INVITED PAPER

Performance Evaluation of Cognitive Radios: Metrics, Utility Functions, and Methodology

Understanding the interdependent nature of the metrics used at the node, network, and application levels and their interactions with radio and network processes in different environments is essential to the development and tuning of cognitive radio networks.

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ABSTRACT | Performance evaluation of cognitive radio (CR) networks is an important problem but has received relatively limited attention from the CR community. Unlike traditional radios, a cognitive radio may change its objectives as radio scenarios vary. Because of the dynamic pairing of objectives and contexts, it is imperative for cognitive radio network designers to have a firm understanding of the interrelationships among goals, performance metrics, utility functions, link/network performance, and operating environments. In this paper, we first overview various performance metrics at the node, network, and application levels. From a game-theoretic viewpoint, we then show that the performance evaluation of cognitive radio networks exhibits the interdependent nature of actions, goals, decisions, observations, and context. We discuss the interrelationships among metrics, utility functions, cognitive engine algorithms, and achieved performance, as well as various testing scenarios. We propose the radio environment map-based scenario-driven testing (REM-SDT) for thorough performance evaluation of cognitive radios. An IEEE 802.22 WRAN cognitive engine testbed is presented to provide further insights into this important problem area.

KEYWORDS | Cognitive radio; game theory; metric; performance evaluation; utility function

I. INTRODUCTION

Formalizing a decades-long trend towards radios that self-optimize in response to changing conditions, cognitive radio (CR) and cognitive wireless networks define a design paradigm for introducing numerous new adaptive algorithms, which enable much higher spectrum utilization, provide more reliable and personal radio services, reduce harmful interference, and facilitate the interoperability or convergence of different wireless communication networks. The term "cognitive radio" was initially coined by Mitola in the late 1990s [43], [44]. In a broad sense, some preliminary CR technologies [e.g., adaptations in transmit power and dynamic channel selection in response to varying radio-frequency (RF) environments] have already been employed in a few existing wireless networks [68] such as cellular networks, cordless phone systems, and wireless local-area networks (WLANs). In a narrow sense, comprehensive situation-awareness and intelligent learning

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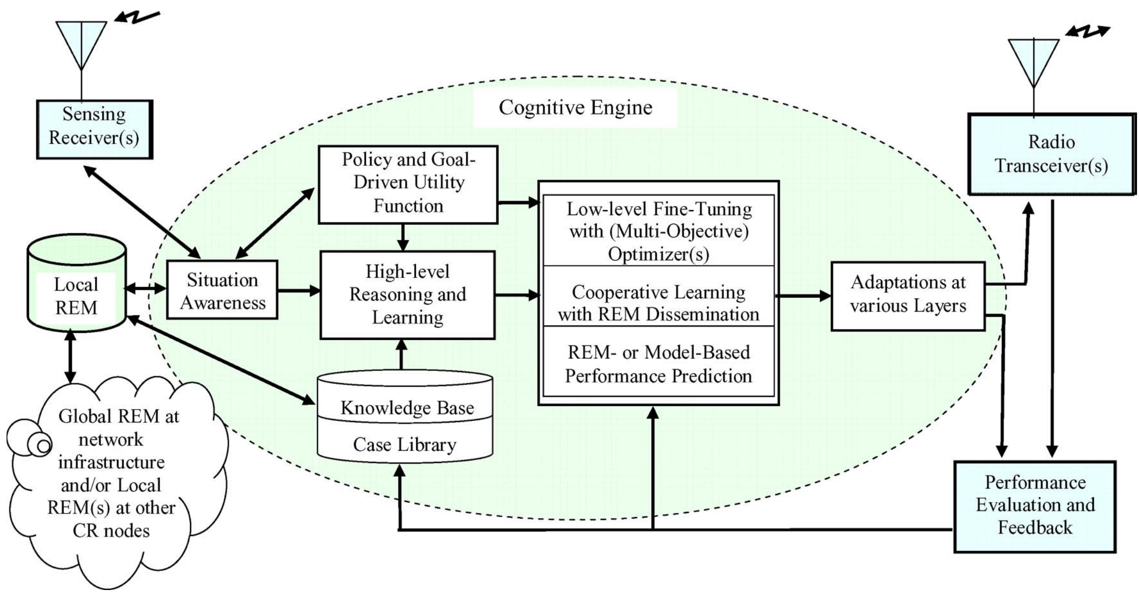

Fig. 1. ***Building blocks of the CR model considered in this paper and the role of performance feedback and utility functions in CE.***

capability, the two defining features of future advanced CRs, have not been realized or fully exploited by current radios.

The CR paradigm is expected to drive the next generation of radio devices and standards to enable a variety of new applications in demanding environments, such as spectrum-sharing networks, natural disasters, civil emergencies, and military operations. Examples of CR-oriented networks include the Defense Advanced Research Projects Agency (DARPA) XG [42] and WNaN programs,[1] IEEE 802.22 wireless regional area network (WRAN) [25] (aiming to support data services in the TV bands as secondary users), IEEE 802.16h (aiming to improve coexistence mechanisms for license-exempt operation), IEEE 802.11h (supporting dynamic frequency selection and transmit power control for WLANs to share spectrum), 802.11y (enabling Wi-Fi-like equipment to operate on a secondary basis in licensed frequency bands), European end-to-end reconfigurability (E^2R) research program [21], and the networks proposed by the White Spaces Coalition [3].

A. Building Blocks of CR

The building blocks and overall system flow of the CR model considered in this paper are illustrated in Fig. 1 [83]. In this model, the radio environment map (REM) is an integrated information structure (i.e., a database) that consists of multidomain information for CR, such as geographical features, available services, spectral regulations, locations and activities of radio devices, policies of user and service providers, and past experience [81], [84]. During operation, the CR observes the operational environment via sensor(s) and obtains necessary situational awareness about the current radio scenario by leveraging the sensing results and REM.

The "brain" or intelligent agent of CR, the cognitive engine (CE), then determines an appropriate utility function based on the policy and goals by considering the specific application or radio scenario. The utility function maps the current state of the CR, usually represented by an array of chosen metrics, to a value for indicating how close the state is towards the desired (or optimal) CR state. The most pertinent performance metric(s) should be taken into account and incorporated into a proper utility function to meet the CR's goal for the specific radio scenario or application.

By leveraging past experience and knowledge, the CE can choose the most efficient reasoning and learning method and make (near) optimal and/or cross-layer adaptations subject to constraints of regulation, policy, and radio equipment capability. Performance feedback is collected from other radio nodes or by sensing the environment, which enables the closure of the CE learning loop. The case library, knowledge base, and REM are updated according to the observed performance results [83], [85].

B. Motivation

Although the notion of CR was introduced in the late 1990s, the wireless community has not converged on a common definition at this time.[2] In fact, different people and organizations have different expectations of what level of intelligence and what capabilities are essential to or

[1] http://www.darpa.mil/sto/solicitations/WNaN/; http://fedbizopps.cos.com/cgi-bin/getRec?id=20070226a1.

[2] See http://support.mprg.org/dokuwiki/doku.php?id=cognitive_radio:definition.

Table 1 Different Assumptions About What Capabilities Are Necessary for Radio to Be Called a Cognitive Radio

Definer	Adapts (Intelligently)	Autonomous	Can sense Environment	Adaptive Transmitter	Adaptive Receiver	Environment "Aware"	Goal Driven	Learn the Environment	Capabilities "Aware"	Negotiate Waveforms	No harmful interference
FCC [14]	√	√	√	√							
Haykin [22]	√	√	√	√	√	√	√	√			
IEEE P1900 [26]	√	√	√	√	√						
IEEE USA [27]	√	√	√	√	√	√					√
ITU-R [30]	√	√	√	√	√	√					
Mitola [44]	√	√	√	√	√	√	√	√	√	√	
NTIA [11]	√	√	√	√	√	√	√				
SDRF CRWG [64]	√	√	√	√	√	√	√		√		
VT CRWG[2]	√	√	√	√	√	√	√	√	√		

merely beneficial to the CR concept, as illustrated in Table 1. Researchers and standardization bodies generally agree that CR should be able to sense the environment and autonomously adapt to changing operating conditions but mainly differ in the levels of situation awareness and cognitive functionality. Such diverse expectations make performance evaluation a great challenge in the design of CR devices and networks.

For CR researchers, establishing or selecting effective performance metrics (called "meters" in [63]) is usually one of the most important and challenging steps towards a successful CR design. Formalizing CR benchmarking methods and performance metrics would help hasten the integration of the CR paradigm into existing wireless networks. First, benchmarking the performance of CRs when coexisting with incumbent radio devices and systems is badly needed by (spectrum) regulators to provide a basis for certifying and regulating CR. Regulators need an effective and efficient way to demonstrate that CR devices or systems will not generate harmful interference to incumbent users. Similarly, CR performance benchmarking is also needed by vendors for type approval testing during the development and production of CRs. Lastly, CR performance benchmarking is needed by service providers for CR network deployment and maintenance as well as spectrum trading/subleasing. Without well-defined performance metrics and benchmarking methods, it would be almost impossible to put CR technologies into practice.

Since a CR may support many disparate applications, there is a broad range of metrics that could be defined and has been used to evaluate CR performance. While a great number of choices are available, care must be taken in selecting performance metrics as the selection will impact many aspects of CR design. To be responsive to changing radio scenarios and the tradeoffs among various (possibly conflicting) objectives, the CE needs to adopt dynamic situation-aware utility functions rather than relying on a single predefined static function.

The dynamic interplay of changing environments, goals, and capabilities (due to learning) implies that creating a generic benchmarking method for CR is nontrivial. First, since the performance of a CR may change over time as it learns and adapts to the environment, measurements taken at one time may not be indicative of its performance at a later time. Secondly, since most CR designs assume cross-layer adaptations, traditional layered testing under static conditions could yield misleading results. Thirdly, since a CR network is generally guided by numerous competing objectives, benchmarking a CR will tend to be a subjective process as users running different applications in their perspective environments will assign different weights to metrics. This is not a problem unique to CR but does highlight the challenge in objective evaluation of a CR system.

C. Scope and Organization

In this paper, we demonstrate CR design tradeoffs by examining the interaction among performance metrics, utility functions, and decision-making processes. We focus on the performance metrics appropriate for dynamic spectrum access and sharing, which have attracted considerable research efforts in the past few years and have significant and immediate impact to commercial, military, and public safety radios [9], [16], [20], [36]. Specifically, this paper reviews candidate CR performance metrics at the node, network, and application levels, examines how CR performance can be tuned in the desired direction by defining and adopting proper metrics and utility functions, and investigates how to efficiently evaluate or validate CR performance under various testing scenarios. We believe that addressing these important issues would be of great interest not only to CR designers and standardization bodies but also to existing/emerging network operators and spectrum regulators. Formalizing performance metrics and evaluation methodologies will also greatly help the research community to make meaningful comparisons between various CE algorithms and accelerate the advancement of CR research.

It is worth noting that the subject is very broad and is hard to fully address in a single paper. However, we expect that this survey would serve as a starting point to attract more attention from the CR community to this important but relatively inadequately addressed problem, as compared to, e.g., spectrum sensing and dynamic spectrum access. We hope these efforts (including ours) will lead to benchmarks and unified evaluation methodologies for CR systems.

The rest of this paper is organized as follows. In Section II, we provide an overview of performance metrics from various perspectives. The interrelationship among performance metrics, utility functions, and the achievable

CR performance is examined from a game-theoretic view in Section III. In Section IV, we present an IEEE 802.22 WRAN base station (BS) CE testbed, which provides first-hand experiences and insights into the methodology of CR network evaluation. Concluding remarks, remaining issues, and suggested directions are provided in Section V.

II. AN OVERVIEW OF CR PERFORMANCE METRICS

In this section, we review performance metrics that can be used for CR performance evaluation at the node, network, and application levels. Regulators, standard organizations, radio equipment vendors, CR network operators/users, and legacy radio network operators/users may have different concerns about CR performance. Therefore, different metrics are needed for these perspectives. In Tables 2 and 3, we provide extensive lists of candidate performance metrics for CR node and CR network, which we nickname "node score card" and "network score card," respectively. Each of these metrics can be used in the CE to drive the operation of a CR. The more general case will be discussed in Section III, where utility functions are used to unify multiple metrics.

A. Node-Level Metrics

Generally speaking, a CR node can be evaluated from the following four domains: i) cognitive functionality, ii) overall node performance, iii) complexity, and iv) technical maturity. Each domain may consist of a set of subdomains or key metrics, as shown in Table 2. For example, cognitive functionality may include subdomains of situation awareness, adaptation, reasoning, learning, and planning. Among these metrics, some performance metrics are

Table 2 Example Node-Level Performance Metrics (or "Node Score Card") for Spectrum-Sharing Networks

Domain		Performance Metrics
Cognitive Functions	Situation Awareness	Location accuracy, availability, integrity, and continuity at various (outdoor/indoor) environment [12]
		RF environment awareness: - Receiver Operation Characteristics (ROC): PU detection rate vs. false alarm rate under various SNR and certain time bandwidth product [55], [78] - Required SNR for PU detection at certain detection rate and false alarm rate [19] - (Total) spectrum sensing time for PU detection for a given sensitivity [73] - Signal classification/recognition functionality [15] - Spectrum opportunity tracking and prediction [79] - Radio channel condition (such as multi-path delay spread and Doppler spread) awareness [59]
		Mobility and trajectory awareness [81]
		Power supply and energy efficiency awareness [81]
		Regulation, mission, context, policy, and priority awareness [64], [65], [81]
	Adaptation Capability	Channel evacuation time when PU (re)appears [42] Cross-layer adaptability Operation channels/bands and switch time between operational channels or bands [42] Antenna pattern adaptability [24] Dynamic range at receiver and transmitter Waveform/air interface flexibility and reconfigurability Routing protocols adaptability
	Reasoning, Decision Making, Planning, and Learning	Overall radio IQ level: "infant," "toddler," "preschool," "child," "adolescent," "teenager," "young adult" [65]
		Reasoning capability [84] - Case/knowledge/policy-based reasoning capability - Case retrieval time
		Decision making capability - Distributed or centralized decision making [80] - Decision-making algorithm convergence time [84], [85]
		Learning capability - Flexibility of learning (type of learning methods supported) [17] - Effectiveness of learning: performance vs. training time: Learning period [77]
Overall Node Performance		Spectrum utilization (in terms of sum throughput, network available time)
		Impact to other SU nodes or incumbent radios, in terms of - Transfer (net utility loss of the other nodes caused by one CR node) [13] - SINR or INR [42]
		Power efficiency (in terms of active time, battery life)
		Communication cost for end users
		Link reliability (in terms of BER, FER, or packet drop ratio) [68]
Node Complexity		In terms of signal processing power requirement, memory footprint, implementation costs, etc.
Technical Maturity		Overall CR node technology maturity
		Maturity of key technologies: - Software Defined Radio [61] - Analog-to-Digital Converter [37], [54] - Multi-band RF transceiver and antennas - Policy conformance enforcement [56] - Artificial Intelligence [16], [17], [53]

Table 3 Example Network-Level Performance Metrics (or "Network Score Card") for Spectrum-Sharing Networks

Domain		Performance Metrics
Cognitive Functions	Situation Awareness	PU, SU awareness: PU/SU detection rate, false alarm rate [12] Policy awareness [81] Awareness of adaptation capability of each node in the network Awareness of network topology, routing protocol and awareness of network status and current goal
	Adaptation Capability	Routing protocol and topology adaptability Cross-layer adaptation capability
	Reasoning, Decision Making, and Learning	Overall network IQ level Decision-fusion overhead [82] Decision-fusion time
Overall Network Performance		Spectrum utilization in terms of - Sum throughput or goodput [10], [79] - Throughput of secondary system [18], [77] - "Packing factor" (or "idle percentage") in frequency, space, and time domains - Spectrum utilization efficiency [28], [32], [33]
		Impact to PU networks or other co-existing SU networks [60], [68] - Increased average packet delay experienced by the incumbent PUs [87] - SINR, INR, or BER degradation at the PU receiver [87] - Increase in call drop rate, handover failure, origination failure, termination failure [68]
		End-to-end metrics: average throughput, delay, packet drop rate, jitter [10]
		Networking metrics: - Rendezvous time (network access time) [42] - Network availability [42] - Rate of convergence [48]
		Network reliability, fairness, scalability, and mobility support [58]
		Network security - Robustness to malicious node [7], [56] - Vulnerability to denial-of-service attack [6]
		Application QoS - Voice quality, e.g., mean opinion score (MOS) [29] - Video quality, e.g., media delivery index (MDI) [74], distortion, and peak-signal-to-noise-ratio (PSNR) - Response time for interactive data applications (e.g., Telnet or World Wide Web) - Throughput for bulk data applications (e.g. FTP or distributed database synchronization)
Network Complexity		In terms of signal processing power requirement, implementation costs, etc.
Technical Maturity		Overall CR core network technology maturity Maturity of key technologies for CR networks: - MANET (scalability) [58] - Policy conformance enforcement [56]

specifically defined for CR, such as channel evacuation time and probability of primary user (PU) detection, as opposed to generic performance metrics that have been widely used in the literature. We focus on such CR-specific metrics in the following.

1) Metrics for Situation Awareness: The performance of a CR network is highly dependent on the extent and quality of information about the radio environment available at each node. The environmental information (situation awareness) can include information (awareness) about the following: location, geographical environment, RF environment, mobility and trajectory, power supply and energy efficiency, regulation and policy, mission, priority, and context awareness [81]. Each type of information has an associated set of metrics for evaluating the quality or extent of the information. For example, location accuracy, availability (in time and space), integrity, and continuity are metrics for evaluating the location awareness of a CR node.

For dynamic spectrum access and spectrum sharing applications, the most critical piece of information for secondary users (SUs) is the presence of PUs. Two complementary metrics are used to evaluate a CR's ability to gain meaningful information about the presence of a PU-probability of detection (P_D) and probability of false alarm ($P_{\rm FA}$). In general, a higher P_D provides greater protection to PUs but is accompanied by a higher $P_{\rm FA}$, which tends to lead to less efficient spectrum utilization. The receiver operation characteristics of a CR depict the PU detection rate versus the false alarm rate under various signal-to-noise ratios (SNRs). Depending on whose interest is of priority, either a targeted P_D or $P_{\rm FA}$ should be set. It is possible to improve P_D without sacrificing $P_{\rm FA}$ by employing cooperative sensing [19], [40], [55].

A CR node may also be aware of the performance of radio devices (both other devices and itself). This includes information such as the linearity of radio transceiver, spurious free dynamic range of the front end, power and frequency of intermodulation products, noise power, battery life and power consumption, cycles, and memory required to implement a particular waveform.

2) Metrics for Assessing Cognitive Functionality: There are different ways to evaluate the cognitive functionality of a CR, such as reasoning, decision making, planning, and learning [65]. "Radio IQ" can be defined to different metaphorical levels of cognitive capability. For example, an infant CR may have limited aware capability, a toddler may have limited adaptation capability, a preschooler may have limited learning capability, an adolescent may avoid making repeated mistakes, and an adult behaves autonomously to reach his/her goals even without inputs from others. Mitola defines a different functional classification of CR as follows: i) preprogrammed, ii) goal driven, iii) context aware, iv) radio aware, v) capable of planning, vi) conducts negotiations, vii) learns environment, viii) adapts plans, and ix) adapts protocols [44]. It should be noted that this latter classification scheme does not assume a strict progression, i.e., a CR may be able to adapt protocols [level ix)] but be unable to negotiate [level vi)].

3) Metrics for Assessing Node Performance: Numerous direct or indirect observations could be used by a CE to evaluate the overall performance of a CR node. We briefly discuss representative performance metrics at different layers.

At the physical layer, commonly used metrics include signal-to-(noise plus interference) ratio (SINR) or interference-to-noise ratio (INR), bit error rate (BER), bandwidth efficiency, and power efficiency. While these metrics are all derived from physical layer observations, they can also be useful for the decision processes in higher layers. For instance, position and link gain information can help improve the performance of topology formation algorithms. Channel coherence times and link SINRs influence link reliability and thus influence the selection of routing algorithms, which is better suited for the level of disruption and mobility.

Example link-layer metrics include the following: collision rates, mean channel access times, overhead ratios, packet drop rate, and frame error rate. Network layer metrics may include mean and peak packet delay, and routing table or routing path change rate (for ad-hoc and sensor networks). Many of these metrics have been used in wireless network performance evaluation in the literature, which, however, are also important for CR performance evaluations [65].

B. Network-Level Metrics

Similarly, we may evaluate a CR network in the following four domains: i) cognitive functionality, ii) overall network performance, iii) complexity, and iv) technical maturity, as shown in Table 3. Some metrics, being evaluated over the entire network, have similar definitions to the corresponding node-level metrics. We focus on the metrics for spectrum utilization efficiency and the DARPA XG program here.

1) Metrics for Spectrum Utilization Efficiency: The ITU-R Handbook on spectrum management presents two different methods for calculating spectrum utilization efficiency (SUE) [28], [32], [33]. In the first method, *spectrum utilization* is determined by the amount of frequency, geometric space, and time used and may be calculated as

$$U = B \times S \times T \tag{1}$$

where U is the amount of spectrum space used ($Hz \times m^3 \times s$), B the spectrum bandwidth, S the geometric space, and T the time. SUE is computed as the ratio of information transferred (denoted as M) to the amount of spectrum utilized as

$$\mathrm{SUE} = M/U = M/(B \times S \times T). \tag{2}$$

The second ITU-R method is based on a special procedure for redesigning the frequencies of operating radio stations and use (3) to calculate the spectrum utilization

$$U = \Delta F/\Delta F_0 \tag{3}$$

where ΔF is the minimal necessary frequency band to permit the functioning of the operational facilities of interest and ΔF_0 the frequency band being analyzed. The lower bound for U is achieved by determining the ΔF of the optimum or near-optimum frequency use algorithm. We can then compute SUE using (2).

2) Metrics Adopted by the DARPA XG Program: The DAPRA XG program used a different set of performance metrics during the 2006 field tests. These performance metrics were defined for the following three scenarios [42].

- The XG network causes no harmful interference to non-XG systems in terms of abandon time (i.e., abandon a frequency channel within 500 ms) or interference limitation (i.e., maintain less than 3 dB SNR degradation at a protected receiver).
- The XG network forms and maintains dynamic connectivity in terms of network formation/rendezvous time (establish an XG network of six nodes within 30 s), network join time (join a node to an existing XG network within 5 s), and channel reestablishment time (reestablish an XG network of six nodes within 500 ms).
- The XG network adds value in terms of reducing spectrum management setup time (no preassigned frequencies increase deployment flexibility) and increasing spectrum access (communications capacity) in terms of 60% or more spectrum occupancy with a six-node XG network.

Note that the above metrics defined for the XG program are used as a threshold for establishing early confidence in the viability of dynamic spectrum access technologies [42].

C. Application Performance Metrics

Although listed in Table 3, application performance metrics are quite different from generic network-level metrics. This is not only because they are the ultimate performance measure but also because they unify the effects of most of the lower layer performance metrics. From this perspective, application metrics are similar to utility functions that will be discussed in Section III. However, utility functions are based on the abstract (and loose) concept of utility, while application metrics aim to model perception of human users.

It is a great challenge to define proper performance metrics for general applications, which are highly diverse from each other. We take video, a spectrum-hungry application, as an example in this section and review performance metrics used in the literature and practice for evaluating the quality of video delivered through a network. Various video performance metrics can be roughly categorized into the following two classes: subjective video quality and objective video quality metrics, which are reviewed in the following.

1) Subjective Performance Metrics: In subjective video quality evaluation, a sufficiently large number of experts view a chosen video sequence (alone or contrasting with the original video clip). Their opinions are collected and analyzed [57]. This approach has been adopted by the ITU-R as in ITU-R BT.500-11 [31]. Subjective video quality represents the ultimate user perceived performance, which effectively unifies the influences of the entire protocol stack. However, such an approach is more expensive and difficult to carry out and repeat. The test results also heavily depend on the expertise and preferences of the viewers, as well as many other factors such as room illumination and display type.

2) Objective Performance Metrics: Objective video quality measures are obtained by directly analyzing the received video flow or the reconstructed video. Such evaluation is easier to carry out than subjective approaches, and the results are easily repeatable. Many objective video quality metrics have been proposed and adopted (see [45], [52], [67] and references therein). Such metrics can be roughly classified according to how they are computed: i) from the received video packet flow, ii) from reconstructed video frames; and iii) from theoretical rate-distortion models. We review representative metrics in each category in the following.

a) Media delivery index (MDI): MDI is a metric computed from received video packet flow. It consists of a two-tuple separated by a column [Delay Factor (DF)| Media Loss Rate (MLR)] [74]. It is designed as a quality indicator for monitoring delivery of real-time data over a network, such as streaming media, MEPG video, and voice over IP. The two-tuple provides an indication of traffic jitter, a measure of deviation from normal flow rates, and a data loss at-a-glance measure for a particular flow [74]. It has been implemented in commercial devices (e.g., Agilent's N2X platform [1]).

Computed from network measurements, MDI is independent of video codec and video sequence. The measurements are easy to carry out with low complexity. Since MDI is measured at the receiver, there is no need for the original video, making it useful for live video applications. On the other hand, MDI should be used with caution. Video quality is usually a very complex function of the network layer statistics. MDI should be used as an indicator for inferring media quality only. Furthermore, for two MDIs with identical MLRs, the subjective video quality may still be very different, since loss pattern has a significant effect on video distortion [38].

b) Peak SNR (PSNR): PSNR is a mean square error (MSE)-based metric that measures the quality by simple pixel-to-pixel comparisons of the reconstructed video with the original video. For a video sequence of K frames, each having $N \times M$ pixels with L-bit depth, PSNR is computed as

$$\begin{cases} \text{MSE} = \frac{1}{N\times M\times L}\sum_{i,j,k}[x(i,j,k) - \bar{x}(i,j,k)]^2 \\ \text{PSNR} = 10 \times \log\frac{L^2}{\text{MSE}} \end{cases} \quad (4)$$

where $x(i,j,k)$ and $\bar{x}(i,j,k)$ are the pixel luminance value in the (i,j) location in the kth frame for the original and reconstructed videos, respectively.

Compared with other metrics, PSNR is easy to compute and well understood. However, the above computation requires the original video, making PSNR not suited for live video applications. It has also been found that sometimes the PSNR does not conform to the subjective video quality very well.

c) Rate-distortion model approach: If we assume that the source statistics are Laplacian distributed and the distortion measure $D(x,\bar{x}) = |x - \bar{x}|$, then there is a closed-form expression for the rate distortion function as $R(D) = \ln(1/\alpha D)$ [72]. Functions with simpler forms can be used to approximate this rate-distortion function [8]. For streaming video, the overall distortion of a reconstructed video D_d can be decomposed into two parts: the distortion caused by signal compression D_e and the distortion caused by transmission errors D_v as [70]

$$D_d = \underbrace{D_0 + \omega/(R - R_0)}_{D_e} + \underbrace{\kappa \times p}_{D_v} \quad (5)$$

where D_0, ω, R_0, and κ are coefficients to be determined for a specific video codec and video sequence and p the packet loss probability.

Such an approach provides closed-form expressions that translate network delivery metrics to video distortion. It is therefore very useful for theoretical studies of video streaming systems [34]. However, the coefficients cannot be directly derived from commonly used signal statistics but need to be estimated by fitting the model to a subset of measured data points from the distortion-rate curve [70]. It is also worth noting that the average video packet loss rate (p) is used. The impact of different loss scenarios is not modeled here [38].

III. FROM METRICS TO UTILITY FUNCTIONS—A GAME-THEORETIC PERSPECTIVE

As shown in Fig. 1, utility function and goal are important components of a CE. Generally speaking, utility is an assignment of values (numbers) to the current operating state such that the closer the CR comes to satisfying some goal, the greater the value assigned to the operating state. A utility function can incorporate a number of performance metrics, which largely depend on the specific application or context and therefore may change over time. As we show in the following, how nodes choose their utility function can significantly impact network behavior. To further complicate matters, how utility functions impact network behavior can vary from situation to situation.

For some CR applications or scenarios, the goal is characterized or dominated by a single objective. In these situations, the utility functions used by a CE could be very simple and defined by some basic function of the goal, such as a monotonic function, a nonmonotonic (convex or concave) function, or a logistic function (i.e., a sigmoid, arc-tangent, a hyperbolic tangent, or the error function). When the goal is characterized by multiobjective or competing objectives, the utility function could be more complicated.

A. Challenging Issues for CR Design

In the following, we first discuss the interdependent nature of actions, goals, decisions, observations, and context. We then present insights into these interdependencies from game models of cognitive radio networks.

1) Network Performance Considerations: If we ignore learning processes that are not generally assumed to running while a network is active [44], the behavior of a CR network is influenced by the following factors.

- *Observations*—the measurements or metrics, e.g., power spectral densities (PSDs), collision frequency, latency, position, by which CRs gain awareness of their operational environment. Observation processes could reside on a single device or be formed through the collective behavior of many devices.
- *Available actions*—the various adaptations, e.g., power, frequency, backoff timers, multiple access techniques, to which the radio is constrained by policy, capability, and/or operational requirements.
- *Decision processes*—the algorithms that map observations to adaptations, e.g., genetic algorithms or local searches. In general, this can be considered to subsume the models used in reasoning processes such as models of the environment, radio capabilities, or network. Additionally, the decision process could reside on a single radio or conceptually span a cluster or the entire network.
- *Goals of the radios*—the objective(s) that guide the decision processes, e.g., maximize SINR, minimize device power consumption, minimize latency, maintain a connected network. These are quantified by utility functions.
- *Operational context*—the conditions in which the CR network operates, e.g., propagation environment, mission, or network topology. Note that in a multilayer CR, the adaptations of one layer could alter the operational context of the processes controlling other layers. For example, higher layer topology choices will dictate which link gains most influence the adaptations of the physical layer (PHY).

As illustrated in Table 4, varying any one of these parameters—observations (O), actions (A), decision process (D), goals (G), or context (C)—can lead to radically different outcomes even when the remaining parameters are held constant. This wide variation in outcomes can be mitigated if we utilize an omniscient centralized controller, but in practice all observations could be imperfect, and a completely centralized solution may not offer the requisite level of responsiveness when scaled to large networks. The issue of scaling indicates that some degree of decision distribution will be necessary even if some adaptations are capable of being performed in a centralized (or collaborative) manner, perhaps in individual clusters. Thus, designing cross-layer CR networks to operate under varying policy constraints, contexts, and goals while achieving desired behavior is a nontrivial task.

2) Modeling Networked Behavior: Because of the interactive nature of CR networks, game theory is an important tool for system modeling and analysis. In a traditional game model of a CR network [47], each CR represents a player, the adaptations available to each CR form the action set of its associated player, and a quantification of each CR's goal supplies the utility function for the associated player. A single iteration of adaptations by a network of CRs can then be modeled as a *normal form game* $\Gamma = \langle N, A, \{u_i\} \rangle$, where N denotes the set of players (CRs) of cardinality n and $i \in N$ specifies a particular player; A represents the adaptation space formed as

Table 4 Even With All Other Parameters Held Constant, Varying the Observations (O), Actions (A), Decision Processes (D), Goals (G), or Context (C) Can Lead to Radically Different Outcomes

			Scenario 1			Scenario 2
Observation	Parameters	O	*Interference at access point from other access points*	Parameters	O	*Interference seen by clients*
		A	Frequency (channel)		A	Frequency (channel)
		D	Lowest interference channel		D	Lowest interference channel
		G	Minimize interference		G	Minimize interference
		C	Tent city		C	Tent city
	Result		Converges to near-optimal frequency reuse pattern [48]	Result		Enters an infinite loop with probability 1 as network scales [51]
Actions	Parameters	O	SINR at cluster head	Parameters	O	SINR at cluster head
		A	*Frequency*		A	*Power*
		D	Maximize goal		D	Maximize goal
		G	Maximize SINR		G	Maximize SINR
		C	Isolated cluster		C	Isolated cluster
	Result		Network tends to converge to low interference states	Result		Network tends to converge to self-jamming states
Decisions	Parameters	O	Collisions	Parameters	O	Collisions
		A	Transmission times		A	Transmission times
		D	*Collaborate on times*		D	*Noncollaboratively choose times*
		G	Minimize collisions		G	Minimize collisions
		C	Isolated cluster		C	Isolated cluster
	Result		Rapid convergence to minimal interference state, adjustable to different user priorities	Result		Slow (if at all) convergence, throughput as low as ALOHA $(1/e)$
Goals	Parameters	O	SINR at cluster head	Parameters	O	SINR at cluster head
		A	Power		A	Power
		D	Maximize goal		D	Maximize goal
		G	*Target SINR*		G	*Maximize SINR*
		C	Isolated cluster		C	Isolated cluster
	Result		If target SINR is feasible, converges to target SINR [78]	Result		Network tends to converge to self-jamming states
Context	Parameters	O	SINR at cluster head	Parameters	O	SINR at cluster head
		A	Power		A	Power
		D	Punish (jam) radios deviating from target SINR		D	Punish (jam) radios deviating from target SINR
		G	Target SINR		G	Target SINR
		C	*Isolated cluster*		C	*Isolated cluster with a jammer*
	Result		Network overcomes defection problems for significant improvement in performance [41]	Result		Network self-jams as it "punishes" the jammer

$A = A_1 \times \cdots \times A_n$, where A_i specifies the action set of player i; $\{u_i\}$ is the set of utility functions, $u_i : A \rightarrow \mathcal{R}$, i.e., the assignment of a real number to every possible combination of choices of actions by the radios to describe the values which the radios assign to points in A. For notational convenience, we use a to denote an action vector wherein each player in the game has chosen an action a_i to refer to the action chosen by player i and a_{-i} to refer to the vector formed by considering all actions other than the action chosen by i.

This basic model can be extended by considering the specific decision rules $d_i : A \rightarrow A_i$ that guide the radios' adaptations and the decision timings T at which the decisions are implemented to form the extended modeling tuple $\langle N, A, \{u_i\}, \{d_i\}, T\rangle$ [47]. With this model, it is sometimes convenient to use $d(a)$ to refer to the collective application of $d_i(a)$ at the times specified by T. To give an intuitive feel for what we are modeling, the term "decision rule" refers to some well-defined process that controls a CR's adaptations, which has presumably been designed to increase the value of u_i with each adaptation. For example, a decision rule may specify discrete steps up or down in transmission power in response to observed channel conditions or may specify a sequence of alternate frequencies to try when interference is detected. However, some CRs are not implemented with well-defined decision rules and are instead only lightly governed by goals, policies, and available adaptations. To handle both cases, we restrict our design framework to a set of decision rules termed *autonomously rational,* which satisfy

$$b_i \in d_i(a), b_i \neq a_i \Rightarrow u_i(b_i, a_{-i}) > u_i(a_i, a_{-i}). \qquad (6)$$

A game theorist would refer to the behavior that results from the use of decision rules of this form as a *better response dynamic*. Similarly, an *exhaustive better response dynamic* occurs when all decision rules satisfy

$$a_i \notin d_i(a) \text{ if } \exists b_i \in A_i : u_i(b_i, a_{-i}) > u_i(a_i, a_{-i}). \qquad (7)$$

Interestingly, even though an exact characterization of a network's behavior depends on all the parameters in $\langle N, A, \{u_i\}, \{d_i\}, T\rangle$, we can gain powerful insights into network behavior by examining just the submodel $\Gamma = \langle N, A, \{u_i\}\rangle$, which neglects the contribution of decision rules and decision timings. For instance, if we assume that the radios are autonomously rational, then we know that Nash equilibria (NE), i.e., action vectors a^* such that $u_i(a^*) \geq u_i(b_i, a^*_{-i})$, $\forall i \in N, b_i \in A_i$, will be steady-states for the network [47]. Likewise, if we know that decision rules are exhaustive better responses, then the NE will be the only steady-states.

Similarly, proper selection of radio utility functions can also be used to guarantee network convergence and stability under very broad assumptions about the radios' decision rules. For example, when we know that Γ constitutes an exact potential game, a game for which there exists a potential function $V : A \rightarrow \mathcal{R}$ such that all utility functions satisfy

$$u_i(b_i, a_{-i}) - u_i(a_i, a_{-i}) = V(b_i, a_{-i}) - V(a_i, a_{-i}), \quad \forall i \in N, \forall a \in A \quad (8)$$

we know the network will converge as long as decision rules are autonomously rational and care is taken to ensure that adaptations are not synchronized. Likewise, we know that when Γ is a potential game, isolated steady-states will be stable as $-V$ constitutes a Lyapunov function [47]. Note that establishing this broad convergence of decision rules is a property unique to potential games [47]. With other normal form game models, only more specific decision rules can be shown to converge. For example, when a CR network can be modeled as a *supermodular game* [47], decision rules that locally optimize each adaptation (known as *best responses* in game theory parlance) will converge, but suboptimal (though autonomously rational) adaptations can become trapped in loops in a supermodular game [47].

The predictability of a network's behavior is significantly enhanced when the network's game model has a single NE, e.g., the power control s-modular games in [2]. However, as the complexity of the operating environment grows and as the extent of the cognitive radios' control increases, it becomes increasingly unlikely that a network will have a single NE. Accordingly, many game theorists focus on developing networks where i) all NE exhibit desirable performance as measured by metrics such as those discussed in Section II; ii) the network rapidly converges to NE with desirable performance [46]; and iii) the network is stable so that minor variations in the operating environment or the makeup of the network do not radically alter network behavior [50]. As with steady-states, a game theorist can also use radio utility functions to guarantee network convergence and stability under very broad assumptions about the radios' decision rules.

B. Utility Function Selection

Clearly, useful insights about the behavior of a CR network can be gleaned by examining its associated game model, particularly when the CR network can be shown to be a *potential* or supermodular game. Beyond serendipitous discovery of a function that satisfies (8), determining if a network can be modeled as a potential game requires an examination of the interrelationships between radios' utility functions. In general, for a network to be modeled as a potential game, a certain symmetry between the radios' utility functions must exist. For continuous, twice differentiable utility functions, the existence of a potential function (and thus existence of a potential game) can be established by demonstrating that (9) holds true

$$\frac{\partial^2 u_i(a)}{\partial a_i \partial a_j} = \frac{\partial^2 u_j(a)}{\partial a_i \partial a_j}, \quad \forall i, j \in N, \forall a \in A. \quad (9)$$

A similar relationship also holds true for supermodular games with action sets that are compact convex subsets of the real number line $\mathcal{R}$, as shown in

$$\frac{\partial^2 u_i(a)}{\partial a_i \partial a_j} \geq 0, \quad \forall i, j \in N, \forall a \in A. \quad (10)$$

More generally, when the radios' utility functions take on one of the forms shown in Table 5, the game is known to be a potential game. Thus if we choose utility functions for CRs to take one of those forms, we will be broadly assured that the network will be convergent and stable.

One downside to this approach is that a potential game is not guaranteed to converge to an optimal point. In fact, it would be odd if it did, as the notation of "optimal" is quite subjective. When working with a particular design objective in mind and when the broad convergence properties of a potential game are desired, the relationship between the design objective and the potential function in the third column of Table 5 should be first examined and then work backwards to the utility functions and implied observations of the second column.

Table 5 Common Exact Potential Game Forms

Game	Utility Function	Potential Function
Coordination Game	$u_i(a) = C(a)$	$V(a) = C(a)$
Dummy Game	$u_i(a) = D_i(a_{-i})$	$V(a) = c,\ c \in \mathcal{R}$
Coordination-Dummy Game	$u_i(a) = C(a) + D_i(a_{-i})$	$V(a) = C(a)$
Self-Motivated Game	$u_i(a) = S_i(a_i)$	$V(a) = \sum_{i \in N} S_i(a_i)$
Bilateral Symmetric Interaction (BSI) Game	$u_i(a) = \sum_{j \in N \setminus \{i\}} \omega_{ij}(a_i, a_j) - S_i(a_i)$, where $\omega_{ij}(a_i, a_j) = \omega_{ji}(a_j, a_i)$	$V(a) = \sum_{i \in N} \sum_{j=1}^{i-1} \omega_{ij}(a_i, a_j) - \sum_{i \in N} S_i(a_i)$
Multilateral Symmetric Interaction (MSI) Game	$u_i(a) = \sum_{S \in 2^N : i \in S} \omega_{S,i}(a_S) + D_i(a_{-i})$, where $\omega_{S,i}(a_S) = \omega_{S,j}(a_S),\ \forall i, j \in S$	$V(a) = \sum_{S \in 2^N} \omega_S(a_S)$

For example, given an arbitrary design objective $O(a)$, a potential game could be created by virtue of a coordination game wherein all radios choose their actions to maximize $O(a)$. In general, however, assigning the radios a utility function that seeks to directly optimize network-wide performance metrics requires that the radios be capable of observing network-wide performance. Thus such an approach would necessitate the additional design of some mechanism for providing this network-wide awareness, e.g., the REM [81]. Alternately, some design objectives have some inherent structure such that the utility functions can be designed to only require locally available observations. For instance, in [48], we first showed that a design objective of minimizing the sum of observed network interference levels in an 802.11 network performing dynamic frequency selection exhibits a natural pairwise symmetry to the interference terms. This permitted us to design an algorithm presented in [49], which employs utility functions that effectively correspond to the bilateral symmetric interaction game but in practice is just the radios minimizing their own observed interference levels. We have since applied similar techniques to permit the adaptation of power control, consider prioritized transmissions, and deployment in an ad-hoc network [50].

So in general the actions, observations, decision rules, utility functions, and operating context are all highly interdependent when examining the performance of a CR network. But if we start from the premise that our utility functions will satisfy the conditions of a potential game, then we can significantly relax the constraints on our decision rules. However, the assurance of convergence and stability is not accompanied by an assurance of optimality. Therefore, when adopting this approach, care must still be given to the design of the observation processes, which can depend on the choice of objective functions if we do not assume the existence of a common knowledge database such as the REM.

C. Interaction Between Metrics, Utility, and Learning

A number of CR design problems can be characterized by several noncommensurable and often competing measures of performance, or objectives. Therefore, essentially, the CR decision-making process is a multiobjective or constrained optimization problem [39], [63], [71]. Unfortunately, there is no generalizable technique for combining multiple goals, as the ideal combination of goals will be heavily dependent on context and, in particular, mission. Several techniques have been proposed for combining goals, including evaluating Pareto dominance, weighted sums of goals, products of normalized goals, or more arbitrary nonlinear transformations.

In general, when the goals of radios are combined with noninteractive performance metrics, where performance is only a function of the radio or cluster's own adaptations, e.g., device power consumption by waveform, then the convergence and stability properties of the network are frequently not affected (though network steady-states may be significantly impacted). However, other combinations can have significant effects on the behavior of the network.

Conceptually, the performance of a CR network can be improved if we permit the network to improve its performance postdeployment by refining its parameters. Models can be refined for better predictions of performance and thus better decisions; new contexts can be recognized and optimal adaptations learned. Learning can proceed by a variety of algorithms, including case-based and knowledge-based learning [84], behavioral learning (e.g., training a neural network or equalizer), and logic-based learning (e.g., induction or deduction). Each learning method has its relative strengths and limitations. Therefore, synergistic combinations of these algorithms are expected to yield better results [84]. We refer interested readers to [17] for more details about these learning techniques.

In a distributed system, learning to improve the accuracy and efficiency of observation and classification processes will generally not negatively impact system robustness. For instance, reducing the bias or variance of existing observations perhaps by better matching models to context (e.g., moving from a Rayleigh to a Rician model when a line-of-sight component is present) or by upgrading to more accurate algorithms (e.g., using a cyclostationarity approach over a simple windowed PSD for signal detection/classification) will generally lead to a system that more closely matches expected performance as observation variance has decreased. However, when learning spawns new processes, it is difficult to guarantee continued robustness of the system.

Again, this will largely not be a problem for centralized or collaborative systems where we can conceptually integrate any combination of observation, actions, decisions, goals, and contexts, but such systems might be limited in scalability, require additional overhead, and have longer response times.

IV. AN 802.22 WRAN CE TESTBED

In Sections II and III, we discussed various choices and interdependencies of performance metrics and utility functions but leave open the question of how to incorporate them in CRs and evaluate their performance. This section provides an extended case study of selecting, incorporating, and evaluating performance metrics and utility functions on a CE testbed developed at Wireless@ Virginia Tech [84]–[86]. Note that the CE testbed was designed for developing real-time radio resource management algorithms at a single 802.22 WRAN BS, which does not fully highlight the game-theoretic perspective. Nevertheless, we aim to provide readers with an interesting case study of how metrics and utilities can be incorporated into a cognitive radio system.

A. Metrics Selection

In IEEE 802.22 WRAN, the services and quality of service (QoS) requirements are quite similar to those in 802.16 WiMAX [25]. We thus consider the following metrics for the CE testbed.

1) u_1: QoS satisfaction of all connections, in terms of the average utility of all downlink and uplink connections between the BS and customer premise equipment (CPE).
2) u_2: spectral efficiency, in terms of the number of available candidate channels after allocating radio resources to a given number of connections. This metric is more important for multicell scenarios or a single cell serving a large number of CPEs.
3) u_3: power efficiency, in terms of the transmit power of individual CPEs. This metric is more important for mobile or portable user devices or overlapping WRANs.
4) u_4: adaptation time when the CE is exposed to a new scenario. Fast adaptation is critical for time-sensitive WRAN applications.

To obtain a convenient measure of the available radio resource at a BS and the requested radio resource from CPEs, a unitless metric, radio resource unit (RRU), was proposed. RRU is an abstraction from physical layer details (such as modulation/coding schemes and channel bandwidth), thus making the developed CE algorithms generic. For example, the required RRU for setting up a connection between the BS and CPE can be estimated by

$$\mathrm{RRU}_{\mathrm{req}} = (1+\alpha)\frac{R}{\beta \times \mathrm{BW}_{sc}} \tag{11}$$

where α is the overhead factor (unitless) that takes into consideration the overhead of the WRAN protocol and can be determined by the WRAN system specifications; R is the data rate of the new connection (in units of "b/s") and determined by the service type; β is the spectral efficiency (in bits/second/hertz) jointly determined by the highest applicable modulation level and channel coding rate; $\mathrm{BW}_{\mathrm{sc}}$ is the bandwidth of the WRAN orthogonal frequency-division multiplexing (OFDM) subcarrier (in hertz) as

$$\mathrm{BW}_{\mathrm{sc}} = (\text{TV Channel Bandwidth})/(\text{FFT Mode}). \tag{12}$$

For orthogonal frequency-division multiple access/time-division duplexing based WRAN, $\mathrm{RRU}_{\mathrm{req}}$ indicates the number of OFDM subcarriers that needs to be allocated.

B. Utility Function Selection

The global utility function for the WRAN CE testbed is defined as

$$u_g = \prod_i (u_i)^{\omega_i} \tag{13}$$

where ω_i is the weight applied to the ith performance metric u_i. Different weight vectors could be applied to adjust the utility function. Similar to the geometric mean, (13) accentuates low utility metrics, thus providing a fair and balanced combination of various performance metrics.

For the WRAN BS CE testbed, the global utility u_g is subdivided between individual CPE utilities (u_{cpe}) and the normalized spectral efficiency of BS (u_{BS}) as

$$u_g = \left(\prod_{i=1}^{N} u^i_{\mathrm{cpe}}\right)^{\omega_{\mathrm{cpe}}/N} \times (u_{\mathrm{BS}})^{\omega_{\mathrm{bs}}} \tag{14}$$

where N is the total number of active CPEs connected with the BS and ω_{cpe} and ω_{bs} are the weights for the geometric mean of individual CPE utilities and the spectral efficiency of the BS, respectively. The weights can be determined by the WRAN operator based on its priority and goal.

There are many candidate utility functions for defining the individual CPE utility and the spectral efficiency of the BS, as shown in Figs. 2 and 3. For the CE testbed, the individual CPE utility represents the user's degree of

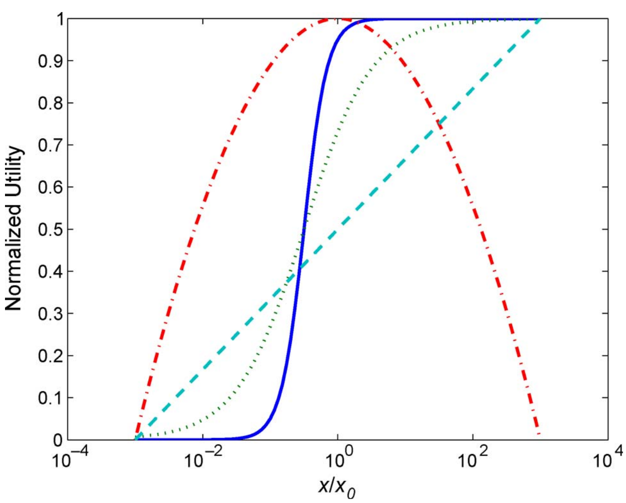

Fig. 2. *Various functions (f_i) that can be used to estimate the utility of individual CPE in the WRAN CE testbed. The one shown with a solid line was used in our experiments.*

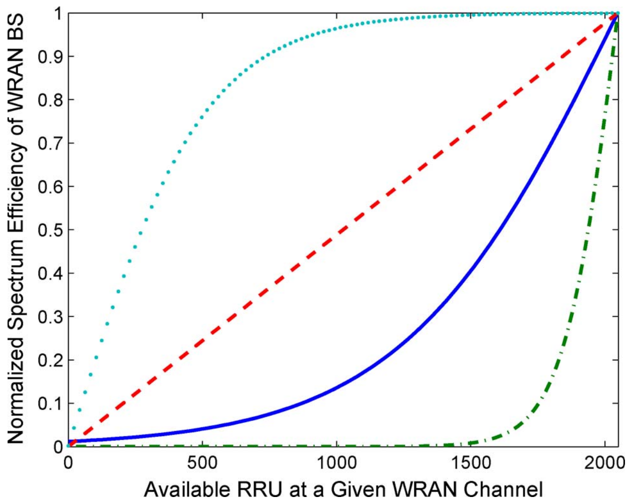

Fig. 3. ***Various BS spectral efficiency function (u^i_{BS}) that can be employed in the WRAN CE testbed. The one shown with a solid line was used in our experiments.***

satisfaction to the overall radio resource management, which is defined as

$$u_{\text{cpe}} = f_1^2\left(P_b^{-1}, P_{b0}^{-1}\right) \times f_2^2(R_b, R_0) \times f_3\left(P_t^{-1}, P_{t0}^{-1}\right) \tag{15}$$

where P_b, R_b, and P_t are the measured or estimated BER, data rate, and transmit power (linear) of the CPE, respectively; and P_{b0}, R_0, and P_{t0} are the target BER, data rate, and transmit power of the CPE, respectively. The f-functions in (15) are modified hyperbolic tangent functions

$$f_i(x, x_0; \eta_i, \sigma_i) = (1/2)\{\tanh[\log(x/x_0) - \eta_i]\sigma_i + 1\}, \quad i = 1, 2, \text{ and } 3 \tag{16}$$

where x and x_0 are the performance metric and its target value, respectively; and η and σ are the threshold and the spread parameter, respectively.[3]

The modified hyperbolic tangent function is a type of sigmoid function that can accommodate a large range of performance variations and capture the value of the service to the user quite naturally [69], [75], [84]. If a solution does not meet the target goal, the utility is decreased sharply. Since solutions that result in excessively high QoS provide little value to the user, the increase of utility is marginal. As can be seen from Fig. 2, the employed utility function in CE testbed is monotonic and bounded by zero and one. The threshold (η) and spread parameter (σ) are chosen such that i) the utility is 0.95 when the metric (x) achieves the target (x_0) and ii) the utility is 0.05 when the metric is one decade away.

The normalized BS spectral efficiency (u_{BS}) is defined as

$$u_{\text{BS}} = \frac{1}{M}\sum_{i=1}^{M} u_{\text{BS}}^i \tag{17}$$

where M is the total number of channels supported by the BS; and u^i_{BS} is the spectral efficiency for the ith WRAN channel and also indicates radio resource utilization of this channel. For the CE testbed, u^i_{BS} is defined as

$$u_{\text{BS}}^i = 1 + \tanh[(\text{RRU}_a - \text{RRU}_c)/\sigma_{\text{RRU}}] \tag{18}$$

where the RRU_a is the number of available RRU for the ith WRAN channel at the BS; RRU_c is the maximal number of available subcarriers of a WRAN channel; and σ_{RRU} is spread parameter for the modified hyperbolic function. u^i_{BS} is also monotonic and bounded by zero and one, as shown in Fig. 3. The rationale to adopt such a modified hyperbolic tangent function (18) is that it helps the CE to squeeze the spectrum used by the WRAN BS through the optimization process. For example, the solution will produce a lower BS utility (u_{BS}) if the CPEs are assigned to subcarriers spread into two or more WRAN channels, as compared to the more spectral efficient solution, in which the CPEs are assigned to subcarriers within the same WRAN channel.

C. CE Performance Evaluation Methodology

As discussed, CE performance evaluation is very challenging for CR developers, equipment vendors, and regulators because CR operates very differently from traditional radios due to its flexibility, learning capabilities, and the demanding or unpredictable operation environments. There is a compelling need for new testing methodologies for CE under various radio scenarios. We believe that the most accurate predictor of the future performance of CR is to emulate it in a similar situation, not unlike the behavior-based interview.

We propose REM-based radio scenario-driven testing (REM-SDT) as a generic approach to evaluating the CE performance [84], [85], as illustrated in Fig. 4. The REM could also be used as a virtual "radio environment generator" together with other test equipment, such as arbitrary waveform generators. The CR under test is subjected to various realistic situations stored in the REM, which could be in form of machine-readable XML files.

[3]Here x refers to a generic variable, which can represent metrics P_b, R_b, and P_t in (15). From the early discussions, we can see that the metrics u_1 (QoS), u_2 (spectral efficiency), and u_3 (power efficiency) have been considered *jointly* to determine the global utility achieved by the WRAN CE, while u_4 (adaptation time) is employed as a stand-alone metric for benchmarking different CE algorithms in this example.

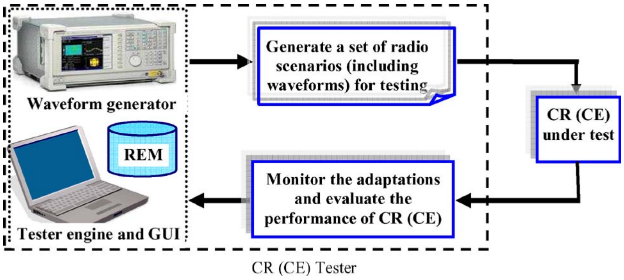

Fig. 4. *Illustration of REM-SDT. CR tester can be viewed as a CR as well.*

One way to generate sufficient testing scenarios is to exploit the REM and apply the Monte Carlo simulation method to produce a large amount of testing scenarios. For example, the CR tester could emulate various PU waveforms with certain usage patterns in certain frequency bands and then measure the performance of the CR under test through its RF emission. This can indicate the cognition levels and the effects of its adaptations. The CR tester can benchmark the performance of the CE under test against that of some baseline CR systems or some performance bounds.

D. CE Testbed Experiment Results

Simulation parameters for the WRAN BS CE testbed are summarized in Table 6. The CE testbed can run different learning algorithms such as local search (LS), genetic algorithm (GA), and REM-enabled case- and knowledge-based learning algorithm (REM-CKL) (see [84] and [86] for details). The CE makes decisions on which TV channel(s) to use, which modulation and coding scheme to be employed by the BS and CPE, the transmit power level of the BS and CPE, and the number of sub-carriers allocated for each connection.

We employ REM-SDT to evaluate the performance of the WRAN CE through a series of test scenarios described in XML files [84]. Note that not only the typical radio scenarios but also extreme scenarios (e.g., the number of active CPEs exceeds the normal capacity of the BS) should be considered when testing the WRAN CE. It turns out to be a cost-efficient testing approach since possible problems can be identified before the CE is deployed in the real network.

In the simulations, a number of new connections are added to the WRAN BS CE testbed, and 25 runs are conducted for each scenario. Note that both GA-based CE and CKL-based CE have been implemented in conjunction with a local search for fine-tuning the final solution. As can be seen from Fig. 5, the WRAN BS CE adapts much faster when using the CKL algorithm than when using the GA, especially under complicated situations. Fast adaptation is critical for time-sensitive WRAN applications, such as evacuating a TV channel for PUs. Fig. 6 shows that the GA-based WRAN CE can produce a consistently better average utility than the LS-based CE or CKL-based CE. It also indicates that the LS and CKL may simply not be able to find a viable solution under some extreme radio scenarios (e.g., when the required RRU from CPEs approaches the capacity limit of a WRAN BS). This is because GA is a generic search and optimization tool that is independent from or insensitive to the specific radio scenario and/or utility function in use. However, the rules and experience employed in CKL may only be useful for closely matched situations with the similar utility function. The case library and knowledge base may need to be updated accordingly when the utility function of CE changes.

Table 6 Simulation Parameters for the WRAN BS CE Testbed

Parameter	Value or Range
No. of BSs	1
Cell Radius	33 km
No. of New Connections	$1 \sim 196$
Distribution of CPEs	Random uniformly distributed or clustered
Types of Service Requested from CPEs and QoS (Target BER)	Voice: 10 kbps, target BER: 10^{-2} Video: 100 kbps, target BER: 10^{-3} Low Data Rate: 250 kbps, target BER: 10^{-6} High Data Rate: 750 kbps, target BER: 10^{-6}
Channel Model	AWGN channel
Multiplexing/Duplexing	OFDMA/TDD (downlink to uplink ratio 3:1)
FFT Mode	2,048 (2,048 sub-carriers per WRAN channel)
(TV) Channel BW	6 MHz
Max. No. WRAN Channels Supported at the BS	8
Protocol Overhead (α)	0.1
RRU_c	2048
σ_{RRU}	800
Weight Vector	$[\omega_{cpe}, \omega_{bs}]$=[0.9, 0.1]

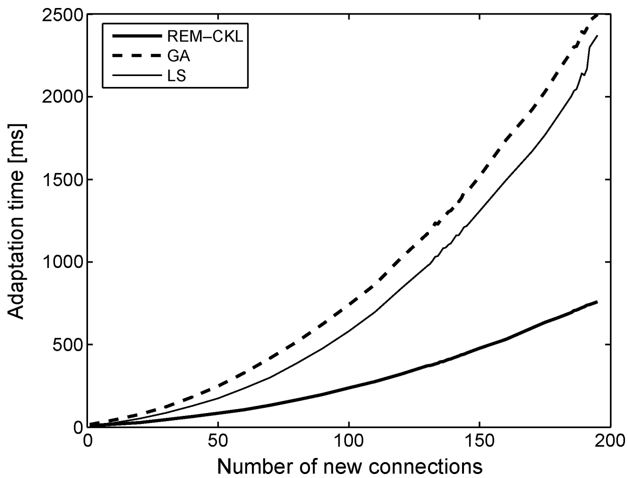

Fig. 5. ***Average adaptation time [84]. By leveraging the REM, the adaptation time of WRAN CE can be greatly reduced.***

Our experiments with the CE testbed also show that the selection of global utility function (geometric mean versus sample average) has a significant impact on the achieved performance of CR network nodes: when the sample average is maximized, the geometric mean might be very low due to the large deviation of individual utilities. It also indicates that the impact of using different global utility functions would be more apparent for a CR network consisting of a small number of nodes. For the CE testbed, the reason to choose geometric mean for the global utility is to provide "fairness" in QoS satisfaction for every CPE regardless of its location in the WRAN service area, since the CPEs might be sparsely distributed in a very large area with the cell radius up to 100 km.

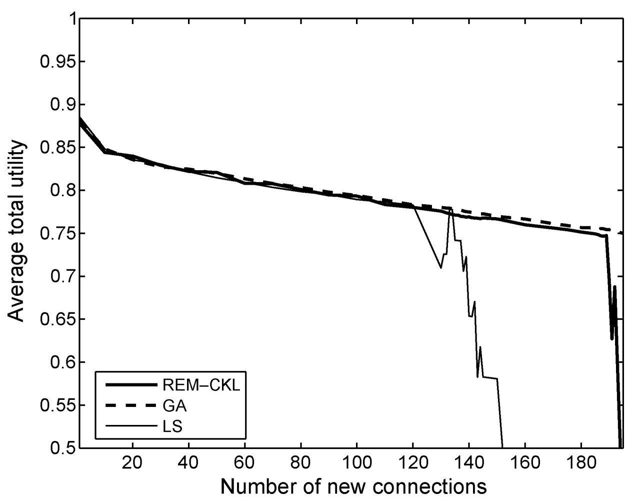

Fig. 6. ***Average total utility [84]. The REM-CKL closely approximates the performance of the more complex GA solution.***

V. CONCLUDING REMARKS

CR is an emerging research area that requires interdisciplinary collaboration and an overhaul of wireless systems design, performance evaluation, network operation, and regulation. While the exact definition of CR is still under debate, CR performance evaluation is an open question. Based on our CR research and development experience, we believe that formalizing CR performance metrics and benchmarking methods will greatly advance the CR research and development. To evaluate the performance of CR for various purposes, a broad spectrum of performance metrics at different levels could be employed, ranging from node-level to network-level and application-level.

This paper also illustrated potential difficulties in translating performance metrics into the utility functions that guide CR adaptations. We saw where varying the choice of observation processes, available actions, decision processes, goals, or operating context can lead to radically different network behavior. We saw that a game model of a CR network enables us to identify network steady-states even when decision processes are not well defined. We also saw that when utility functions are designed to have symmetrical relationships between the radios, network convergence and/or stability can be guaranteed for a broad range of conditions, though optimality is a harder and more subjective condition to satisfy.

For CR, the cognition capability relies on dynamically choosing the proper performance metrics and updating utility functions for decision making and learning. REM-based scenario-driven CR testing was proposed as a promising approach to CR emulation and benchmarking. Most CR network simulations require involvement at both the PHY and higher layers. However, the commonly used wireless network simulation tools are mostly designed for traditional wireless network simulation and mainly focused on layer-2 and layer-3. It is critical to incorporate faithful PHY models into these tools (or to improve their existing PHY models) without greatly increasing the code complexity and simulation execution time. How to make tradeoffs among CR network simulation fidelity (for various layers), reliability, and complexity as well as incorporating the dynamic environmental information is a challenging issue. The performance metrics and utility functions employed in the studied WRAN CE testbed were defined in a heuristic manner. Alternate metrics or refined utility functions that can improve achievable performance of a WRAN merits further research. Other interesting research issues include i) development of a generic CR network simulation and testing tool (perhaps based on the REM-SDT approach); ii) standardization of the performance metrics and benchmarking methods for specific CR networks; and iii) applying game theory to coexisting 802.22 WRAN networks operated by different service providers, where multiple BS share the spectrum and make interactive decisions. ■

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