Cognitive Radio Systems: State of the art

V. Le Nir and B. Scheers

Cognitive radio has been introduced by Mitola in 1999 as an extension to software radio [1] (Stevens USA). Cognitive radio extends the software radio with radio-domain model-based reasoning about etiquettes (set of RF bands, air interfaces, protocols, and spatial and temporal patterns that moderate the use of the radio spectrum). Cognitive radio enhances the flexibility of personal services through a Radio Knowledge Representation Language (RKRL). This language represents knowledge of radio etiquette, devices, software modules, propagation, networks, user needs, and application scenarios in a way that supports automated reasoning about the needs of the user. This empowers software radios to conduct expressive negotiations among peers about the use of radio spectrum across fluents of space, time, and user context. With RKRL, cognitive radio agents may actively manipulate the protocol stack to adapt known etiquettes to better satisfy the user's needs. This transforms radio nodes from blind executors of predefined protocols to radio-domain-aware intelligent agents that search out ways to deliver the services the user wants even if that user does not know how to obtain them. Software radio provides an ideal platform for the realization of cognitive radio. More detail can be found in his disseration [2]. In [3] (FCC USA), the federal commission on communications concludes that more flexibility is needed in today's wireless networks. In [4] (McMaster CA), Haykin addresses three fundamental tasks in cognitive radio: radio-scene analysis, channel-state estimation and predictive modeling, transmit-power control and dynamic spectrum management. In his article, the following definition of cognitive radio is given: "Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- highly reliable communications whenever and wherever needed
- efficient utilization of the radio spectrum"

In [5] (Georgia Tech USA), the authors provide a brief overview of the cognitive radio technology and the xG network architecture. Moreover, the xG network functions such as spectrum management, spectrum mobility and spectrum sharing are explained in detail. The influence of these functions on the performance of the upper layer protocols such as routing and transport are investigated and open research issues in these areas are also outlined. Finally, the cross-layer design challenges in xG networks are discussed. The discussions provided in this survey strongly advocate spectrum-aware communication protocols that consider the spectrum management functionalities. This cross-layer design requirement necessitates a rethinking of the existing solutions developed for wireless networks.

1 Programming languages

As cognitive radio extends the possibility of current wireless systems, the languages of cognitive radio need to improve compared to current languages. Below you will find current researches for cognitive radio languages which tries to take ideas from artificial intelligence (AI) languages.

In [6] (Boston USA), the authors make a comparison between imperative (procedural) languages and declarative languages for the programming of cognitive radio systems. Imperative or procedural languages are C/C++, Java FORTRAN languages where an algorithm is written sequentially and explains how the system should react given known parameters. Declarative languages do not tell how but rather what to do, i.e. a collection of facts (clauses) and goals provided by the users. The how is left to the inference engine which finally make the decision. Declarative languages are more “cognitive” than imperative languages but their software can take longer time to reach a decision. The authors propose to use a language called Ontology Web Language (OWL) for cognitive radio systems. In [7] (DARPA USA), the authors discuss about extending the reach of cognitive radio. They note that 802.22 or defense advanced research project agency (DARPA) have already lead to prototype to sense the channel and to efficiently use dynamic spectrum allocation (DSA) algorithms. The main challenge in cognitive radio is broader, i.e. how to build artificial intelligence mechanism such that users cannot learn bad behaviors. New languages need to be developed to communicate between cognitive radio users (It is one of the main objective of DARPA to develop such a language). The authors propose to use a system strategy reasoner (SSR) that will take the decisions for the bandwidths, waveforms and policy conformance reasoners (PCR) to care about the social behavior of the users. On big challenge for cognitive radio is the adaptive network topology to reduce the interference between users in a dense environment. A possibility is to organize small LANs between neighbors at their own frequency, but as the time goes reorganization of the network is done adaptively. A second challenge is to reduce the cost and the power of each node while maintaining good performance by cooperation. Stability is another challenge, as ten users can force ten other users to change their frequencies, but this will affect again ten other users... An interesting remark is about the information needed to the cognitive radio receiver, is it worth the cost of calculating the CSI, parameters?

In [8] (Stevens USA), Mitola review the different visions of cognitive radio architecture. He states that cognitive wireless networks (CWN) significantly expands the research framework and architecture evolution possibilities to a mix of ad hoc and fixed wireless networks with self-awareness and greater spectrum efficiency; to substantial memory in the network and to distributed machine learning. The cognitive radio can be extended to various application, such as cognitive vision, speech recognition and translation. A quality of information QoI is presented where the metric takes into account the quantity, precision, recall, accuracy, detail, timeliness and validity of the information. Finally, when performing spectrum scanning, the GPS as well as radar bands and space bands cannot be seen. Moreover, the classical AM radio allow the signal to be heard at -6dB from the noise floor (Mayday). The objective of cognitive radio is to avoid jamming the existing bands. In [9] (SRI International USA), the authors describe CoRaL, which is a new language, based on a subset of first-order logic with types, for expressing policies that allow opportunistic spectrum access while not causing interference. CoRaL satisfies the requirements of having expressive constructs for numerical constraints, supporting efficient reasoning, and being verifiable. They have made the language extensible in several ways so that unanticipated policy types can, we hope, still be encoded. A complete specification of CoRaL will be released publicly as soon as we obtain permission from DARPA.

2 Spectrum sensing

Lots of work have been done at the university of Berkeley on spectrum sensing by Wild, Mishra, Cabric, Brodersen, Tandra etc.

In [10] (Berkeley USA), the authors tackle the problem of detecting the primary users, noting that it is difficult to detect very weak primary signals due to the uncertainty in the noise variance and the SNR wall. Therefore, some authors have proposed the idea of using a strong pilot tone for the primary transmitters. Other authors have proposed the use of cooperation among the cognitive radios to improve the detection. The authors propose to exploit the local oscillator leakage power emitted by the RF front end of primary receivers. This technique exploits the fact the primary receivers actually couples back through the input port and radiates out of the antenna. Of course, this leakage is low and require nodes close to the primary receivers that send information to the cognitive users. In [11] (Berkeley USA), the authors propose cooperative sensing among cognitive radio. They state that a secondary user must be significantly more sensitive in detecting than the primary receiver. The authors propose the radio sensitivity as a metric for cooperative gain, radio sensitivity of cooperative users can be as high as the path loss model if the multipath effects are mitigated by cooperation. In [12] (Berkeley USA), the authors try to improve the robustness of the spectrum sensing for low SNRs. A technique called run-time noise calibration that was proposed to detect the presence of a signal by its narrowband pilots (matched filter) is extended to cyclostationary signals (PAM with zero at even bins or 50%-duty-cycle). In [13] (Berkeley USA), the authors study the spectrum sensing for low SNRs. They notice that in practice, as the number of sample increases the SNR of the signal to be detected decreases until a SNR wall is reached due to noise uncertainty. Even for cyclostationarity test, the SNR wall can be decreased but not completely eliminated. This is due to the scale of the signal feature which is similar to the scale of the fading process or noise. The authors propose to use transmit signal whose scale is much larger (macroscale) than the uncertainties (fading and noise). A on/off transmit vector signal is proposed, as well as Gaussian transmit vectors with different transmit powers to reduce the SNR walls. These strategies have an effect on the detection by secondary users since they have to compute sufficient statistics.

In [14] (Berkeley USA), the authors present a feasibility study of spectrum-sensing techniques using a research testbed platform for exploration and demonstration of cognitive radio systems. This testbed is used for an experimental study of a set of prominent candidate techniques proposed in the literature for implementation of spectrum sensing functionality. They first consider three physical layer signal processing approaches based on energy, pilot, and feature detection. limits, and implementation issues. The physical layer spectrum-sensing study shows that the conventional detection techniques behave differently in negative SNR regimes and are particularly sensitive to the radio receiver circuitry impairments. In the case of energy detection, noise is the fundamental limitation, while frequency and clock uncertainties pose implementation complexity constraints for pilot and feature detection. Further research is needed to develop robust pilot and feature detectors in the presence of radio impairments in a negative SNR. On higher layers, multiple sensors can exploit channel and user diversity, but the achievable gains are strong function of the node separation. In addition, multiple antennas can be used for increased sensitivity through a simple noncoherent combining, but the gain depends on the spatial channel profiles. Further research is needed for robust cooperation strategies that can optimally exploit versatile physical layer spectrum sensing capabilities. In [15] (Berkeley USA), the authors discuss about recognizing spectrum holes. They notice that the primary users have no rational reason to trust the secondary users assurances, and this results in asymmetric uncertainty. To reflect this tension and to allow a unified treatment of spectrum sensing, this paper has introduced two distinct metrics. To guarantee safety, the “fear of harmful interference” from the detector must be kept low enough no matter which radio deployment and environmental model turns out to be true.

The university of Florida has worked on spectrum sensing techniques (Arslan and Yucek).

In [16] (Florida USA), the authors propose a sensing method for identifying the unused spectrum for opportunistic transmission by estimating the RF transmission parameters of primary users. The primary users are identified by matching the a priory information about their transmission characteristics to the features extracted from the received signal. The application of the proposed sensing method to WiMAX mobile stations for finding the active channels during initial network entry is also discussed as a case study. In [17] (Florida USA), the authors develop methods for identification of orthogonal frequency division multiplexing (OFDM) signals and estimation of fundamental OFDM parameters. They use autocorrelation and cyclostationary methods. In [18] (Florida USA), the authors present a survey of spectrum sensing methodologies for cognitive radio is presented. Various aspects of spectrum sensing problem are studied from a cognitive radio perspective and multi-dimensional spectrum sensing concept is introduced. Challenges associated with spectrum sensing are given and enabling spectrum sensing methods are reviewed. The paper explains the cooperative sensing concept and its various forms.

The university of Georgia Tech (Akyildiz, Ganeson, Chowdhury, Ma etc.) has also worked on spectrum sensing.

In [19] (Georgia Tech USA), the authors exploit spatial diversity in multiuser networks to improve the spectrum sensing capabilities of centralized cognitive radio (CR) networks. They develop a fixed and a variable relay sensing scheme. The fixed relay scheme employs a relay that has a fixed location to help the cognitive network base station detect the presence of the primary user. The variable relay sensing scheme employs cognitive users distributed at various locations as relays to sense data and to improve the detection capabilities. In [20] (Georgia Tech USA), the authors propose a new approach for spectrum sensing without any change to the working of existing de facto mesh protocols. Then, an analytical model is proposed that allows mesh routers to estimate the power in a given channel and location due to neighboring wireless LAN trafc, thus creating a virtual map in space and frequency domains. These models are used to formulate the task of channel assignment within the mesh network as an optimization problem, which is solved in a decentralized manner. In [21] (Georgia Tech USA), the authors review the different spectrum sensing schemes based on energy detection, matched filter and cyclostationarity detection. Then they propose the use of multicarrier techniques and TDCS as possible candidates for the physical layer of a CR network. Both of them are able to flexibly switch the transmission off in the subset of carriers occupied by the primary users.

The following works have been performed by UCLA.

In [22] (UCLA USA), the authors present a new approach to relaxing RF component requirements in a Weaver architecture receiver that utilizes spectrum sensing and adaptation. The motivation behind the paper was to develop and quantify the performance of a receiver that can survey its environment and adaptively tune its hardware to ease the Radio front-end requirements. In [23] (UCLA USA), the authors provide an overview of the challenges and possible solutions for the design of collaborative wideband sensing in CR networks. It is argued that collaborative spectrum sensing can make use of signal processing gains at the physical layer to mitigate strict requirements on the radio frequency front-end and to exploit spatial diversity through network cooperation to significantly improve sensing reliability. They introduce a linear fusion scheme for collaborative sensing and a multiband joint detection framework for wideband sensing. They also present efficient algorithms to optimize the sensing performance. Implementation issues of the proposed sensing algorithms in a wideband CR system have been discussed from a multi- layer networking perspective. In [24] (UCLA USA), the authors study the propagation issues in cognitive radio. They provide a comprehensive overview of the propagation channel models that will be used for the design of cognitive radio systems.

The following works have been done by the university of Hong-Kong.

In [25] (Honk Kong HK), the authors note that spectrum sensing cannot guarantee accurate detection of the interference in many practical situations. Hence, it is crucial to design robust receivers to combat the in-band interference. The authors propose a simple pilot aided interference detection method. To combat the residual interference that cannot be detected by the interference detector, they further propose a robust joint interference detection and decoding scheme. In [26] (Honk Kong HK), the authors propose a cooperative spectrum sensing for cognitive radio networks. Cooperative spectrum sensing is shown to be a powerful method for dealing with the hidden terminal problem. However, under realistic scenarios, where the reporting channels are subject to fading and/or shadowing, the performance of cooperative spectrum sensing can be severely limited. To address this and other cooperative spectrum sensing challenges, various potential solutions are presented. They also show that dynamic spectrum can be fully utilized through a number of cognitive relay nodes. The so-called cognitive wireless relay network can support seamless data service for cognitive users while causing zero-interference to primary systems.

An important work has been performed by Haykin at the McMaster university based on the multi-taper method.

In [27] (McMaster CA), Haykin presents a tutorial exposition of the Multi-Taper Method (MTM), which is expandable to perform spacetime processing and timefrequency analysis. Then, the author presents cyclostationarity, viewed from the Loeve and Fourier perspectives. Finally, the author gives experimental results, using Advanced Television Systems Committee digital television and generic land mobile radio signals, followed by a discussion of the effects of Rayleigh fading.

Another important work has been performed by Jallon at the CEA-LETI.

In [28] (CEA FR), the author develops an algorithm for detection of DVB-T signals based on their second-order statistics, as the TV band channels will be released for an opportunistic access. The detection algorithm is based on the cyclostationarity of the signal based on the cyclic prefix knowing the useful symbol duration. A two hypothesis test is used to detect the presence of a signal.

Another important work has been done by Oner and Jondral from the university of Karlsruhe.

In [29] (Karlsruhe GER), the authors present a strategy for the extraction of the CAI based on exploiting the distinct cyclostationary characteristics of the primary network and secondary network signals and demonstrates, via simulations, its application on a specic spectrum pooling scenario, where the primary network is a GSM network and the secondary network is an OFDM based WLAN system.

Below are some work from different universities.

In [30] (Infocomm SFP), the authors study the spectrum sensing based on statistical covariances matrices of the received signal. The scenario is the spectrum sensing in the TV bands VHF/UHF, where there could be wireless microphones interferers. For spectrum sensing, there is also noise uncertainty due to two effects. The first effect is the noise uncertainty due to the components of the receiver, time varying thermal noise. The second effect is the environment noise uncertainty due to intentional or unintentional transmitters. These uncertainties make difficult to estimate accurately the noise power. The proposed test is based on the ratio between the sum of all elements of the covariance matrix and the diagonal elements of the covariance matrix. As the noise and the signal have different properties (signal can be correlated due to the sampling, the structure of the signal, etc. while the noise is independent and identically distributed, or we can pre-whiten the noise). The technique can also be used for multi-antenna systems. The authors prove that their algorithm is better than energy detection when there is noise uncertainty.

In [31] (Michigan USA), the authors discuss about the spectrum sensing in 802.22 for TV bands, where the delay for spectrum sensing is fixed at 2 seconds and where the probability of false alarm (Pfa) and probability of misdetection (Pmd) is fixed at 0.1. The authors propose collaborative sensing using an energy detector compared to a more complex feature detector. They notice that the impact of multipath fading is insignificant in detecting a DTV signal by the energy detector due to its frequency diversity over the 6 MHz band, but the shadow fading is more important. Feature detection for DTV includes pilot energy detection, synchronization with a known data segment, or cyclostationary detection. They study also the sensor density for collaborative sensing, noting that Mishra has also stated that a few tens of sensors provide as much collaborative gain as many more correlated sensors whose collaborative gain is limited by geographical correlation in shadowing. They study also the sensing mechanism in 802.22, where a fast (energy) or fine (feature) sensing are performed, and propose an in-band sensing algorithm that optimize the sensing period while satisfying the conditions and minimize the sensing overhead. They conclude that the energy detector performs better than the other detectors under consideration.

In [32] (SUPELEC FR), the authors propose to use random matrix theory for cooperative spectrum sensing. The authors propose a new detection strategy when the number of samples is in the same order as the number of nodes. In this case, the convergence to an identity matrix is no longer valid, and the authors propose to use random matrix theory to derive a new detector that works well compared to the energy detector.

In [33] (California Davis USA), the authors study the channel selection issue of secondary users in spectrum-agile communication systems, focusing on the sensing-based approach.

In [34] (Genova IT), the authors deal with a distributed decision approach to solve the problem of spectrum sensing for Cognitive Terminals in a known indoor environment. On going researches are centered on the resolution of multiple hypothesis distributed decision test, taking into account new air interfaces such as multi-carrier techniques, and new methodologies for a joint estimation of position and modes.

In [35] (Dublin IR), the authors demonstrate how cyclostationary signatures can be exploited to overcome a number of the challenges associated with network coordination in emerging cognitive radio applications and spectrum sharing regimes. In particular we show their uses for signal detection, network identication and rendezvous and discuss these in the context of dynamic spectrum access.

3 Spectrum Management

3.1 Network information theory

Network information theory is very important as it gives the achievable capacity of the networks. A current solution for cognitive radio to exploit the capacity is to exploit the iterative-waterfilling algorithm, but this solution is sub-optimal.

In [36] (stanford USA), Wei Yu discusses about competition and cooperation in multi-user communication environments. In his thesis, the iterative waterfilling algorithm is described where each user maximize its rate considering the crosstalk of the other user constant.

In [37], Wei Yu extends the iterative waterfilling scheme to the weighted rate sum maximization. The algorithm called modified iterative waterfilling (MIW) is distributed but not autonomous (requires message passing between the users).

In [38], the authors compare the algorithms of iterative waterfilling (IW) and autonomous spectrum balancing (ASB) which are completely autonomous, modified iterative waterfilling (MIW) and SCALE and distributed spectrum balacing (DSB) which require message passing between users, and finally optimum spectrum balancing and iterative spectrum balancing which are centralized operations.

In [39], the authors study the convergence of the fixed margin iterative waterfilling algorithm.

In [40], the authors propose to improve the fixed margin iterative waterfilling algorithm using power pricing. Their objective function is to minimize the total power subject to rate constraints and power constraints. The power price mechanism scale with direct channel of each user, i.e. users ries to reach their target rates using high frequencies first.

A lot of work has been done by the university of Harvard concerning network information theory for cognitive radios.

In [41] (Harvard USA), the authors discuss about the achievable rates in cognitive radio channels. The cognitive radio channel is dened as a two-sender, two-receiver interference channel in which sender 2 obtains the encoded message sender 1 plans to transmit. They consider two cases: in the genie-aided cognitive radio channel, sender 2 is noncausally presented the data to be transmitted by sender 1 while in the causal cognitive radio channel, the data is obtained causally. The cognitive radio at sender 2 may then choose to transmit simultaneously over the same channel, as opposed to waiting for an idle channel as is traditional for a cognitive radio. The main result is the development of an achievable region which combines GelfandPinkser coding with an achievable region construction for the interference channel. In the additive Gaussian noise case, this resembles dirty-paper coding, a technique used in the computation of the capacity of the Gaussian multiple-input multiple-output (MIMO) broadcast channel.

In [42] (Harvard USA), the authors survey the current proposals for cognitive radio deployment, and present a new, potentially more spectral efficient model for a wireless channel employing cognitive radios; the cognitive radio channel. This channel models the simplest scenario in which a cognitive radio could be used and consists of a 2 Tx, 2 Rx wireless channel in which one transmitter knows the message of the other. They obtain fundamental limits on the communication possible over such a channel, and discuss future engineering and regulatory issues.

In [43] (Harvard USA), the authors describe the capacity region of a system with two transmitters and two receivers by the time-sharing region, interference channel region, cognitive channel region (the cognitive user knows the message of the primary user) and two-transmit-antenna broadcast channel region. The cognitive channel multiplexing gain equals unity as the interference channel multiplexing gain. Results on ad-hoc networks say that for n nodes without cooperation the per user network capacity decreases as $1/sqrt(n)$ when $n \to \inf$. However, when coordination is possible between the nodes, the per user capacity approaches a constant. The authors propose to study an ad-hoc cognitive network with single-hop transmission given the presence of a primary user. In the case, the per user capacity approaches a constant.

In [44] (Harvard USA), the authors outline some recent results on the fundamental information theoretic and communication theoretic limits of cognitive networks. They first discussed how, for small networks, different levels of cognition, or information about the wireless environment, in the secondary node(s) leads to different achievable rate and capacity regions. In large networks, they provide the throughput scaling law for three cognitive networks. Turning attention to the design of network parameters and communication protocols, the interference seen by the primary receivers from cognitive radios is of great importance. They outline examples of interference analyzes and their impacts in cognitive networks with beacons and with primary exclusive regions.

Similar work has been performed at the university of California Irvine:

In [45] (California Irvine USA), the authors present the throughput potential of cognitive radio from a theoretical perspective. Considering opportunistic communication as a baseline, they investigate the throughput improvements offered by the overlay methods. Channel selection techniques for opportunistic access such as frequency hopping,frequency tracking, and frequency coding are presented. The trade-off between regulation and autonomy inherent in the design and performance of cognitive networks is examined through a simple example, which shows that the optimal amount of licensing is equal to the duty cycle of the traffic arrivals.

In [46] (California Irvine USA), the authors investigate the capacity of opportunistic communication in the presence of dynamic and distributed spectral activity, i.e., when the time varying spectral holes sensed by the cognitive transmitter are correlated but not identical to those sensed by the cognitive receiver. These capacity results are used to determine the benets of any feedforward and feedback information.

Another important work has been performed at Stanford university in collaboration with the university of California Irvine

In [47] (Stanford USA, California Irvine USA), the authors describe the cognitive radio from an information theoretic perspective. They describe the three network paradigms, i.e. spectrum underlay (UWB transmission by secondary users), overlay (knowledge of the primary user messages, known other articles as a cognitive channel) and interweave (opportunistic communication by searching spaces in time or frequency). Underlay cognitive radio can be considered as a Z channel with a power constraint at the cognitive transmitter. In overlay cognitive radio (or cognitive radio channels), secondary users know the primary messages and can perform DPC.

Below are listed other work conducted by other universities.

In [48] (Edinburgh UK), the authors study the sum rate maximization of a system with two transmitters and two receivers. The authors show that for a fixed power of one of the transmitters, the other user should use either none or full power to maximize the sum rate capacity. Then, they derive some conditions on the SNR and the channel values such that we can choose between simultaneous and single transmission. Simulation results are performed for random nodes in a disk.

In [49] (McMaster CA), the authors propose a robust transmit power control based on the iterative waterfilling algorithm. They show that their algorithm is robust to joining-leaving events while the conventional iterative waterfilling algorithm will have convergence problems. The focus of the paper is the transmit-power control in cognitive radio networks, considering a noncooperative framework. Moreover, tools from control theory are used to study both the equilibrium and transient behaviors of the network under dynamically varying conditions.

In [50] (Marvell HK), the authors develop, analyze, and simulate a new suite of DSM algorithms for DSL interference-channel models called autonomous spectrum balancing (ASB). The ASB algorithms utilize the concept of a reference line, which mimics a typical victim line in the interference channel. In ASB, each modem tries to minimize the harm it causes to the reference line under the constraint of achieving its own target data-rate. Since the reference line is based on the statistics of the entire network, rather than any specic knowledge of the binder a modem operates in, ASB can be implemented autonomously without the need for a centralized spectrum management center.

In [51] (Singapore SGP), the authors study single-input multiple output multiple access channels (SIMO-MAC) for the CR network. Subject to interference constraints for the primary users as well as peak power constraints for the secondary users, two optimization problems involving a joint beamforming and power allocation for the CR network are considered: the sum-rate maximization problem and the SINR balancing problem.

In [52] (SUPELEC FR) the authors study the downlink multiuser Multiple Input Multiple Output-Orthogonal Frequency Division Multiple Access (MIMO-OFDMA) system for margin adaptive Multiuser Eigenmode Transmission (MET) with perfect channel state information at the transmitter. In margin adaptive objective,Base Station (BS) has to satisfy individual Quality of Service (QoS) constraints of the users subject to transmit power minimization. They propose a sub-optimal two step solution which decouples beamforming from subcarrier and power allocation. First a reduced number of user groups are formed and then the problem is formulated as a convex optimization problem. Finally an efficient algorithm is developed which allocates subcarriers to these user groups.

In [53] (Hong Kong HK), the authos extend the iterative waterfilling algorithm for interference channel to MIMO interference channels.

In [54] (Infocomm SGP, Stanford USA), the authors study the margin adaptive or the rate adaptive optimization problems for MIMO OFDM schemes. This paper can be considered as a reference paper for the power minimzation subject to rate constraints or the data rate maximization subject to power constraints.

3.2 Game theory, Auctioning

Game theory include potential games, S-modular games, target SINR games. A good review of these games and their applications in cognitive radio has been done by Virginia Tech (Neel, MacKenzie...).

In [55], Neel exaplain in his PhD disseration how game theory can be used in cognitive radio.

The university of Berkeley (Etkin, Tse, Sahai) and the university of Boston have also lead some important works.

In [56] (Berkeley USA), the authors propose game theoretic analysis showing that in many cases, the fair and efcient operating point can be enforced through punishment strategies. Moreover, the rates that can be obtained with the punishment strategies are essentially the best that one can hope for in a non-cooperative setting. Therefore their results are tight and quantify the best achievable performance with lack of cooperation.

In [57] (Boston USA, Berkeley USA), the authors consider spectrum enforcement in cognitive-radio systems. They develop a hierarchical coding architecture with enforced silences that allows a primary user to both identify the source of interference and assign the blame to the guilty set of cognitive radios if harmful interference turns out to be due to spectrum violation. In [58] (Berkeley USA), the authors explore a model of deterrence in which radios that have been convicted of misbehaving are sentenced to finite jail sentences.

The university of Maryland has conducted the following works on game theory.

In [59] (Maryland USA), the authors provide a game theoretical overview of dynamic spectrum sharing from several aspects: analysis of network users behaviors, efficient dynamic distributed design, and optimality analysis. They claim in their conclusion that, to ensure efficient and fair spectrum sharing in next-generation networks, more research is needed along the lines of game theoretical study. In [60] (Maryland USA), the authors investigate two game-theoretical mechanism design methods to suppress cheating and collusion behavior of selfish users: a self-enforcing truth-telling mechanism for unlicensed spectrum sharing and a collusion-resistant multistage dynamic spectrum pricing game for licensed spectrum sharing. With the Bayesian mechanism design, the selfish users have no incentive to cheat and can achieve cooperative unlicensed spectrum sharing under the threat of punishment. With collusion-resistant dynamic spectrum pricing, licensed spectrum resources are efficiently distributed among multiple primary and secondary users, and user collusion is effectively suppressed by setting up the optimal reserve price in the auction. In [61] (Qualcomm USA, Maryland USA), the authors model the spectrum allocation in wireless networks with multiple selsh legacy spectrum holders and unlicensed users as multi-stage dynamic games. In order to combat user collusion, they propose a pricing-based collusion-resistant dynamic spectrum allocation approach to optimize overall spectrum efciency, while not only keeping the participating incentives of the selsh users but also combating possible user collusion. The simulation results show that the proposed scheme achieves high efciency of spectrum usage even with the presence of severe user collusion.

The university of Manitoba also conducted research in this domain.

In [62] (Manitoba CA), the authors present an overview of the different energy harvesting technologies and the energy saving mechanisms for wireless sensor networks. The related research issues on energy efficiency for sensor networks using energy harvesting technology are then discussed. To this end, they present an optimal energy management policy for a solar-powered sensor node that uses a sleep and wake-up strategy for energy conservation. The problem of determining the sleep and wake-up probabilities is formulated as a bargaining game. The Nash equilibrium is used as the solution of this game. In [63] (Manitoba CA), the authors address the problem of spectrum pricing in a cognitive radio network where multiple primary service providers compete with each other to offer spectrum access opportunities to the secondary users. By using an equilibrium pricing scheme, each of the primary service providers aims to maximize its prot under quality of service (QoS) constraint for primary users. They formulate this situation as an oligopoly market consisting of a few firms and a consumer. A repeated game among primary service providers is formulated to show that the collusion can be maintained if all of the primary service providers are aware of this punishment mechanism, and therefore, properly weight their prots to be obtained in the future.

Another important work has been done by the university of Rome.

In [64] (Rome IT), the authors propose and analyze a totally decentralized approach to design cognitive multiple-input, multiple- output (MIMO) transceivers, satisfying a competitive optimality criterion, based on the achievement of Nash equilibrium. To take full advantage of all the opportunities offered by wireless communications, we assume a fairly general MIMO setup, where the multiple channels may be frequency channels, time slots and/or spatial channels. Whenever available, multiple antennas at the secondary transmitters could be used, for example, to put nulls in the antenna radiation pattern of secondary transmitters along the directions identifying the primary receivers, thus enabling the share of frequency and time resources with no additional interference. Our initial goal is to provide conditions for the existence and uniqueness of NE points in a game where secondary users compete against each other to maximize their performance, under the constraint on the maximum (or null) interference induced on the primary users. The next step is then to describe low-complexity totally distributed techniques able to reach the equilibrium points of the proposed games, with no coordination among the secondary users.

Another important work has been done by UCLA.

In [65] (UCLA USA), the authors describes some techniques based on game theory for cognitive radio networks. They describe spectrum access games as repeated games or stochastic games. Various fairness rules can be imposed by the central spectrum moderator (CSM), such as weighted sum maximization of rate or utilities among participating user, envy-free fairness solution, or egalitarian solutions. Stackelberg equilibrium can be shown to outperform Nash equilibrium in the distributed power-control game.

Below are listed some works by other universities.

In [66] (Columbia CA, California Davis USA), the authors consider dynamic spectrum access among cognitive radios from an adaptive, game theoretic learning perspective. Spectrum-agile cognitive radios compete for channels temporarily vacated by licensed primary users in order to satisfy their own demands while minimizing interference. For both slowly varying primary user activity and slowly varying statistics of fast primary user activity, they apply an adaptive regret based learning procedure which tracks the set of correlated equilibrium of the game, treated as a distributed stochastic approximation. This procedure is shown to perform very well compared with other similar adaptive algorithms.

In [67] (Broadcom CA), the authors propose a public safety and commercial spectrum sharing strategy via intelligent network pricing and call admission control. They provide a precise characterization of the performance objectives of such a sharing strategy, which is to maximize the commercial revenue while guaranteeing a low blocking probability to public safety calls.

In [68] (Stevens USA), the authors explore the price dynamics in a competitive market consisting of spectrum agile network service providers and users.

In [69] (Vanu USA), the authors examine the inter-linked technical and economic issues associated with markets for DSA-based wireless services. This analysis to make technical and policy recommendations supporting the commercial success of DSA technology. Once DSA technology is widespread, we can expect reduced entry costs for new service providers to speed up product and business lifecycles. The technology also will enable new value chains and business models for providing communication services.

In [70] (Docomo JP), the authors describe a centralized spectrum sharing based on auctioning and a decentralized spectrum sharing based on game theory. The authors propose a method to optimize the overall resource usage in an inequality aversion policy where all the player are altruists in order to maintain a high level of allocated resources while the standard policy would fail.

In [71] (New Jersey Tech USA), the authors propose and analyze an implementation whereby a primary link has the possibility to lease the owned spectrum to an ad hoc network of secondary nodes in exchange for cooperation in the form of distributed space-time coding. The investigated model is conveniently cast in the framework of Stackelberg games.

Concerning auctioning, the university of California Santa Barbara has worked on this topic

In [72] (California Santa Barbara USA), a general framework for wireless spectrum auctions is proposed. In [73] (California Santa Barbara USA), the authors propose auctioning to share the spectrum between secondary users.

4 Waveform for cognitive radio

The topic of waveform is very important in cognitive radio to make use of the vacant bands efficiently. In military systems the waveforms should have low probability of detection and/or interception. Usual techniques are spread spectrum and frequency hopping techniques, but we would like to use the advantage of OFDM, i.e. low receive complexity. Below are listed some work about OFDM and TDCS which are the possible candidates for the waveforms in cognitive radio systems. Some work also consider feature suppression of OFDM since OFDM has high probability of detection and interception.

In [74] (Raytheon USA), the author describes communication electronic warfare systems. Low probability of detection (LPD) attemps to hide the presence of the signal either in the noise with a direct-sequence spread spectrum (DSSS) or in frequency using frequency-hopping spread spectrum (FHSS). If the signal is detected, then low probability of interception (LPI) or low probability of exploitation (LPE) techniques can be used such that it is difficult to extract the information contained in it. FHSS has LPI, other time hoping techniques such as push to talk are also LPI. DSSS has LPD. Emission control (EMCON) is another LPD/LPI/LPE technique that reduce transmission power during operations.

In [75] (Rockwell USA), the authors propose to use a frequency jitter for OFDM signals to mask OFDM signatures. Indeed, for low number of subcarriers, the spectral lines of OFDM signals can provide some information about the rate of the signal. For frequency hopped OFDM (FH-OFDM), time jitter can be also used to confuse the intercept receiver and remove strong spectral lines at the hop and symbol rate.

In [76] (Florida USA), the authors propose to add random data between CP-OFDM symbols in order to suppress cyclostationarity signatures of the OFDM signals. The autocorrelation peaks still exist but the cyclic peaks do not exist anymore owing to the extra data added between OFDM symbols. The authors propose also several methods such as adaptive cyclic prefix size or variation of the FFT size to change the symbol duration randomly and therefore confuse the intercepting receiver.

In [77] (Docomo JP), the authors propose to use a waveform defined by the OFDM modulation with induced cyclostationarity for recognition between secondary users. The cyclostationarity can be induced by inserting OFDM symbols in the frame with known cyclic frequencies (insertion of pilots in the frequency domain at given location), or by employing dedicated carriers in the OFDM symbols. A multiple hypothesis problem is also used for detection by comparing the received cyclic autocorrelation function and the CAF candidates stored in advance.

In [78] (Florence IT), the authors propose to interleave the subcarriers on a symbol basis and then to use a frequency-hopped pattern according to square or triangular pattern. As pointed out by the authors, the frequency-hopped pattern used in Bluetooth can be cracked easily but brute force, therefore more complex frequency-hopped pattern should be used to secure future communications.

In [79] (China Sichuan CHN), the authors investigate performance in term of BER of the OFDM-based TDCS in realistic CR contexts. According to the analyzes and simulation results, it is observed that the OFDM-based TDCS operates better in random spectrum availability contexts than in continuous spectrum availability ones. Geometrical explanations are provided to give some insights to this phenomenon. Based on the explications, a new interleaved OFDM-based TDCS is proposed. Computer simulation results verify that the new proposal outperforms the OFDM-based TDCS without an interleaver, especially in the scenario where the percentage of available spectrum is rather low.

In [80] (China Sichuan CHN), the authors analyze the BER performance of interleaved OFDM-based TDCS in the AWGN channel in the multi-user cognitive radio context. A successive interference cancellation algorithm based on statistic ordering is proposed in the multipath fading channel.

In [81] (China Sichuan CHN), the authors propose a soft-demodulation algorithm of TDCS signals in fading channels and its efficient IFFT-based implementation. This implementation only introduces negligible complexity increase in the receiver; however, it brings performance improvement and makes it possible to efficiently and iteratively soft-decode coded data.

In [82] (China Harbin CHN), the authors demonstrate fractional Fourier domain communication system (FrFDCS) using transform domain processing as having enhanced interference avoidance capability under adverse environmental conditions. The basic idea for this system is to synthesize an intelligent adaptive waveform in the fractional Fourier domain at both the transmitter and receiver for avoiding spectral crowded regions. This approach offers better bit error performance in contrast to other conventional interference mitigation techniques which process the signal at the receiver only.

In [83] (Air Force Research Laboratory USA), the authors give a brief tutorial on transform-domain communication system (TDCS), OFDM, and MC-CDMA. The primary goal of this article is to give a detailed description of the TDCS transmitter and receiver systems and to highlight the fundamental differences relative to OFDM and MC-CDMA. The fundamental idea in TDCS is to synthesize a smart adaptive waveform to avoid interference at the transmitter instead of the more traditional mitigating of interference at the receiver. Unlike OFDM and MC-CDMA, TDCS has very little exposure in the current literature.

In [84] (Virginia Tech USA), the authors identify a threat to spectrum sensing, which we call the primary user emulation (PUE) attack. In this attack, an adversarys CR transmits signals whose characteristics emulate those of incumbent signals. The highly exible, software-based air interface of CRs makes such an attack possible. The authors show that a PUE attack can severely interfere with the spectrum sensing process and signicantly reduce the channel resources available to legitimate unlicensed users.

In [85] (Delft NL), the authors introduce the modulation strategies employed to realize a coexistence between the CR-based rental system and the licensed system. This is done in such a way that the cognitive users are invisible to the licensed users. We consider the rental user accesses the unoccupied licensed user band in overlay fashion. Of the several modulation techniques, it is the OFDM that is considered to be a strong candidate due to its spectrum access flexibility by notching its carriers on the position of licensed user band. OFDMs main drawback is that its high sidelobes will interfere with the neighboring licensed user band. Techniques such as windowing, adjacent carriers deactivation, cancellation carriers, multiple choice sequence, and a combination of all these techniques as the solutions used to mitigate the sidelobes problem have been overviewed. Single carrier modulation for a CR system, known as TDCS, is also studied by the authors. The technique requires the spectrum occupancy information and relies for its data detection on the correlation properties of the generated random sequence used to construct its waveform.

In [86] (NEC Labs USA), the authors present we present an overview of anti-jamming coding techniques that are suitable for the purpose of link maintenance in cognitive radio systems. Since the equivalent channel for anti-jamming coding in cognitive radio can be modeled as an erasure channel, several classes of erasure coding techniques are presented including the conventional erasure codes, low-density parity-check (LDPC) codes, rateless codes, as well as the more recent piecewise coding. They discuss the pros and cons of these erasure codes in the context of cognitive radio. Among these coding schemes, the rateless coding and structured piecewise coding are currently two major effective approaches to anti-jamming coding in cognitive radio systems.

5 Cognitive radio networks

Cognitive radio networks include spectrum sensing and spectrum management. However, one would need to optimize both spectrum sensing and spectrum management as a whole, and possibly consider the MAC Layer also in the objective function. This is referred as cross-layer optimization.

The university of Berkeley and the university of Berlin have proposed techniques to build a cognitive radio network.

In [87] (Berkeley USA, Berlin GER), the authors propose a cognitive radio approach for usage of virtual unlicensed spectrum (CORVUS). In their white paper, the authors review the work that has been done on cognitive radio, from Mitola's work to the work on cognitive radio and spectrum pooling architecture developed at the University of Karlsruhe (Weiss and Jondral) and the work done by DARPA on the neXt Generation (XG) program. CORVUS operates in a large spectrum pool. The metrics that are used for evaluation are the total throughput and the fairness, the delay and load, the cognitive radio interference, the power. The physical layer functions are the spectrum sensing, the channel quality estimation, data transmission. The link layer functions are the group management (of secondary user group when joining/leaving event); link management, medium access control (MAC). In [88] (Berkeley USA, Berlin GER), the authors also present the cognitive radio approach for usage of virtual unlicensed spectrum (CORVUS). In [89] (Berkeley USA), the authors discuss about the underlay as well as overlay strategies for use in cognitive radio systems. They also present the testbed used for cognitive radio, along with the spectrum sensing techniques based on cyclostationarity. In [90] (Berlin GER), the authors propose to understand the dynamics of spectrum usage in licensed bands, focusing on the cellular band. Using a unique dataset collected inside a cellular network operator, they analyze the usage in cellular bands and discuss the implications of our results on enabling DSA in these bands.

Another cognitive radio network has been proposed by Lucent and the university of Stevens.

In [91] (Lucent Bell Labs USA, Stevens USA), the authors propose a Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile- access network (DIMSUMnet) architecture that uses coordinated dynamic spectrum access (DSA). In fact, the authors argue that most of the research on DSA focused on the DARPA XG program for free-for-all opportunistic spectrum access for peer-to-peer ad-hoc communications, typically targeting military applications. The authors propose a middle approach where several networks can be controlled by a single spectrum broker, therefore not employing DSA at the device level but at the network level by coordinated DSA. In [92] (Stevens USA), the authors investigate continuous-time Markov models for dynamic spectrum access in open spectrum wireless networks. Both queuing and no queuing cases are considered. Analytical results are derived based on the Markov models.

Another cognitive radio network has been proposed by WinLab, the university of Kansas and the university of Carnegie.

In [93] (Winlab USA, Kansas USA, Carnegie USA), the authors propose and architecture call CogNet. In [94] (Kansas USA), the authors present the details of a portable, powerful, and flexible software-defined radio development platform called the Kansas University Agile Radio (KUAR). The primary purpose of the KUAR is to enable advanced research in the areas of wireless radio networks, dynamic spectrum access, and cognitive radios. They describe the KUAR hardware implementation and software architecture and present example application of the KUAR to modulation, spectrum measurement, channel estimation, and rapid configuration and adaptation. In [95] (Carnegie USA), the authors compare the different models for spectrum sharing. With sharing between primary users, it has been shown that cooperation can increase the capacity of a network when the number of user increases. With sharing between primary and secondary users, secondary users should not harm primary users, this can be done by adding external location information (for instance by GPS).

The university of Karlsruhe have also their vision on cognitive radio networks.

In [96] (Karlsruhe GER), the authors starts with a brief section that underlines the paramount importance of the mobile radio communications channel. Then, spectrum issues are discussed to emphasize the reasons for spectrum scarcity as well as the importance of dynamic spectrum allocation. Some remarks about the development of software defined radio from digital radio lead to a discussion of the most important engineering aspects of CR, for example, location and spectrum awareness, transmission power control, and signal analysis. They recommend to first tackle the radio communications problems of CR, such as location and spectrum awareness, transmission power control, and signal analysis.

Lots of work have been performed at the university of California Davis, Cornell and the Army Research Lab (Zhao, Swami, Geirhofer, Jung, Chen etc.)

In [97] (California Davis USA, Cornell USA, Army Research Lab USA), the authors propose decentralized cognitive MAC protocols that allow secondary users to independently search for spectrum opportunities without a central coordinator or a dedicated communication channel. They develop an analytical framework for opportunistic spectrum access based on the theory of Partially Observable Markov Decision Process (POMDP). This decision-theoretic approach integrates the design of spectrum access protocols at the MAC layer with spectrum sensing at the physical layer and trafc statistics determined by the application layer of the primary network. In [98] (California Davis USA), the authors identify basic components, fundamental trade-offs, and practical constraints in opportunistic spectrum access. They introduce a decision-theoretic framework based on the theory of partially observable Markov decision processes. This framework allows us to systematically tackle the optimal integrated design and quantitatively characterize the interaction between signal processing for opportunity identification and networking for opportunity exploitation. In [99] (California Davis USA, Army Research Lab USA), the authors gives a survey of dynamic spectrum access (DSA). They provide an overview of major technical and regulatory issues in opportunistic spectrum access (OSA). In [100] (California Davis USA), the authors consider a scenario in which secondary users can opportunistically access unused spectrum vacated by idle primaries. In such a spectrum-agile system, a critical and unique issue is the fast and reliable evacuation of secondary users upon the return of primary users. In [101] (Cornell USA), the authors focuses on applying DSA in the time domain by exploiting idle periods between bursty transmissions of multi-access communication channels and addresses WLAN as an example of practical importance. A statistical model based on empirical data is presented, and it is shown how to use this model for deriving access strategies. The coexistence of Bluetooth and WLAN is considered as a concrete example. In [102] (Cornell USA, Army Research Lab USA), the authors design a cognitive radio that can coexist with multiple parallel WLAN channels while abiding by an interference constraint. The interaction between both systems is characterized by measurement and coexistence is enhanced by predicting the WLANs behavior based on a continuous-time Markov chain model. Cognitive Medium Access (CMA) is derived from this model by recasting the problem as one of constrained Markov decision processes. In [103] (California Davis USA), the authors study the effect of multiple primary user protection requirements on secondary user policy making and performance under the assumption of both exponential and general idle time distributions of primary users. In [104] (California Davis USA), the authors consider a scenario where secondary users can opportunistically access unused spectrum vacated by idle primaries. They introduce two metrics to protect primary performance, namely collision probability and overlapping time. They present two spectrum access schemes using different sensing, back-off, and transmission mechanisms. In [105] (California Davis USA, Army Research Lab USA), the authors design distributed spectrum sensing and access strategies for opportunistic spectrum access (OSA) under an energy constraint on secondary users. Both the continuous and the bursty trafc models are considered for different applications of the secondary network. In each slot, a secondary user sequentially decides whether to sense, where in the spectrum to sense, and whether to access. By casting this sequential decision-making problem in the framework of partially observable Markov decision processes (POMDP), they obtain stationary optimal spectrum sensing and access policies that maximize the throughput of the secondary user during its battery lifetime. They also establish threshold structures of the optimal policies and study the fundamental tradeoffs involved in the energy-constrained OSA design.

The university of California Santa Barbara has also performed some work on cognitive radio networks

In [106] (Microsoft CHN, California Santa Barbara USA), the authors propose a distributed coordination approach that handles spectrum heterogeneity without relying on the existence of a preassigned common control channel. In [107] (California Santa Barbara USA), the authors propose a proactive spectrum access approach where secondary users utilize past observations to build predictive models on spectrum availability, and intelligently plan channel usage to maximize utilization and minimize disruptions to primary users. In [108] (California Santa Barbara USA), the authors propose a proactive spectrum access approach where secondary users utilize past channel histories to make predictions on future spectrum availability, and intelligently schedule channel usage in advance. In [109] (California Santa Barbara USA), the authors study the efficiency and complexity of a distributed spectrum allocation algorithm using explicit user coordination. Users self-organize into coordination group to approximate and optimal assignment. In [110] (California Santa Barbara USA),the authors introduce a distributed spectrum management architecture where nodes share spectrum resource fairly by making independent actions following spectrum rules. They present ve spectrum rules to regulate node behavior and maximize system fairness and spectrum utilization, and analyze the associated complexity and overhead. In [111] (California Santa Barbara USA), the authors consider the problem of providing stable and efficient spectrum access in dynamic spectrum networks. The authors propose SPART as a new DSA architecture that treat stability and efficiency as the first priority using proactive planning. In [112] (California Santa Barbara USA), the authors introduce a distributed spectrum management architecture where nodes share spectrum resource fairly by making independent actions following spectrum rules. In [113] (California Santa Barbara USA), the authors propose FLEX as a distributed architecture for WiFi access points to dynamically access spectrum to adapt to varying user traffic demands and maximize user satisfaction. In [114] (California Santa Barbara USA), the authors propose a systematic framework to produce conflict graphs based on physical interference characteristics.

The university of Colorado has also performed some work on cognitive radio

In [115] (Colorado USA), the authors describe a method for selecting from a number of potential configurations to fulfill the communication requirements of a CR network. By using accepted statistical methods, they show how parameters at the physical, data link, network, and application layers interact to affect performance. They build upon this parametric insight with our presentation of a technique for predicting radio performance. In [116] (Colorado USA), the authors propose an opportunistic scheduling in a system where a basestation serves multiple users based on temporal fairness (resources to be allocated to every user), utilitarian fairness (throughput to be allocated to every user as a fraction of the overall throughput), minimum-performance guarantee (throughput constraints on every user) The different policies can be solved as an integer linear program called the maximal weighted bipartite matching problem in graph theory or the assignment problem in combinatorial optimization. The authors choose the Hungarian algorithm that gives the optimal solution of these problems in polynomial time.

Some other important works are:

In [117] (MIT USA), the authors notice that frame synchronization is important for packet transmission, especially in a network of cognitive radios. The authors focuses on both the continuous transmission of variable-length frames and bursty transmission of frames, which arise, for example, in multimedia encoded video streaming. The paper puts forth important performance metrics, namely the expected time to complete frame synchronization and the probability of correct acquisition within a given duration. In [118] (MIT USA), the authors provide an overview of some of the driving factors that limit the performance of optical links and highlight some of the potential opportunities for the signal processing community to make substantial contributions.

In [119] (Virginia Tech USA), the authors describe the vision of cognitive radio at Virginia Tech. They highlight that optimizing a single objective such as maximization of rates, minimization of BER, maximization of the SINR... lead to poor solutions because they ignore other important objectives such as delay, spectral occupancy, power expenditure, or computational complexity. Genetic algorithms is known to provide optimal solution with multiple objectives, but they are usually slow to converge, and are unable to learn from past experiences. An average-case based decision maker can help the genetic algorithm to choose between certain utility functions having this previous knowledge. For spectrum sensing, they propose a distributed approach to use the cyclic spectrum to detect the signals, classify them by an automatic modulation classifier (AMC), and send them to a fusion center. They also propose game theory to solve utility optimization problems for multiple users.

In [120] (Department of defense USA), the authors describe a concrete model for a generic cognitive radio to utilize a learning engine. The goal is to incorporate the results of the learning engine into a predicate calculus-based reasoning engine so that radios can remember lessons learned in the past and act quickly in the future. They also investigate the differences between reasoning and learning, and the fundamentals of when a particular application requires learning, and when simple reasoning is sufficient. The basic architecture is consistent with cognitive engines seen in AI research. The focus of this article is not to propose new machine learning algorithms, but rather to formalize their application to cognitive radio and develop a framework from within which they can be useful.

In [121] (MITRE USA), the authors propose a frequency-agile cognitive radio by a cognitive channel assignment for WiMAX systems. Currently, WiMAX uses a fixed channel assignment (fixed for each base station) or a dynamic one (every channel can be used by every base station if it is not busy). A listen before talk (LBT) spectrum access is proposed that performs a spectrum sensing to see if it can transmit in the band and then transmit while keeping low interference to the primary receiver. The authors draw the non interference condition for downlink, i.e the distance related to the interference caused by a CR node should be lower than the difference between the detection distance from the primary user and the coverage distance of the primary user $d_{int} \leq d_{det} - d_{cov,p}$. For uplink, similar derivation can be drawn, which leads to $d_{int} \leq d_{det} - d_{cov,p} - d_{cov,a}$.

In [122] (Stanford USA), the authors propose a spectrum agile solution that allows a secondary packet switched network (for instance MB-OFDM) to dynamically choose the best channel knowing that there is interference from a primary network (for instance 802.11). The approach is based on a geometrical variable according to the traffic and the sensing is performed through energy detection. This requires previous knowledge of the traffic parameters, either by listening to the channel or gradually learns the best channel by a measure of quality (energy waste minimization or successful packet transmission, costs) using a Bayesian predictive model.

In [123] (UCLA USA), the authors propose to add a new dimension to existing wireless multimedia systems by enabling autonomous stations to dynamically compete for communication resources through adjustment of their internal strategies and sharing their private information. They focus on emerging spectrum agile wireless networks, where developing an efficient strategy for managing available communication resources is of high importance. The proposed dynamic resource management approach for wireless multimedia changes the passive way stations are currently adapting their joint source-channel coding strategies according to available wireless resources.

In [124] (Philips USA, Qualcomm USA, Michigan USA), the authors investigate the issue of using spectrum agility to improve both spectrum utilization and secondary devices performance. They establish a simple mathematical model and provide performance benchmarks for general spectral-agile communication.

The results based on this model have shown that the channel utilization of a spectral-agile device is improved by 35 to 200% when compared to the cases of no agility, depending on the number of channels, their average channel load, the number of spectral- agile devices.

In [125] (Shared Spectrum Company USA), the authors propose to evaluate the performance of cognitive radio networks by defining the interrelationships among metrics, utility function, cognitive engine algorithms and they evaluate the results by testing scenarios.

In [126] (Clemson USA), the authors propose a low-complexity adaptive transmission protocol for use in cognitive radio networks whose links have unknown and possibly time-varying propagation losses as a result of such phenomena as slow fading or variations in shadowing.

In [127] (Uppsala SWE), the authors propose a survey of the literature on the problem of designing transmit codes and receive filters for radar.

In [128] (Ionnina GR), the authors aim at presenting an emerging new methodology for statistical inference that ameliorates certain shortcomings of the EM algorithm. This methodology is termed variational approximation and can be used to solve complex Bayesian models where the EM algorithm cannot be applied. Bayesian inference based on the variational approximation has been used extensively by the machine learning community since the mid-1990s when it was first introduced.

In [129] (EADS FR), the authors show how the adaptive coded modulation introduction in the satellite downlink enables greatly enhanced system performance but also has a profound impact on the way the system and some of the key system components are designed.

In [130] (Military Academy USA), the authors focus on battery constraints to determine if an attack is present. This research proposes that resident monitoring of the demands placed on a batterys current (mA) and other system processes can be used as an early-warning, trip-wire-like sensor for mobile hosts as a means to block attacks as well as to identify them.

In [131] (Cincinnati USA), the authors point out key challenges that are impeding the rapid progress of wireless mesh network (web in the sky). They examine each layer of the network and discuss the feasibility of some state-of-the-art technologies/protocols for adequately addressing these challenges. They also provide broader and deeper insight to many other issues that are of paramount importance for the successful deployment and wider acceptance of WMNs.

In [132] (Dublin IR), the authors look at the principles and significant potential of teamwork in cognitive networks. These concepts represent a new evolutionary stage in the development of cognitive radio and cognitive networks, where wireless communication progresses from an individual, device-centric approach toward group and team behavior. This creates the potential for more effective and more robust communication solutions when deemed necessary. These include group formation, distributed co-ordination, goal and role identification, accountability, and reward mechanisms for the outcomes of team behavior.

In [133] (Texas USA), the authors describe potential technology for the next-generation WPAN, namely UWB, 60 GHz millimeter-wave-based WPAN, and

ZigBee and gives an overview of related standardization and regulation issues.

In [134] (Meiji JP), the authors study the optimization of the pulse-UWB parameters to lower the impact on OFDM systems, such as MB-OFDM and IEEE 802.11a.

5.1 Cognitive radio in UHF/VHF bands

For military applications, we are interested in building a cognitive radio network in the VHF/UHF bands. Therefore, studying the work that has been done on cognitive radio in the civilian bands are of great importance. Below are listed some work on cognitive radio networks (overlay) for the UHF/VHF bands.

In [135] (STmicroelectronics USA), the authors notice that for 802.22 WRAN, to perform reliable sensing, in the basic operation mode on a single frequency band (non-hopping mode), one must allocate quiet times, that is, periodically interrupt data transmission that could impair the QoS of WRAN. This critical issue can be addressed by an alternative operation mode proposed in 802.22 called dynamic frequency hopping (DFH), where WRAN data transmission is performed in parallel with spectrum sensing without interruptions. DFH community is a mechanism that coordinates multiple WRAN cells operating in the DFH mode, such that efficient frequency usage and reliable channel sensing are achieved.

In [136] (Ghent BE), the authors study the interference cancellation of narrowband VHF legacy systems for the use of an overlay multi-carrier VHF system. As the multi-carrier system can be modeled as a Gaussian signal, the estimation of the narrowband VHF legacy systems reduces to the estimation of the number of interferers, their amplitudes and carrier frequencies.

In [137] (Docomo JP), the authors study the optimization of the pulse shaping to suppress a NBI with known carrier frequency using cyclic wiener filtering.

In [138] (Minnesota USA), the authors propose a programmable wireless radio using non contiguous OFDM on the free detected bands for secondary users. The existing technique for NC-OFDM are to zero pad the subcarriers of the primary users or to use a transform decomposition. However these approaches have many drawbacks and the authors propose a modified Cooley-Tukey FFT/IFFT approach. The scenario used in their paper is the 802.22 standard for opportunistic access of licensed TV bands using OFDMA (each user has a set of subcarrier in the frequency domain). The receiver front end consists of parallel downconverters and narrowband low pass filters. As narrowband low pass filter can overlap, a maximum ratio combining is used to recover the data in the bands which overlap.

In [139] (Colorado USA), the authors study the technical and economical aspects of cognitive radio broadband wireless access in urban and rural areas for the TV bands. In urban areas, there is little unused spectrum in the TV bands, the customer density is high and the system can operate using short range access points. In rural areas, the available spectrum is greater and access points need to use longer ranges to efficiently cover the sparse customers.

In [140] (Georgia Tech USA), the authors discusses about 802.22 which corresponds to the exploitation of the vacant bands for TV channels. They describe a setup where DTV is transmitting and study the impact of the interference to the DTV receiver. Without interference, the DTV receivers show a clear image at -83.5 dBm but loose their image at -83.6 dBm, thus any interference larger than this level caused by a secondary transmitter will cause harmful impact to the primary. Therefore the authors study and show some measurements the interference of a WRAN signal in channel N on the DTV interference in adjacent channels. They also study the interference caused by undesired DTV signal into the DTV signal.

In [141] (Philips USA), the authors presents the IEEE 802.22 standard.

6 Cognitive radio Ad-hoc networks

Building a military cognitive radio networks will also consider ad-hoc networks. Mobile ad-hoc networks (MANETs) are therefore very important for the study. Below are listed some work about MANETs and cognitive radio ad-hoc networks.

In [142] (China Beijing CHN, California Santa Barbara USA), the authors proposes to couple the problem of dynamic spectrum management and route selection as efficient spectrum allocation in dynamic spectrum systems is a challenging problem, particularly for multi-hops transmissions. They compare a decoupled design where the two tasks are carried out independently by MAC and network layer and a collaborative design which integrates them into a single task at the network layer- network layer selects route and schedules conflict-free channel usage on the route. For the decoupled problem, route selection can be based on a simple algorithm like the shortest-hop routing (the path with the least number of hops is chosen). The spectrum management is done by MAC coordination protocol such as HDMAC to coordinate time and spectrum selection for each transmission. This is optimal for single-hop transmission, but far from optimal for multi-hop transmissions. The algorithm needs to find all feasible channel assignment combinations and estimates the end-to-end throughput performance for each combination. The authors propose a centralized approach although they say we would need a decentralized approach for large scale networks. They observe that the collaboration design leads to linear throughput growth with the number of available channels. This further illustrates the importance of collaboration between network and MAC layers.

In [143] (Electro-Communications JP), the authors consider multi-hop transmission of cognitive users that use the same band as primary users. This problem is quite complex since primary users can cut the path between secondary users. The authors propose a multi-band approach to avoid the route interference by the primary network. Ad-hoc secondary networks with small power have been proposed to lower the interference to primary systems, therefore the coverage of a secondary user is much smaller than the coverage of a primary user. The authors propose to modify the multi-route routing algorithm since it has been designed without a primary network. The routing mechanism send packets to all available channels, the neighboring nodes evaluate the quality of the link for each channel, and finally the neighboring nodes choose the best channel. Therefore, the routes are chosen such that channel with interference from primary users are not selected. The authors show the performance improvements using two or three frequency bands.

In [144] (California Davis USA, Cornell USA), the authors propose and analyze an energy-aware traffic-adaptive routing strategy for large-scale mobile ad hoc networks (MANETs). Referred to as Energy-Aware GEolocation-aided Routing (EAGER), this protocol optimally blends proactive and reactive strategies for energy efficiency. Specifically, EAGER partitions the network into cells and performs intracellular proactive routing and intercell reactive routing. The cell size and the transmission range are optimized analytically. By adjoining cells around hot spots and hot routes in the network, EAGER is capable of handling time-varying and spatially heterogeneous traffic conditions.

In [145] (California Santa Barbara USA), the authors consider the problem of multi-hop routing in an ad-hoc network using cognitive radios by introducing spectrum-aware routing (SPEAR). They notice that distributed approaches are known to be flow-unaware, and cannot optimize end-to-end multi-hop performance. They conclude that we need a distributed end-to-end approach to optimize route performance, while allowing flexibility in channel usage to cope with spectrum heterogeneity. The principle is also based on multiple route selection by collecting a bounded number of routes and choosing the optimal route based on maximum end-to-end throughput, hop count, and other potential routing metrics. Each node performs spectrum sensing and maintains a list of locally available channels. SPEAR uses TDMA-style channel scheduling if two flows pass by the same node at the same time.

In [146] (Virginia Tech USA), the authors characterize the behavior and constraints for multi-hop cognitive radio network from multiple layers, including modeling of spectrum sharing and sub-band division, scheduling and interference constraints, and ow routing. They develop a mathematical formulation with the objective of minimizing the required network-wide radio spectrum resource for a set of user sessions. Since the formulated model is a mixed-integer non-linear program (MINLP), which is NP-hard in general, they develop a lower bound for the objective by relaxing the integer variables and using a linearization technique. Subsequently, they design a near-optimal algorithm to solve this MINLP problem.

In [147] (Hong-Kong HK), the authors discuss how to conduct efcient spectrum management in ad hoc cognitive radio networks while taking the hardware constraints (e.g., single radio, partial spectrum sensing and spectrum aggregation limit) into consideration. A hardware-constrained cognitive MAC, HC-MAC, is proposed to conduct efcient spectrum sensing and spectrum access decision. They identify the issue of optimal spectrum sensing decision for a single secondary transmission pair, and formulate it as an optimal stopping problem. A decentralized MAC protocol is then proposed for the ad hoc cognitive radio networks.

In [148] (California San Diego USA), the authors propose a cognitive radio based multi-user resource allocation framework for mobile ad hoc networks using multi-carrier DS CDMA modulation over a frequency-selective fading channel.

In [149] (Michigan USA), the authors propose new techniques to leverage two optimizations for cognitive radio networks that are specic to such contexts: opportunistic channel selection and cooperative mobility. They present a new formal model for mobile wireless ad-hoc networks (MANETs) consisting of cognitive radio capable nodes that are willing to be moved (at a cost). They develop an effective decentralized algorithm for mobility planning, and powerful new filtering and fuzzy based techniques for both channel estimation and channel selection.

In [150] (Texas USA), the authors propose the cross-layer based opportunistic multi-channel medium access control (MAC) protocols, which integrate the spectrum sensing at physical (PHY) layer with the packet scheduling at MAC layer, for the wireless ad hoc networks.

In [151] (Georgia Tech USA), the authors present the important features of cognitive radio Ad-Hoc Networks (CRAHNs), along with the design approaches and research challenges that must be addressed. Spectrum management in CRAHNs comprises spectrum sensing, sharing, decision, and mobility. Each of these functions are described in detail from the viewpoint of multi-hop infrastructureless networks requiring cooperation among users. In [152] (Georgia Tech USA), the authors presents cognitive radio ad-hoc networks (CRAHNs).

7 Related topics

Another topic of importance in cognitive radio is the acquisition of the user location.

In [153] (Berkeley USA), the authors study the positioning of an object in an UWB sensor network by deriving its Cramer Rao Lower Bound (CRLB). They also study the positioning of multiple objects using Euclidean coordinates and polar coordinates.

In [154] (Florida USA), the authors propose a location awareness engine architecture is proposed for the realization of location awareness in cognitive radios and networks. The proposed architecture consists of location estimation and/or sensing, seamless positioning and interoperability, statistical learning and tracking, security and privacy, mobility management, and location-based applications. However, the focus of their article is on location-based applications where they demonstrate the utilization of location information in cognitive wireless networks by presenting some representative location-assisted network optimization applications such as location-assisted spectrum management, network planning and expansion, and handover. The study unveils that location information can be used in cognitive wireless networks to optimize network performance.

Another great topic of importance is the study of the combination between the MAC and the physical layer.

In [155], the authors study the optimization of a stability-optimal transmission policy for multiple-antenna multiple-access channel. In their work, the weights in the weighted rate sum are replaced by queues length that varies in time.

In [156], the authors also introduce queues instead of weights in the optimization problem for interference channels. The problem is soved using non-autonomous algorithms.

In [157], the authors give an explaination on the max weight algorithm for centralized and distributed applications. The max weight algorithm say that the optimal scheduler at the MAC level is the weighted rate sum maximization where the weights correspond to the queues of the users.

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