Performance Analysis of Cognitive Radio Networks Using Cross-layer Design Approaches

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Abstract. This thesis studies the performance of both opportunistic spectrum access (OSA) and spectrum sharing (SS) cognitive radio networks (CRNs) using cross-layer design (CLD) approaches in order to provide reliable and optimum packet transmission at the medium access control (MAC) layer with quality of service (QoS) guarantees, to optimize the secondary user (SU) performance given the primary user (PU) protection and to realize the impact of imperfect spectrum sensing at the MAC layer. The reliable and optimum packet transmission at the MAC layer with QoS guarantees is accomplished by the combination of adaptive modulation with hybrid automatic repeat request (HARQ) protocol in OSA CRNs. The SU's performance is maximized by formulating a convex optimization problem for the SU's capacity over the power control (PoC) and spectrum sensing (SpSe) that is solved with an iterative subgradient method which results in optimal power allocation and sensing threshold selection. Finally, the impact of imperfect SpSe at the MAC layer is realized by modelling the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) and the SpSe as two state Markov processes and thus obtaining the joint steady state distribution that encompasses the parameters of both mechanisms.

1 Introduction

Third-generation (3G) and beyond 3G mobile communication systems must provide interoperability with the Internet, increase throughput for mobile devices, and optimize their operation for multimedia applications. The limited ability of traditional layered architectures to exploit the unique nature of wireless communication has fostered the introduction of cross-layer design (CLD) solutions that allow optimized operation for mobile devices in the modern heterogeneous wireless environment. In this thesis, we first present the major cross-layer design solutions that handle such problems, and discuss cross-layer implementations with a focus on functional entities that support cross-layer processes and the respective signaling. In addition, we consider the associated architectural complexity and communication overhead they introduce. Furthermore, we point out the major open technical challenges in the cross-layer design research area. Finally, we conclude our article with a summary of cross-layer approaches developed thus far and provide directions for future work [1].
Besides, cognitive radio is considered as one of the most important enablers for achieving enhanced spectral efficiency in wireless communications. In the sequel, in this thesis, we present a cross-layer design for reliable data transmission over a cognitive radio network which combines adaptive modulation at the physical layer and hybrid automatic repeat request at the data link layer. The cognitive radio network follows the principles of opportunistic spectrum access that utilises an optimal power adaptation policy for channel allocation. The obtained numerical results denote that the considered approach achieves significant spectral efficiency improvement and therefore it could be deployed in wireless communication networks that encompass cognitive capabilities. Furthermore, we assess the introduced interference and we show that it can be kept within levels that do not jeopardise our design [2].

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Furthermore, we study the problem of maximizing spectral efficiency of cognitive radio network deployments subject to an interference constraint and under specific quality of service (QoS) guarantees. The interference constraint corresponds to the upper limit of the received power that can be tolerated at the licensed users' due to transmissions from unlicensed users. The QoS guarantees stem from the requirements imposed by the applications running at the users' terminals. A cross-layer design is adopted that maps the user's requirements into delay related QoS guarantees at the data link layer and error probability QoS guarantees at the physical layer. The obtained numerical results provide important insights regarding the impact of the considered constraint and guarantees on the achievable spectral efficiency of cognitive radio networks [3].

Moreover, a joint optimal power allocation and sensing threshold selection for capacity maximization at the secondary user (SU) in spectrum sharing (SS) cognitive radio networks (CRNs) is proposed. Hence, both optimal power allocation and spectrum sensing is considered in the SS CRNs model. The obtained results show that such a joint optimal selection improves the performance of the SU by maximizing its capacity [4]. Besides, we propose capacity optimization through sensing threshold adaptation for sensing-based cognitive radio networks. The objective function of the proposed optimization is the maximization of the capacity at the secondary user subject to transmit power and sensing threshold constraints for protecting the primary user. After proving the concavity of capacity on sensing threshold, the problem is solved using the Lagrange duality decomposition method in conjunction with a subgradient iterative algorithm. The numerical results show that the proposed optimization can lead to significant capacity maximization for the secondary user as long as this is affordable to the primary user [5].

Finally, we introduce a cross-layer design (CLD) of carrier sensing multiple access with collision avoidance (CSMA/CA) at the medium access control (MAC) layer with spectrum sensing (SpSe) at the physical layer for cognitive radio networks (CRNs). The proposed CLD relies on a Markov chain model with a state pair containing both the SpSe and the CSMA/CA from which we derive the transmission and collision probabilities. The derived probabilities can be used as performance criteria to evaluate the performance of specific CRNs when they are deployed in a distributed coordination fashion that is prone to collisions [6].

The rest of this document is organized as follows. In Section 2, we describe the major results of this thesis that are namely the spectral efficiency of CRNs under interference constraint and with QoS guarantees, the joint optimal power allocation and spectrum sensing threshold selection for SS CRNs and the CLD of CSMA/CA with SpSe in CRNs. We conclude this document with the overall conclusions derived from the investigations accomplished within the framework of this thesis.

2 Performance analysis of cognitive radio networks using cross-layer design techniques

In this section we present two main results of this thesis. First, the spectral efficiency of CRNs under interference constraint and QoS guarantees and second the joint optimal power allocation and sensing threshold selection for SS CRNs

2.1 Spectral efficiency of cognitive radio networks under interference constraint and QoS guarantees

In this section we focus on the approach in order the SU be able to share efficiently the same spectrum band with PU via CR and we model the respective procedures. To this end, this study reveals the impact of the adoption of an interference constraint at the PU on the spectral efficiency of the SU.

We assume a CR networking layout with a PU and a SU as depicted in Fig. 1 where the channel allocation technique that is adopted follows the principles of the spectrum underlay paradigm of CRNs since it encompasses an interference power as we will describe below. Both transmitters and receivers are considered as users with the notation PU-Tx and PU-Rx for users of the primary network (PN) and SU-Tx and SU-Rx for the users of the secondary network. The channel power gains from SU-Tx to SU-Rx and PU-Rx are denoted by γ_{11} and γ_{12}, respectively, and from PU-Tx to PU-Rx and SU-Rx by γ_{22} and γ_{21}, respectively. Channel power gains γ_{12} and γ_{21} are considered as interference for PU-Rx and SU-Rx respectively [7].

With the considered channel allocation technique both PU-Rx and SU-Rx are using the same frequency band (e.g. f_1) and henceforth both should transmit in a way that achieves a reasonably high transmission rate without causing too much interference to each other [7]. Besides, we consider that the SU-Rx exploits spectrum sensing to discover more than one spectrum bands in the wideband range $\{f_1, f_2, \ldots, f_8\}$ and thus it is able to settle in more than one spectrum bands [8]. Spectrum sensing is one of the most important tasks for terminals with cognitive capabilities and that is why the corresponding users are denoted as cognitive ones [9]. It should be noted that the considered channel allocation technique give access priority to PU-Rx as implemented in a spectrum sharing system in general.

For studying the maximization of the spectral efficiency of SU-Rx that is subject to the transmit and interference power constraints, we analyze first the channel allocation technique. Both constraints are related to SU-Tx power transmission as we will discuss later. Then, we continue with the technique, by which the SU-Rx is able to sense the available spectrum bands offered in a wideband regime, in order to present its spectral efficiency per unit bandwidth. This means that the network can simultaneously offer more sub channels and thus a gain is manifested in terms of spectral efficiency per unit bandwidth in the whole networking system.

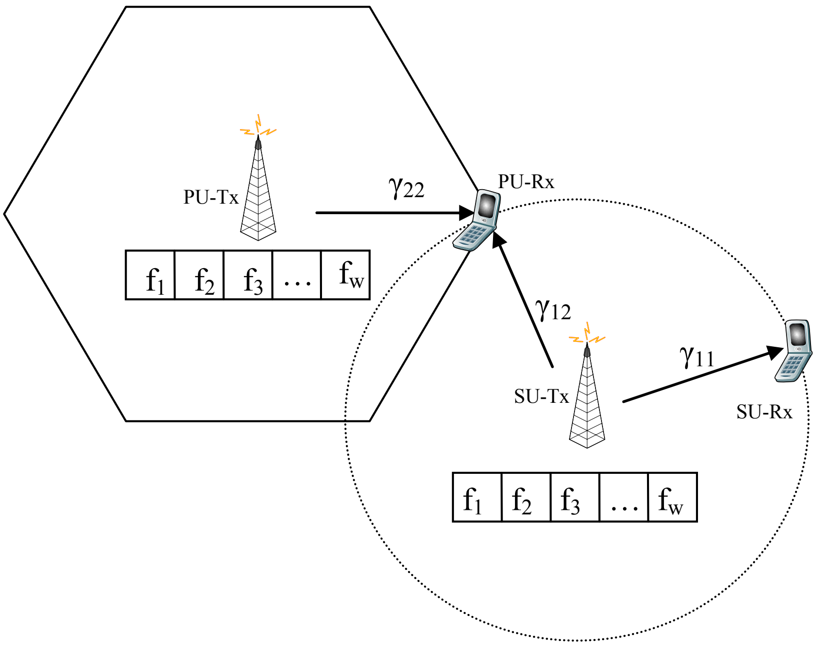

Fig. 1. Cognitive Radio Network Model

In figure 2 we present the potential gain in spectral efficiency per unit bandwidth that is achieved when the considered CRN deployment exploits also spectrum holes in the spectrum range. As previously mentioned the SU-Rx is able to sense the spectrum bands in order to transmit throughout the sensed vacant bands. We include the aforementioned power constraints and QoS guarantees in such a CR system and we depict the spectral efficiency gain achieved. The results obtained by applying the optimal power allocation policy for the following interference power constraints levels $-10dB$, $0dB$, $10dB$ and $20dB$ are depicted with blue lines. With black lines are illustrated the results with QoS guarantees equal to $p_{loss} = 0.001$ and $R_{\max} = 0$, while the red lines show the results when $p_{loss} = 0.001$ and $R_{\max} = 4$. From the presented curves we conclude that as the received CNR increases, the network behavior tends toward the no cognition case since no spectral gain is exhibited something that was evident in figure 3 either. This can be explained from the fact that when the cutoff level γ_{11}^{*} is very low, the possibility for a vacant band is bigger than when this value is higher where more power is poured within each channel and the user with the higher priority occupies the whole bandwidth. This is accomplished (i.e. $\gamma_{11}^{*} \to 0$) indeed at lower average CNR regions when the worst case scenario is considered e.g. in case of a tight interference power constraint $-10dB$.

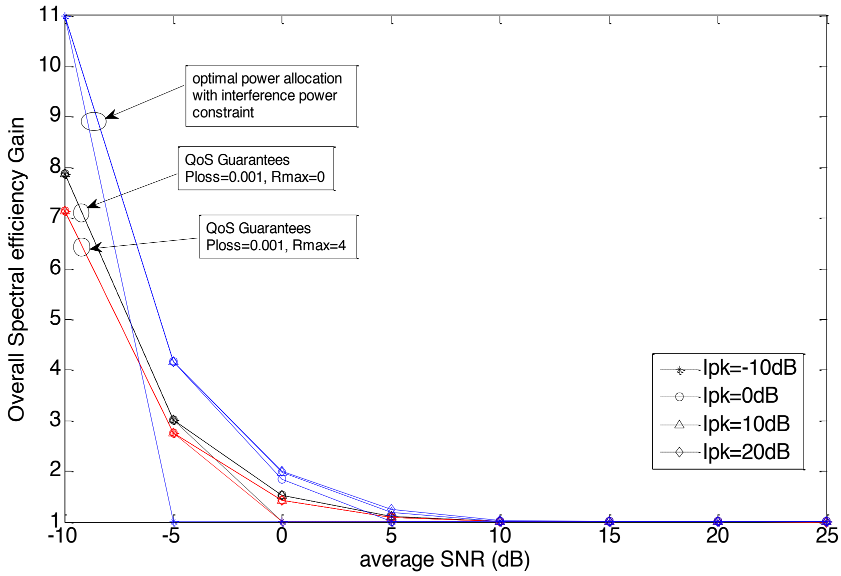

Fig. 2. Performance Gain in Spectral Efficiency under interference constraints

In general an interference power constraint affects the system in terms of vacant band i.e. band in which the threshold is above the cutoff value and it makes the system to downgrade its performance. In addition to that, the incorporation of QoS guarantees downgrade the performance gain achieved from such a system and makes it to operate as a conventional one in lower CNR regions. However, this is expected since on the other hand the constraints guarantee the QoS that can be offered by the network in order to satisfy the users' requirements. The presented approach could be extended further by assuming a multi-carrier modulation technique such as orthogonal frequency division multiple access (OFDM) that is most frequently considered for the implementation of CRNs. This extension requires a proper formulation of the analysis and assessment presented in this paper that will introduce some extra parameters (e.g. guard interval, number of OFDM symbols, etc) in order to correctly obtain the spectral efficiency gain that will now achieved per subcarrier. This extension can be considered as a future work.

2.2 Joint Optimal Power Allocation and Sensing Threshold Selection for SS CRNs

In spectrum sharing (SS) cognitive radio networks (CRNs), optimal power allocation (OPA) and spectrum sensing (SpSe) are used for the protection of the primary user (PU) from harmful interference caused by the secondary user (SU). Furthermore, for capacity maximization of the SU, the main parameters related to OPA, i.e. the SU's transmit power, P_t, is adapted according to the received signal-to-noise ratio (SNR), γ_s, and related to SpSe, i.e. sensing threshold, η, and sensing time, τ, for a given sensed SNR, γ, need to be also carefully selected [10]. Previous studies on SU's capacity maximization include SS CRNs models with SpSe [12], [13] or without SpSe [11], [10]. For the former and more general case, the optimization presented in [6] is considered over P_t and τ assuming η to be constant. In [13] although the effects of η as a variable are studied, the research is focused on the interference caused to the PU rather than the optimization of the SU's capacity. Thus, a more general approach is presented in this letter where a jointly OPA and SpSe threshold selection is considered so that the SU's capacity is maximized over P_t and η.

Figure 3 illustrates the performance of C_s obtained from the joint optimization problem in (2), versus η, for different values of γ and P_{av}. As in [7] and [13], for the performance evaluation results we have assumed that for Rayleigh fading channels the channel power gains (exponentially distributed) are assumed with unit mean, AWGN with variance $N_0 = 1$ and $\pi_1 = 0.4$. Furthermore, for the OPA, the constraint on peak interference power is assumed to be $I_{pk} = 0dB$ while for the SpSe, $\tau = 1ms$ [14]. The performance evaluation results obtained clearly show that C_s increases as γ decreases and/or P_{av} increases while its improvement becomes negligible when $P_{av} < I_{pk}$.

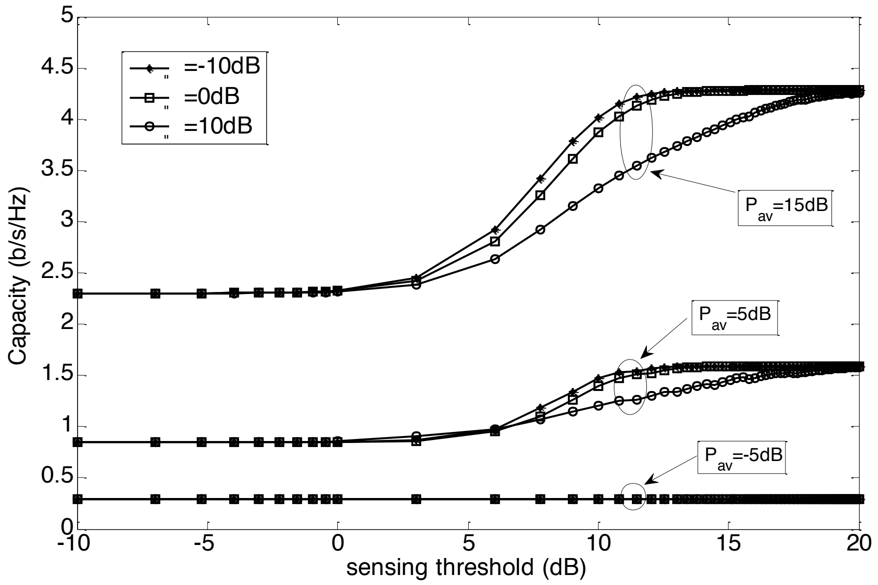

Fig. 3 Capacity C_s vs. sensing threshold η for different γ and P_{av} assuming $I_{pk} = 0dB$

Figure 4 illustrates the throughput computed as $\xi_s = (T - \tau / T)C_s$ based on the SpSe and frame transmission models that have been proposed in [6], where T is the frame duration, $T - \tau$ is the frame duration for data transmission and C_s is taken from (1). Therefore ξ_s represents the transmitted bits per frame, is the performance metric at the secondary link and it is maximized over the sensing time τ for different optimal probabilities of detection p_d^* using the maximization in (2). The performance results have been obtained for $T = 100ms$, $P_{av} = 15dB$, $I_{pk} = 0dB$ and $\gamma = -10db$. Furthermore, different target values of p_d^* are assumed that correspond to specific SpSe thresholds, η^*. However, these η^* values are identical for each target value p_d^* as depicted in Fig. 2. This is reasonable since the maximization problem is assumed over τ and not over η. This also shows that a proper selection of η for the SpSe and P_t for the OPA provides an additional C_s maximization to the one achieved by the joint optimization over P_t and τ.

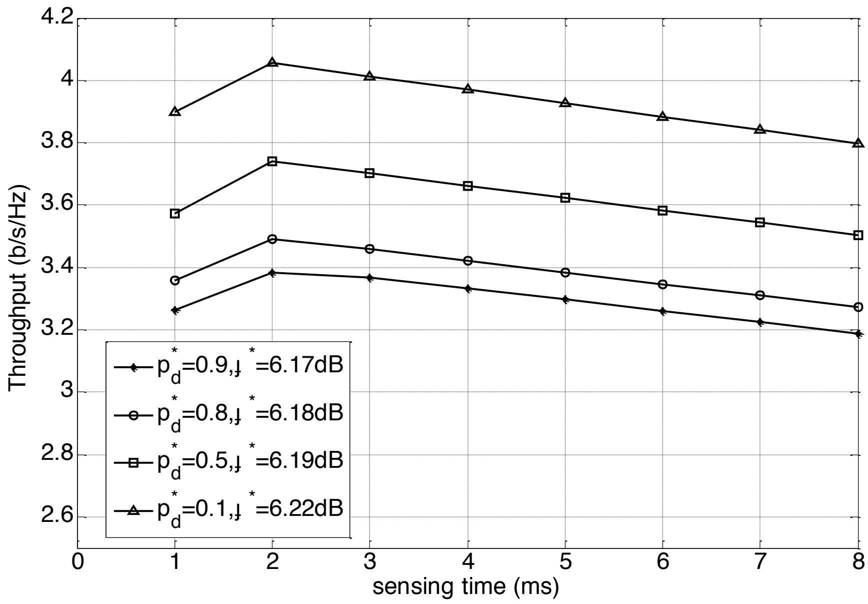

Fig. 4 Throughput ξ_s vs. sensing time, τ for different optimal p_d^* with $P_{av} = 15dB$ and $I_{pk} = 0dB$

A joint OPA and SpSe threshold selection for capacity maximization at the SU in SS CRNs has been proposed. This joint optimization leads to further capacity maximization as compared to the one achieved by joint optimization over the transmit power and sensing time. This maximization has also shown that the capacity can be further improved by properly selecting the SpSe threshold based on the sensed SNR.

2.3 Cross-layer Design of CSMA/CA with Spectrum Sensing for CRNs

In cognitive radio networks (CRNs), the channels' availability is manifested via spectrum sensing (SpSe) at the physical layer [15] and subsequently the packet transmission is accomplished through an appropriate medium access control (MAC) layer technique [16]. It has been recognized that the imperfect SpSe at the physical layer have an impact on the performance at the MAC layer [20]. To this end, the authors in [21] propose a cross-layer design (CLD) between the SpSe at the physical layer and the MAC layer in general in which a constraint on collision probability dictates the operating characteristics of SpSe. In this thesis, we introduce a cross-layer design (CLD) of SpSe at the physical layer with a specific MAC layer technique, the well-known carrier sensing multiple access with collision avoidance (CSMA/CA) protocol. Based on the CLD presented in [17], the Markov chain model of CSMA/CA presented in [18] and the Markov chain model of SpSe presented in [19], we derive the transmission and collision probabilities that can be used to evaluate the deployment of CSMA/CA protocol in CRNs. In [20] the authors present a cross-layer performance analysis of CSMA/CA in case of imperfect SpSe but they neither consider the well established exponential backoff nor a Markov chain model for multi-channel SpSe of CRNs.

We have derived both numerical and simulation results in order to validate the proposed CLD. We assume that the sensed SNR is equal to $\gamma_p = -15dB$ and the sensing time equal to $T_s = 2ms$ for primary channels with frequency $f_p = 6MHz$. Fig.5 shows the transmission probability τ (left part) and the collision probability p_c (right part) versus the number of stations n for different probabilities of detection P_d, backoff stages m and minimum contention window W. The results obtained considering one channel i.e. $C = 1$ with an activity probability equal to $a = 0.5$. The solid lines depict the case of $m = 3$ and $W = 32$, the dashed lines depict the case of $m = 3$ and $W = 64$, and the dotted dashed lines the case of $m = 5$ and $W = 32$. Since the depiction of all simulation results would make them indistinguishable, we depict them for the cases of $P_d = 1$ and $P_d = 0.9$ with $m = 3$ and $W = 64$ with circles and stars and without line. From the figure is obvious that a low probability of detection e.g. $P_d = 0.1$, results in high transmission probability τ. Furthermore, high contention window values e.g. $W = 64$ (dashed lines) and/or backoff stage e.g. $m = 5$ (dotted dashed lines) result in a lower transmission probability τ, although a high contention window value gets the transmission probability lower. We also notice that the collision probability p_c is proportional to the transmission probability τ.

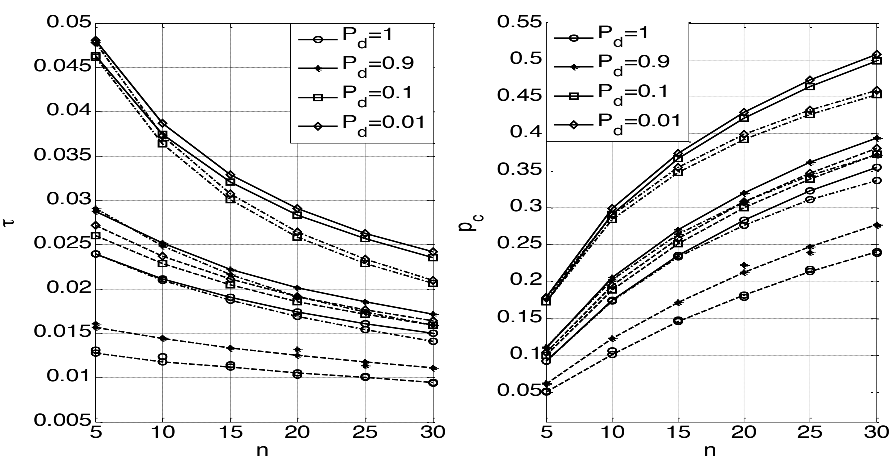

Fig. 5. Transmission probability τ (left part) and collision probability p_c (right part) vs. number of stations n for different probabilities of detection P_d with backoff stage $m = 3$ and contention window $W = 32$ (solid lines), with $m = 3$ and $W = 64$ (dashed lines) and with $m = 5$ and $W = 32$ (dotted dashed lines).

Fig. 6 shows the transmission probability τ and collision probability p_c versus the number of stations n for different values of channels' activity a and number of channels C. The results obtained considering a probability of detection equal to $P_d = 0.5$, a backoff stage equal to $m = 3$ and a contention window equal to $W = 32$. The solid lines depict the case of $a = 0$, $a = 0.5$, $a = 0.8$ and $C = 1$, the dashed lines depict the case of $C = 3$ and the dotted dashed lines the case of $C = 6$ considering the same activities for all cases. We also depict the simulation results in case of activity $a = 0.8$ and channels $C = 3$ with squares without line. Obviously, a high probability of activity e.g. $a = 0.8$ results in a lower transmission probability τ. Furthermore, for a high number of sensed channels e.g. $C = 6$, the transmission probability τ increases. As previously, the collision probability p_c is proportional to the transmission probability τ.

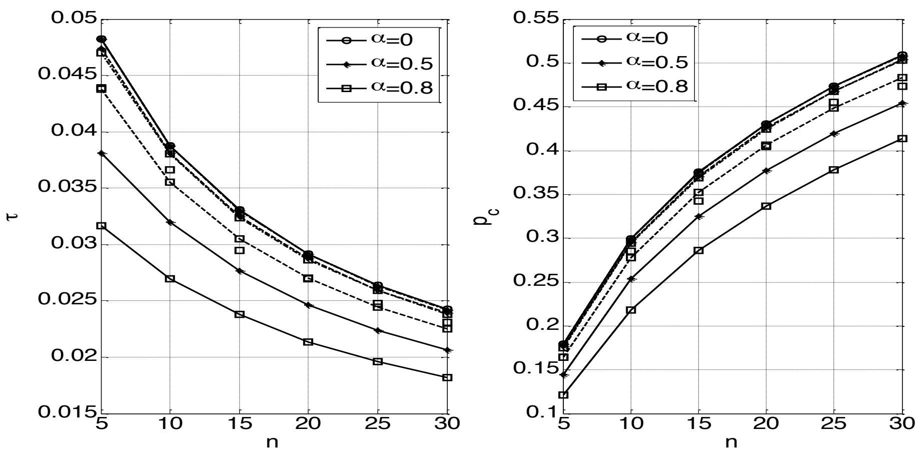

Fig. 6. Transmission probability τ (left part) and collision probability p_c (right part) vs. number of stations n for different activities a with $C = 1$ channels (solid lines), with $C = 3$ channels (dashed lines) and with $C = 6$ channels (dotted dashed lines).

3 Conclusions

In this thesis, we present a CLD over an OSA-based CRN that provides reliable data transmission. In particular, we study the achieved spectral efficiency over fading channels and the potential gain in OSA-based CRNs. The CRN model which allows for OSA to SUs by sensing the spectrum's vacant buds from the licensed network is provided. In order to provide reliable data transmission in the new wireless communication network we adopt adaptive modulation and automatic repeat request at the physical and data link layer respectively. The obtained results show the improvement in spectral efficiency versus the average SNR of the fading channel.

Finally, the introduced interference in such a network is assessed and we show that it can be kept within levels that do not affect the operation of the considered overlay communication system.

Besides, we analytically derived the maximum spectral efficiency achieved at the physical layer of a CRN under interference power constraint with QoS guarantees. Based on an optimal power allocation strategy at the physical layer of the SU we introduced delay related QoS guarantees through a cross-layer model. The specific cross-layer model combines the adaptive modulation and ARQ at the physical and data link layer, respectively that gives us the ability to evaluate the achievable spectral efficiency over fading channels. The impact of the imposed constraints on the spectral efficiency is analyzed via numerical results assuming a Rayleigh fading channel. It is shown that the spectral efficiency cannot be increased up to an average CNR value that is equal to the interference power constraint. Besides, we evaluate the gain in spectral efficiency that is defined in the case that the SU is able to sense a spectrum range of vacant channels. Finally we showed that a proper selection of the constraints and guarantees at the SU can make the operation of the overall CRN more efficient.

Furthermore, we study the capacity optimization for sensing-based cognitive radio networks over sensing threshold. In particular, we consider a sensing-based spectrum sharing CRN in which both power control and spectrum sensing are employed for the PU's protection. The proposed optimization is proved to be a convex optimization problem that we solve using the Lagrange dual decomposition method. A subgradient iterative algorithm provides the optimum values for both transmit power and sensing threshold of the power control and spectrum sensing, respectively. The numerical results show the SU's capacity maximization achieved through sensing threshold adaptation and the corresponding capacity loss that can be afforded at the PU.

Finally, we have introduced a cross-layer design of SpSe and CSMA/CA from which we have derived the transmission and collision probabilities. We rely on discrete time Markov chain model with a state pair for modeling both SpSe and CSMA/CA processes that result in a joint stationary probability which incorporates the parameters of SpSe and CSMA/CA at the physical and the MAC layer respectively.

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