CDMA system to protect the licensed user and the secondary user's communications not to be intermitted. The uplink of an STBC MC-CDMA system is comprised of two transmitting antennas and one receiving antenna with M users, when the licensed users occupy $(N-K)$ sub-carriers, we assume that the licensed users use carriers from $(K+1)$ to N. The output SIR for the k-th user can be expressed as[7]

$$\gamma_k(p_k) = \omega_k \frac{\left|\sum_{n=1}^{K} r_{k,1}\right|^2 p_k}{\sum_{i\neq k,i=1}^{M}\left|\sum_{n=1}^{K} I_{m,1}\right|^2 p_i + K\delta^2\sum_{n=1}^{N} B} \tag{1}$$

where p_k is the k-th user's transmitted power, B is the bandwidth of each subcarrier, and $\omega_k = \sum_{n=1}^{K} Bd_{k,n}$ is the k-th user's spectrum bandwidth. To be consistent with the general power control problem for wireless communication systems, we express the above equation as

$$\gamma_k(p_k) = \frac{h_{kk}p_k}{\frac{1}{\omega_k}\sum_{i\neq k,i=1}^{M} h_{ki}p_i + v_k} \tag{2}$$

where h_{ki} is the defined link gain between the transmitter of user i and the receiver of user k. v_k is the noise power at the receiver of user k. Let C_k denote the user throughput of user k, which is defined as the number of bits that can be successfully sent to this user within each transmitted symbol. We get[6]

$$C_k(\omega_k, \gamma_k(p_k)) = \omega_k \log_2(1 + \ell\gamma_k(p_k)) \tag{3}$$

where $\ell = 1.5/[-\ln(5\mathrm{BER})]$ which is defined by the modulation level and the BER.

III. Joint Bandwidth Allocation, Adaptive Modulation and Power Control

Let $p_k^{\max}$ and ϖ represent the maximum transmission power and bandwidth, for the optimum power $\hat{p}$ and bandwidth $\hat{\omega}$, the k-th user's maximal throughput $U(M,\omega_k,\gamma_k(p_k))$ can be expressed as

$$\left.\begin{aligned} U(M,\omega_k,\gamma_k(p_k)) &= \arg\max_{\hat{\omega},M,\hat{p}} C_k(M,\omega_k,\gamma_k(p_k)) \\ \text{s.t.} &\begin{cases} 0 \le p_k \le p_k^{\max} \\ 0 \le \omega_k \le \varpi \end{cases} \end{aligned}\right\} \tag{4}$$

Substitute Eq.(2) into Eq.(3) yields

$$C_k(\omega_k, \gamma_k) = \omega_k \log_2\left(1 + \omega_k \frac{\ell h_{kk} p_k}{\sum_{i\neq k,i=1}^{M} h_{ki}p_i + \omega_k v_k}\right) \tag{5}$$

Since $y = x\log(1+ax)$, $0 \le x \le X$ and $a > 0$ ($\mathrm{BER} \ll 1$) is the monotonically increasing function of x, the maximal y can only be achieved if $x = X$. In other words, when the k-th user's bandwidth is ϖ, the performance of system is optimal.

1. Adaptive modulation technique

Consider the performance of BPSK, QPSK, M-QAM modulations in AWGN channel, the BER of M-QAM modulation is shown to be well approximated by[6,8]

BPSK: $$\mathrm{BER}=\frac{1}{\sqrt{2\pi}}\int_{\sqrt{2\gamma}}^{\infty}e^{-x^2/2}dx=Q\left(\sqrt{2\gamma}\right) \quad (6)$$

QPSK: $$\mathrm{BER}\approx\frac{2}{\sqrt{2\pi}}\int_{\sqrt{2\gamma}}^{\infty}e^{-x^2/2}dx=2Q\left(\sqrt{2\gamma}\right) \quad (7)$$

M-QAM: $$\mathrm{BER}\approx 0.2\exp^{(-1.5\gamma/(M-1))},\quad M=2^j, j=1,2,\cdots,J \quad (8)$$

where γ is the SIR. As QPSK and 4-QAM are good approximations for the same γ, rearranging Eq.(8), we get[6]

$$M(\gamma)=1+\frac{1.5}{-\ln(5\mathrm{BER})}\gamma=1+\ell\gamma \quad (9)$$

It is also a good approximation for a Rayleigh fading channel[6]. The BER at the output of the detector of a user should satisfy BER $\le\varepsilon$, which is a prespecified value.

2. Transmit Power Control Game (TPCG)

In Ref.[4–6], the authors assumed that the SIR>>1 in high SIR scenarios and transformed Shannon capacity $C_k(\omega_k,\gamma_k)$ into a convex optimization problem. In this paper we solve the problem based on the game theory without the high SIR constraint and consider the following utility function

$$J_k\left(p_k,\gamma_k\left(p_k\right)\right)=\alpha_k\varpi\log_2\left(1+\ell\gamma_k\left(p_k\right)\right)-\beta_k p_k \quad (10)$$

where a_k is the constant nonnegative weighting factor. J_k is connected with the k-th user throughput and efficient power control.

$$\beta_k=\sum_{j\ne k,j=s}^{M}\left(\frac{\omega_j h_{kj}}{\sum\limits_{l\ne j,k}^{M}h_{js}p_s+\omega_j\upsilon_j}\right)$$

is the k-th user's adaptive function of throughput per unit with the total interference.

Now we describe the algorithm for power updates, let $G=[M,\{P\},\{J_k(\cdot)\}]$ denote the TPCG where $M=\{1,2,\cdots,M\}$ is the index set for the users currently in the cognitive radio system. $p=[p_1\ p_2\ \cdots\ p_M]^{\mathrm{T}}$ is the strategy set, and $J_k(\cdot)$ is the utility function of user k. The corresponding Nash equilibrium strategies are those power vectors $\hat{\boldsymbol{p}}$ having the property that no individual user can increase its utility. Formally, the TPCG is expressed as

$$J_k\left(\hat{p}_k,\gamma_k\left(\hat{\boldsymbol{p}}\right)\right)\ge J_k\left(p_k,\gamma_k\left(p_k,\hat{\boldsymbol{p}}_{-k}\right)\right),\quad \forall p_k,\forall k=1,2,\cdots,M \quad (11)$$

Applying the necessary condition for Nash equilibrium, taking the first-order derivation of utility in Eq.(10) with respect to p_k, and let $I_{k(p_{-k})}=(1/\varpi)\sum_{i\ne k,i=1}^{M}h_{ki}p_i+\upsilon_k$, we obtain

$$\frac{\partial J_k}{\partial p_k}=\alpha_k\varpi\frac{\ell}{\left(1+\ell\gamma_k\left(p_k\right)\right)\ln 2}\frac{h_{kk}}{I_k}-\beta_k=0 \quad (12)$$

Substituting Eq.(2) into Eq.(12) and isolating p_k, we can express the required power in terms of the given and measured quantities as

$$p_k=\frac{\alpha_k\varpi}{\beta_k\ln 2}-\frac{1}{\varpi\ell h_{kk}}\sum_{i\ne k,i=1}^{M}h_{ki}p_i-\frac{\upsilon_k}{\ell h_{kk}} \quad (13)$$

Using above equation, we can apply the modified Newton algorithm. The corresponding numerical iteration function is given by

$$p_k^{(n+1)}=\frac{\alpha_k^{(n)}\varpi}{\beta_k^{(n)}}-\frac{1}{\varpi\ell h_{kk}}\sum_{i\ne k,i=1}^{M}h_{ki}p_i^{(n)}-\frac{\upsilon_k}{\ell h_{kk}}=\Re_k\left(p_k^{(n)}\right) \quad (14)$$

3. Adaptive Modulation and TPCG (M-TPCG) algorithm

(1) Initialization For each user k, $\mathrm{BER}_k^{(\mathrm{int})}=\varepsilon$, $\beta_k^{(0)}\ge 0$, and $p_k^{(0)}=\delta$;

(2) TPCG algorithm power update User k updates its power according to Eq.(14), and get $\hat{p}_k$ and $\hat{\gamma}_k$;

(3) Let $\ell^{(\mathrm{int})}=1.5/[-\ln(5\varepsilon)]$, according to Eq.(9), choose the modulation mode. From Eq.(8) get the actual BER and have $\ell^{(\mathrm{end})}=1.5/[-\ln(5\mathrm{BER})]$;

(4) For given values of $\hat{\gamma}_k$ and $\ell^{(\mathrm{end})}$, get $C_k(\omega_k,\gamma_k(p_k))$ and $T(\omega,\gamma(\hat{p}))$ according to

$$C_k(\omega_k,\gamma_k(p_k))=\omega_k\log_2(1+\ell^{(\mathrm{end})}\gamma_k(p_k)),$$
$$T(\omega,\gamma(\hat{p}))=\sum\nolimits_{k=1}^{M}\omega_k\log_2(1+\ell^{(\mathrm{end})}\gamma_k(p_k))$$

4. NASH equilibrium and its existence for TPCG

Using the implicit function theorem, we establish the existence of a solution for the Nash algorithm equations, the considered system of algebraic equations in Eq.(13) is given by

$$F_k\left(p_k, p_{-k}, \alpha_k, \beta_k, \hbar_{kk}, \hbar_{ki}, v_k\right) = -p_k + \frac{\alpha_k \varpi}{\beta_k} - \frac{1}{\varpi \ell h_{kk}} \sum_{i \neq k, i=1}^{M} h_{ki} p_i - \frac{v_k}{\ell h_{kk}} = 0 \tag{15}$$

Since the Jacobian matrix in Eq.(15) has −1 on the main diagonal and ϖ is very large, the nonzero results of Eq.(15) must existence, and the solution of TPCG algorithm exists. In Yates' framework[9], the power vector is adjusted by an iterative function $p_k^{(n+1)} = \Re(p_k^{(n)})$, an iterative function $\Re(p_k)$ is called standard if it satisfies the following two conditions. Monotonicity: If, $p_k^{'} \geq p_k$ then $\Re(p_k^{'}) - \Re(p_k) \geq 0$; and Scalability: For all $\alpha > 1$, $\alpha\Re(p_k) > \Re(\alpha p_k)$.

$$\Re_k\left(p_k^{'}\right) - \Re_k\left(p_k\right) == \alpha_k \varpi \left[\frac{\beta_k\left(p_s\right) - \beta_k\left(p_s^{'}\right)}{\beta_k\left(p_s\right)\beta_k\left(p_s^{'}\right)}\right] + \frac{1}{\varpi \ell h_{kk}}\left[\sum_{i \neq k, i=1}^{M} h_{ki} p_i - \sum_{i \neq k, i=1}^{M} h_{ki} p_i^{'}\right] \tag{16}$$

Since $\beta_k(p_s) > \beta_k(p_s^{'}), \hat{p} \leq \hat{p}^{\max}$, $\alpha_k \varpi^2 \gg 1$, we have $\Re_k\left(p_k^{'}\right) \geq \Re_k(p_k)$. The monotonicity is proved.

$$\alpha\Re_k\left(p_k\right) - \Re_k\left(\alpha p_k\right) = \alpha_k \varpi \left[\sum_{j \neq k, j=s}^{M} \left(\frac{\alpha \varpi h_{kj}}{\sum_{l \neq j,k}^{M} h_{js} p_s + \varpi v_j}\right) - \sum_{j \neq k, j=1}^{M} \left(\frac{\varpi h_{kj}}{\sum_{s \neq j,k}^{M} \alpha h_{js} p_s + \varpi v_j}\right)\right] \tag{17}$$

As $\alpha > 1$, $\dfrac{\alpha}{\sum_{l \neq s,k}^{M} h_{js} p_s + \omega_j v_j} > \dfrac{1}{\sum_{s \neq j,k}^{M} \alpha h_{js} p_s + \omega_j v_j}$, we get $\alpha\Re_k(p_k) > \Re_k(\alpha p_k)$. The Scalability is proved. If $\alpha_k \varpi \gg 1$, the power vector in TPCG algorithm converges to the fixed point.

IV. Simulation Results

To illustrate the advantages of the proposed algorithm, we compare the maximal throughput algorithm named TP-TMAX in Ref.[6] and the proposed TPCG algorithm under different BER constraints. In this simulation, we also compare the performance of the adaptive modulation named MP-TMAX with the proposed M-TPCG algorithm under the change of user's bandwidth. We assume the length of guard interval is more than channel delay, the frequency-selective fading channel is four-ray Rayleigh model, the delay is one chip period and 4dB fading between two adjacent paths, the spread is performed with Walsh codes. One hundred different scenarios are generated. Our initial power for all users is $p_k^{(0)} = 1 \times 10^{-10}$mW, $p_k^{\max} = 50$mW and $\alpha_k^{(n)} = 300/n$, TP-TMAX iteratively updates the power according to the following equation[6]

$$p_k^{(i+1)} = \frac{1}{\sum_{j \neq k, j=1}^{K} \frac{h_{jk}}{I_{j\left(p_{-j}^{(i)}\right)}}} = \frac{1}{\sum_{j \neq k, j=1}^{K} \frac{h_{jk} h_{jj} p_j^{(i)}}{\gamma_j\left(p_j^{(i)}\right)}} \tag{18}$$

Fig.2 and Fig.3 show the change of the total throughput versus the total power evolution under different subcarrier numbers and different BERs. From the figures, the M-TPCG algorithm dramatically increases the system capacity. For the same power consumption, the throughput is increased by about 2 times. The total power consumed by the TMAX algorithm and TP-TMAX algorithm are higher than the proposed algorithms.

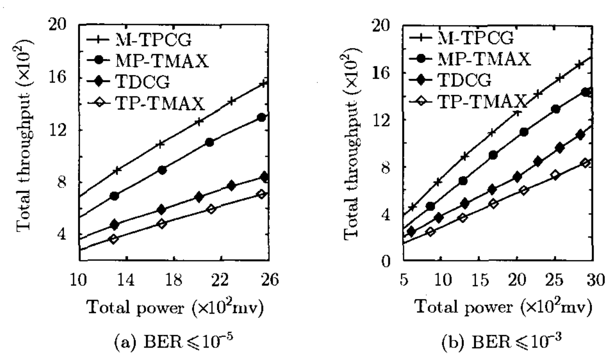
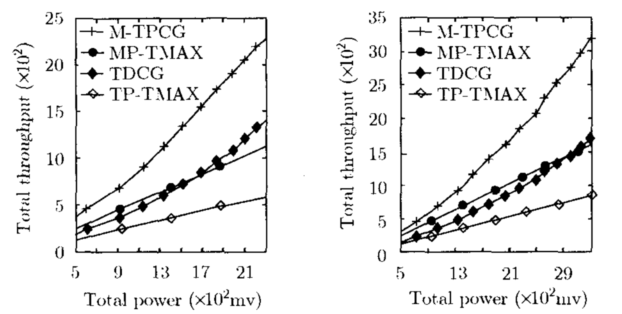


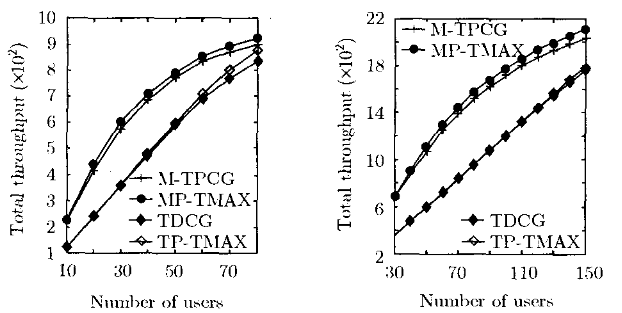
Fig.2 The tradeoff between the throughput and power for N=128

Fig.4 and Fig.5 show the change of the total throughput versus the number of users under different subcarrier numbers and different BERs. From the figure, the throughput obtained by M-TPCG algorithm is maximal with the increase of spectrum bandwidth (*e.g.*, in Fig.5(b)). The proposed games have near-optimal system performance.



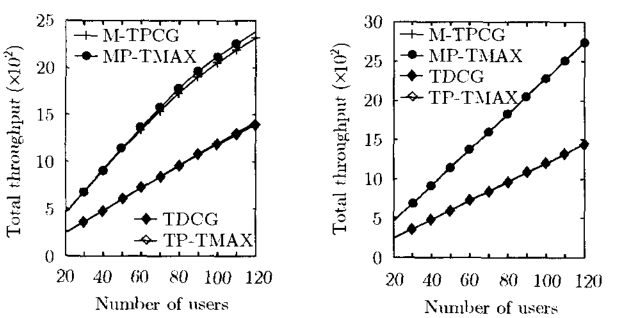
(a) BER ⩽ 10^{-5} (b) BER ⩽ 10^{-3}

Fig.3 The tradeoff between the throughput and power for N=512



(a) BER ⩽ 10^{-5} (b) BER ⩽ 10^{-3}

Fig.4 Total throughput versus number of users for N=128



(a) BER ⩽ 10^{-5} (b) BER ⩽ 10^{-3}

Fig.5 Total throughput versus number of users for N=512

V. Conclusions

A cross-layer design which combines bandwidth, adaptive modulation and power control algorithm, the M-TPCG algorithm, is developed. Simulation results show that the M-TPCG algorithm can achieve the maximal system throughput and the TPCG algorithm can regulate their transmitter powers and enhance the total throughput effectively, the performance of the cognitive radio system is thereby improved obviously.

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