QOS-DRIVEN ALLOCATION SCHEMES IN SPECTRUM LEASING COGNITIVE RADIO NETWORKS

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Abstract

In this paper, the cooperative spectrum leasing process between the primary user (PU) and the secondary user (SU) in an overlay cognitive radio network under the Decode and Forward (DF) cooperative protocol is studied. Assuming that both users have specific Quality of Service (QoS) requirements and participate in a three-phase leasing process, a heuristic joint power and time allocation scheme for maximizing the effective capacity of the PU while guaranteeing a minimum effective capacity for the SU is introduced based on convex optimization theory. The numerical results prove the superiority of the proposed mechanism compared to other less sophisticated allocation schemes and noticeable observations for its performance are made under various network parameters.

1. INTRODUCTION

As the diversification of the wireless users' demands grows fast due to the vast amount of hand-held devices and the complex wireless environment, the more challenging users' QoS requirements must be satisfied considering in parallel the increasing bandwidth requirements. The spectrum's scarcity in modern wireless communication systems is a great challenge that can be alleviated with the employment of Cognitive Radio (CR) technique [1]. In a CR Network (CRN) the licensed PUs (non-cognitive users) coexist with the unlicensed SUs (cognitive users) in the same spectrum band. The CRN operation is based either on the commons model, where the PUs are oblivious to the presence of SUs or the property rights model (known as spectrum leasing), similar to our scenario, where the PUs cooperate with the SUs so as to ameliorate their performance and the cooperative protocols that are mostly employed are the amplify-and-forward (AF) protocol, the decode-and-forward (DF) protocol and the compress-and-forward (CF) protocol. Additionally, both types of users apply one of the three basic dynamic spectrum access (DSA) techniques: overlay, interweave or underlay. Generally, the employment of the overlay approach, similar to our scenario, leads the SU to act as relay for the PU by devoting a part of its own transmission power to eliminate the impact of the interference caused to the primary transmission and simultaneously the SU acquires time for its own (secondary) transmission.

A significant challenge for modern communications is provision of higher QoS level for the wireless applications. Towards this direction, the effective capacity concept, which is defined as the maximum constant arrival rate, supported by the channel to guarantee a QoS requirement [2], is particularly convenient for analysing the statistical QoS performance of wireless transmissions where the service process is driven by the time-varying wireless channel.

Furthermore, a recent significant work in resource allocation mechanisms for CRNs related with our paper is [3]. More specifically, the presented work investigates a heuristic joint power and time allocation mechanism for the maximization of the highest priority user's, the PU's, effective capacity under an overlay approach using the DF cooperative protocol, taking also into account the SU's effective capacity requirement and the maximum SU's instantaneous power transmission to treat with a more realistic scenario.

2. SYSTEM MODEL AND GENERAL CONSIDERATIONS

We consider a three-phase transmission scenario of one PU and one SU in an overlay CRN configuration. Specifically, Figure 1 depicts that the transmission frame has duration of T_f and is divided in three phases: the "primary communication" and the "cooperative" phases, lasting $0.5*t_{PT}$ unit times respectively and the "leasing" phase which lasts

$\left(T_f - t_{PT}\right)$ unit times where $t_{PT} = k_{PT}T_f$ $(0 \le k_{PT} \le 1$ and the parameter k_{PT} expresses the PU's normalized transmission duration. In particular, first phase is used by the primary transmitter (PT) sending its data to the corresponding primary receiver (PR) and to the secondary transmitter (ST), while in the second phase the ST relays the primary signal and in the third phase the latter transmits its own data to the corresponding secondary receiver (SR).

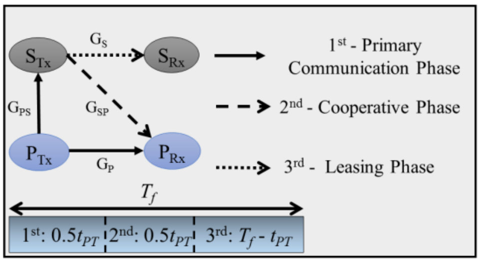


Figure 1. System Model

The wireless links of our model suffer from fading phenomena which are modelled according to Rayleigh distribution, Additive White Gaussian Noise (AWGN) which is modelled as zero-mean independent Gaussian random variable with noise power σ^2 and path loss attenuation according to a loss factor n. Moreover, as it can be seen in Figure 1, the total power gains of PT-PR, PT-ST, ST-PR and ST-SR links are denoted as G_P, G_{PS}, G_{SP} and G_S, respectively. Finally, we must depict that the channels are modelled as independent random variables that remain invariant during a frame, but vary over successive frames.

The time-varying nature of wireless channels which, also, is considered in our scenario and the large variation in the services which are provided by synchronous wireless networks make critical the users' QoS satisfaction which is investigated by the employment of the effective capacity metric, i.e. $E_c(\theta)$ This metric is specified by the QoS exponent θ which is interpreted as the delay QoS exponent [2]. A smaller θ leads to a slower decay rate which implies a looser QoS requirement, while larger θ expresses a more stringent QoS constraint. In the following paper, the normalized effective capacity $E_{c,n}(\theta)$ (bits/sec/Hz), which is defined as the $E_c(\theta)$ divided by the term WT_f, is used and W refers to the system's spectral bandwidth.

3. QOS-DRIVEN JOINT TIME AND POWER ALLOCATION MECHANISM (JTPA)

Due to the lack of space the function $f(G_1,P_1,G_2,P_2) = \left(1+\left(G_1P_1+G_2P_2\right)/\sigma^2\right)$ is defined for a more compact mathematical analysis. Based on the f function, the system's model notations and considering the fixed DF relaying scheme the PU's rate due to the cooperation with the SU is expressed by

$$R_{PU}^{coop} = \frac{Wt_{PT}}{2}\min\left\{\log_2\left(f(G_{PS},P_P,0,0)\right),\log_2\left(f(G_P,P_P,G_{SP},P_S)\right)\right\}$$

where P_P describes the PT's constant transmission power level and P_S depicts the ST's transmission power level, the same for both "cooperative" and "leasing" phases", that is below the ST's maximum power level P_{Smax}. Similarly, the PU's rate without the SU's cooperation, R_{PU}^{dir}, is expressed as $R_{PU}^{dir} = WT_f\log_2\left(f\left(G_P,P_P,0,0\right)\right)$ and the SU's rate, R_{SU}, is defined as

$$R_{SU} = W(T_f - t_{PT})\log_2\left(f\left(G_S,P_S,0,0\right)\right).$$

Based on the aforementioned rate expressions which are measured in *bits per frame* and defining the PU's and SU's normalized QoS exponents for simplicity as $a_j = a_j(\theta_j) = \theta_j WT_f/\ln(2)$ where $j \in \{PU, SU\}$, the final expressions of the corresponding normalized effective capacities, where $\mathrm{E}[\cdot]$ represents the expected value function, are described similarly with the $E_{c_{PU},n}^{coop}$ which is defined as $E_{c_{PU},n}^{coop}(P_S,k_{PT},\alpha_{PU}) = -\frac{1}{\alpha_{PU}\ln(2)}\ln\left(\mathrm{E}\left[\max\{f_1, f_2\}\right]\right)$

where $f_1 = f_1(k_{PT},a_{PU}) = \left(1+G_{PS}P_P/\sigma^2\right)^{-\frac{\alpha_{PU}k_{PT}}{2}}$,

$$f_2 = f_2(P_S,k_{PT},a_{PU}) = \left(1+(G_PP_P+G_{SP}P_S)/\sigma^2\right)^{-\frac{\alpha_{PU}k_{PT}}{2}}$$

The proposed **J**oint **T**ime and **P**ower **A**llocation algorithm (**JTPA**) refers to the optimization of the PU's effective capacity ($E_{c_{PU},n}^{coop}$) given a minimum value (E_{SU}) for the SU's normalized effective capacity ($Ec_{SU,n}$) satisfying the constraint $Ec_{SU,n}(\alpha_{SU}) \ge E_{SU}$ and the PU computes both the SU's transmission power level (P_S) and the optimal normalized duration of its own transmission (k_{PT}). Formally, considering that for each timeslot

$0 \le P_S \le P_{S\max}$ and $0 \le k_{PT} \le 1$ due to the system scenario and defining $F(E_{SU}) = e^{-\alpha_{SU}\ln(2)E_{SU}}$, the optimization problem is expressed as:

$$\begin{aligned} &\max_{P_S, k_{PT}} E^{coop}_{c_{PU},n}(P_S, k_{PT}, a_{PU}) \square \min_{P_S, k_{PT}} \mathrm{E}\left[\max\{f_1, f_2\}\right] \\ &\text{s.t. } \mathrm{E}\left[\left(1+(G_S P_S)/\sigma^2\right)^{-a_{SU}(1-k_{PT})}\right] \le F(E_{SU}) \end{aligned} \quad (1)$$

The **JTPA** problem is not convex, so we treat it heuristically in two steps: first over the SU’s cooperative transmission power P_S and then over the duration of the primary transmission k_{PT}. So the equation $f_1=f_2$ results in the closed form expression $P_S^* = \left((G_{PS} - G_P)P_P\right)/G_{SP}$ which must satisfy the constraint $0 \le P_S^* \le P_{S\max}$. Hence, the substitution of the P_S^* in the objective function of (1) simplifies the optimization problem as $\mathrm{E}\left[\max\{f_1, f_2\}\right] \square \mathrm{E}[f_1]$ and is easily concluded that the modified objective function of (1) is convex versus k_{PT} and has a global optimal solution k_{PT}^* which is obtained using the Lagrangian approach

$$L = \mathrm{E}[f_1] + \lambda\left(\mathrm{E}\left[\left(1+(G_S P_S)/\sigma^2\right)^{-a_{SU}(1-k_{PT})}\right] - F(E_{SU})\right),$$

where λ is determined from the SU’s minimum effective capacity requirement of (1). The optimal solution k_{PT}^* is defined as:

$$k_{PT}^* = -\frac{\ln\left[\dfrac{2\lambda a_{SU}\ln(f(G_S, P_S, 0, 0))}{\alpha_{PU} f^{a_{SU}}(G_S, P_S, 0, 0)\ln(f(G_{PS}, P_P, 0, 0))}\right]}{\ln\left[f^{\frac{\alpha_{PU}}{2}}(G_{PS}, P_P, 0, 0) f^{a_{SU}}(G_S, P_S, 0, 0)\right]} \quad (2)$$

Finally, for comparison reasons, we examine two other allocation schemes that both treat with a Constant PU’s **T**ime duration satisfying the SU’s minimum effective capacity constraint and the SU’s **P**ower **A**llocation strategy is based either on the expression of P_S^*, called as **PA/CT** mechanism**,** or on a **C**onstant SU’s power level P_S, called as **CP/CT** mechanism.

4. SIMULATION RESULTS

In this Section, we investigate the performance of the proposed mechanism in MATLAB. The wireless channels are modelled as unit mean Rayleigh channels with path loss attenuation *n*=4. For the rest of the system parameters, without loss of generality, we assume T_f=1sec, σ^2=1, *W*=1Hz, α_{PU}=10 bit^{-1}, α_{SU}=0.01 bit^{-1}, P_P=P_{Smax}=1 W, d_{PTPR} =1 m and d_{STSR}=d_S= $d_{PTPR}/10$ to model the smaller SU’s geographical deployment. Furthermore, any variations in the above mentioned values are been noticed in the corresponding figures. For the following analysis, we also consider the factor $\rho = d_{PTST}/d_{STPR}$ which describes the accurate position of the ST and three, indicatively, different ST’s positions as the latter approaches the PR are examined, i.e. *ρ*=1, *ρ*=1.5 and *ρ*=2.33 respectively. Moreover, the values of the metrics have been computed through 10^4 Monte-Carlo simulations of the fading channel conditions that have been enough in order to have converged results.

Figure 2 presents the increase of the Ec_{PU} as the k_{PT} increases for both cooperative schemes, i.e. PA/CT and CP/CT and the better performance of the former scheme, based on the relation of P_S^*, in comparison with the SU’s constant power cooperative scheme. Moreover, the aforementioned cooperative mechanisms outperform the corresponding metric of PU’s direct transmission after smaller values of k_{PT} as the ST comes closer to PT showing that the PT is more benefited when the relay is closer. In parallel, in Figure 3 is apparent the decrease of the Ec_{PU} either as the α_{PU} or the E_{SU} becomes stricter explained by the corresponding results of Figure 4 (a). Additionally, in PU’s terms the superiority of the proposed JTPA scheme is obvious compared with the PA/CT and CP/CT schemes. Finally, the PU is more benefited as the ST’s cooperative power level increases.

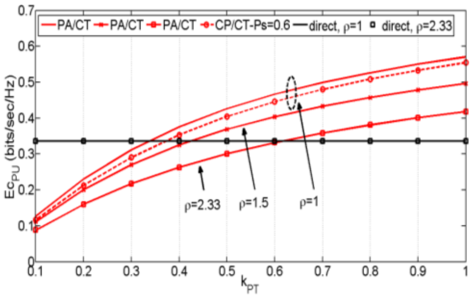


Figure 2. PU’s Normalized Effective Capacity vs the k_{PT}

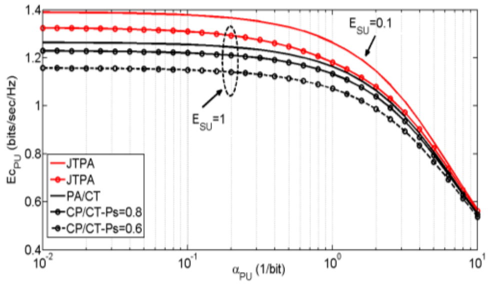
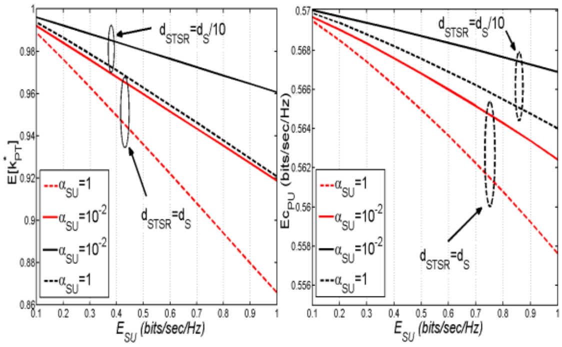


Figure 3. PU’s Normalized Effective Capacity vs the a_{PU} for ρ=1

Considering the JTPA scheme in Figure 4 (a), (b) and assuming the proportionality of the Ec_{PU} with the k_{PT} by Figure 2, it is easily explained the amelioration of the Ec_{PU} as d_{STSR} or α_{PU} decreases in Figure 4 (b) due to the corresponding increase in the $\mathrm{E}\left[k_{PT}^{*}\right]$ as depicted in Figure 4 (a).



(a) (b)

Figure 4. (a) Mean value of k_{PT} and (b) PU's Normalized Effective Capacity vs the E_{SU} for ρ=1

5. CONCLUSION

An overlay CRN has been studied and the cooperative JTPA allocation mechanism is proposed from the PU's side to determine the duration of the cooperation and the SU's transmission power. Besides the benefits of cooperation among PU and SU compared to PU's direct transmission, the application of the JTPA scheme leads to further PU's benefits compared to less sophisticated schemes as the simulation results reveal.

References

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