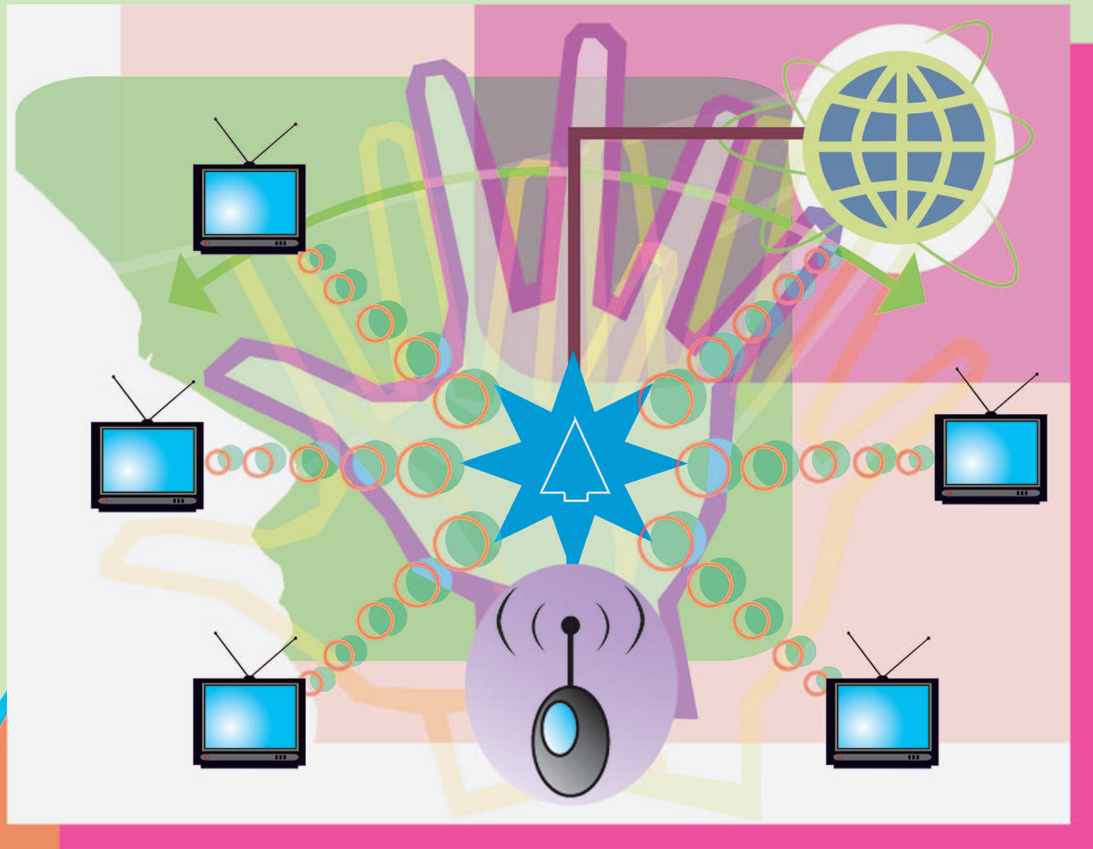

COGNITIVE RADIO NETWORK MANAGEMENT

Cheng-Xiang Wang, Hsiao-Hwa Chen, Xuemin Hong, and Mohsen Guizani

A a serious bottleneck for media-hungry communication systems. While being so expensive and becoming increasingly scarce, the radio spectrum is still significantly underutilized. A recent study by the Federal Communication Commission (FCC) Spectrum Policy Task Force [1] revealed vast temporal and geographic variations in the spectrum utilization, ranging from 15–85% in the bands below 3 GHz, while even dramatically lower at frequencies above 3 GHz. This imbalance between the spectrum scarcity and spectrum underutilization is a major hurdle, preventing wireless communication systems from providing high data rate services, which require a significant amount of the radio spectrum. The confronted challenging task is how to efficiently utilize and share the radio spectrum. Cognitive radio (CR) [2]–[16] has therefore been proposed as a revolutionary technology that enables a CR (secondary) network to borrow the radio spectrum from an existing incumbent (primary) network.

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Ever since its term was coined by Joseph Mitola in 1999 [2], CR has demonstrated an exceptional promise for future wireless communication systems. One of the most widely used definitions for a CR is a radio being able to dynamically sense its surrounding environment and locate unused or underutilized spectrum segments in a target spectrum pool and then adapt to the real-time conditions of its operating wireless channels by adjusting its transmission parameters in a way that causes no harmful interference to the primary users of the spectrum [3], [4]. Through the efficient utilization of the spectrum by exploiting the existence of unused or underutilized spectrum, the CR technology is expected to greatly improve the overall system performance without compromising the services of the primary network. In the near future, CRs might start to operate first at two frequency bands: 400–800 MHz (UHF TV bands) and 3–10 GHz [7].

Tuning in to Real-Time Conditions

The ultimate goal of applying the CR technology is to establish a CR network that is capable of delivering a multitude of fixed and mobile wireless services, such as voice, video streaming, and wireless Internet access. Therefore, to guarantee the quality of service (QoS) is crucial for the CR network to deliver different services according the parameters specified in the service level agreement (SLA). With the dramatically increased physical-layer flexibility and complexity, effective QoS management of a large-scale CR network is extremely challenging. Policy-based management is a promising methodology that can provide a means to achieve this goal.

Policy-based management was initially proposed as an approach to automate the management of large-scale networks and distributed systems. Policy is defined as a set of rules to administer, mange, and control access to the network resources. Policies can be designed in advance [8] or created dynamically [9] to fulfill certain goals. Policy goals are the business objectives or desired states intended to be maintained by a policy system. Policies and their goals can be represented in different levels, ranging from business goals to device specific configuration parameters. For example, providing reliable multimedia streaming services to targeted customers can be considered as a business level policy. On the networking level, it is translated into networking policies characterized by the availability, delay, jitter, throughput, and packet loss ratio. The networking policies are further mapped to the physical-layer policies specified in terms of bandwidth and received signal-to-noise-and-interference ratio (SNIR). Business-level abstraction is a key element that leads to the simplification of the network management. It allows the administrator to define policies in terms of a language closer to the real-world business needs rather than in terms of the specific technology needed to deploy it. From this perspective, policy-based management system can be regarded as a case of cross-layer design where the optimization goal is given at the application layer (business goals) and protocols (policies) are designed to accomplish this goal with best efforts. In other words, the application layer is in control and other layers adapt to it.

Conventional policy-based management systems cannot be directly applied to a CR network. The main reason is that conventional wired and wireless systems have independent physical layers to adapt to instructions from the upper layers. In contrast, the physical layer of a CR has an opportunistic nature and is tightly coupled with the primary network. A conflict might arise when the CR physical layer wants to adapt to the application layer instructions and the primary network at the same time. A solution to this is to separate the physical-layer functionality of CR into two parts: resource discovery and adaptive transceiver. The information collected by resource discovery is sent to the policy generator at the application layer to make business level policies. The adaptive transceiver then configures its parameters based on the upper-layer instructions. This policy-based management for CR

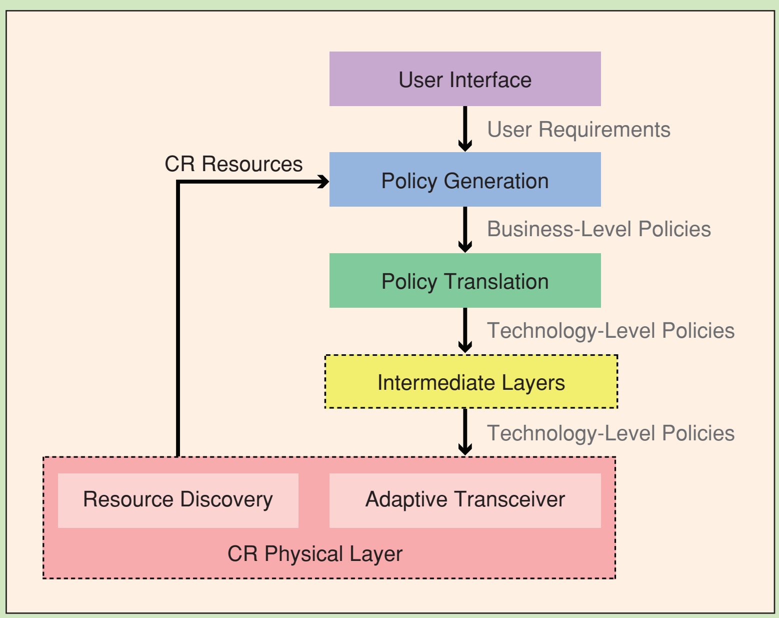

FIGURE 1 A generic policy-based management architecture for CR networks.

WITH THE DRAMATICALLY INCREASED PHYSICAL-LAYER FLEXIBILITY AND COMPLEXITY, EFFECTIVE QOS MANAGEMENT OF A LARGE-SCALE COGNITIVE RADIO NETWORK IS EXTREMELY CHALLENGING.

network is illustrated in Figure 1, which is a modified version of [10, Figure 2].

This article aims to provide an overview of the essential functionalities in the resource discovery block and discuss its impact on making business level policies of a CR network. The following section addresses spectrum sensing, a key component of the resource discovery block. Next, the mechanisms of forming a CR network and sharing the public CR resources among multiple CR users is discussed, followed by the capacity analysis of a simple CR network, given as an example of resource discovery. Finally, some conclusions are drawn.

Spectrum Sensing

The first fundamental cognitive task of a CR is to use spectrum sensing for determining spectral availability. Apparently, for the design, performance evaluation, and practical implementation of CR systems, it is of paramount importance to have a reliable strategy for the spectrum holes detection. This requires that the physical layer of CR networks should exploit all available degrees of freedom (time, frequency and space) in order to identify modes currently available for transmission.

The spectrum sensing functionality in CR systems can be divided into two subtasks: occupancy sensing and identity sensing. Occupancy sensing is to detect the spectrum occupancy in the local area and identify the unused spectra (white spaces free of RF interferers) and underutilized spectra (gray spaces partially occupied by low-power interferers). Established signal interception techniques, such as energy-based detection, can be applied to occupancy sensing. Identity sensing is used to distinguish between the licensed usage of spectra and the opportunistic usage of spectra by other CR users. Such distinction is crucial in a scenario with dense CR users. Since the licensed usage of spectra is well protected, the public white spaces are likely to be shared by multiple CR users in a competitive or negotiable manner. This subtask of identity sensing is unique for CR systems and is perhaps more challenging.

Spectrum sensing is best addressed as a cross-layer design problem [7]. In the following, we will first address physical-layer sensing methods, followed by the medium access control (MAC)

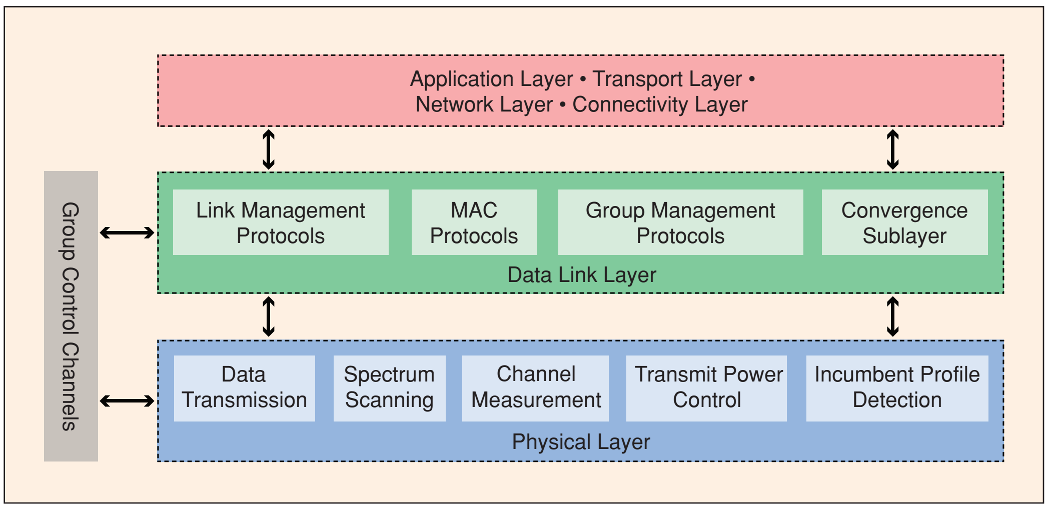

FIGURE 2 A generic layered protocol architecture for a CR system.

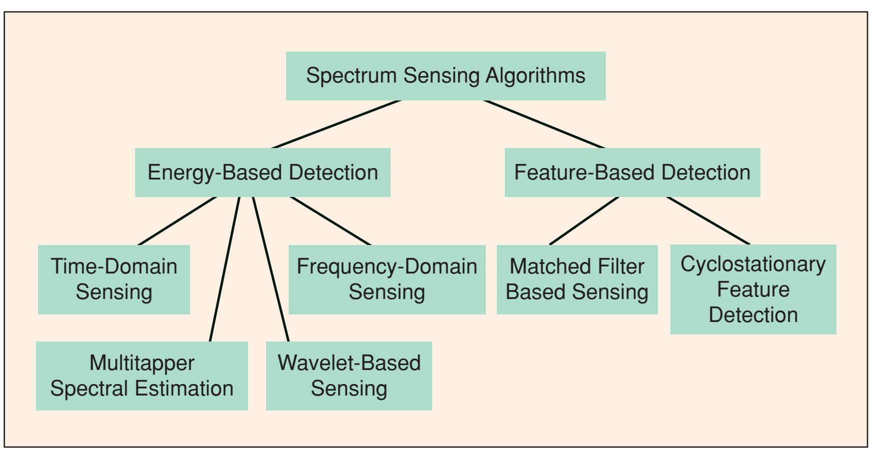

FIGURE 3 CR spectrum sensing algorithms.

protocol design. A generic layered protocol architecture for a CR system is illustrated in Figure 2.

Physical-Layer Sensing Methods

Several metrics can be used to evaluate the performance of spectrum sensing algorithms. Bandwidth, resolution, and real-time capability are the widely employed metrics. Bandwidth refers to the spectrum range that is covered by the sensing CR. A wider bandwidth leads to a greater capacity of CR systems. Resolution is the smallest spectrum step based on which the whole bandwidth range is quantized. Real-time capability is the time that it takes for a CR to reliably sense the environment and then make adaptive decisions. Due to the time variant characteristics of wireless channels, in general, the sensing latency should not exceed the coherence time of the channel. It is obvious that there is a tradeoff among the above three metrics. The spectrum sensing algorithm design is essentially to find an optimized tradeoff. The feasibility of using different algorithms for CR spectrum sensing has been investigated in the literature. As illustrated in Figure 3, they can roughly be classified into two categories: energy-based detection and feature-based detection.

Energy-based detection has been extensively used in radiometry. It can be performed in both the time and frequency domains. In the time domain, a bandpass filter is normally applied to the target signal in a particular frequency region, and the energy of the signal samples (after the filter) is then measured [11]. In the frequency domain, the simplest energy detector is based on the fast Fourier transform (FFT) of the time domain signal [7]. There exist some other energy detectors that are based on wavelet [12] and multitapper spectral estimation [4]. The principle of energy detector is to evaluate the power spectral density (PSD) of received signals in the local area and then set thresholds, based on which white and gray spaces are defined. The energy detector requires no prior knowledge of other systems which are operating in band. Hence, the processing requirement is generally lower. In addition, less time is required to achieve a reliable sensing conclusion. A major drawback of the energy-based sensing method is that it is prone to false detections, especially at low signal-to-noise ratios (SNRs). Another drawback is that it can not distinguish between the spectrum usage of the primary user and that of the secondary users. These drawbacks can be overcome by using feature-based sensing methods, which usually take into account the correlation with known signal patterns.

The feature-based detection assumes that a CR has the physical-layer prior knowledge of other in-band radio services. The information is then used for the reliable detection. The optimal way of the feature-based detection is matched filtering, since it maximizes the received SNR. For the matched-filtering processing, a CR should have the entire decoding information such as the bandwidth, center frequency, modulation scheme, and baud rate. The main advantage of a matched filter is that, due to its coherency, it requires less time to achieve a high processing gain and the detection error probability is low. However, the processing requirement for the matched filtering is high. Also, the time latency introduced by the matched filtering is relatively large since additional channel training and tracking are needed to decode properly. In addition, with a matched-filter detection, a CR would need a dedicated receiver for every primary user class.

CONVENTIONAL POLICY-BASED MANAGEMENT SYSTEMS CANNOT BE DIRECTLY APPLIED TO A CR NETWORK.

A suboptimal method called *cyclostationary feature detection* was proposed in [7] to solve the complexity and latency problems of the matched filtering scheme. Modulated signals, in general, have their built-in periodicity. This periodicity is typically introduced intentionally in the signal format so a receiver can exploit it for the parameter estimation such as carrier phase, pulse timing, or direction of arrival. This then can be used for the detection of a random signal with a particular modulation type in a background of noise and other modulated signals. A common analysis of stationary random signals is based on the autocorrelation function and PSD. On the other hand, cyclostationary signals exhibit correlation between widely separated spectral components due to spectral redundancy caused by periodicity. The distinctive feature of spectral redundancy makes signal selectivity possible. With cyclostationary feature detection, the sensing focuses on identifying certain cyclostationary characteristics of in-band systems, rather than trying to decode and recover the whole sequence of information using a matched filter. The analysis shows that the cyclostationary feature detection has advantages due to its ability to differentiate modulated signals, interference, and noise in low SNR ratios. Such a method can reduce the processing requirement while still maintaining a decent detection error probability.

From this analysis, both energy-based detection and feature-based detection have advantages and disadvantages. While the energy-based detection is more general, the feature-based detection outperforms it in sensing reliability and sensing convergence time. The feature-based sensing, however, is only possible when

SPECTRUM SENSING IS BEST ADDRESSED AS A CROSS-LAYER DESIGN PROBLEM.

the target primary user signal contains known signal patterns. Energy-based sensing and feature-based sensing exhibit similar performance at high SNR. The energy-based sensing, however, works poorly at low SNRs, while the feature-based sensing can achieve good performance even at low SNRs. The complementary characteristics of the energy detector and feature detector incites us to combine these two techniques as proposed in [7]. In this case, the CR spectrum sensing function is divided into two stages: coarse sensing and fine sensing. Coarse sensing refers to the energy-based detection technique. It quickly and roughly scans the wideband spectrum and identifies some potential spectrum holes that can be used. These potential spectrum holes are further processed in the fine sensing stage by using a feature-based detector. Advanced signal processing techniques are then applied to manage the interference.

Cooperative Spectrum Sensing

The performance of the physical-layer spectrum sensing techniques is limited by the received signal strength, which may be severely degraded due to multipath fading and shadowing. In a practical shadowing environment, cognitive users may receive drastically different signal strengths and thus different SNRs at different locations. One solution to this problem is to use a very large sensing gain to account for the worst-case shadowing scenarios. A more promising solution is to allow the sensing information to be shared among local cognitive users so that the spectrum sensing is performed collectively rather than individually across different network layers. The obtained physical-layer spectrum usage status is reported to the MAC layer. The MAC will then allocate the available spectrum to establish a safe CR link. In such a scenario, cooperative sensing will reduce the probability of interference to a primary user and consequently may alleviate the problem of detecting the primary user. In cooperative sensing we rely on the variability of signal strengths at various locations. We expect that a large network of CRs with sensing information exchanged between neighbors would have a better chance of detecting the primary user if compared to individual sensing.

One problem in cooperation is how to combine the results of various users, which may have different sensitivities and sensing times. It may be necessary to perform a certain form of weighted combining. The cooperation also introduces the need for a control channel. Wideband RF front-end tuners/filters can be shared between the control channel and normal CR reception/transmission. Furthermore, when multiple CR groups are active simultaneously, the control channel bandwidth needs to be shared. With a dedicated frequency band, a carrier sense multiple access (CSMA) scheme may be desirable. For a spread spectrum control channel, different spreading sequencing could be allocated to different groups of users. In addition, to further improve the sensing reliability, the advantage of a MAC protocol that exploits cooperation among many cognitive users was investigated in [7]. A general block diagram is given in Figure 4, illustrating the cross-layer functions relevant to spectrum sensing.

CR Networks Analysis

In this section, we will analyze how each node in a CR network should be designed and configured regarding the network's overall performance. Several tools are currently available for the analysis and modeling of multiuser CR systems. In his original work, Mitola addressed that CR networks are self-organizing, just like an ant colony [2]. This network description borrows mainly from the concepts of machine learning and artificial intelligence. The most popular tool for analyzing CR networks is Game Theory [4], [13]. Subsequently, we will only concentrate on the game theoretic analysis of CR networks.

In a CR network, all the devices are capable of sensing the environment and effectively adjusting their transmission parameters in response to the current local channel conditions and QoS specifications. These transmission parameters include the transmission rate, transmission power, frequency, modulation scheme, coding scheme, multiple access method, and a route to the final destination in a multihop network. The choice of these parameters will greatly influence the performance of all the other users in the

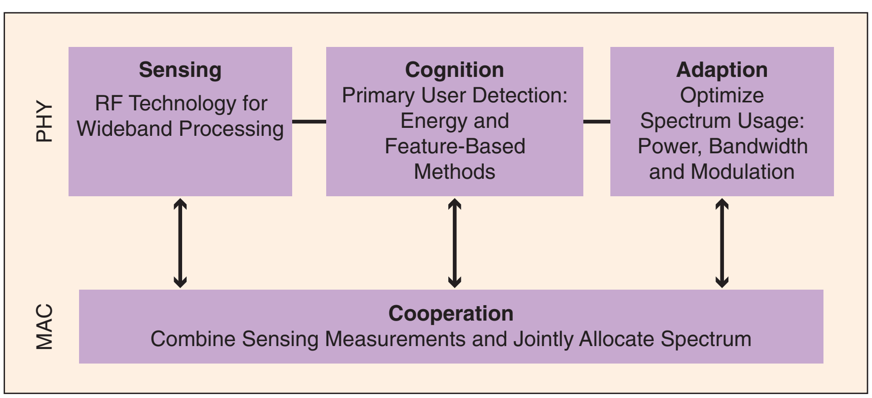

FIGURE 4 The cross-layer functions in relevance to spectrum sensing [7].

network. Let us take an example of the transmission power control. If all users' power levels are fixed, the increase of one user's power would increase its SINR. However, the action of raising one user's power will consequently increase the interference perceived by other users. This will result in the reduction of the other users' SINRs and induce them to increase their own power levels as well. There are several confronted tasks; e.g., how to analyze such a conflict situation, what are the conditions to make the network reach a steady state, and what is the definition of a steady state.

As a set of mathematical tools for analyzing the interaction of decision makers with conflicting objectives, game theory is suitable to answer the above questions. Game theory has widely been applied to the areas of economy and computer networking. A CR network can be regarded as a chaotic game, trying to find the equilibrium of conflicting actions that meet the node's operational goals across different networking layers for a specific environment. A game playing procedure can be used to model the interaction among a group of users sharing a common spectrum resource. The overall network performance, i.e., the outcome of the game, could then be predicted using a game theoretic formulation.

A CR network can be modeled as a game as follows [13]. The CRs in the network are considered as the decision makers in the game. The player's action set refers to a set of physical-layer parameters, which are allowed to be chosen by a CR. Some of these parameters are transmission power, frequency, bandwidth, modulation, channel coding, and antenna pattern. Based on the action sets, the game action space is then formed. Preference relations over the game action space are formed by an exhaustive evaluation of the adaption algorithms. Objective functions are formulated by mapping the preference relations to the real number axis so that preference action vectors are larger than less-preferable action vectors. By using this game model, the network performance of CR can be analyzed. It follows that the steady-state conditions of the networks can be identified as the first stage of network planning.

THE MOST POPULAR TOOL FOR ANALYZING CR NETWORKS IS GAME THEORY.

CR Network Capacity Analysis

In this section, we will discuss the capacity of a simple CR network, where N primary users $X_i\ (i = 1, \ldots, N)$ and M CR users coexist and are all uniformly distributed in a circular cell with radius R. A CR access point (AP) is deployed at the center of the cell. Here, we will restrict our capacity analysis to the uplink of the CR network, where multiple CR users transmit information to the central CR AP.

We assume that after spectrum sensing, underutilized spectra with a total bandwidth of W are discovered. CR transmitters are allowed to transmit signals with the bandwidth W under an interference-tolerant condition that the average interference experienced by any primary receivers is below a threshold I_0 [14]. Such an average received interference power constraint is reasonable when the interfering signal is subjected to fast fading, which is valid especially for mobile vehicular applications. Multiple CR users transmit in orthogonal time-division channels, which means that only one target CR user is scheduled in a time slot to transmit with an allowable power P. The distance from the target CR user to the AP is denoted as r. Such a CR network is illustrated in Figure 5. When the average interference power is constrained, it follows that

$$E\left\{P \cdot h_i^I\right\} = P \cdot E\left\{h_i^I\right\} \leq I_0 \quad (i = 1, \ldots, N), \qquad (1)$$

where h_i^I is the gain of corresponding interference channel connecting the CR transmitter and the ith primary receiver X_i, $E\{\cdot\}$ is the statistical average operator, and I_0 is the maximum average interference power that the primary receivers can tolerate. In [14], the derivation was given regarding the probability density function (PDF) $f_{P_{\max}}(x)$ of the maximum allowable transmit power $P_{\max}$ as a function of N and r/R. Figure 6 shows the theoretical and simulated $f_{P_{\max}}(x)$ as a function of the normalized power $P_{\max}/P_{\lim}$ with $r/R = 0.5$ and different values of N, where $P_{\lim}$ is the greatest achievable power. The

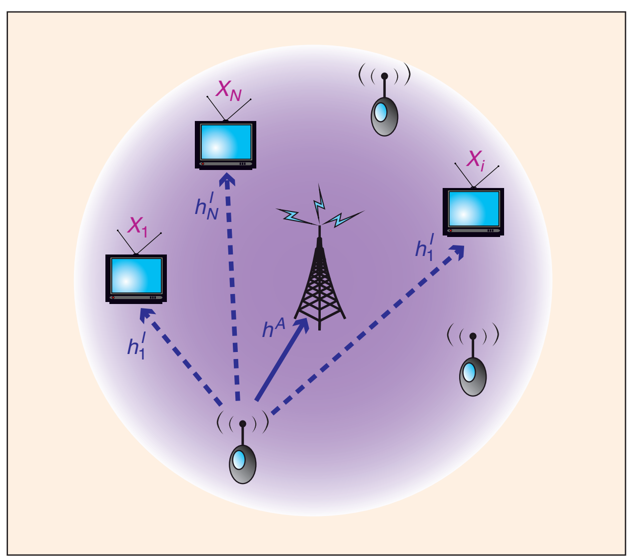

FIGURE 5 A CR-based central access network.

IT IS HIGHLY EXPECTED THAT THE APPROPRIATE COMBINATION OF POLICY-BASED MANAGEMENT AND CR WILL LEAD FUTURE WIRELESS COMMUNICATIONS.

results agree with the intuition that with the increase of N, $P_{\max}$ takes greater probabilities at smaller values. In Figure 7, the PDFs $f_{P_{\max}}(x)$ are shown with $N = 5$ and different values of r/R. The results tell us that a CR user closer to the cell has a greater probability of transmitting in a larger transmit power. Comparing Figure 6 with Figure 7, we can see that the PDF reacts more dramatically to the change of N. This means that compared with r, N is a more dominant factor which impacts the power dynamics.

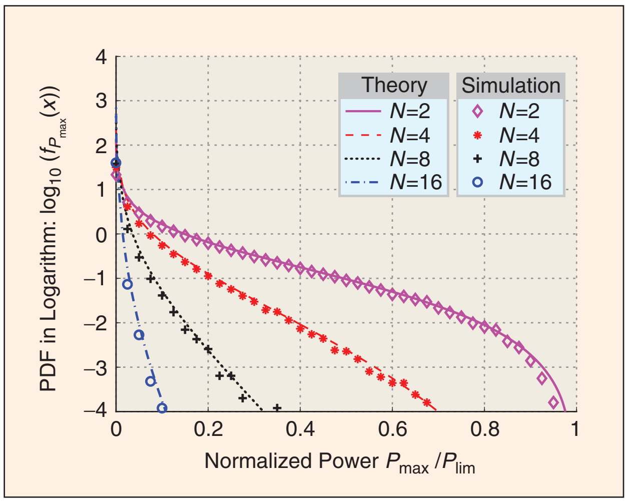

FIGURE 6 The PDF of $P_{\max}$ in logarithm $\log_{10}(f_{P_{\max}}(x))$ with $r/R = 0.5$ and different values of N.

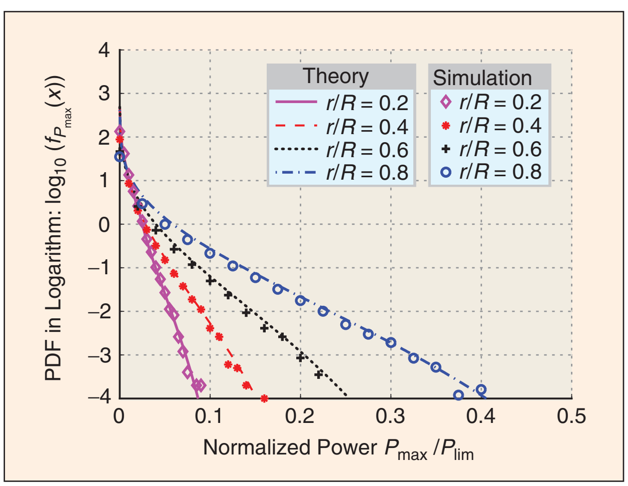

FIGURE 7 The PDF of $P_{\max}$ in logarithm $\log_{10}(f_{P_{\max}}(x))$ with $N = 5$ and different values of r/R.

When the target CR user transmits with the maximum power $P_{\max}$ and bandwidth W to communicate with the CR AP, the link capacity is given by

$$C = W \log_2\left(1 + \frac{P_{\max} h^A}{N_o}\right), \qquad (2)$$

where N_0 is the corresponding noise power and h^A is the channel gain between the target CR user and the AP. The channel gain h^A is modeled as a product of three factors: the pathloss, Log-normal shadowing, and Rayleigh multipath fading. Taking the statistical expectation of C over $P_{\max}$ and h^A will give the ergodic capacity $\bar{C}$ as a function of N and r. When the cell radius R is set to be 1,000 m to simulate a typical macrocell scenario, theoretic and simulated results of $\bar{C}$ are plotted with $I_0/N_0 = 10$ (Figure 8). From Figure 8, we have the following observations: 1) With a smaller number of primary users N, better spectrum efficiency is achievable at the expense of higher power consumption; 2) given r/R, the capacity decreases quickly with the increasing N; and 3) given N, the capacity decreases quickly with the increasing r/R.

Figure 8 also tells us that the overall capability of the CR network depends largely on the number of the primary users N. Moreover, the capability of an individual CR user varies dramatically based on its instant location. The application layer should be aware of such variations to make reasonable business level policies.

Conclusion

The regulatory agencies have been pushed by the increasing demand for wireless ubiquitous connectivity

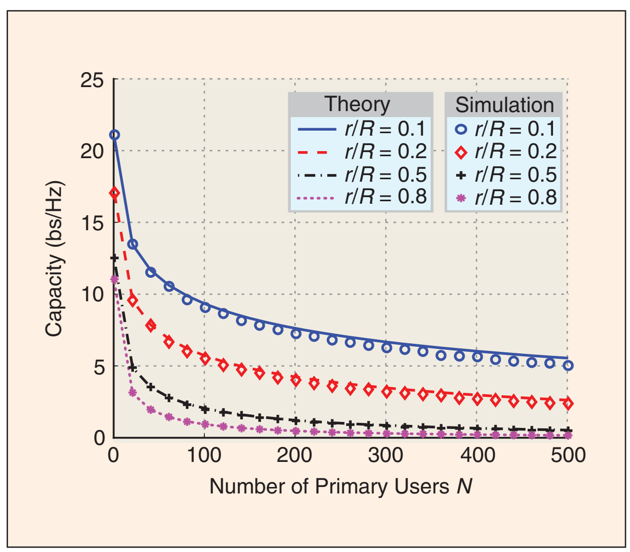

FIGURE 8 The ergodic capacity of a CR-based central access network as a function of N with different values of r/R ($I_0/N_0 = 10$).

A CR NETWORK CAN BE REGARDED AS A CHAOTIC GAME.

to be ever more aggressive in providing innovative ways to use spectra efficiently. Driven by these new opportunities, the future radio systems should look for the optimized architecture, circuit, and algorithm as a whole. In this article, we have investigated both the unique merits and the challenging tasks of combining policy-based management philosophy with CR technologies. Some example analysis have also been discussed. It is highly expected that the appropriate combination of policy-based management and CR will lead future wireless communications.

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