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The Achievable Rate of Interweave Cognitive Radio in the Face of Sensing Errors

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***Abstract*—Cognitive radio (CR) systems are potentially capable of mitigating the spectrum shortage of contemporary wireless systems. In this paper we provide a brief overview of CR systems and the important research milestones of their evolution, along with their standardization activities, as a result of their research. This is followed by the detailed analysis of the interweave policy based CR network (CRN) and by a detailed comparison to the family of underlay based CRNs. In the interweave based CRN, sensing of the Primary User's (PU) spectrum by the Secondary Users (SU) has remained a challenge, because the sensing errors prevent us from fulfilling the significant throughput gains that the concept of Cognitive Radio (CR) promises. Since missed detection and false alarm errors in real-time spectrum sensing cannot be avoided, based on a new approach we quantify the achievable rates of the interweave CR by explicitly incorporating the effect of sensing errors. The link between the PU transmitter and the SU transmitter is assumed to be fast fading. Explicitly, the achievable rate degradation imposed by the sensing errors is analyzed for two spectrum sensing techniques, namely for Energy Detection and for Magnitude Squared Coherence based detection. It is demonstrated that when the channel is sparsely occupied by the PU, the reusing techniques that are capable of simultaneously providing low missed detection and false alarm probabilities, cause only a minor degradation to the achievable rates. Furthermore, based on the achievable rates derived for underlay CRNs, we compare the interweave CR and the underlay CR paradigms from the perspective of their resilience against spectrum sensing errors. Interestingly, in many practical regimes the interweave CR paradigm outperforms the underlay CR paradigm *in the presence of sensing errors*, especially when the SNR at the SU is below 10dB and when the SNR at the PU is in the range of 10-40 dB. Furthermore, we also provide rules of thumb that identify regimes, where the interweave CR outperforms the underlay CR.**

Keywords*—ODFM, Interweave, missed detection, false alarm, achievable rate.

I. Introduction

While certain parts of the frequency spectrum are crowded by users, most part of the spectrum still remains largely unoccupied [1]. Due to this *spectrum imbalance*, along with the command and control spectrum allocation policy of the Federal Communications Commission (FCC) and the recent proliferation of wireless devices, new Dynamic Spectrum Access (DSA) techniques are needed.

Cognitive radio (CR) is capable of mitigating this problem [2]–[4]. Diverse cognitive radio approaches have been suggested in the literature, but the three most popular ones are the interweave CR based on opportunistic spectrum access, the underlay CR and the overlay CR based spectrum sharing [5], [6]. Each approach relies on its own set of assumptions concerning the information about the Primary User (PU). For example, in the ideal case of the interweave CR the spectrum sensing schemes provide knowledge about the PU's presence for the Secondary User (SU). In the ideal case of the underlay CR the channel state estimation schemes provide the information concerning the channel quality of the links between the SU and the PU. Finally, in the overlay CR arrangement, the SU is provided with the PUs message/codebook either in a causal or non causal manner.

Although numerous information theoretic contributions have been made based on the overlay and the underlay CR assumption, the interweave CR paradigm has received limited attention. The associated practical developments demonstrate that spectrum sensing remains far from perfect [7]–[9]. Hence the effect of sensing errors has to be incorporated into the information-theoretic studies of the achievable rates. Furthermore, to the best of our knowledge there have been no comparative studies of all of the above paradigms in the presence of diverse channel parameters and user constraints, albeit the authors of [10] provided comparisons of the interweave CR and the underlay CR, while ensuring the minimum outage probability for the PU. However, we concentrate our attention more on the basic channel parameters to specifically highlight the practical scenarios, where any of the specific approaches is better.

The objective of this paper is hence to fill this gap and evaluate the performance of the practical interweave CR, followed by an in-depth comparison of two popular CR approaches/paradigms, such as the interweave CR and the underlay CR. The attainable performance is measured in terms of both the achievable rate of the SU and the sum rate. We assume non-ideal cognition for the interweave CR and ideal cognition for the underlay CR. Hence, our comparisons will be more focused on identifying the various regimes where *the interweave CR outperforms the underlay CR*. In this context we note that we need tight achievable rate expressions for the underlay CR. Hence, we rely on the achievable rate expressions

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derived in [11]. A characteristic of these achievable rates derived for the underlay CR are that they ensure maintaining its original full single-link rate for the PU, while limiting the SUs transmission rate. This makes our comparison a fair one, since no new interference temperature or no different power constraints is involved.

The parameters, which form the basis of our comparisons are the probability of sensing errors, the probability of the channel being free, the average interference coefficients and finally the SNRs at both the PU and the SU. We will demonstrate that interestingly, there are various regimes of practical interest, where despite encountering spectrum sensing errors, the interweave CR provides a higher rate for the SU as well as a higher sum rate to the SU and PU together, than the underlay CR. Furthermore, we will demonstrate that this is especially true, when we have reasonably low sensing error probabilities, a moderate probability of the PU's channel being free, while having SNRs at the SU below 10dB and an SNR in the range of 10-40dB at the PU. Moreover, the supremacy of the interweave CR is further extended when the interference is lower. Hence, in the traditional underlay CR concept of maintaining low interference so that the PU remains less affected constitutes a strong assumption and in this context the interweave CR outperforms the underlay CR.

The contributions of this paper are as follows,

- A practical channel model incorporating spectrum sensing errors is proposed. The achievable rates of this channel model have been characterized based on the assumption that all the links are flat-fading channels and undergo fast fading. The effects of spectrum sensing errors have been discussed and it is shown that the probability of missed detection is highly critical in the presence of strong interference, whereas the impact of the false alarm probability becomes highly critical in the weak interference scenarios.
- A performance comparison of the interweave CR and the underlay CR is provided as a function of the channel parameters, power constraints, spectrum sensing errors and PU occupancy. It is shown that there are several practical regimes, where the interweave CR outperforms the underlay CR in the face of spectrum sensing errors. We also provide rules of thumb that can be used to decide, which particular approach is better for a given set of channel parameters, power constraints, spectrum sensing errors and PU occupancy.
- Finally, we consider a typical application of our results where an OFDM scenario is considered. Diverse situations are considered, where the interweave CR is seen to outperform the underlay CR and where it fails to do so. The spectrum sensing techniques considered are the energy detector and the magnitude squared coherence based one.

The paper is structured as follows. Section II provides a brief overview of CRNs, followed by a discussion of their standardization activities in Section III. Section IV introduces both the interweave CR based opportunistic spectrum access, as well as the underlay CR based spectrum sharing and describes the parameters that form the basis of our comparison. The system model for the interweave CR and the underlay CRs is described in Section V. Section VI quantifies the achievable rates of both the interweave CR and of the underlay CR. Section VII provides our comparison results of the interweave CR against the underlay CR and provides rules of thumb for the feasibility of the interweave CR. In Section VIII an OFDM scenario is considered and characterized. Finally, in Section IX we provide design guidelines, concluding remarks and open problems for future research. For convenience, we summarize the various abbreviations and symbols used in Tables I and II, respectively.

TABLE I: Abbreviations

Abbreviation	Expansion
PU	Primary User
SU	Secondary User
PUT	PU transmitter
SUT	SU transmitter
PUR	PU receiver
SUR	SU receiver
CR	Cognitive radio
CRN	Cognitive radio network
SNR	Signal to noise ratio
SNR_p	SNR at PUR
SNR_s	SNR at SUR
FCC	Federal Communications Commission
AWGN	Additive white Gaussian noise
BER	bit error rate
DSA	Dynamic spectrum access
OSA	Opportunistic spectrum access
SS	Spectrum sharing
ED	Energy detection
MSCD	Magnitude squared coherence detection
BAC	Binary asymmetric channel
Bern	Bernoulli
TR	Transmitter to receiver
TT	Transmitter to transmitter
CDF	cumulative distribution function
fa	false alarm
md	missed detection
$faed$	false alarm energy detection
$mdmsc$	missed detection magnitude squared coherence
$famsc$	false alarm magnitude squared coherence
$mded$	missed detection energy detector

II. Overview of Cognitive Radio Solutions

Cognitive Radio (CR) techniques have been conceived for mitigating the problem of spectrum scarcity by exploiting that some part of the spectrum remains largely unoccupied, whilst some other parts may be overcrowded. The problem arises because of the prevalent 'command and control' policy of the regulatory bodies around the world, where an operator/user - namely a licensed user - purchases a spectrum band from the authorities and hence obtains the sole rights to transmit

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TABLE II: List of symbols

Variable	Description
p	Probability of primary inactivity
p_{md}	Probability of missed detection
p_{fa}	Probability of false alarm
p_{mded}	p_{md} for Energy Detector
p_{faed}	p_{fa} for Energy Detector
p_{mdmsc}	p_{md} for Magnitude squared coherence Detector
p_{famsc}	p_{fa} for Magnitude squared coherence Detector
a	Average interference coefficient from PU to SU
b	Average interference coefficient from SU to PU
H_{pp}	Instantaneous interference coefficient from PU to PU
H_{ps}	Instantaneous interference coefficient from PU to SU
H_{ss}	Instantaneous interference coefficient from SU to SU
H_{sp}	Instantaneous interference coefficient from SU to SU
P_p	Average transmit power constraint of the PU
P_s	Average transmit power constraint of the SU
SNR_p	$10 \log P_p$
SNR_s	$10 \log P_s$
X_p	PU transmitted codeword/signal
X_s	SU transmitted codeword/signal
Y_p	PU received codeword/signal
Y_s	SU received codeword/signal
Z_p	AWGN at PU receiver
Z_s	AWGN at SU receiver
S_p	State of PU transmission
S_s	Equivalent noise at the PU receiver
Z_{se}	Equivalent noise at the SU receiver
C_{pi}	Achievable rate bound of the PU for the interweave CR
C_{si}	Achievable rate bound of the SU for the interweave CR
C_{pu}	Achievable rate bound of the PU for the underlay CR
C_{su}	Achievable rate bound of the SU for the underlay CR
R_{pi}	Achievable rate of the PU for the interweave CR
R_{si}	Achievable rate of the SU for the interweave CR
R_{pu}	Achievable rate of the PU for the underlay CR
R_{su}	Achievable rate of the SU for the underlay CR
$\mathbb{E}_H(\bullet)$	Expected value of $\bullet$ wrt to the distribution of H

in that band in a particular geographical location. The idea of cognitive radio is to change the current policy by suggesting ideas that allow an unlicensed or secondary user to coexist with the licensed user provided that the reception quality requirements of the licensed user are still satisfied. *For the sake of achieving this goal, the SU should be equipped with Dynamic Spectrum Access (DSA) techniques. Four different DSA approaches have been conceived for Cogntive Radio in the literature [12], [13]*, as shown in Fig. 1, which are briefly described as follows:

- *The Commons model:* In this approach the spectrum is distributed amongst all users equally with no preference to any particular user. Each user is expected to adhere to some *etiquette* and self-regulate itself to avoid imposing excessive interference.
- *The Exclusive Use model:* This model provides exclusive use of the spectrum to the licensed user. However, this model still provides a degree of flexibility for the licensed user, who is at liberty to lease it to unlicensed users in exchange for any potential remuneration or for other gains. *This approach has been discussed in [14], [15] in the form a Stackelberg's game and in [16] in the form of a Bertrand game.*
- *Opportunistic spectrum access:* Unlike the above-mentioned exclusive use model, this approach allows the unlicensed user to make use of any available opportunity arising, because the licensed user is not transmitting - provided that these opportunities are perfectly identified. Naturally, practical imperfect sensing has to be used, which has to be sufficiently reliable for maintaining the quality-of-service (QoS) requirement of the licensed user. This approach is also termed as the interweave approach in the literature. In this paper we study this specific approach in detail for those practical cases, which are unable to identify the opportunities perfectly.
- *Spectrum Sharing:* This approach was conceived for simultaneous transmission of both the licensed and of the unlicensed user, provided that the unlicensed user respects the required QoS stated by the licensed user. This can be achieved in two ways, namely by using the (i) Underlay philosophy, where the unlicensed user either maintains the interference below the maximum tolerable interference and transmits at a rate that allows the licensed user to cancel the interference, so that the outage constraint of the licensed user is satisfied, (ii) Overlay regime, where the unlicensed user overhears the licensed user's message. The unlicensed user then performs sophisticated coding at its transmitter for protecting against the interference caused by the licensed user at its receiver so as to improve its performance.

The commons model and the exclusive use models are also mentioned here despite the fact that the usual focus on opportunistic spectrum access and spectrum sharing.

Next we briefly outline the various techniques developed by CR researchers.

A. CR Techniques

Numerous techniques have been proposed to the address the various issues that arise in cognitive radio research. For a detailed review the motivated readers are referred to [7], [17]–[32] and the references therein. They are as summarized in Fig. 2.

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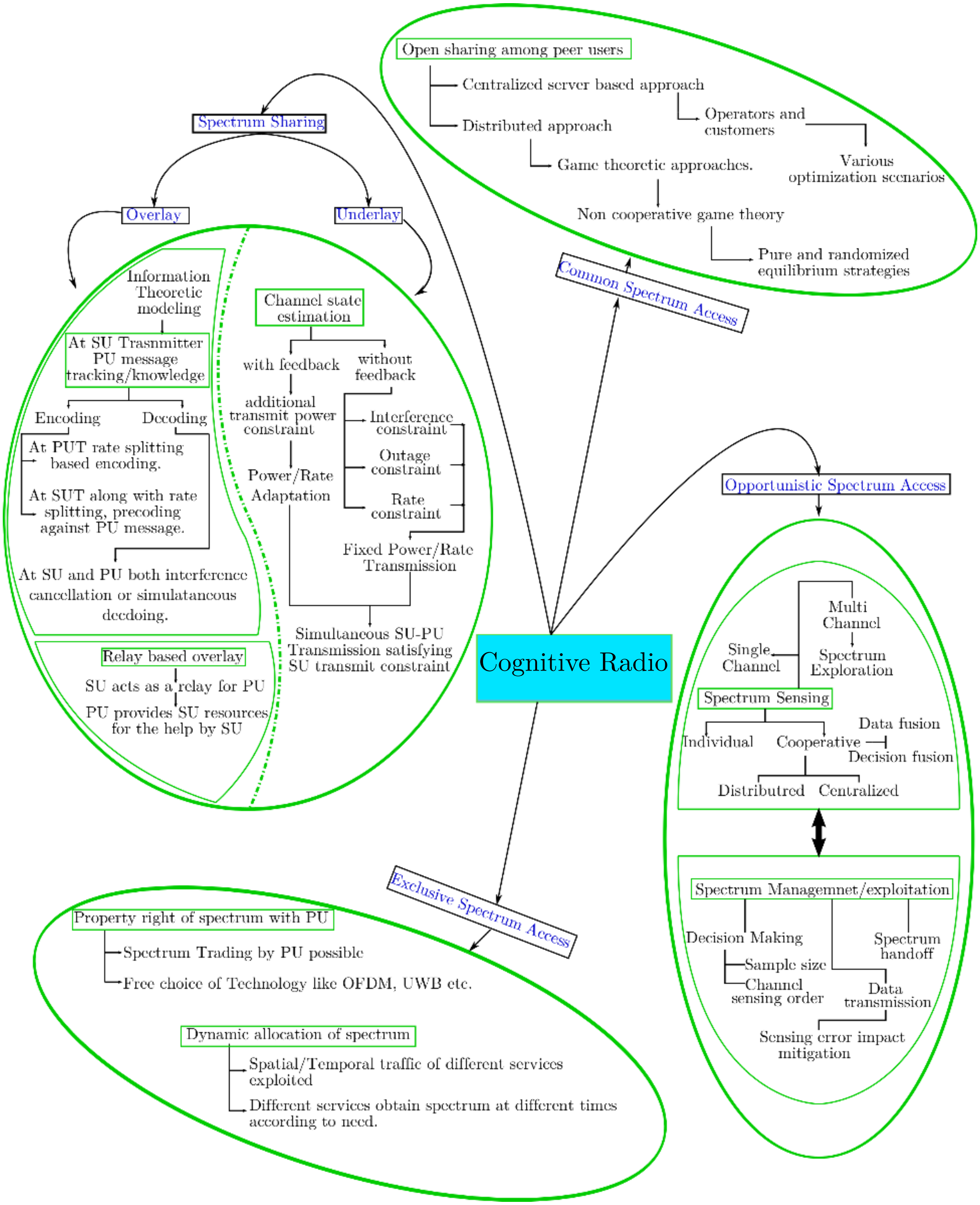

Fig. 1: An overview of the approaches in Cognitive Radio

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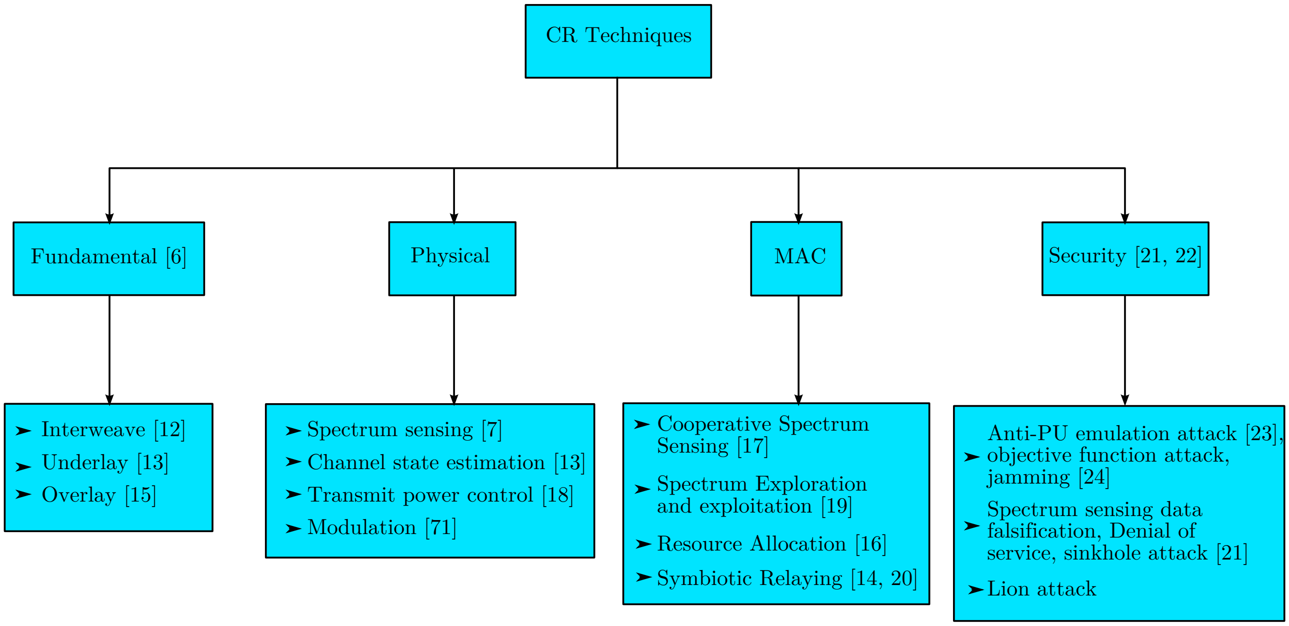

Fig. 2: A summary of CR Techniques with relevant references

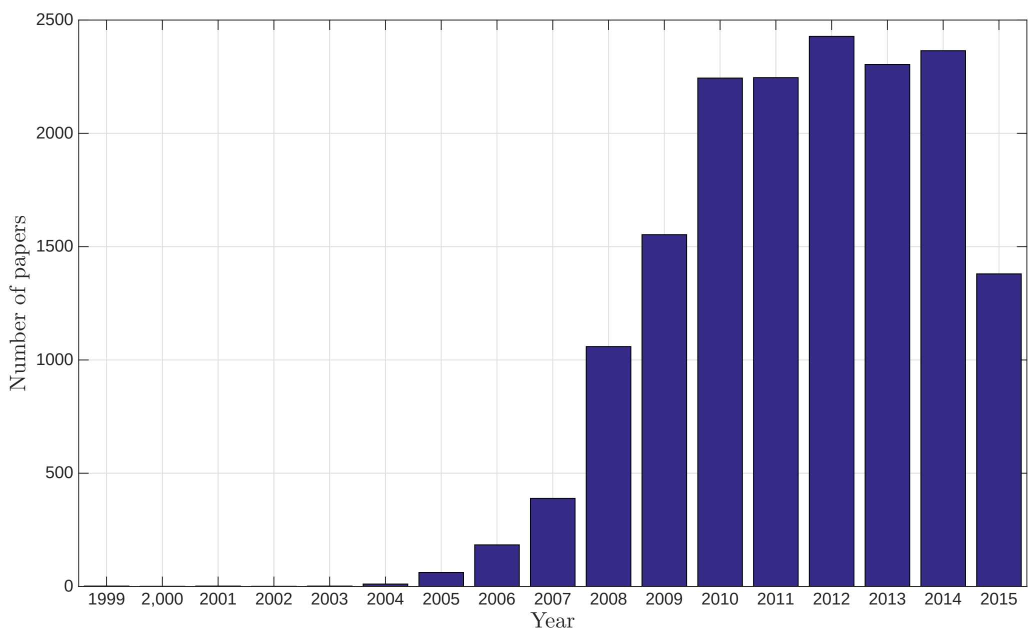

Fig. 3: The number of papers on CR per year from 1999-2015, as per IEEE explore database. The list of 2015 is still on the increase.

B. CR research

The numerous techniques that have been proposed for CR. A key word search for "cognitive radio" in the IEEE explore database yielded a total of more than 16,000 papers that are related to CR. The associated year-by-year distribution is shown in Fig. 3.

We capture these contributions in TABLE III at a glance, whith a special emphasis on those that have had significant impact on the various topics in CR over the years since 1999, when Mitola [2] proposed the concept of CR.

As it becomes evident from the above time-line of research in CRNs, it is but natural that parallel efforts were also made to standardize the best solutions, so that the installation and deployment of devices that rely on the concept of CR and DSA results in indsutry-wide compatibility. In the next section we capture these standardization activities that are related to CR.

III. Standardization Activities in Cognitive Radio

In this section we briefly describe the numerous standardization activities that have been undertaken in the year 2000 or so. Some of these directly address the core issues of CR systems, such as spectrum sensing, dynamic frequency selection, etc. By contrast, others deal with issues that are also of substantial interest to cognitive radio systems, such as their coexistence and transmit power control issues. We provide a brief survey of the standardization activities on cognitive radio by various organizations, as seen in TABLEs IV,V,VI.

Firstly, in TABLE IV we describe the development of the standards undertaken by the IEEE Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC). These activities are related to dynamic spectrum access based radio systems and networks, which were motivated by improving the spectral efficiency. These led to the development of new techniques and methods for DSA that include the management of the radio transmission interface. These standards have also addressed the issue of compatibility and coordination of diverse wireless technologies that include network management and information sharing. In what follows we briefly describe the standardization activities of these working groups over the years.

The 1900.1-2008 standard provides the definitions and explains the key concepts in the spectrum management, as well as in cognitive radio policy-defined radio, adaptive and software defined radio and related technologies, while also describing how these technologies are interrelated. The 1900.2-2008 recommended practice describes the beneficial potential of coexistence between two users either in the same or indifferent bands. In order to facilitate distributed decision making, the 1900.4-2009 standard defines building blocks, namely (i) network resource managers, (ii) device resource managers and (iii) the specific information to be exchanged between these building blocks. The IEEE 1900.5 standard defines the policy language (PL) requirements and policy architecture for policy based DSA radio systems. The 1900.5.1 defines vendor-independent PL for managing the functionality and behavior of DSA systems. Furthermore, 1900.5.2 defines a sophisticated strategy for modeling spectrum 'consumption'. The IEEE 1900.6 standard defines the interfaces and data structures that are required for exchanging the sensing-related information to improve the interoperability between the spectrum-sensors and the client of different manufacturers. This was followed by the IEEE 1900.6.1 amendment, where procedures, protocols and message format specifications have been provided for the exchange of sensing-related data, control information and configuration information between spectrum-sensors and their clients. The IEEE 1900.7 working group aims for specifying the radio interface that includes the MAC and PHY layers of white space DSA-aided radio systems supporting both fixed and mobile operations in white space frequency bands. For a detailed description of the scope of each standard the reader is referred to the TABLE IV.

The first standard motivated by the existence of the CR technology and related to the coexistence of unlicensed wireless devices with licensed TV broadcasting led to the IEEE 802.22 standards and to the associated recommended practices. In what follows we briefly discuss this standardization activity. The IEEE 802.22-2011 standard defines the Physical (PHY) and Medium Access Control (MAC) layer specifications by describing the policies and procedures that are to be followed while operating in the TV band, namely in the 54 MHz to 862 MHz. Simultaneously, the goal of the IEEE 802.22.1-2010 standard is that of protecting the low power licensed users (PUs) operating in the TV band from the harmful interference imposed by the license-exempt (SUs) devices. The recommended practice of IEEE 802.22.2-2012 standards establishes the engineering practices involved in the installation and deployment of IEEE 802.22 systems. Spectrum characterization and occupancy sensing (SCOS) are defined in the IEEE 802.22.3-2014 family of standards. In the first amendment, namely in IEEE 802.22a-2011 a new clause is defined in the existing 802.22 standard for the management and control plane interfaces as well as for the procedures to be obeyed for operation in the TV band. Furthermore, the amendment IEEE 802.22b-2011 specifies an alternative PHY and MAC for operation in the very high frequency (VHF)/ ultra high frequency (UHF) bands. For a detailed description of the scope of each standard the interested reader is referred to TABLE V.

Finally, some further standardization efforts undertaken by different WGs are mentioned in TABLE VI. Most of these activities are related to the coexistence issues in TV white spaces, as detailed in 802.19.1-2014, 802.15.4m-2014, 802.11af-2013, ECMA 392, while 802.11h-2003 discusses dynamic frequency selection and transmit power control in the 5 GHz band in Europe. For details of the scope of these standards please refer to TALE VI.

IV. Opportunistic Spectrum Access, Spectrum Sharing and the basis of comparison

The parameters that form the basis of our comparison will be discussed immediately after describing both the interweave and the underlay CR philosophy. The readers are also referred to Table III where a brief history of the achievements over the past decade and a half have been enlisted.

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TABLE III: Time-line of important contributions in CR.

Year	Contribution
1999	Mitola introduced the idea of an intelligent radio and coined the term cognitive radio in [2]. Also, he proposed the future research on identifying how cognitive radios learn best about the internal tuning of parameters and external structuring of the radio environment.
2002	FCC's Spectrum-Policy Task Force [1] reported the shortcomings of "command and control" policy by highlighting the spectrum imbalance that prevailing amongst the various bands.
2004	Sahai *et. al.* proposed the fundamental limits for detection under noise uncertainty in [33]. Propose transmission on known pilots for improved performance. Meanwhile Cabric *et. al.* described the implementation issues associated with spectrum sensing in [34] while mentioning the use of matched filter, energy and cyclo-stationary feature based detectors for spectrum sensing. They also suggested the use of cooperation for better performance
2005	Haykin described the cognitive radio functionality and the steps involved in the so called cognitive cycle in [3]. A real time test-bed on a multi-FPGA emulation engine for experiments at the PHY and link layer were carried out in [35]. Simultaneously, the essential features of the first worldwide standard, IEEE 802.22, based on CR were described in [36].
2006	First attempt to characterize the fundamental limits for overlay based CR was made in [37]. Meanwhile, the first spectral occupancy studies were reported in [38] that justified the idea of CR. Initial attempts to design MAC protocols for spectrum sharing networks were carried out in [39]. Design aspects of a software defined radio were described in [40] and for UWB cognitive radio were done in [41]
2007	Gastpar studied in [42], the capacity of multi transmitter channels with receiver side constraints for spectrum sharing. Concurrently, Ghasemi and Sousa studied the fundamental limits for spectrum sharing in fading environments in [43] where they showed that fading can be boon under certain conditions. A decentralized MAC design for opportunistic spectrum access for ad-hoc network that utilizes a stochastic decision theoretic approach was proposed in [44] by Zhao *et. al.*. Simultaneously in [39], a social-optimal formulation for the centralized approach and a game theoretic formulation for a decentralized approach was considered to model and optimize the trade-off between the interference temperature constraint for the PU and quality-of-service for the SU. Machine learning based methods were first proposed in [45] where a generic model for cognitive radio with a learning engine was proposed. Ganesan and Li demonstrated in [46], [47], a cooperation strategy that employs relaying thereby exploiting the spatial diversity to improve the spectrum sensing performance. Jafar *et. al.* incorporate the ideal sensing into capacity calculations and describe the notion of distributed spectral activity in [17].
2008	Correlation among cooperating spectrum sensors with a decision fusion approach was considered in [48] where a linear quadratic fusion strategy is proposed and compared to the linear fusion strategy. Embedding a cylco-stationary signature in the PU signal to shorten the sensing duration was advocated in [49]. A model for aggregate interference at the PU imposed by a group of SU is expressed in terms of the system parameters of a sensing-based CR network in [50]. A novel multi-antenna approach to optimize the trade-off between the SU transmission rate and the SU transmit power constraint was proposed in [51]. In [52] a cross layer framework is proposed that integrates the spectrum sensing and packet scheduling at the MAC layer that considers MAC layer queuing. In [53] the idea of cognitive network economics and pricing was introduced. One of the first papers [54] on solving a security issue, namely the problem of PU emulation by a SU proposes a transmitter verifications scheme that can distinguish the PU signal from that of an attacker. Optimizing the trade-off between sensing duration and achievable throughput for energy detection was demonstrated in [55]. A linear decision fusion approach that maximizes the probability of detection for a given probability of false alarm was proposed in [56].
2009	Proposing a cognitive MAC involving multiple independent and correlated channels, [57] proposed an optimal order in which the channel sensing should be performed. The discussion of the first standard for wireless regional area networks was provided in [58], which also included comparison of this standard with IEEE 802.16e standard. Modeling a fading environment for CR networks, [59] developed an optimal power allocation strategy and described the ergodic and outage capacities. In [60] random matrix theory is used to obtain probability distribution of the test statistics for spectrum sensing, which are obtained using the maximum, minimum and average eigenvalues.
2010	An improved Energy Detector was proposed in [61] where, the traditional squaring operation of signal amplitude is replaced with an arbitrary positive power operation. Analysis of the ergodic capacity of the SU for the underlay, the overlay and the hybrid for a single user case was performed in [62]. Neural networks were used in [63] to predict the availability of spectrum for the SU. Li and Han addressed the issue of malicious SUs that deliberately send false reports to gain PU spectrum access and develop a defense strategy against PU emulation attack in [64], [65] respectively. Application of CR concepts in femtocell networks envisioning a multi-tired opportunistic spectrum access in the next generation of cellular networks was demonstrated in [66]. A comprehensive review of the standardization activity in cognitive radio and dynamic spectrum access focusing on IEEE P1900 and IEEE SC41 while also shedding light on the relation of these standards is provided in [67]. Ghosh *et. al.* proposed a statistical model for spectrum occupancy over time and frequency domain [68] that is motivated by actual measurements. Capacity and BER analysis for underlay based CR systems was provided in [69] where imperfect channel state were assumed.
2011	Rabbachin *et. al.* in [70] used the theory of truncated stable distributions to model the aggregate interference caused to a PU in a CR network. Addressing the drawbacks of the Poisson modeling for PU activity Canberk *et. al.* in [71] present a new model based on first-difference filter clustering and temporal correlation statistics. Exploration, exploitation and competition for CR MAC using tools of game theory that aim to maximize the total throughput was proposed in [72]. An improvement on the ergodic and capacity of spectrum sharing cognitive radio resulting from simultaneous sensing and data transmission was reported in [73]. In [74] the authors proposed a two-level MAC strategy where, in the first level the PU detection probability is maintained so as to satisfy the PU and in the second level the SU uses two sets of protocols to maximize it rate in a random access setting.
2012	Ergodic capacity for a spectrum sharing cognitive radio under imperfect channel state assumption was quantified in [18]. In [75] the authors design protocols for establishing pairwise rendezvous (communication links) that enables every node pair to rendezvous with every available channel in decentralized CR networks. Zhang *et. al.* assumed imperfect channel state information in a CR relay network to provide the outage probability derived over Rayleigh fading channel in [76].
2013	In [77] Bao *et. al.* assumed a spectrum sharing scenario that consists of a SU sender, multiple SU relays, a SU destination and a PU receiver for which, they derive closed-form expressions for the outage probability (OP), average symbol error probability (SEP), and ergodic capacity of the SU network. Park *et. al.* in [78] propose an energy-harvesting SU transmitter with the objective of establishing the spectrum sensing rule that would maximize the expected total throughput where the energy is available only causally and collisions are to be kept below a threshold.
2014	Cognitive radio capability of spectrum sensing is invoked in [79] at the access points connected to a femtocell so as to avoid the severe interference caused by the micro cell base station. Gains achieved through cooperation in the form of relaying of the PU data via the SU networks was demonstrated in [19], [80].
2015	As an application of cognitive radio capability, in [81] a routing protocol for the advanced metering infrastructure that enhances the already standardized routing protocol for lossy and low power networks. Energy efficiency is optimized in [82] within the underlay CR scenario where the channel state information knowledge is imperfect albeit the error in estimation is bounded.

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TABLE IV: IEEE Standards relating to cognitive radio: The 1900 series.

Standard	Title	Scope
1900.1-2008	IEEE Standard Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management Amendment 1: Addition of New Terms and Associated Definitions	This standard provides definitions and explanations of key concepts in the fields of spectrum management, cognitive radio, policy-defined radio, adaptive radio, software-defined radio, and related technologies. The document goes beyond simple, short definitions by providing amplifying text that explains these terms in the context of the technologies that use them. The document also describes how these technologies interrelate and create new capabilities while at the same time providing mechanisms supportive of new spectrum management paradigms such as dynamic spectrum access.
1900.1a-2012	IEEE Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence Between Radio Systems	An amendment to the published IEEE Std 1900.1-2008 to add new terms and definitions.
1900.2-2008	IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks	This recommended practice will provide technical guidelines for analyzing the potential for coexistence or in contrast interference between radio systems operating in the same frequency band or between different frequency bands.
1900.4-2009	IEEE Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks	The building blocks comprising (i) network resource managers, (ii) device resource managers, and (iii) the information to be exchanged between the building blocks, for enabling coordinated network-device distributed decision making that will aid in the optimization of radio resource usage, including spectrum access control, in heterogeneous wireless access networks are defined. The standard is limited to the architectural and functional definitions at a first stage.
1900.4.1-2013	IEEE Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks	Interfaces and service access points defined in IEEE Std 1900.4TM are described in detail, enabling distributed decision making in heterogeneous wireless networks and obtaining context information for this decision making.
1900.4a-2011	IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks Amendment 1: Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands	Additional components of the IEEE 1900.4 system are defined in this amendment to enable mobile wireless access service in white space frequency bands without any limitation on used radio interface (physical and media access control layers, carrier frequency, etc.).
1900.5-2011	IEEE Standard for Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems.	The IEEE Std 1900.5TM-2011 standard defines a vendor-independent set of policy-based control architectures and corresponding policy language requirements for managing the functionality and behavior of dynamic spectrum access networks. The scope of the IEEE 1900.5 WG is set by this standard and assigned project authorization requests (PAR) of which there are currently two (P1900.5.1 and P1900.5.2).
P1900.5.2	Method for Modeling Spectrum Consumption	This standard defines an analytical framework of necessary modeling constructs which can be used to express the boundaries of spectrum consumption by any transmitting or receiving device. The standard documents a machine readable data exchange schema for the purpose of transferring these spectrum consumption models (SCM) between automated systems. This standard serves as a loose coupler for the spectrum management enterprise by providing all spectrum communities of interest a common way to express spectrum consumption. Further, the standard enables the creation of algorithms that can rapidly evaluate compatibility among SCMs and quickly perform spectrum management tasks such as finding reuse opportunities or optimizing spectrum assignments to maximize spectrum utilization. To achieve this goal, the SCMs must be sufficient in that the algorithms can perform these functions using the models alone without dependence on external databases of system or environmental characteristics. This standard defines a vendor-independent generalized method for modeling spectrum consumption of any type of use of RF spectrum and the attendant computations for arbitrating the compatibility among models. The methods of modeling are chosen to support the development of tractable algorithms for determining the compatibility between models and for performing various spectrum management tasks that operate on a plurality of models. The modeling methods are exclusively focused on capturing spectrum use but are defined in a schema that can be joined with other schemata related to spectrum management.
P1900.5.1	Standard Policy Language for Dynamic Spectrum Access Systems	The purpose of this standard is to define a policy language for inter-operable, vendor-independent control of Dynamic Spectrum Access functionality and behavior in radio systems and wireless networks. This standard defines the relationship of that policy language to the needs of at least the following constituencies: the regulator, the operator, the user, and the network equipment manufacturer.This standard defines a vendor-independent policy language for managing the functionality and behavior of dynamic spectrum access networks based on the language requirements defined in IEEE 1900.5 "Standard Policy Language Requirements and System Architectures for Dynamic Spectrum Access Systems".
1900.6-2011	IEEE Standard for Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems.	The interfaces and data structures required to exchange sensing-related information in order to increase interoperability between sensors and their clients developed by different manufacturers are defined in this standard. The logical interface and supporting data structures are defined abstractly without constraining the sensing technology, client design, or data link between sensor and client. It further elaborates on the service access points, service primitives, as well as generic procedures used to realize this information exchange, are defined by this standard.
1900.6a-2014	IEEE Standard for Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and Other Advanced Radio Communication Systems - Amendment 1: Procedures, Protocols, and Data Archive Enhanced Interfaces	Included in this amendment to IEEE Std 1900.6(TM) are procedures, protocols, and message format specifications for the exchange of sensing related data, control data, and configuration data between spectrum sensors and their clients. In addition, specifications for the exchange of sensing related and other relevant data and related interfaces between the data archive and other data sources have been added.
1900.7	IEEE Standard for Radio Interface for White Space Dynamic Spectrum Access Radio Systems Supporting Fixed and Mobile Operation	This standard specifies a radio interface including medium access control (MAC) sublayer(s) and physical (PHY) layer(s) of white space dynamic spectrum access radio systems supporting fixed and mobile operation in white space frequency bands, while avoiding causing harmful interference to incumbent users in these frequency bands. The standard provides means to support P1900.4a for white space management and P1900.6 to obtain and exchange sensing related information (spectrum sensing and geolocation information).

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TABLE V: IEEE Standards relating to cognitive radio: The 802.22 series.

802.22-2011	IEEE standard for Cognitive wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands	This standard specifies the air interface, including the cognitive medium access control layer (MAC) and physical layer (PHY), of point-to-multipoint wireless regional area networks comprised of a professional fixed base station with fixed and portable user terminals operating in the VHF/UHF TV broadcast bands between 54 MHz to 862 MHz.
802.22.1-2010	IEEE Standard for Information Technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements Part 22.1: Standard to Enhance Harmful Interference Protection for Low-Power Licensed Devices Operating in TV Broadcast Bands	This standard defines the protocol and data formats for communication devices forming a beaconing network that are used to protect low-power, licensed devices operating in television broadcast bands from harmful interference generated by license-exempt devices, such as Wireless Regional Area Networks (WRAN), intended to operate in the same bands. The devices being protected are devices licensed as secondary under Title 47, Part 74, Subpart H in the USA and equivalent devices in other regulatory domains
802.22.2-2012	IEEE Recommended Practice for Information Technology - Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN) - Specific requirements - Part 22.2: Installation and Deployment of IEEE 802.22 Systems	Engineering practices for the installation and deployment of IEEE 802.22 systems are discussed in this recommended practice.
802.22.3-2014	IEEE Standard for Spectrum Characterization and Occupancy Sensing	This Standard defines a Spectrum Characterization and Occupancy Sensing (SCOS) System. It specifies measurement parameters and device behaviors. It includes protocols for reporting measurement information that enable coalescing the results from multiple such devices. The standard leverages interfaces and primitives that are derived from IEEE Std. 802.22-2011, and uses any on-line transport mechanism available to achieve the control and management of the system. Interfaces and primitives are provided for conveying value added sensing information to various spectrum sharing database services. This standard specifies a device operating in the bands below 1 GHz and a second device operating from 2.7 GHz to 3.7 GHz.
802.22a-2011	IEEE Standard for Information Technology–Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)–Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands Amendment: Management and Control Plane Interfaces and Procedures and enhancement to the Management Information Base (MIB)	This amendment defines a new clause for Management and Control Plane Interfaces and Procedures to the existing IEEE Std 802.22-2011 for operation in VHF/UHF TV broadcast bands between 54 MHz and 862 MHz. The Management Information Base (MIB) structure enhancements include changes to comply with the ASN.1 format and support for the new clause. Modifications to the existing clause on Primitives for Cognitive Radio Capabilities to align it with the content in the MIB clause and the new clause are also defined.
802.22b-2011	IEEE Standard for Information Technology–Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)–Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands Amendment: Enhancement for Broadband Services and Monitoring Applications	This amendment specifies alternate Physical Layer (PHY) and necessary Medium Access Control Layer (MAC) enhancements to IEEE Std. 802.22-2011 for operation in Very High Frequency (VHF)/Ultra High Frequence (UHF) TV broadcast bands between 54 MHz and 862 MHz to support enhanced broadband services and monitoring applications. The standard supports aggregate data rates greater than the maximum data rate supported by the IEEE Std. 802.22-2011. This standard defines new classes of 802.22 devices to address these applications and supports more than 512 devices in a network. This standard also specifies techniques to enhance communications among the devices and makes necessary amendments to the cognitive, security & parameters and connection management clauses. This amendment supports mechanisms to enable coexistence with other 802 systems in the same band.

A. *Opportunistic Spectrum Access - Interweave*

It has been observed that while “some” parts of the electromagnetic spectrum remain occupied, most of the popular licensed band is underutilized. Hence there are plenty of opportunities for an unlicensed SU to enhance the achievable data rates by efficiently exploiting the underutilized part of the spectrum. Therefore substantial efforts have been dedicated to developing techniques for assisting the SU, either working in isolation [7]–[9] or cooperating with other SUs [22], [46], [83], to identify and exploit the available spectral opportunities in the licensed band [84]–[87] without affecting the PU. However, a major associated difficulty is the imperfect nature of spectrum sensing. These imperfections primarily arise owing to (i) real-time decision making, which limits the number of PU signal samples considered (ii) the PU's signal is subjected to fades, hence spectrum sensing is carried out at low average SNRs and (iii) Noise and interference effects. Fortunately, co-operative spectrum sensing is capable of mitigating these effects. However, in such a scenario the overhead and complexity of spectrum sensing increases for each additional co-operating CR. Since these imperfections have been neglected in the literature be totally avoided, Section IV of our paper derives the achievable rates of the interweave CR as a function of these spectrum sensing errors.

There is a paucity of literature [88], [89] quantifying the impact of sensing errors on the performance of such systems. In [88] an OFDM scenario was considered. However, the focus was on analysing the impact of the sensing errors on the BER, rather than on the achievable rate. Hence, we propose to close this open problem under the assumption that the spectrum sensing link between the PU Transmitter and the SU transmitter is fast fading.

B. *Spectrum Sharing - Underlay*

There are different notions of spectrum sharing. One of the most popular version is the underlay CR based spectrum sharing [10], [6], [43], [62], [90]–[95]. In the underlay CR regime the basic cognition hinges on near-instantaneously estimating the interfering link gains at least at the receivers, but in the advanced case also at the transmitters. Moreover, the traditional approach of the underlay CR introduces a parameter referred to as the *interference temperature* that limits the aggregate

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TABLE VI: IEEE Standards relating to cognitive radio: Miscellaneous efforts

802.19.1-2014	IEEE standard for information technology-telecommunications and information exchange between systems - Local and Metropolitan Area Networks - Specific Requirements: TV White Space Coexistence Methods	Radio technology independent methods for coexistence among dissimilar television band devices (TVBDs) and dissimilar or independently operated networks of TVBDs are specified in this standard.
802.15.4m-2014	IEEE Standard for Local and metropolitan area networks - Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) - Amendment 6: TV White Space Between 54 MHz and 862 MHz Physical Layer	In this amendment to IEEE Std 802.15.4(TM)-2011, outdoor low-data-rate, wireless, television white space (TVWS) network requirements are addressed. Alternate physical layers (PHYs) are defined as well as only the medium access control (MAC) modifications needed to support their implementation
802.11af-2013	IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Television White Spaces (TVWS) Operation	Enhancements to the IEEE 802.11 physical layers (PHYs) and medium access control (MAC) sublayer to support operation in the white spaces in television bands are defined.
ECMA-392-2012	MAC and PHY for Operation in TV White Space	This Standard specifies a medium access control (MAC) sub-layer and a physical (PHY) layer for personal/portable cognitive wireless networks operating in TV bands. This Standard also specifies a MUX sublayer for higher layer protocols. This Standard specifies a number of incumbent protection mechanisms which may be used to meet regulatory requirements.
802.15.2-2003	Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Bands	This recommended practice addresses the issue of coexistence of wireless local area networks and wireless personal area networks. These wireless networks often operate in the same unlicensed band. This recommended practice describes coexistence mechanisms that can be used to facilitate coexistence of wireless local area networks (i.e., IEEE Std 802.11b1999)and wireless personal area networks (i.e., IEEE Std 802.15.1-2002)
802.11h-2003	Dynamic spectrum and transmit power management extensions in the 5 GHz band in Europe	This amendment specifies the extensions to IEEE 802.11TM for wireless local area networks (WLANs) providing mechanisms for dynamic frequency selection (DFS) and transmit power control (TPC) that may be used to satisfy regulatory requirements for operation in the 5 GHz band in Europe
802.16.2-2004	Coexistence of Fixed Broadband Wireless Access Systems	IEEE Std 802.16.2 provides the IEEE recommended practice for local and metropolitan area networks with regard to the coexistence of fixed broadband wireless access systems. The recommended practice provides recommendations for the design and coordinated deployment of fixed broadband wireless access systems in order to control interference and facilitate coexistence. It analyzes appropriate coexistence scenarios and provides guidance for system design, deployment, coordination, and frequency usage. It generally addresses licensed spectrum between 2 GHz and 66 GHz, with a detailed emphasis on 3.5 GHz, 10.5 GHz, and 23.5-43.5 GHz.

interference that a group of SUs is allowed to impose on any PU, so that despite the interference, the PU still achieves its target data rate. This interference temperature limit can either be imposed as a peak interference constraint or as an average interference constraint. These constraints translate to either peak transmit power or to an average transmit power constraint at the transmitters. Some contributions in the literature do consider information theoretic channel models [90], however, they do so for the sake of characterizing the rate penalty that the PU faces due to the SU's transmission. Some other studies [95], [10] impose a constraint on the SU's transmission so as to avoid violating the minimum tolerable PU outage probability.

Since the objective of our work is to compare the achievable rate of the interweave CR against that of the underlay CR in terms of the basic channel parameters both in terms of the SU rate and the sum rate, we rely on the achievable rates that are derived for the underlay CR in [11]. These rates are based on a similar system model to ours and assists us in our comparison. The main reason for adopting these rates is that in quantifying the achievable rates no new parameter is introduced and the only constraint imposed on the SU is its rate constraint.

C. OSA - Interweave CR vs SS - Underlay CR

The Interweave and the underlay CRs constitute different approaches/solutions conceived for mitigating the underutilization of the radio spectrum. A natural question that arises is, which one should be preferred under what circumstances? Moreover, how does the variation of any parameter of interest affect this preference. A partial answer concerning the grade of cognition is provided in [6]. More detailed reflections are provided in [95], [96], where the basis of comparison is the outage that the PU suffers due to the SU's transmission. In contrast to this, we perform comparisons on the basis of the ergodic capacity of both the interweave CR as well as of the underlay CR as a function of the basic channel parameters and side information. To perform a more elaborate comparison and to seek answers to our questions, we have to be cognizant of the diverse circumstances and the parameters that lead to these. Therefore, in this contribution our comparisons are made with respect to the following fundamental parameters:

1) PU's free channel probability p, that is the probability that a channel is free from PU occupancy.
2) PU and SU average transmit power constraints P_p and P_s.
3) Average interference coefficients a for the PU-SU link and b for the SU-PU link.
4) Probability p_{fa} of false alarm and probability p_{md} of missed detection.

The basis of the comparison is to check the feasibility of opting for the interweave CR. We say that using the interweave CR is feasible for $p, P_p, P_s, a, b, p_{fa}$ and p_{md} or simply the interweave CR is feasible at a given SU rate, if the achievable SU rate is higher for the interweave CR than for the underlay CR. Similarly, we say that using the interweave CR is feasible for $p, P_p, P_s, a, b, p_{fa}$ and p_{md} or simply the interweave CR is feasible at a given sum rate, provided that the achievable sum rate is higher in the interweave CR than in the underlay CR.

In the next section we describe our system model for the interweave CR and develop the achievable rates in the presence of spectrum sensing errors.

V. System Model - Interweave

Let us consider an interweave CR system, where the PU is transmitting at random. Let p be the probability that the PU is not transmitting. *There are two types of links, namely (i) the PU transmitter to SU transmitter (PUT - SUT) link, (ii) the link of each transmitter to each receiver, namely the links (PUT-SUR, PUT-PUR, SUT-SUR and SUT-PUR). The SU senses the presence of the PU with the aid of spectrum sensing applied to the PUT - SUT link.* The spectrum sensing is assumed to be imperfect subject to the two basic types of sensing errors, namely to missed detection and to false alarm[1]. Let $S_p = \{0, 1\}$ represent the PUs state of transmission, with $S_p = 1$ indicating that the PU is transmitting. Let $S_s = \{0, 1\}$ be formulated as

$$S_s = \bar{S}_p\bar{Z}_1 + S_pZ_2,\ Z_1 \sim \text{ Bern}(p_{fa}),\ Z_2 \sim \text{ Bern}(p_{md}), \tag{1}$$

where, the probability p_{fa} of false alarm quantifies the probability that the PU is absent and yet the SU mistakenly deems it to be present. Similarly, the probability p_{md} of missed detection represents the probability that the PU is present and yet the SU deems it to be absent. Here, $Z_1 \sim \text{Bern}(p_{fa})$ denotes the Bernoulli distribution, namely the probability of $\{Z_1 = 1\} = p_{fa}$. *To verify (1), we observe that when $S_p = 1$, then $S_s = 1$ w.p. $PrZ_2 = 1$, which is p_{md}, i.e. $P[S_s = 1|S_p = 1] = Pr[Z_2 = 1]p_{md}$. Similarly, $P[S_s = 1|S_p = 0] = Pr[Z_1 = 0] = 1 - p_{fa}$.*

We may also derive a relationsjip for S_p in terms of S_s. Although, in physical reality S_p does not depend upon S_s, we can write the following.

$$S_p = 1,\ \text{either when } S_s = 0 \text{ or } S_s = 1, \tag{2}$$

implying that if the PU transmits, either the SU does not transmit due to correct detection, or alternatively, due to missed detection it decides to transmit. Similarly,

$$S_p = 0,\ \text{either when } S_s = 0 \text{ or } S_s = 1, \tag{3}$$

that is, when the PU does not transmit, the SU due to a false alarm does not transmit, or due to a opportunity detection transmits. Thus,

$$\begin{aligned} S_p = 1 \text{ w. p. } & \frac{Pr[S_p = 1]Pr[S_s = 1|S_p = 1]}{Pr[S_s = 1]} \\ &= \frac{(1-p)p_{md}}{(1-p)p_{md} + p(1-p_{fa})} \text{ if } S_s = 1 \text{ and} \\ S_p = 1 \text{ w. p. } & \frac{Pr[S_p = 1]Pr[S_s = 0|S_p = 1]}{Pr[S_s = 0]} \\ &= \frac{(1-p)(1-p_{md})}{(1-p)(1-p_{md}) + pp_{fa}},\ \text{if } S_s = 0. \end{aligned} \tag{4}$$

$$\begin{aligned} S_p = 0 \text{ w. p. } & \frac{Pr[S_p = 0]Pr[S_s = 0|S_p = 0]}{Pr[S_s = 0]} \\ &= \frac{ppfa}{(1-p)(1-p_{md}) + pp_{fa}} \text{ if } S_s = 0 \text{ and} \\ S_p = 0 \text{ w. p. } & \frac{Pr[S_p = 0]Pr[S_s = 1|S_p = 0]}{Pr[S_s = 1]} \\ &= \frac{p(1-p_{fa})}{(1-p)p_{md} + p(1-p_{fa})},\ \text{if } S_s = 1 \end{aligned} \tag{5}$$

We thus have, the following relationship

$$S_p = \bar{S}_s\bar{Z}_3 + S_sZ_4,\ Z_3 \sim \text{ Bern}(p_3),\ Z_4 \sim \text{ Bern}(p_4), \tag{6}$$

where

$$p_3 = \frac{pp_{fa}}{(1-p)(1-p_{md}) + pp_{fa}}$$

and

$$p_4 = \frac{(1-p)p_{md}}{(1-p)p_{md} + p(1-p_{fa})}.$$

This can be verified as follows. When $S_s = 1$, then $S_p = Z_4$ and when $S_s = 0$, then $S_p = \bar{Z}_3$. Then $S_p = 1$ w.p. $Pr[Z_4 = 1]P[S_s = 1] + Pr[Z_3 = 0]P[S_s = 0]$. *This probability can be verified to be $(1 - p)$. Similarly, we can verify for the case of $S_s = 0$.* The situation is shown in Fig. 4.

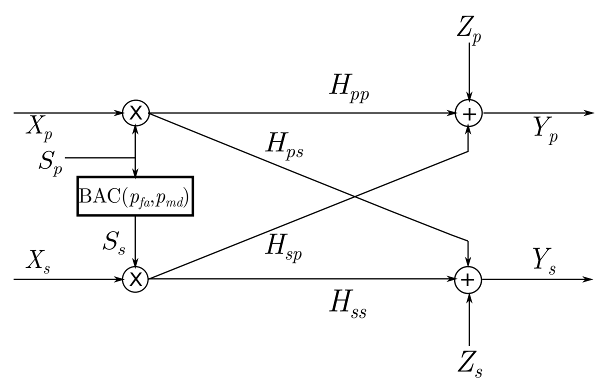

Fig. 4: The Interweave Cognitive Radio Channel with Imperfect Spectrum Sensing

[1]Spectrum sensing algorithms operating under practical real-time constraints will have non-zero sensing errors. Hence, our comparison have practical implications for designing realistic systems.

The output versus the input relationship is modelled as follows,

$$Y_p = S_p(H_{pp}X_p + H_{sp}X_sS_s) + Z_p, \quad (7)$$
$$Y_s = S_s(H_{ss}X_s + H_{ps}X_pS_p) + Z_s \quad (8)$$

where, Y_p and Y_s represent the output of the channel at the PU and SU respectively in response to the input X_p at the PU and X_s at the SU. Furthermore, Z_p and Z_s represent the zero-mean unit variance additive white Gaussian noise (AWGN). The fading coefficients H_{pp}, H_{sp}, H_{ps} and H_{ss} describe the fading links, as shown in Fig. 4. The magnitude of these coefficients satisfy $\mathbb{E}[|H_{pp}|^2] = 1$, $\mathbb{E}[|H_{sp}|^2] = b^2$, $\mathbb{E}[|H_{ps}|^2] = a^2$ and $\mathbb{E}[|H_{ss}|^2] = 1$, where a and b are positive real-valued numbers. The PU transmits its messages at a rate R_{pi}, while the SU transmits at a rate R_{si}.

The achievable rate of the interweave CR will depend upon the nature of fading on the transmitter to receiver (TR) links and the transmitter to transmitter (TT) link. If the fading on the TR link is slow, then we are unable to define the ergodic achievable rate. Hence, we assume that the TR fading process is a non-dispersive, independently fading uncorrelated ergodic process which implies that the channel coding can be performed over multiple coherence intervals for averaging out both the effects of fading and of the sensing states.

The TT link however, can be of two types (i) Slow fading, in which case the coherence interval on this link spans multiple coherence intervals on the TR links (ii) Fast fading or uncorrelated fading, in which case the coherence interval on all the links is assumed to be the same (which is possible by assuming coherence interval of the specific link that fades faster). In this paper the coherence interval on both the TT and TR links is assumed to be the same.

For the interweave CR, we also assume that the spectrum sensing is performed during each coherence interval of the TT link. This is necessary, because the presence of fading is one of the important reasons for sensing errors. Since the fading process is ergodic, the sensing process is also ergodic. This implies that in a fast-fading TT link, each of the four possible combinations of (S_p, S_s) in a coding block occur with probabilities close to their actual distribution. This observation will be exploited later to find an effective noise process, which is used for characterizing the ergodic achievable rate regions for the scenario, where the TT link undergoes uncorrelated fading.

A. System Model-Underlay

Similar to the interweave CR philosophy, in the underlay CR system the PU is transmitting at random. However, in contrast to the interweave CR, the SU transmits at a low rate so that the PU and SU can coexist, without the PU having to reduce its original single user rate rate. Hence, in the same notation as the interweave CR, the definition of S_p is the same and the SU state $S_s = 1$ with probability 1. The channel is shown in Fig. 5, which is modelled as follows, with the variables as describe in the case of the interweave CR,

$$Y_p = H_{pp}S_pX_p + H_{sp}X_s + Z_p, \quad (9)$$
$$Y_s = H_{ps}S_pX_p + H_{ss}X_s + Z_p. \quad (10)$$

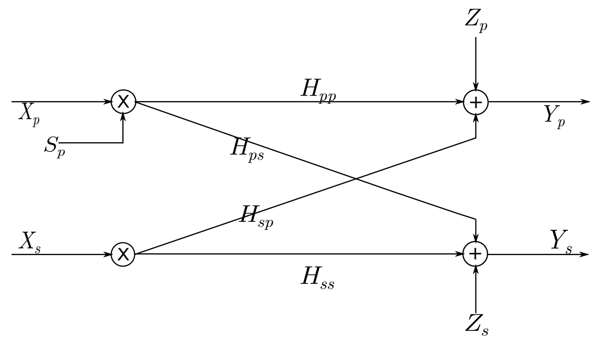

Fig. 5: Underlay Channel Scenario.

We declare that the PU receiver faces ergodically strong interference if $b > 1$, while it faces ergodically weak interference if $b \leq 1$. Similarly the SU receiver is deemed to face ergodically strong interference if $a > 1$ and ergodically weak interference, if $a \leq 1$.

The question that we ask now is what rate R_{pu} can be achieved by the SU subject to the fact that the PU rate R_{su} is the same as that in the original point-to-point scenario in the absence of interference from the SU? The answer to this may be derived from the Han-Kobayashi achievable region for the two-user interference channel. The two users of the interference channel in our case are the PU and the SU. The details of this will follow in Section V. But first in the next section, we will derive the achievable rates of the interweave CR with the aid of the system model mentioned above.

VI. Achievable rates of the Interweave Paradigm

A. Effective noise observation

In order to develop achievable rate expressions, we first derive the effective noise observed by both the PU and the SUs, where the TT link undergoes uncorrelated fading. Hence, coding is performed over multiple sensing instances and over the fading instances of the TR link. As observed above, since the fading process of the TT link is stationary and ergodic, the probabilities of missed detection and false alarm evaluated over a sufficiently high number of sensing instances tend to the actual probabilities. Hence, if we treat interference as noise in a given block, the effective noise at any of the receivers is an average of two noise processes. Hence, the effective noise is a linear combination of the two different noise distributions viz. (i) when there is only the standard AWGN (ii) and when there interference plus noise with the interference treated as noise.

Hence, we have the following baseband equations

$$Y_p = H_{pp}X_pS_p + Z_{pe}, \quad (11)$$
$$Y_s = H_{ss}X_sS_s + Z_{se}. \quad (12)$$

The distributions of Z_{pe} and Z_{se} are as described in Lemma 1.

***Lemma 1*:** The expected values of the effective noise Z_{pe} at the PU and Z_{se} at the SU is zero. The variances of Z_{pe} and

Z_{se} respectively are as follows

$$\text{var}[Z_{pe}] = 1 + p_{md}b^2 P_s \quad (13)$$

$$\text{var}[Z_{se}] = \frac{(1-p)p_{md}}{(1-p)p_{md} + p(1-p_{fa})} \quad (14)$$

Proof: We have by definition,

$$\text{var}[Z_{pe}] = \text{var}[H_{sp}S_pS_sX_s + Z_pS_p]. \quad (15)$$

Note that we are interested only in the scenario when $S_p = 1$ and hence according to (1) we have $S_s = Z_2$. Thus,

$$\begin{aligned}\text{var}[Z_{pe}] &= \text{var}[H_{sp}X_sZ_2] + \text{var}[Z_p] \\ &= \text{var}[H_{sp}X_s](\mathbb{E}[Z_2]^2 + \text{var}[Z_2]) + 1 \\ &= \text{var}[H_{sp}]\text{var}[X_s]\mathbb{E}[Z_2^2] + 1 \\ &= 1 + p_{md}b^2P_s. \end{aligned} \quad (16)$$

Following similar arguments we arrive at

$$\text{var}[Z_{se}] = \text{var}[H_{ps}S_pS_sX_p + Z_sS_s]. \quad (17)$$

Note that we are interested only in the scenario when $S_s = 1$ and hence according to (6) we have $S_p = Z_4$. Thus

$$\begin{aligned}\text{var}[Z_{se}] &= \text{var}[H_{ps}X_pZ_4] + \text{var}[Z_s] \\ &= \text{var}[H_{ps}X_p](\mathbb{E}[Z_4]^2 + \text{var}[Z_4]) + 1 \\ &= \text{var}[H_{ps}]\text{var}[X_p]\mathbb{E}[Z_4^2] + 1 \\ &= 1 + \frac{(1-p)p_{md}}{(1-p)p_{md} + p(1-p_{fa})}a^2P_p. \end{aligned} \quad (18)$$

■

Note that in practice the effective noise is not necessarily Gaussian. In fact we do not assume any specific distribution for H_{sp} and H_{ps}, although their statistical mean and variance is specified by our system model.

We now recall a result due to Pinsker and Ihara [97], which gives us a lower bound on achievable rate of a channel contaminated by a non-Gaussian noise. Let Z_{pg} be a Gaussian random variable with zero mean and a variance of $1+p_{md}b^2P_s$.

Lemma 2**:** Consider two channels with the same input X and that the noise of channel 1 is AWGN with a variance σ^2. The noise of channel 2 is not Gaussian, but the distribution has a zero mean and a variance of σ^2. If the capacity of the AWGN channel is denoted by C_g and that of the non-Gaussian channel is denoted by C_n, then we have $C_n \geq C_g$.

Next, using the above knowledge we formulate a simple achievable rate region.

B. Result I - Achievable rates for Interweave

In light of Lemma 2 we can state the following result for characterizing the achievable rates for the PU and the SU based on the effective noise as follows.

Theorem 1**:** The average ergodic achievable rates of the PU R_{pi} and that of the SU R_{si} derived for the channel model in (7) is given by,

$$R_{pi} \leq C_{pi}, \quad R_{si} \leq C_{si}, \quad (19)$$

where we have

$$C_{pi} = (1-p)\mathbb{E}_{|H_{pp}|}\left[\log\left(1 + \frac{H_{pp}^2P_p}{1+p_{md}b^2P_s}\right)\right] \quad (20)$$

$$C_{si} = \bar{p} \times \mathbb{E}_{|H_{ss}|}\left[\log\left(1 + \frac{H_{ss}^2P_s}{1 + \left(\frac{(1-p)p_{md}}{\bar{p}}\right)a^2P_p}\right)\right]. \quad (21)$$

where $\bar{p} = (1-p)p_{md} + p(1-p_{fa})$ is the unconditional probability of the SU transmitting.

Proof: Since, the interference is treated as noise and it is not removed by an interference canceller, only point-to-point scenarios are considered. Moreover, by exploiting of channels associated with causal state information at the receiver, we arrive at the achievable rate of the PU formulated as follows

$$\begin{aligned}R_{pu} &\leq I(X_p; Y_p|S_p, H_{pp}) \\ &= P(S_p = 1)I(X_p : Y_p|H_{pp}, S_p = 1) \\ &= (1-p)I(X_p; Y_p|H_{pp}) \\ &= (1-p)\mathbb{E}_{|H_{pp}|}\left[\log\left(1 + \frac{H_{pp}^2P_p}{1+p_{md}b^2P_s}\right)\right].\end{aligned}$$

Similarly, the achievable rate of the SU can be derived by noting that $P(S_s = 1) = (1-p)p_{md} + p(1-p_{fa})$. The distribution used for generating the signaling codebooks of the PU obeys $X_p \sim \mathcal{N}(0, P_p)$ while that of the SU obeys $X_s \sim \mathcal{N}(0, P_s)$. ■

Given this achievable rate expression, we now embark on analysing the effects of sensing errors.

C. Effect of sensing errors

Naturally, the achievable rate is expected to be reduced in the presence of sensing errors. To get a better understanding of how these errors affect the achievable rates, we plot the regions of the simultaneously achievable rates for a couple of spectrum sensing techniques, namely for an energy detector (ED) and for a magnitude squared coherence detector (MSCD). The probabilities of missed detection and false alarm for each of these techniques can be analytically described. For the energy detector, the probability of false alarm for an amplitude modulated PU signal is [98]:

$$p_{fa} = 1 - P\left(\frac{\tau_{ed}}{2}, L\right), \quad (22)$$

while the probability of missed detection is

$$p_{md} = Q_{\chi^2}\left(\tau_{ed}, 2L, \frac{MLP_s}{2\sigma^2}\right), \quad (23)$$

where τ_{ed} is the threshold of the ED, against which the test statistic is compared, while $N = ML$ is the number of samples used for ED, L is the number of overlapping segments of the data each having M samples. Here $\frac{P_s}{\sigma^2}$ is the average received SNR. By mathematical elimination of the variable τ_{ed} from (22) and (23), the relationship between p_{faed} and p_{mded} for

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the energy detector is derived as follows

$$p_{faed} = 1 - P\left(\frac{Q_{\chi^2}^{-1}\left(p_{md}, 2L, \frac{MLP_s}{2\sigma^2}\right)}{2}, L\right), \quad (24)$$

where $Q_{\chi^2}^{-1}(p, \nu, \delta)$ is the inverse non-central chi-square distribution function having ν degrees of freedom and having the positive non-centrality parameter δ evaluated at probability p, while $P(a, x)$ in (24) is the lower incomplete Gamma function.

Similarly, the relationship of p_{famsc} and p_{mdmsc} can now be derived, which turns out to be,

$$p_{mdmsc} = P_{CDF}\left(\left(1 - p_{fa}^{\left(\frac{1}{L-1}\right)}\right)|L, |\gamma|^2\right), \quad (25)$$

where γ^2 is the magnitude squared coherence of the PU signal [98]. The function P_{CDF} is as defined in 26 In 26 the function ${}_2F_1(-l, 1-L; 1; |\gamma^2||\hat{\gamma}|^2)$ is the hypergeometric function (please see [99] for more details).

These functions are plotted for $SNR = 10\log\frac{P_s}{\sigma^2} = \{-24, -26\}dB$, using the values of $L = 32, M = 256$. All the other values are assumed to be in harmony with [98].

The rate region for a spectrum sensing technique characterized by $p_{md} = f_d(p_{fa})$ or $p_{fa} = g_d(p_{md})$ is given by

$$\begin{aligned}\mathcal{R}_{id} = \{R_{pi}, R_{si}|0 < R_{pi} \leq C_{pi}(p, p_{md}),\\ 0 < R_{si} \leq C_{si}(p, p_{fa}, p_{md}),\\ \text{such that } p_{md} = f_d(p_{fa}) \text{ or } p_{fa} = g_d(p_{md})\}, \quad (27)\end{aligned}$$

where C_{pi} and C_{si} are given in (20) and (21), respectively.

As an example, the achievable rate regions are plotted for Rayleigh fading communication links covering all possible combinations of p_{fa} and p_{md} for the above detectors, where the probability of the PU channel being free was set to $p = 0.25, 0.5$ and 0.75 in Fig. 6 at the average received SNR values of $-24dB$ and $-26dB$ for both the ED and the MSC. These plots are also compared to the ideal scenario of having no spectrum sensing errors. The ideal rate region is given by [5]

$$\begin{aligned}\mathcal{R}_{id} = \{R_{pi}, R_{si}|0 < R_{pi} \leq (1-p)\mathbb{E}[\log(1 + H_{pp}^2 P_p)],\\ 0 < R_{si} \leq (1-p)\mathbb{E}[\log(1 + H_{ss}^2 P_s)]\}. \quad (28)\end{aligned}$$

From Fig. 6 we observe that

- For the low-performance ED there is a significant rate reduction due to spectrum sensing errors.
- For the higher-performance detector MSCD, the rate is only slightly reduced at high values of p. However, a significant rate loss of the PU is observed even for the MSCD at low value of p.
- The SU is unable to achieve its full rate even at extreme values of p_{fa} and p_{md}, which is due to its dependence on both p_{md} and p_{fa} as well as owing to the fact that C_{si} is an increasing function of p_{md} and a decreasing function of p_{fa}.
- Across the three different values of p, we observe that

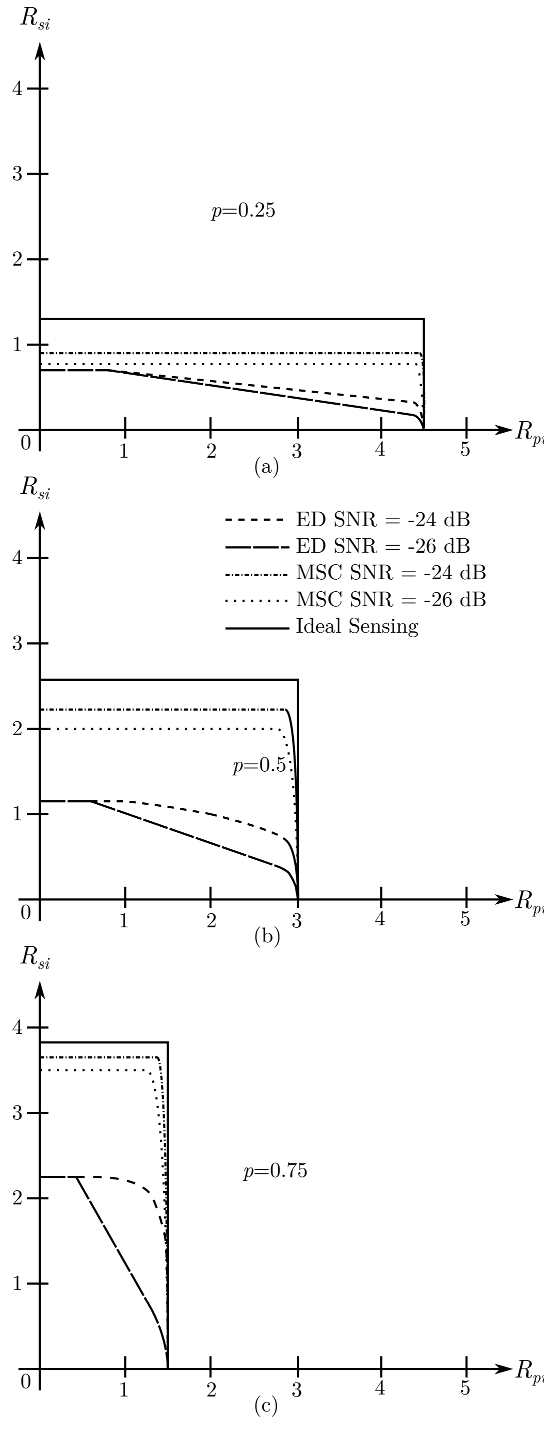

Fig. 6: The rate region for $p = 0.25, 0.5$ and 0.75 for ED and MSCD at average received SNRs of $= 24dB$ and $-26dB$ compared to the rate achieved via ideal sensing.

$$P_{CDF}(|\hat{\gamma}|^2|L,|\gamma|^2) = |\hat{\gamma}^2| \left[\frac{1-|\gamma|^2}{1-|\gamma^2||\hat{\gamma}|^2}\right]^L \sum_{l=0}^{L-2} \left[\frac{1-|\hat{\gamma}|^2}{1-|\gamma^2||\hat{\gamma}|^2}\right]^l {}_2F_1(-l,1-L;1;|\gamma^2||\hat{\gamma}|^2), \tag{26}$$

the R_{si} that is the SU rate is higher for the lower values of PU occupancy probabilities p. With p the achievable rate of the PU decreases and that of the SU increases.

Having quantified the achievable rate of the interweave CR subjected to realistic spectrum sensing errors, we now recite the achievable rates of the underlay CR based on [11].

D. Achievable rates of the Underlay CR

The achievable rates of the system model defined in Section II-*B* were derived in [11]. They are reproduced here for completeness.

Theorem 2: *An achievable rate expression for the SU subject to the condition that the required rate of the PU of* $\mathbb{E}_{(H_{pp})}\left[\log\left(1+H_{pp}^2P_p\right)\right]$ *is met is given by*

$$C_{su} = \begin{cases} \min\left(C_{su1}, C_{su2}\right) & \textit{if } a \leq 1 \textit{ and } b > 1, \\ \min\left(C_{su1}, C_{su3}, C_{su4}\right) & \textit{if } a > 1 \textit{ and } b > 1, \\ C_{su1} & \textit{if } b \leq 1, \end{cases}$$

where, $C_{su1} = \mathbb{E}_{(H_{pp},H_{sp})}\left[\log\left(1+\frac{H_{sp}^2P_s}{1+H_{pp}^2P_p}\right)\right]$, $C_{su2} = \mathbb{E}_{(H_{ss},H_{ps})}\left[\log\left(1+\frac{H_{ss}^2P_s}{1+H_{ps}^2P_p}\right)\right]$, $C_{su3} = \mathbb{E}_{(H_{ss})}\left[\log\left(1+H_{ss}^2P_s\right)\right]$, $C_{su4} = \mathbb{E}_{(H_{ss},H_{ps})}\left[\log\left(\frac{1+H_{ps}^2P_p+H_{ss}^2P_s}{1+H_{pp}^2P_p}\right)\right]$.

Moving now beyond the performance of individual approaches, in the next section we compare the interweave CR and the underlay CR using these achievable rate expressions.

VII. Comparison of the Interweave CR and the Underlay CR

In the previous section we characterized the achievable rate regions of the interweave CR. Following this we briefly recited the achievable rate expression for the underlay CR from [11]. We now compare these two paradigms utilizing our achievable rate expressions. For the interweave CR, the system that we have assumed relied on the realistic imperfect spectrum sensing characterized by the error probabilities of (p_{fa}, p_{md}), whereas for the underlay CR the system that we have assumed is an ideal one. Hence, we wish to study the impact of the sensing errors for the sake of ascertaining, when the interweave CR outperforms the underlay CR.

Since we rely on the ergodic achievable rates, it remains an open challenge to provide a mathematical analysis of the comparison. Here we provide a detailed graphical analysis supported by mathematical analysis wherever possible.

Our comparison is divided into two parts. Firstly, a comparison is made wrt to the achievable rates of the SU only, followed by our comparisons wrt to the achievable rates of both the SU and PU.

Basically we are interested in ascertaining what values of $p, a, b, P_p, P_s, p_{md}$ and p_{fa} does the following relationship be valid for:

$$M_s(p,a,b,P_p,P_s,p_{md},p_{fa}) = C_{si} - C_{su} > 0. \tag{29}$$

$$M(p,a,b,P_p,P_s,p_{md},p_{fa}) = C_{si} + C_{pi} - C_{su} - C_{pu} > 0. \tag{30}$$

The term $M_s(p,a,b,P_p,P_s,p_{md},p_{fa})$ represents the amount by which the achievable rate of the SU is higher for the interweave CR than for the underlay CR. Similarly, the term $M(p,a,b,P_p,P_s,p_{md},p_{fa})$ is the amount by which the the achievable sum rate is higher for the interweave CR than for the underlay CR.

We now formally define the domain of *superiority* of the interweave CR.

Definition: *Interweave CR is superior to the underlay CR in terms of the SU rate if we have* $M_s > 0$*, and the interweave CR is superior to the underlay CR in terms of the sum rate if we have* $M > 0$.

Since there are five parameters, namely $p, a, b, P_p,$ and P_s, analysing their variation simultaneously is not feasible. Hence, we group the parameters as follows. We commence by analysing the PU free probability p separately, followed by studying the effect of each individual parameter.

To compare the interweave CR and the underlay CR in terms of the SU rate or the sum rate as a function of the various parameters, we structure our analysis based on the value of average interference coefficients as follows:

- When the interference at the PU is ergodically weak - i.e we have $b \leq 1$ - we refer to this as Regime I.
- If the interference at the PU is ergodically strong and that at the SU is ergodically very weak - i.e. we have $b > 1$ and $a \leq a_1$, where for a given b, a_1 is that specific value of a, where we have $C_{s1} = C_{s2}$ - then we refer to this as Regime II.
- Provided that the interference at the PU is ergodically strong and that at the SU is ergodically weak - i.e. we have $b > 1$ and $a_1 < a \leq 1$ - we refer to this as Regime III.
- In case the interference at the PU is ergodically strong and that at the SU is also ergodically strong - i.e. we have $b > 1$ and $1 < a \leq a_2$, where for a given b, a_2 is that specific value of a, where we have $C_{s1} = C_{s4}$ - we refer to this as Regime IV.
- If the interference at the PU is ergodically strong and that at the SU is ergodically moderately strong - i.e. we have $b > 1$ and $a_2 < a \leq a_3$, where for a given b, a_3 is that specific value of a, where we have $C_{s4} = C_{s3}$ - then we refer to this as Regime V.

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- Finally, provided that the interference at the PU is ergodically strong and that at the SU is ergodically very strong - i.e. we have $b > 1$ and $a > a_3$ - we refer to this as Regime VI.

This structure is adopted in light of the fact that the rate-expressions of the underlay CR vary according to the specific levels of the interference imposed by the PU on the SU and vice versa.

A. Effect of p

The effect of the PUs activity is straightforward to analyse. Fig. 7 plots those specific values of p_{fa} and p_{md}, for which the interweave CR is superior to the underlay CR. Since the missed detection is more of a critical event, a low missed detection probability below 0.2 is required for an average sensing SNR of -20dB. Accordingly, the interweave CR is superior to the underlay CR in those particular regimes where p, is higher than say 0.5 for an average interference coefficients of $a = 1$ and $b = 1$.

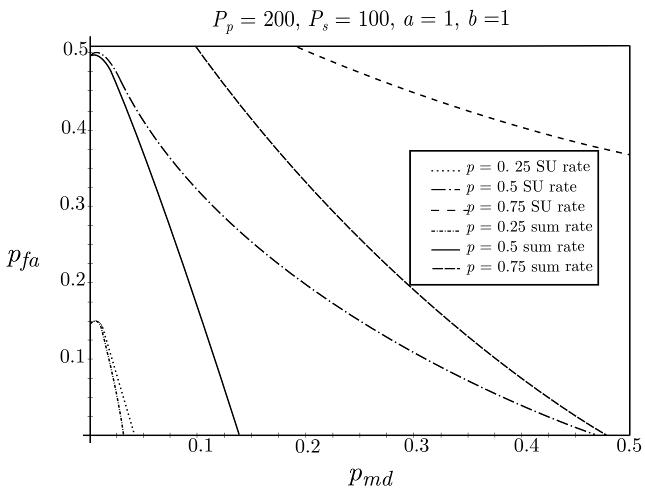

Fig. 7: The values of p_{fa} and p_{md}, where the interweave CR is better than the underlay CR. The area inside the curves is where the interweave CR is better. The plot is generated for $P_p = 200,\ P_s = 100,\ a = 1, b = 1$

TABLE VII provides a detailed summary of the aforementioned regimes outlining the domains of superiority for the interweave CR over the underlay CR.

B. Effect of Transmit Power Constraints P_p and P_s

Let us now continue by generating basic plots for analysing the region of superiority of the interweave CR over the underlay CR in terms of P_p and P_s. We fix the value of the PU activity probability to one of the three values $p = \{0.25, 0.5, 0.75\}$. Then, we fix a spectrum sensor, which can provide us with three values $p_{md} = \{0.1, 0.2, 0.3\}$. Additionally, we fix the value of average interference coefficients (a, b) to be from the following set of five pairs $(a, b) = \{(1, 1), (0.5, 0.5), (0.5, 1.5), (1.5, 0.5), (1.5, 1.5)\}$. Corresponding to each value of p_{md} and the pair (a, b), we look for the specific values of p_{fa} that the spectrum sensor should provide, such that the interweave CR becomes superior to the underlay CR. This value of p_{fa} will be a function of both the Signal to Noise Ratio (SNR) of $SNR_p = 10\log_{10} P_p$ at the PU and that of $SNR_s = 10\log_{10} P_s$ at the SU. The range of each SNR is spans from $10dB$ through to $40dB$ in steps of $1dB$.

A basic observation with regards to transmit power constraint can be inferred from Fig. 8 through to Fig. 13. Each of these figures comprises sub-plots, which portray $P_s \times P_p$ vs p_{fa} for a particular value of p_{md}, a and b. It can be concluded that the higher the SNR_p of the PU and the lower the SNR_s of the SU the more beneficial it is to use the interweave SNR. However, at very high values of SNR_p the benefits of the interweave CR experienced start to erode even at low SNR_s. This can be readily observed in Fig. 8 and 9. This is because at very high values of SNR_p and low values of p, the PU rate in the underlay CR starts to dominate, hence reducing the impact of the other rates, whereas at relatively low powers the PU rate of the underlay CR remains comparable to that of the other rates of the system described in Fig. 1.

C. Effect of average interference coefficients a and b

In the underlay CR scenario the values of a and b are crucial in deciding, what specific rate is achievable for the SU. Hence, we expect a and b to be of high importance in deciding the most beneficial paradigms.

- Regime I, $b \leq 1$ - Observe from Theorem 1 that for the interweave CR the rate of the SU does not depend upon b. However, in light of Theorem 2 it can readily be seen that for the underlay CR the SU rate is an increasing function of b. Hence, the region of superiority for the interweave CR decreases as b tends towards unity. By contrast, observe from Theorem 1 that the sum rate in the interweave CR is a decreasing function of b while that of the underlay CR, again by Theorem 2, is an increasing function of b because the PUs rate is fixed in the underlay CR. Hence, the region of superiority for the interweave CR expressed in terms of the sum rate decreases with b more rapidly than it decreases in terms of only the SU rate. Viewing this phenomenon from a different perspective, this means that as the interference coefficient b decreases, the superiority of the interweave CR increases. This is especially so in the cases where $a > 1$. It is important to note that even though the PU imposes a high interference on the SU, yet the interweave CR remains superior as a benefit of the SU to PU interference. Hence, the traditional the underlay CR is not a good solution in these regimes.
- Regime II, $b > 1$ and $a \leq a_1$ - By observing similar trends in the rate expressions of this regime, we infer that the system's behavior under this regime is the same as for $b < 1$. The important point to note is that although the interweave CR continues to remain superior to the underlay CR in this regime, the gap between the two approaches remains lower when compared to the case

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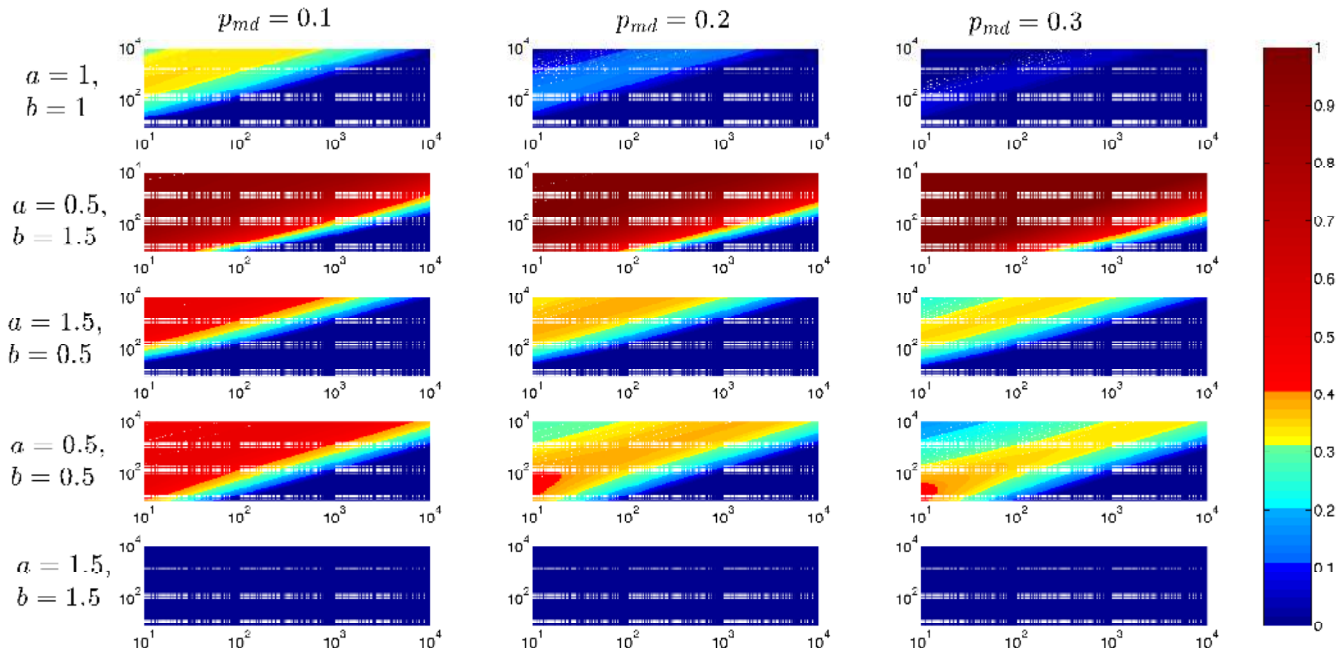

Fig. 8: The maximum values of p_{fa} for a given value of p_{md} that are beneficial for the interweave CR as a function of both P_s (X$-$ axis) and P_p (Y$-$ axis) for various combinations of a and b as well as for $p = 0.25$. The performance criterion used for identifying the region of dominance for the interweave CR is the SU rate

of $b < 1$. This is because in the underlay CR for $b > 1$ successive interference cancellation is utilized at the PU receiver for mitigating the effect of the interference imposed by the SU on the PU, whereas there is no such provision in the interweave CR.

- Regime III, $b > 1$ and $a_1 < a < 1$ - We observe from Theorem 2 that in the underlay CR, the rate of the SU is a decreasing function of a, whereas it is an increasing function of b up to a certain value a_1, which depends on b and it is constant in terms of a beyond that. In the interweave CR the value of the SU rate decreases with a, although the associated reduction is more substantial for the underlay CR, since the interference is treated as noise. By contrast, in the interweave CR the SU rate is obtained by treating the interference as noise after scaling it down by a value of $\frac{(1-p)p_{md}}{(1-p)p_{md}+p(1-p_{fa})}$, which is less than unity. This implies that the interference is only partially treated as noise. Hence in this regime the domain of superiority is shifted more towards the interweave CR and the gap increases with the interference coefficients. The situation is less clear in terms of the sum rate. Explicitly, the sum rate of the interweave CR decreases with both of the interference coefficients a and b. By contrast, for the underlay CR it decreases with a and increases with b up to a certain value a_1, which depends on b and then remains constant. In the interweave CR the rate for the PU is also obtained by treating the partial interference as noise, as it was mentioned above about the SU rate. By contrast, for the underlay CR we have a PU rate, where all the interference is cancelled out while for the SU all the interference is treated as noise. Hence, this regime may be further subdivided into regimes, where the interweave CR is superior to the underlay CR and vice versa.
- Regime IV, V and VI, $b > 1$ and $a > 1$ - In light of Theorems 1 and 2, in this regime both the sum rate and the SU rate of the underlay CR increase with a and b. By contrast, they both decrease in the case of the interweave CR. Hence, the region of superiority for the interweave CR decreases with both a and b in terms of the SU rate as well as the sum rate.

D. Rules of thumb

In this section we provide basic rules of thumb that can be used for deciding, which specific approach is superior to the other. A general rule of thumb is that high values of p, low values of p_{md}, p_{fa}, low values of SNR_s, high values of SNR_p and low values of a, b will all lead to the interweave CR being attractive. Typically, this would entail values like $p \geq 0.5, p_{md} \leq 0.2, p_{fa} \leq 0.4, SNR_p > 10dB, SNR_s < 20dB, a \leq 1$ and $b \leq 1$. In what follows, we shall present

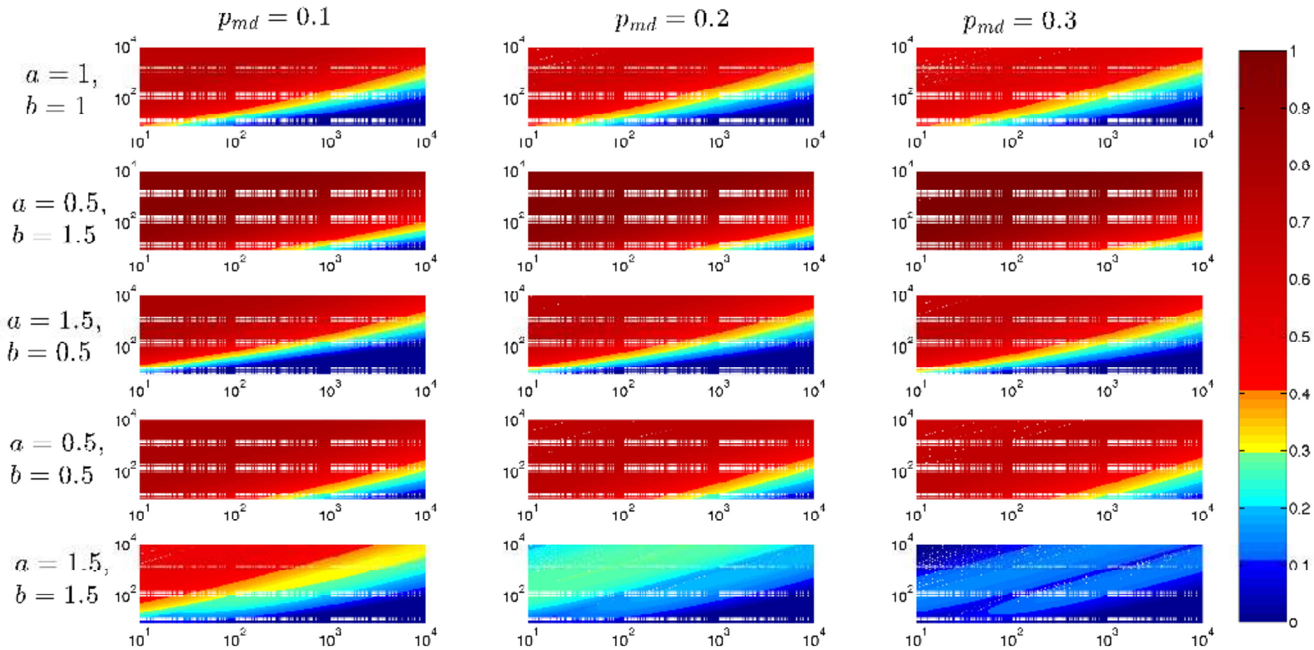

Fig. 9: The maximum values of p_{fa} for a given value of p_{md} that are beneficial for the interweave CR as a function of both P_s (X− axis) and P_p (Y− axis) for various combinations of a and b as well as for $p = 0.5$. The performance criterion used for identifying the region of dominance for the interweave CR is the SU rate

TABLE VII: Feasibility of the Interweave CR in terms of a and b

Regime → / Parameter ↓	I - $b \leq 1$	II - $b>1$ and $a \leq a_1$	III - $b>1$ and $a_1<a\leq 1$	IV - $b>1$ and $1<a\leq a_2$	V - $b>1$ and $a_2<a\leq a_3$	VI - $b>1$ and $a>a_3$
Average interference coefficient PU-SU link a	Feasibility of interweave wrt both SU and sum rate increases as a decreases with rate s_1. The rate of increase is the same for SU and sum rate.	Feasibility of interweave wrt both SU and sum rate increases as a decreases with rate s_1. The rate of increase is the same for SU and sum rate.	Feasibilty of interweave wrt SU rate increases with a. Feasibility of interweave wrt sum rate increases with a if p_{md} and p_{fa} are simultaneously small enough.	Feasibility of interweave wrt both SU and sum rate increases as a decreases with rate $s_2>s_1$. The rate of increase is the same for SU and sum rate.	Feasibility of interweave wrt both SU and sum rate increases as a decreases with rate s_1. The rate of increase is the same for SU and sum rate.	Feasibility of interweave wrt both SU and sum rate increases as a decreases with rate s_1. The rate of increase is the same for SU and sum rate.
Average interference coefficient SU-PU link b	Feasibility of interweave wrt both sum rate and SU rate increases with decrease in b. The rate of increase is more in sum rate	Feasibility of interweave wrt both sum rate and SU rate increases with decrease in b. The rate of increase is more in sum rate	Feasibility of interweave wrt SU rate increases with decrease in b for values near unity. For values away from unity feasibility remains constant. For sum rate the feasibility always increases with decrease in b	Feasibility of interweave wrt SU rate increases with decrease in b for values near unity. For values away from unity feasibility remains constant. For sum rate the feasibility always increases with decrease in b	Feasibility of interweave wrt both sum rate and SU rate increases with decrease in b. The rate of increase is more in sum rate	Feasibility of interweave wrt SU rate is constant in b and that with sum rate increases with decrease in b The rate of increase is more in sum rate

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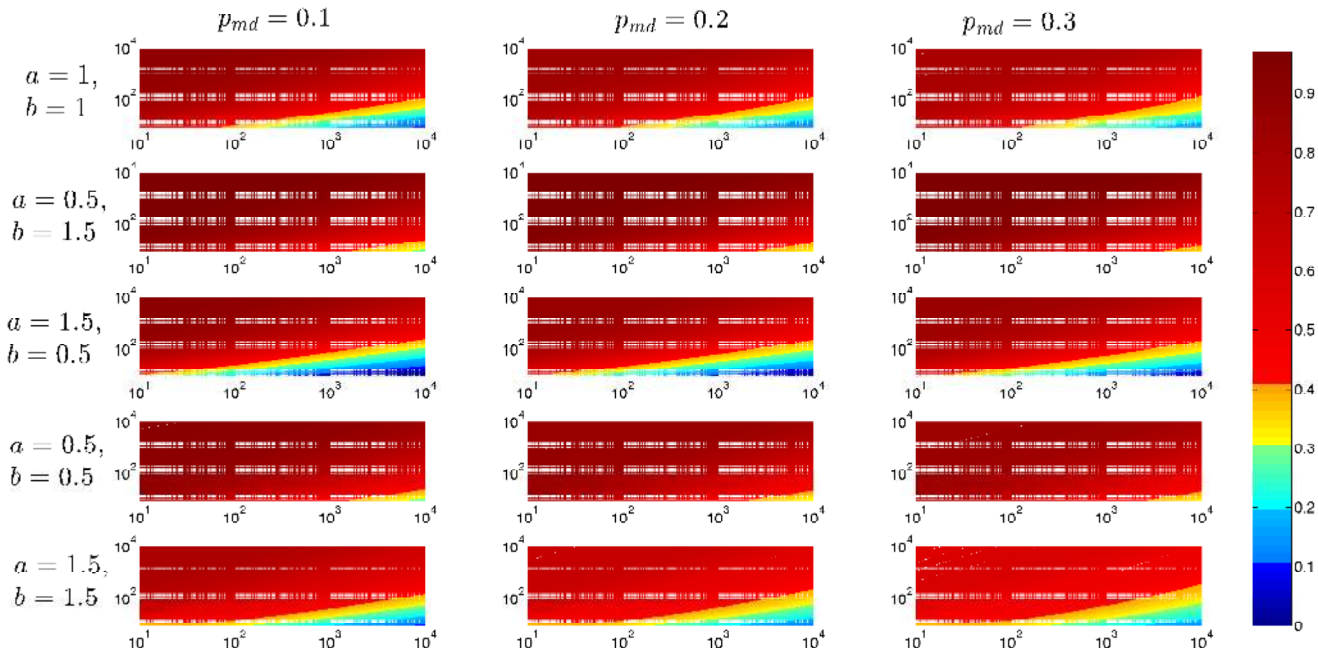

Fig. 10: The maximum values of p_{fa} for a given value of p_{md} that are beneficial for the interweave CR as a function of both P_s (X− axis) and P_p (Y− axis) for various combinations of a and b as well as for $p = 0.75$. The performance criterion used for identifying the region of dominance for the interweave CR is the SU rate

further scenarios, where the interweave CR is beneficial. Again, broadly divided into two parts, first we present our findings in terms of the SU rate in Tables VIII - X, followed by our findings for the sum rate in Tables XI - XIII. The relations between SNR_p and SNR_s are approximate relations that are obtained for a given range of SNRs, spanning from $10dB$ to $40dB$. To obtain these relations we refer to Fig. 8 through to 13. Each sub-plot in the set of plots of each figure is configured to show 5 distinct regions, namely where the interweave CR is superior to the underlay CR if for a given p_{md} value (i) $p_{fa} \leq 0.1$, (ii) $0.1 < p_{fa} \leq 0.2$, (iii) $0.2 < p_{fa} \leq 0.3$, (iv) $0.3 \leq p_{fa} \leq 0.4$, (v) $0.4 \leq p_{fa} \leq 0.5$. We are interested in three regions, namely in (i) $p_{fa} \leq 0.2$, (ii) $p_{fa} \leq 0.3$, (iii) $p_{fa} \leq 0.4$. Since, the value of p_{md} directly affects the PUs transmission rate, the PU imposes a particular value of p_{md} on the SU. The SU then determines the best possible value of the p_{fa} that it can obtain with the aid of its spectrum sensor for a given set of conditions. As an example, let the required value be $p_{md} = 0.2$ and assign furthermore the values of $p = 0.5$, $a = 1$ and $b = 1$. Then Figs. 9 and 12 show us the particular values of P_s and P_p that offer us a value of p_{fa}, which the sensor is capable of meeting. In every such scenario we use linear relations of the form $SNR_p = mSNR_s + c$. We identify the minimum number of such linear equations that can model these curves to a reasonable accuracy. As an example based on Fig. 8 and $a = 1, b = 1, p = 0.25$ as well as $p_{md} = 0.2$, the relationship between SNR_p and SNR_s required for ensuring $p_{fa} \leq 0.4$ is given by

$$SNR_p > \frac{16}{17} SNR_s + \frac{112}{17},$$

as mentioned in Table VIII. The relationships can also be obtained for other regimes of interest using a similar procedure.

E. Discussions

Although the parameter variations experienced in some regimes reduce the region of superiority for the interweave CR, yet in most practical cases of the parameters a, b, P_p, P_s and (p_{fa}, p_{md}) the interweave CR is beneficial both in terms of the SU's rate as well as in terms of the sum rate. This can be attributed to the efficient nature of the interweave CR in exploiting the resources. In contrast to the underlay CR, in the interweave CR the focus is on transmitting at full rate. By contrast, in the underlay CR the transmission of unnecessarily low-rate messages even at those instances, when the PU is absent degrades the attainable spectral efficiency. This tendency becomes even more prominent, if we consider the practical limitations imposed by the realistic channel state estimation in the underlay CR.

Furthermore, a major point of favor for the interweave CR is that in this comparison we have assumed the employment of only the perfect point-to-point capacity achieving codes for the interweave CR instead of any sophisticated coding techniques.

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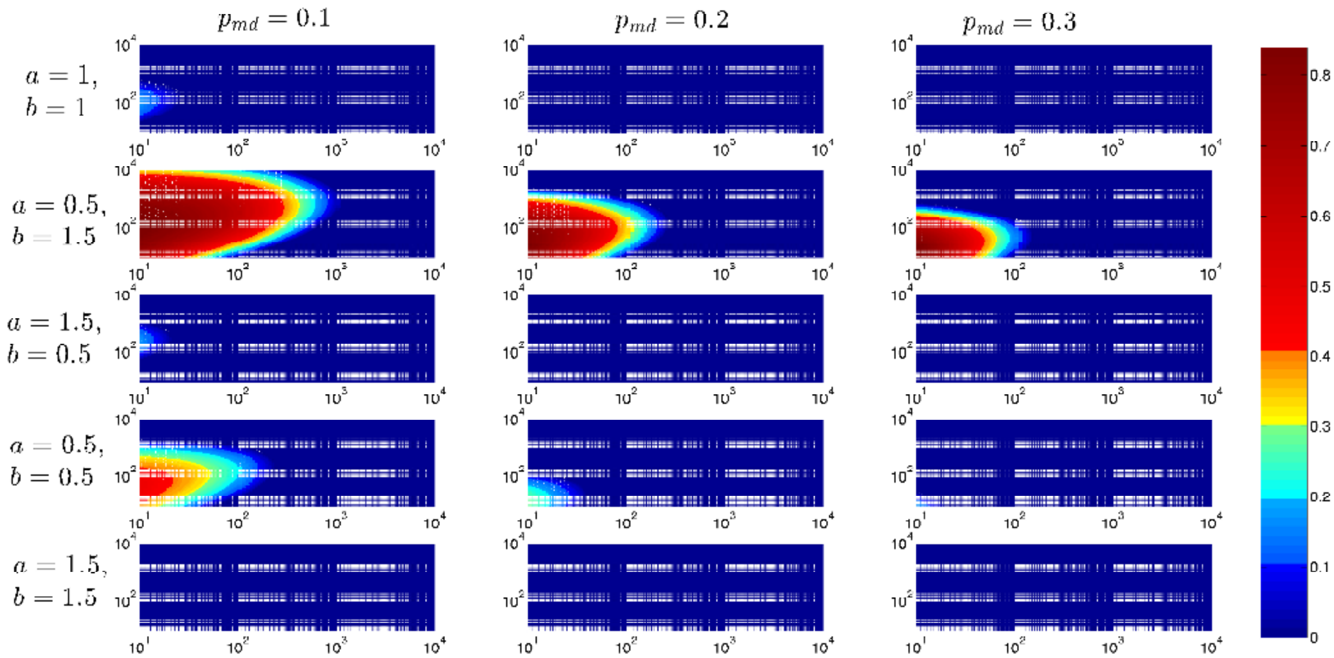

Fig. 11: The maximum values of p_{fa} for a given value of p_{md} that are beneficial for the interweave CR as a function of both P_s (X− axis) and P_p (Y− axis) for various combinations of a and b as well as for $p = 0.25$. The performance criterion used for identifying the region of dominance for the interweave CR is the sum rate

If the availability of side information allows us to perform rate-partitioning based joint coding techniques, then the achievable rate of the interweave CR will drastically increase. Hence, if we assume the availability of the required side information for the interweave CR, then we are able to conceive a new approach for CR systems that amalgamates the advantages of the interweave CR as well as the underlay CR and allows us to employ sophisticated joint coding techniques for improving the overall performance. We note that there are some approaches that have indeed highlighted the use of hybrid strategies for the interweave CR and the underlay CR [100]–[102]. However, in contrast to our solution, these models combine the standard interweave CR model with the interference-limited underlay CR model. As a further development the authors of [101] considered the SU relay assisted model instead of a simple point-to-point model.

VIII. Application to an OFDM scenario relying on an Energy Detector

Let us now consider the ubiquitous Orthogonal Frequency Division Multiplexing (OFDM) which is capable of operating in dispersive wide-band scenarios. Each subcarrier is subject to a flat fading channel, where the fading process is *iid* over both the time and frequency domains as well as stationary and ergodic. There are on an average N PUs supported by a total of S sub-carriers, where $N < S$ and hence, the probability of a channel being unoccupied by a PU is defined as $p = 1 - \frac{N}{S}$. CR techniques are proposed because the value of p in some bands is high whereas it is expected to be lower in some other bands causing spectral domain fluctuations. Devices (SUs) which operate in frequency bands associated with low values of p will have to aim for transmitting in the bands having a high value of p. They can either achieve this opportunistically as in the interweave CR, where the SU will transmit only on the condition, if it senses the PU to be absent; or alternatively they can share the spectrum as in the underlay CR by transmitting simultaneously without imposing any degradation on the PU.

Let us assume the SU is equipped with an energy detector. The probability of false alarm for energy detection as a function of missed detection for the given fixed parameters is as given in (24).

Assuming that independently another SU is equipped with magnitude squared coherence detector, we have the functional relationship $p_{md} = f(p_{fa})$ for convenience and is as given in (25).

Let us now characterize both of these detectors in Fig. 14 by considering a communication scenario where we have $p = 0.5$, $SNR_p = 20dB$, $SNR_s = 15dB$, $a = 1$ and $b = 1$. We assume that there are two scenarios corresponding to two different average received SNRs at the SU transmitters namely to $-24dB$ and to $-26dB$ as shown in the Fig. 14. Let us assume that the required value of p_{md} that is dictated by the

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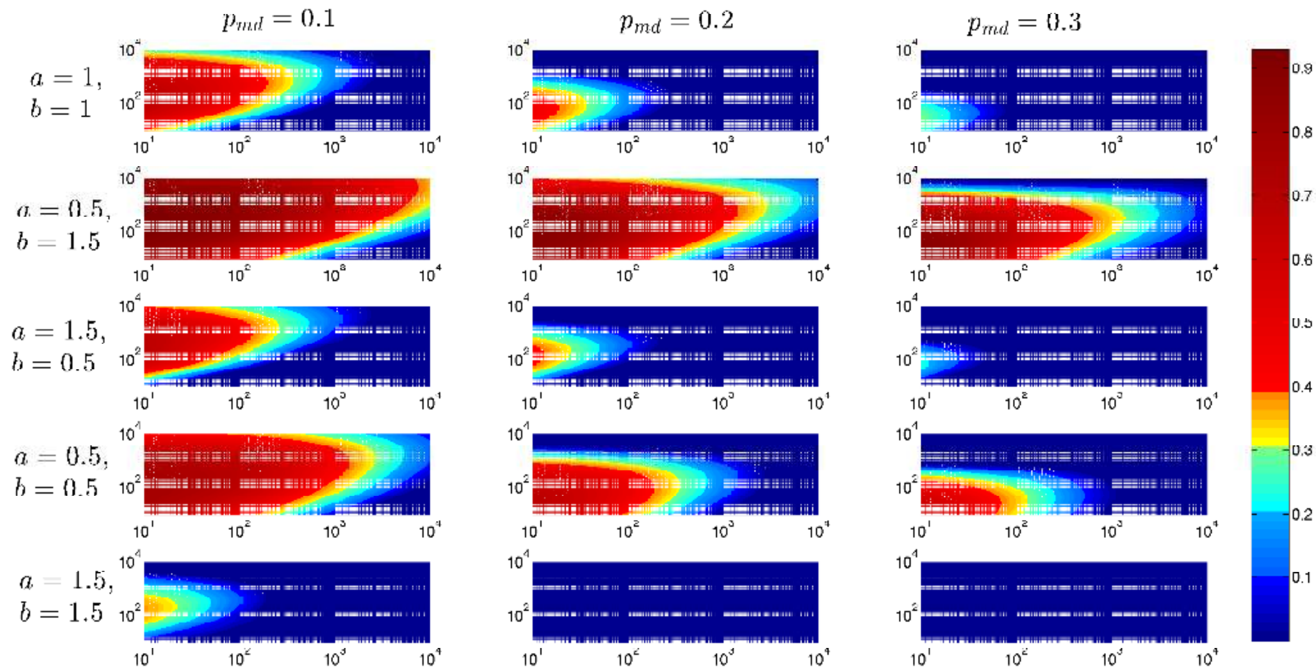

Fig. 12: The maximum values of p_{fa} for a given value of p_{md} that are beneficial for the interweave CR as a function of both P_s (X$-$ axis) and P_p (Y$-$ axis) for various combinations of a and b as well as for $p = 0.5$. The performance criterion used for identifying the region of dominance for the interweave CR is the sum rate

PUs rate is $p_{md} \leq 0.3$ and the criterion for comparison is the sum rate. We opt for $p_{md} = 0.3$ since this would provide the best value of p_{fa}. The ED operating at $-26dB$ can at best offer $p_{fa} = 0.37$ and at $-24dB$ the best that can be $p_{fa} = 0.23$, as seen from Fig. 14. It can be observed from Figs. 9 and 12 that at these values the ED allows the interweave CR to outperform the underlay CR at -24dB but not at $-26dB$. However, since the performance of the MSC detector is better than that of the ED, it allows the interweave CR to become more beneficial than the underlay CR at both average received SNR values.

Let us now consider another situation, where there is a flexibility in choosing the transmit power for the SU whilst requiring a $p_{md} \leq 0.2$. In this case if we opt $p_{md} = 0.2$ then again the ED will portray the interweave CR in a more beneficial light than the underlay CR at -24dB, but not at $-26dB$. However, if we choose $p_{md} = 1$, then the ED will make the interweave CR more attractive than the underlay CR for a choice of $SNR_s = 10dB$ for both $-24dB$ and $-26dB$. Naturally, a similar analysis can also be carried out for various other situations. This leads us to a simple design guideline that can be used in deciding which of the two paradigms is useful.

IX. Conclusions, Design Guidelines and Open Problems

A. Design Guidelines

Based on the analysis provided in this paper, some fundamental design guidelines may be formulated for choosing a preferred approach, when deploying a cognitive radio system.

1) The most dominant design criterion is constituted by the specific quality-of-service (QoS) requirement of the PU.
2) Given the required QoS, the highest tolerable probability of missed detection p_{mdmax} is calculated.
3) This is followed by the careful choice of the spectrum-sensor from those available.
4) Having chosen the spectrum-sensor, we calculate the minimum probability of false alarm p_{famin} that can be simultaneously achieved with p_{mdmax}. [2]
5) Now, if the SU rate is the most dominant design criterion, then given this value of p_{famin}, the value of C_{si} - which is a function of p_{msmax} and p_{famin} - is compared against C_{su}. If C_{si} is found to be higher than C_{su}, then the interweave paradigm is selected. Otherwise the underlay paradigm is preferred.
6) However, if the sum rate is the dominant decision criterion, then $C_{pi} + C_{si}$ is compared against $C_{pu} + C_{su}$.

[2] Note that if the QoS requirement of the PU is stringent, then the value of p_{mdmax} may tend to zero, which would tend the value of p_{famin} to unity.

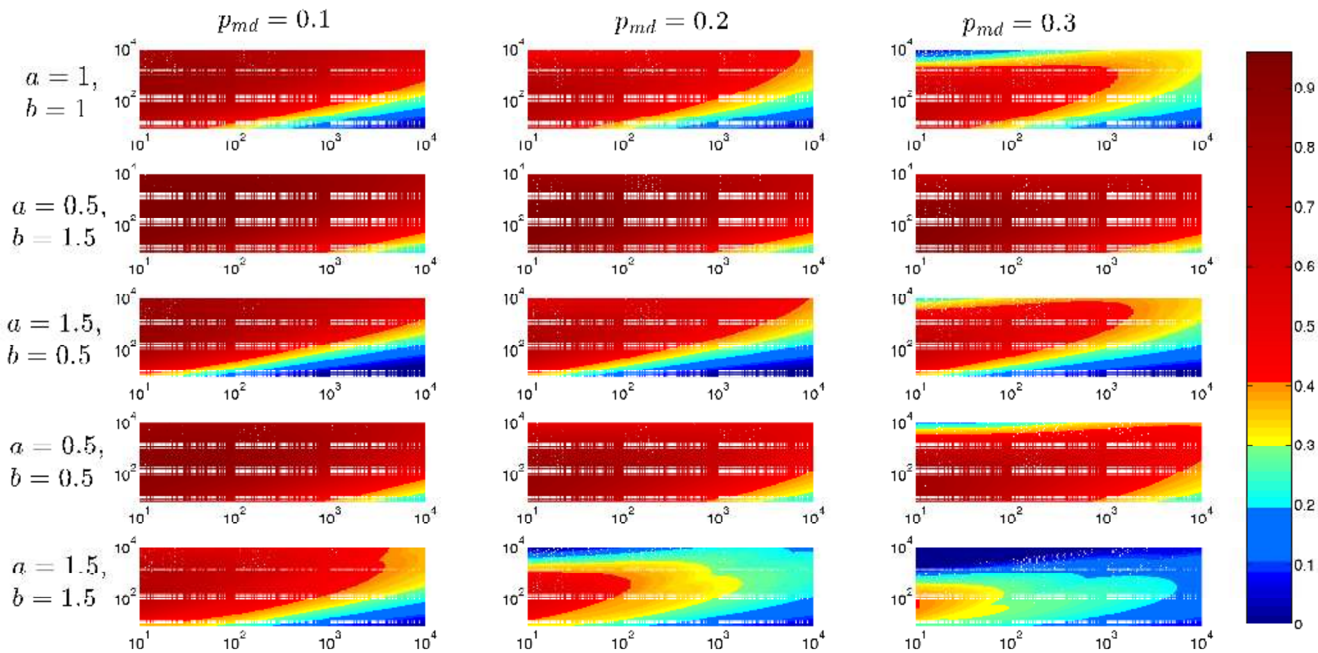

Fig. 13: The maximum values of p_{fa} for a given value of p_{md} that are beneficial for the interweave CR as a function of both P_s (X− axis) and P_p (Y− axis) for various combinations of a and b as well as for $p = 0.25$. The performance criterion used for identifying the region of dominance for the interweave CR is the sum rate

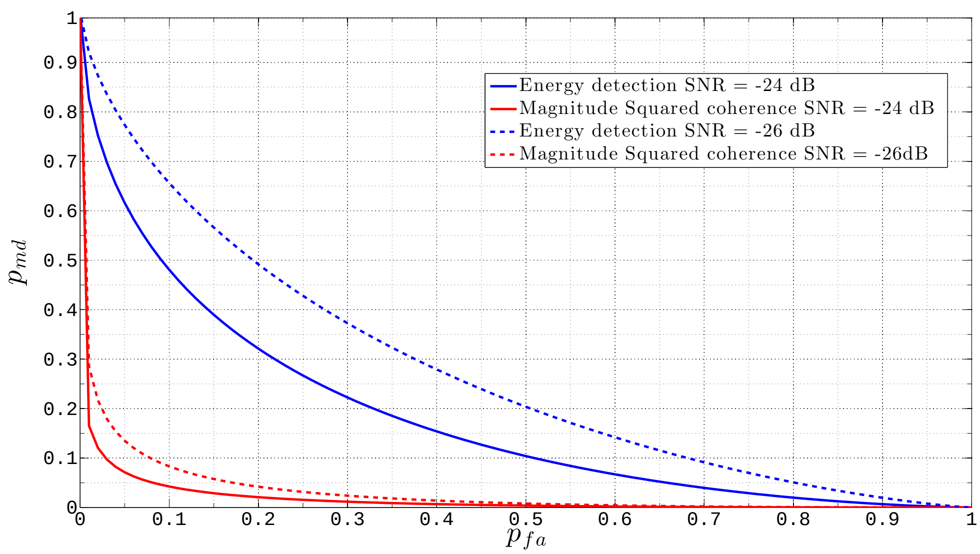

Fig. 14: ED and MSC detector for two different average received SNRs of $-24dB$ and $-26dB$.

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TABLE VIII: $p = 0.25$ only SU

(a,b)	p_{md}	$p_{fa} \leq 0.2$	$p_{fa} \leq 0.3$	$p_{fa} \leq 0.4$
(1,1)	0.1	$SNR_p > \frac{16}{17}SNR_s + \frac{112}{17}$	$SNR_p > \frac{40}{41}SNR_s + \frac{420}{41}$	NPC
	0.2	NPC	NPC	NPC
	0.3	NPC	NPC	NPC
(0.5,0.5)	0.1	$SNR_p > \frac{17}{21}SNR_s - \frac{113}{21}$	$SNR_p > \frac{58}{65}SNR_s - \frac{248}{39}$	$SNR_p > \frac{43}{48}SNR_s - \frac{13}{3}$
	0.2	$SNR_p > \frac{15}{17}SNR_s - \frac{175}{17}$	$SNR_p > \frac{17}{19}SNR_s - \frac{167}{19}$	$SNR_p > \frac{19}{21}SNR_s - \frac{151}{21}$
	0.3	$SNR_p > \frac{23}{27}SNR_s - \frac{679}{54}$	$SNR_p > \frac{27}{31}SNR_s - \frac{703}{62}$	$SNR_p > \frac{31}{34}SNR_s - \frac{373}{34}$
(1.5,0.5)	0.1	$SNR_p > \frac{55}{52}SNR_s + \frac{25}{13}$	$SNR_p > \frac{41}{46}SNR_s + \frac{487}{46}$	$SNR_p > \frac{53}{58}SNR_s + \frac{1148}{87}$
	0.2	$SNR_p > \frac{22}{25}SNR_s + \frac{46}{5}$	$SNR_p > \frac{15}{16}SNR_s + \frac{89}{8}$	NPC
	0.3	$SNR_p > \frac{235}{238}SNR_s + \frac{1907}{258}$	$SNR_p > \frac{40}{43}SNR_s + \frac{460}{43}$	NPC
(0.5,1.5)	0.1	$SNR_p > \frac{147}{148}SNR_s - \frac{387}{74}$	$SNR_p > \frac{5}{9}SNR_s + \frac{25}{9}$	$SNR_p > \frac{18}{17}SNR_s - \frac{10}{17}$
	0.2	$SNR_p > \frac{52}{49}SNR_s - \frac{316}{49}$	$SNR_p > \frac{59}{54}SNR_s - \frac{227}{54}$	$SNR_p > 3SNR_s - 19$
	0.3	$SNR_p > \frac{75}{68}SNR_s - \frac{155}{17}$	$SNR_p > \frac{8}{7}SNR_s - \frac{134}{21}$	$SNR_p > \frac{16}{3}SNR_s - \frac{146}{3}$
(1.5,1.5)	0.1	NPC	NPC	NPC
	0.2	NPC	NPC	NPC
	0.3	NPC	NPC	NPC

TABLE IX: $p = 0.5$ only SU

(a,b)	p_{md}	$p_{fa} \leq 0.2$	$p_{fa} \leq 0.3$	$p_{fa} \leq 0.4$
(1,1)	0.1	$SNR_p > \frac{75}{116}SNR_s - \frac{25}{29}$	$SNR_p > \frac{111}{158}SNR_s + \frac{63}{158}$	$SNR_p > \frac{19}{25}SNR_s + \frac{12}{5}$
	0.2	$SNR_p > \frac{48}{65}SNR_s \frac{46}{13}$	$SNR_p > \frac{205}{252}SNR_s - \frac{257}{126}$	$SNR_p > \frac{63}{73}SNR_s + \frac{248}{365}$
	0.3	$SNR_p > \frac{85}{101}SNR_s + \frac{4891}{805}$	$SNR_p > \frac{208}{245}SNR_s - \frac{774}{245}$	$SNR_p > \frac{86}{95}SNR_s + \frac{39}{95}$
(0.5,0.5)	0.1	$SNR_p > \frac{55}{96}SNR_s - \frac{89}{12}$	$SNR_p > \frac{39}{64}SNR_s - \frac{263}{40}$	$SNR_p > \frac{17}{40}SNR_s - \frac{1}{5}$
	0.2	$SNR_p > \frac{112}{205}SNR_s - \frac{1774}{204}$	$SNR_p > \frac{18}{31}SNR_s - \frac{224}{31}$	$SNR_p > \frac{2}{3}SNR_s + \frac{23}{3}$
	0.3	APC	$SNR_p > \frac{145}{231}SNR_s - \frac{2533}{231}$	$SNR_p > \frac{43}{63}SNR_s - \frac{1277}{126}$
(1.5,0.5)	0.1	$SNR_p > \frac{27}{50}SNR_s + \frac{27}{5}$	$SNR_p > \frac{271}{450}SNR_s + \frac{284}{45}$	$SNR_p > \frac{31}{45}SNR_s + \frac{61}{9}$
	0.2	$SNR_p > \frac{17}{30}SNR_s + \frac{13}{3}$	$SNR_p > \frac{55}{84}SNR_s + \frac{104}{21}$	$SNR_p > \frac{37}{50}SNR_s + \frac{28}{5}$
	0.3	$SNR_p > \frac{33}{56}SNR_s + \frac{41}{74}$	$SNR_p > \frac{2}{3}SNR_s + \frac{62}{15}$	$SNR_p > \frac{23}{30}SNR_s + \frac{14}{3}$
(0.5,1.5)	0.1	$SNR_p > \frac{87}{124}SNR_s - \frac{1341}{124}$	$SNR_p > \frac{17}{35}SNR_s - \frac{92}{35}$	$SNR_p > \frac{75}{86}SNR_s - \frac{425}{43}$
	0.2	$SNR_p > \frac{49}{62}SNR_s - \frac{453}{31}$	$SNR_p > \frac{236}{155}SNR_s - \frac{3881}{255}$	$SNR_p > \frac{235}{249}SNR_s - \frac{1003}{83}$
	0.3	$SNR_p > \frac{245}{288}SNR_s - \frac{1289}{72}$	$SNR_p > \frac{312}{329}SNR_s - \frac{5224}{329}$	$SNR_p > SNR_s - \frac{29}{2}$
(1.5,1.5)	0.1	$SNR_p > \frac{253}{450}SNR_s + \frac{302}{45}$	$SNR_p > \frac{32}{45}SNR_s + \frac{65}{9}$	$SNR_p > \frac{113}{125}SNR_s + \frac{209}{25}$
	0.2	$SNR_p > \frac{125}{139}SNR_s + \frac{785}{139}$	NPC	NPC
	0.3	NPC	NPC	NPC

If the former is found to be higher, then the interweave paradigm is selected. Otherwise the underlay paradigm is chosen.

B. Concluding Remarks

In this paper we have provided a brief overview of CR techniques and described the various standardization activities in the field of CR and DSA. Moreover, we conceived novel approaches for characterizing the achievable rates of the interweave CR. Explicitly, we developed a model for the interweave CR based on the effective noise observation. We demonstrated the impact of the spectrum sensing errors on the achievable rate region with the aid of the ED and MSCD. Based on a rate-limited model for the underlay CR we provided comparisons between the interweave and the underlay CRs on the basis of various parameters of interest and explicit rules of thumb were inferred as a guide for selecting, which specific approach is better. We demonstrated that there are various regimes of practical interest, where the interweave CR is more beneficial than the underlay CR. These regimes include the scenarios, where the spectrum is sparsely occupied. If however, the spectrum is heavily occupied, both techniques become challenged.

C. Open Problems

Since, we have tried to answer the most fundamental problem, a variety of open problems can be framed as a result. Solutions to these problems will certainly help researchers understand the gains that are achieved using ideas of CR and will let us know the best possible approach

TABLE X: $p = 0.75$ only SU

(a,b)	p_{md}	$p_{fa} \leq 0.2$	$p_{fa} \leq 0.3$	$p_{fa} \leq 0.4$
(1,1)	0.1	$SNR_p > \frac{19}{50}SNR_s - \frac{7}{5}$	$SNR_p > \frac{301}{678}SNR_s - \frac{401}{678}$	$SNR_p > \frac{18}{35}SNR_s + \frac{8}{35}$
	0.2	$SNR_p > \frac{42}{115}SNR_s - \frac{208}{115}$	$SNR_p > \frac{68}{145}SNR_s - \frac{284}{145}$	$SNR_p > \frac{39}{70}SNR_s - \frac{8}{7}$
	0.3	$SNR_p > \frac{9}{26}SNR_s - \frac{133}{65}$	$SNR_p > \frac{24}{53}SNR_s - \frac{112}{53}$	$SNR_p > \frac{23}{36}SNR_s - \frac{73}{18}$
(0.5,0.5)	0.1	APC	APC	$SNR_p > \frac{145}{252}SNR_s - \frac{359}{63}$
	0.2	APC	APC	$SNR_p > \frac{9}{16}SNR_s - \frac{19}{2}$
	0.3	APC	APC	APC
(1.5,0.5)	0.1	$SNR_p > \frac{37}{100}SNR_s + \frac{13}{5}$	$SNR_p > \frac{162}{385}SNR_s + \frac{1528}{385}$	$SNR_p > \frac{33}{70}SNR_s + \frac{37}{2}$
	0.2	$SNR_p > \frac{95}{273}SNR_s + \frac{659}{273}$	$SNR_p > \frac{50}{121}SNR_s + \frac{420}{121}$	$SNR_p > \frac{69}{148}SNR_s + \frac{953}{185}$
	0.3	$SNR_p > \frac{182}{555}SNR_s + \frac{1156}{555}$	$SNR_p > \frac{111}{272}SNR_s + \frac{199}{68}$	$SNR_p > \frac{41}{84}SNR_s + \frac{29}{7}$
(0.5,1.5)	0.1	APC	APC	$SNR_p > \frac{3}{5}SNR_s - \frac{19}{2}$
	0.2	APC	APC	$SNR_p > \frac{19}{31}SNR_s - \frac{1661}{155}$
	0.3	APC	APC	$SNR_p > \frac{11}{15}SNR_s - \frac{47}{3}$
(1.5,1.5)	0.1	$SNR_p > \frac{19}{50}SNR_s - \frac{7}{5}$	$SNR_p > \frac{117}{265}SNR_s + \frac{37}{265}$	$SNR_p > \frac{6}{13}SNR_s + \frac{46}{13}$
	0.2	$SNR_p > \frac{16}{41}SNR_s - \frac{494}{205}$	$SNR_p > \frac{40}{131}SNR_s + \frac{758}{131}$	$SNR_p > \frac{205}{378}SNR_s + \frac{373}{189}$
	0.3	$SNR_p > \frac{14}{31}SNR_s - \frac{816}{155}$	$SNR_p > \frac{25}{47}SNR_s - \frac{415}{141}$	$SNR_p > \frac{19}{30}SNR_s - \frac{2}{15}$

in a given scenario. Some of these problems are enumerated as follows:

1) **A possible future research direction will seek a hybrid paradigm that is capable of combining the cognitions that the SU is able to perform both in the underlay CR and the interweave CR in order to combine the advantage of underlay i.e. maintaining the PU QoS and at the same time opportunistically utilize white spaces like the interweave paradigm. This would achieve better rates for both the SU and PU.**
2) **Furthermore, research is also required to establish the effect the imperfection in channel state estimation in the underlay paradigm. This is especially important practically where the links are fast fading and the time window to estimate the channel state relative to data transmission is very narrow.**
3) **Contrary to this the case where the users are able to feedback the perfectly estimated channel state to their transmitters needs to be investigated for the optimal power allocation schemes with regards to maximizing the SU rate and/or the sum rate. This would be an important case study when the links are slow fading. In this scenario it would be practical for both measurement of the channel state and feedback within one coherence time.**

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TABLE XI: $p = 0.25$ sum rate.

(a, b)	p_{md}	$p_{fa} \leq 0.2$	$p_{fa} \leq 0.3$	$p_{fa} \leq 0.4$
(1,1)	0.1	Some value	NPC	NPC
	0.2	NPC	NPC	NPC
	0.3	NPC	NPC	NPC
(0.5,0.5)	0.1	$\frac{18}{11}SNR_s - \frac{196}{11} < SNR_p < \frac{644}{11} - \frac{12}{11}SNR_s$	$\frac{9}{5}SNR_s - \frac{94}{5} < SNR_p < \frac{296}{5} - \frac{6}{5}SNR_s$	$\frac{9}{5}SNR_s - 17 < SNR_p < 58 - \frac{6}{5}SNR_s$
	0.2	$3SNR_s - 44 < SNR_p < 38 - \frac{8}{11}SNR_s$	$\frac{11}{4}SNR_s - \frac{147}{4} < SNR_p < \frac{399}{10} - \frac{9}{16}SNR_s$	$\frac{10}{3}SNR_s - \frac{130}{3} < SNR_p < 39 - SNR_s$
	0.3	$7SNR_s - 116 < SNR_p < \frac{91}{2} - \frac{3}{2}SNR_s$	$6SNR_s - 92 < SNR_p < \frac{292}{7} - \frac{10}{7}SNR_s$	$6SNR_s - 86 < SNR_p < \frac{282}{7} - \frac{10}{7}SNR_s$
(1.5,0.5)	0.1	$4SNR_s - 20 < SNR_p < 68 - 4SNR_s$	NPC	NPC
	0.2	NPC	NPC	NPC
	0.3	NPC	NPC	NPC
(0.5,1.5)	0.1	$\frac{11}{6}SNR_s - \frac{47}{3} < SNR_p < 39 - \frac{9}{10}SNR_s$	$2SNR_s - 14 < SNR_p < \frac{71}{2} - \frac{3}{4}SNR_s$	$\frac{5}{2}SNR_s - 15 < SNR_p < 34 - SNR_s$
	0.2	$SNR_p < 32 - \frac{3}{2}SNR_s$, $SNR_s \leq 12$	NPC	NPC
	0.3	NPC	NPC	
(1.5,1.5)	0.1	NPC	NPC	NPC
	0.2	NPC	NPC	NPC
	0.3	NPC	NPC	NPC

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TABLE XII: $p = 0.5$ sum rate

(a,b)	p_{md}	$p_{fa} \leq 0.2$	$p_{fa} \leq 0.3$	$p_{fa} \leq 0.4$
(1,1)	0.1	$\frac{11}{7}SNR_s - \frac{95}{7} < SNR_p < \frac{520}{9} - \frac{8}{9}SNR_s$	$\frac{20}{13}SNR_s - \frac{110}{13} < SNR_p < \frac{640}{13} - \frac{10}{13}SNR_s$	$\frac{19}{13}SNR_s - \frac{60}{13} < SNR_p < \frac{630}{13} - \frac{11}{13}SNR_s$
	0.2	$2SNR_s - 16 < SNR_p < \frac{265}{6} - \frac{7}{6}SNR_s$	$\frac{11}{6}SNR_s - \frac{25}{3} < SNR_p < 37 - SNR_s$	$4SNR_s - 28 < SNR_p < 38 - \frac{3}{2}SNR_s$
	0.3	$\frac{7}{2}SNR_s - \frac{57}{2} < SNR_p < \frac{103}{3} - \frac{4}{3}SNR_s$	NPC	NPC
(0.5,0.5)	0.1	$SNR_p > \frac{15}{13}SNR_s - \frac{275}{13}$	$SNR_p > \frac{4}{3}SNR_s - \frac{70}{3}$	$SNR_p > \frac{7}{4}SNR_s - \frac{121}{4}$
	0.2	$\frac{11}{6}SNR_s - \frac{79}{2} < SNR_p < \frac{536}{7} - \frac{8}{7}SNR_s$	$\frac{10}{11}SNR_s - \frac{130}{11} < SNR_p < \frac{215}{2} - \frac{5}{2}SNR_s$	$\frac{10}{9}SNR_s - \frac{130}{9} < SNR_p < \frac{840}{11} - \frac{20}{11}SNR_s$
	0.3	$\frac{5}{2}SNR_s - 45 < SNR_p < 39 - \frac{1}{2}SNR_s$	$\frac{15}{8}SNR_s - 35 < SNR_p < \frac{435}{11} - \frac{5}{11}SNR_s$	$\frac{17}{8}SNR_s - \frac{379}{8} < SNR_p < \frac{513}{13} - \frac{9}{26}SNR_s$
(1.5,0.5)	0.1	$\frac{11}{9}SNR_s - \frac{2}{9} < SNR_p < 76 - \frac{3}{2}SNR_s$	$SNR_s + 3 < SNR_p < \frac{125}{2} - \frac{9}{8}SNR_s$	$\frac{17}{11}SNR_s - \frac{16}{11} < SNR_p < \frac{437}{8} - \frac{9}{8}SNR_s$
	0.2	$\frac{13}{7}SNR_s - \frac{39}{7} < SNR_p < 76 - \frac{3}{2}SNR_s$	$2SNR_s - 5 < SNR_p < \frac{81}{2} - \frac{5}{4}SNR_s$	$3SNR_s - 12 < SNR_p < 65 - 4SNR_s$
	0.3	Some values near $SNR_p = 20dB$ and $SNR_s = 10dB$	NPC	NPC
(0.5,1.5)	0.1	$\frac{5}{6}SNR_s - \frac{35}{3} < SNR_p < 210 - 5SNR_s$	$\frac{10}{11}SNR_s - \frac{130}{11} < SNR_p < 120 - \frac{20}{7}SNR_s$	$\frac{10}{9}SNR_s - \frac{130}{9} < SNR_p < \frac{800}{9} - \frac{20}{9}SNR_s$
	0.2	$\frac{13}{5}SNR_s - \frac{262}{5} < SNR_p < \frac{583}{14} - \frac{9}{14}SNR_s$	$\frac{11}{5}SNR_s - \frac{181}{5} < SNR_p < \frac{81}{2} - \frac{3}{4}SNR_s$	$\frac{10}{3}SNR_s - \frac{170}{3} < SNR_p < \frac{407}{10} - \frac{9}{10}SNR_s$
	0.3	$\frac{8}{3}SNR_s - \frac{154}{3} < SNR_p < \frac{261}{8} - \frac{9}{16}SNR_s$	$8SNR_s - 150 < SNR_p < \frac{291}{8} - \frac{7}{8}SNR_s$	$SNR_p < \frac{256}{7} - \frac{8}{7}SNR_s$ and $SNR_s \leq 18$
(1.5,1.5)	0.1	$\frac{13}{16}SNR_s - \frac{71}{6} < SNR_p < \frac{269}{6} - \frac{7}{6}SNR_s$	$2SNR_s - 5 < SNR_p < \frac{139}{3} - \frac{5}{3}SNR_s$	NPC
	0.2	NPC	NPC	NPC
	0.3	NPC	NPC	NPC

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TABLE XIII: $p = 0.75$ sum rate

(a, b)	p_{md}	$p_{fa} \leq 0.2$	$p_{fa} \leq 0.3$	$p_{fa} \leq 0.4$
(1,1)	0.1	$SNR_p > \frac{4}{7}SNR_s - \frac{34}{7}$	$SNR_p > \frac{12}{19}SNR_s - \frac{62}{19}$	$SNR_p > \frac{9}{11}SNR_s - \frac{52}{11}$
	0.2	$SNR_p > \frac{4}{7}SNR_s - \frac{34}{7}$	$SNR_p > \frac{3}{4}SNR_s - 5$	$SNR_p > \frac{29}{22}SNR_s - \frac{273}{22}$
	0.3	$\frac{4}{7}SNR_s - \frac{34}{7} < SNR_p < SNR_s + 17$	$SNR_s - 10 < SNR_p < \frac{615}{19} + \frac{5}{19}SNR_s$	$\frac{7}{5}SNR_s - \frac{62}{5} < SNR_p < \frac{713}{21} - \frac{2}{21}SNR_s$
(0.5,0.5)	0.1	APC	$SNR_p > \frac{4}{5}SNR_s - 18$	$SNR_p > \frac{4}{5}SNR_s - 14$
	0.2	APC	$SNR_p > \frac{3}{5}SNR_s - 11$	$SNR_p > \frac{7}{10}SNR_s - 11$
	0.3	APC	APC	$SNR_p > \frac{7}{10}SNR_s - 11$
(1.5,0.5)	0.1	$SNR_p > \frac{12}{23}SNR_s + \frac{26}{23}$	$SNR_p > \frac{17}{27}SNR_s + \frac{49}{27}$	$SNR_p > \frac{7}{10}SNR_s + 3$
	0.2	$SNR_p > \frac{1}{2}SNR_s + 2$	$SNR_p > \frac{9}{14}SNR_s + \frac{16}{7}$	$SNR_p > SNR_s$
	0.3	$SNR_p > \frac{1}{2}SNR_s + 2$	$SNR_p > \frac{21}{29}SNR_s + \frac{59}{29}$	$SNR_p > SNR_s$ and $SNR_p \leq 33$
(0.5,1.5)	0.1	APC	$SNR_p > \frac{4}{5}SNR_s - 18$	$SNR_p > \frac{4}{5}SNR_s - 14$
	0.2	APC	$SNR_p > SNR_s - 25$	$SNR_p > SNR_s - 19$
	0.3	APC	$SNR_p > \frac{4}{5}SNR_s - 18$	$\frac{14}{11}SNR_s - \frac{296}{11} < SNR_p < \frac{2}{5}SNR_s + \frac{110}{3}$
(1.5,1.5)	0.1	$SNR_p > \frac{9}{16}SNR_s - \frac{7}{2}$	$SNR_p > \frac{15}{22}SNR_s - \frac{25}{11}$	$SNR_p > \frac{23}{26}SNR_s + \frac{15}{3}$ and $SNR_s \leq 36$
	0.2	$\frac{11}{18}SNR_s - \frac{31}{9} < SNR_p < \frac{4}{9}SNR_s + \frac{644}{19}$	$SNR_s - 5 < SNR_p < \frac{409}{11} - \frac{7}{22}SNR_s$	$\frac{14}{11}SNR_s - \frac{8}{11} < SNR_p < \frac{391}{11} - \frac{5}{11}SNR_s$
	0.3	$\frac{17}{15}SNR_s - \frac{224}{15} < SNR_p < \frac{803}{27} - \frac{2}{27}SNR_s$	$10 < SNR_p < 26$ and $SNR_s < 20$	Some values near $SNR_p = 20dB$ and $SNR_s = 10dB$

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