INVITED PAPER

Cognitive Radio Architecture Evolution

Systems for automatic selection of radio bands and operating modes are evolving to meet user needs at specific times and places.

By Joseph Mitola, III, *Senior Member IEEE*

ABSTRACT | The radio research community has aggressively embraced cognitive radio for dynamic radio spectrum management to enhance spectrum usage, e.g., in ISM bands and as secondary users in unused TV bands, but the needs of the mobile wireless user have not been addressed as thoroughly on the question of high quality of information (QoI) as a function of place, time, and social setting (e.g. commuting, shopping, or in need of medical assistance). This paper considers the evolution of cognitive radio architecture (CRA) in the context of motivating use cases such as public safety and sentient spaces to characterize CRA with an interdisciplinary perspective where machine perception in visual, acoustic, speech, and natural language text domains provide cues to the automatic detection of stereotypical situations, enabling radio nodes to select from among radio bands and modes more intelligently and enabling cognitive wireless networks to deliver higher QoI within social and technical constraints, made more cost effective via embedded and distributed computational intelligence.

KEYWORDS | Architecture; cognitive radio; quality of information (QoI); software defined radio (SDR)

I. INTRODUCTION

When introduced in 1998–1999 [1], [2], cognitive radio emphasized enhanced quality of information (QoI) for the user, with spectrum agility framed as a means to an end and not as an end in itself. The first research prototype cognitive radio (CR1), for example, learned to turn on Bluetooth to exchange business cards wirelessly when the user's speech dialog—sensed via (simulated) speech recognition—exhibited the characteristics of a prototypical setting of "introductions," meeting new people. This intelligent agent embedded in the personal digital assistant (PDA) was unique in that it had not been programmed to do this, but rather learned this behavior via case-based reasoning (CBR) from its user's prior manual exchange of electronic business cards. CR1 associated the user's prior manual use of the PDA's Bluetooth radio to exchange business cards with cues in the speech domain such as phrases like, "May I introduce," and "Very pleased to meet you." CR1 thus synthesized a CBR template to [<Power-up Bluetooth/>, <Exchange Business-cards/>, <Power-down Bluetooth/>] autonomously and could learn by being told (not via rules previously programmed into it) etiquettes for sharing radio spectrum with legacy radios. Intelligent agents like CR1 observe the environment in which they are embedded in order to learn to formulate plans and execute actions that respond intelligently to the user in the environment. These early contributions stimulated many ideas for cooperative spectrum sharing [3], capturing the imagination.

During the past five years, the world's radio research and engineering communities have been developing software defined radio (SDR) and cognitive radio (CR) for dynamic radio spectrum sensing, access, and sharing [4]–[6], revealing many regulatory, business, market, and open architecture needs implicit in the broad potential that cognitive radio architecture (CRA) introduces[1] [7]. Radio architectures—from wearable nodes and radio access points to the larger converged networks—have evolved from the niche market of single-band single-mode car phones of the 1970s to today's ubiquitous multiband-multimode fashion statements. This paper characterizes architecture evolution, including the near-term multimedia heterogeneous networks that converge traditional cellular architectures with Internet hot spots. This paper also

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The author is with the Charles V. Schafer Schools of Engineering and Science and the School of Systems and Enterprises, Stevens Institute of Technology, Hoboken, NJ 07030 USA (e-mail: jmitola@stevens.edu).

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[1]See www.sdrforum.org/CRWG.

looks ahead towards the establishment of sentient spaces [8]–[10], integrated wireless environments that merge wireless technologies with increasing interplay of radio engineering with related information services of computer vision [11] and human language technologies (HLTs) [12].

II. ORGANIZATION

This paper first reviews the concept of architecture in Section III, including prototypical architectures for dynamic spectrum and embedded agents. It then describes the apparent lack of a comprehensive metalevel architecture for distributed heterogeneous networks and their related metalevel superstructures, including regulatory rule-making and spectrum auctions. Section IV characterizes the changes in use case that drive wireless architecture, showing how the historically significant striving for ubiquity and high data rate is beginning to give way to evolved value propositions in which appropriately high quality of service (QoS) is merely the starting point for QoI. Section V therefore develops the potential for greater integration of cross-discipline information sources like video surveillance and human language technology in future cognitive radio architectures. To help guide this evolution, QoI is characterized along its several dimensions in Section VI, while Section VII offers a review of challenges and opportunities before the conclusion of Section VIII.

III. COGNITIVE RADIO ARCHITECTURES

Radio architecture is a framework by which evolving families of components may be integrated into an evolving sequence of designs that synthesize specified functions within specified constraints (design rules) [13]. A powerful architecture facilitates rapid, cost-effective product and service evolution. An open architecture is available to the public, while a proprietary architecture is the private intellectual property of an organization, government entity, or nonpublic consortium. Fig. 1 illustrates functional components integrated to create an SDR device, which may be wearable, mobile, or a radio access point in a larger network.

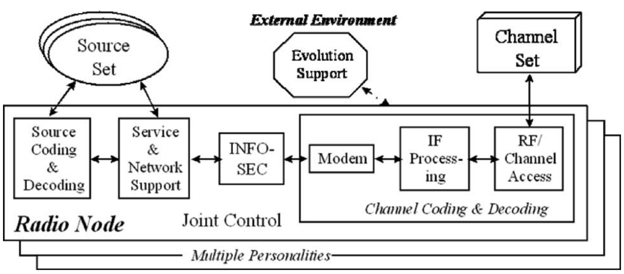

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Fig. 1. *Set theoretic model of SDR architecture [14].*

The set of information sources of Fig. 1 includes speech, text, Internet access, and multimedia content. Today's commercial radio-frequency (RF) channel sets have typically four chip sets [GSM 900, GSM1800, code-division multiple access (CDMA), and Bluetooth, for example], evolving in the near term to a dozen band-mode combinations with smart antennas and multiple-input multiple-output (MIMO) emerging [15]. In addition, a channel-set may include a cable interface to the public switched telephone network (PSTN) (IP or SDH) as well as a radio access point. Any functions may be null in any realization, eliminating the related components and interfaces from a given product for product tailoring and incremental evolution.

With the continued progress of Moore's law, increasingly large fractions of such functionality are synthesized in chipsets with software-definable parameters; in the field-modifiable firmware of field-programmable gate arrays (FPGAs); in software for niche instruction set architectures (e.g., digital signal-processing chips); and increasingly on blade server(s) and single-chip arrays of general-purpose processors like IMEC Belgium's SIMD4 [16].

Today's SDRs often are synthesized from reusable code bases of millions of lines of code [17], the deployment, management, and maintenance of which poses configuration challenges. The SDR software typically is organized as radio applications objects layered upon standard infrastructure software objects for distributed processing such as the SDR Forum's software communications architecture (SCA),[2] which originally was based primarily on CORBA[3] [18]. The Object Management Group's evolved SCA has a platform independent model with platform specific models for software-based communications.[4] Infrastructure layers of such architectures are illustrated in the larger context of Fig. 2. Prior to circa 2005, such architecture was overkill for handsets, but radio access networks have grown to millions of lines of code consisting of the kinds of software objects with the types of layering illustrated in the figure, and now applicable to handsets and systems on chip (SoC). As Mähönen (RWTH, Aachen, Germany) was among the first to clearly differentiate [19], software radio and cognitive radio are "interlinked and are family members, but they also have distinctive roadmaps" as the evolution of cognitive radio architecture illustrates. Again from Mähönen, "There are still formidable hardware and algorithm development problems (such as AD/DA-converters ...) before full (ideal) all-in-one software radio can be built." However, "the basic paradigm in the cognitive radios is to provide technologies, which enable radio to

[2]See www.sdrforum.org and www.jtrsjpeo.gov.

[3]www.omg.org/corba.

[4]The development of the SDR Forum's SCA was sponsored in 1996 by the Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force towards an industry standard open architecture for SPEAKeasy II evolving to the Joint Tactical Radio System (JTRS) in 1997; as of May 2008, the JTRS program configuration-managed the U.S. Department of Defense configuration of the SDR Forum's SCA.

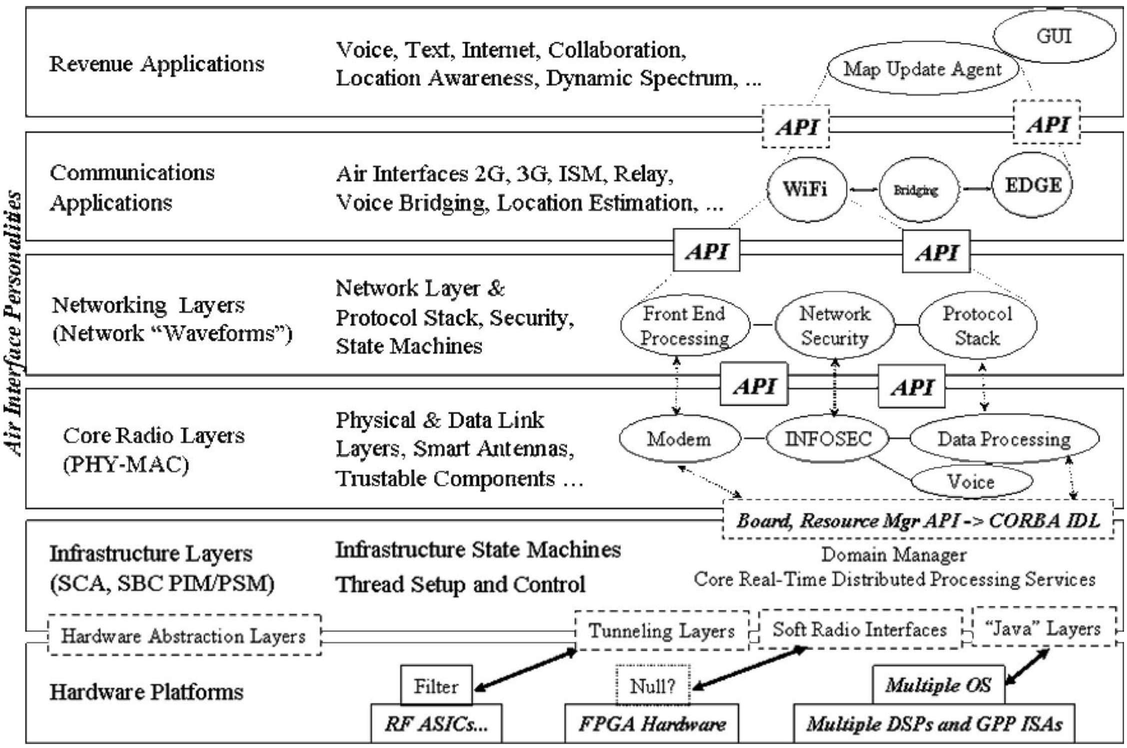

Fig. 2. *Software complexity of wireless devices and infrastructure leads to object and API layering [13].*

reason about its resources, constraints, and be aware of users/operators' requirements and context."

What are the resources and constraints? Arguably since the early 1900s, conventional radio architecture has been constrained by government regulatory frameworks accurately characterized as lanes in the road: bands large and small allocated to specific uses, in the public interest. That regulatory regime addressed the public interest within the constraining economics of radio devices and related infrastructure (such as large, expensive television broadcast towers). This was economically efficient (arguably Pareto efficient) from the "transistor radio" and television era to the deployment of first- and second-generation cellular radio. However, today's low-cost multiband multimode wearable wireless fashion statements; the proliferation of cellular infrastructure; the gigabit per second core IP networks; and wireless local-area network (WLAN) consumer products have proliferated wireless access points of all sorts in the home, workplace, and, seemingly, just about everyplace else in developed economies. The new wireless ubiquity and heterogeneity offers rapidly emerging alternatives to the lanes in the road that include dynamic spectrum access.

A. Dynamic Spectrum Access

Briefly, dynamic spectrum access is the process of increasing spectrum efficiency via the real-time adjustment of radio resources, e.g., via a process of local spectrum sensing, probing, and the autonomous establishment of local wireless connections among cognitive nodes and networks. As originally proposed, cognitive radio envisioned real-time spectrum auctions among diverse constituencies, using for one purpose, such as cellular radio, spectrum allocated and in use for another purpose, such as public safety, and vice versa, in order to multiply the number of radio access points for public safety and to more efficiently use public safety spectrum commercially during peak periods [1]. Although that initial example has yet to be fully realized, the U.S. Federal Communications Commission encouraged the application of that technology to the secondary use of underutilized television spectrum, such as in an ad hoc, short-range WLAN in spectrum that is allocated to another primary purpose, such as broadcast television. In addition, the principles of cognitive radio for dynamic spectrum also apply to enhance the efficiency of use within and across each "lane in the road," such as via the intelligent selection among multiple alternative physical (PHY) media access control (MAC) layers (alternative lanes in the spectrum road) by cognition across network, transport, and application layers of the protocol stack [20]. Researchers characterize the advantages of short-term localized dynamic spectrum auctions [21], [22], including rigorous and comprehensive treatments in the European Community (EC)'s precompetitive End to End Reconfigurability program [23]. In spite of commercial proposals [24], only long-term large-capacity anonymous leasing appears to be established in the marketplace.[5]

The endorsement of the FCC for cognitive radio in secondary markets offered opportunities for improved spectrum utilization [25]. In addition, the National Institute of Information and Communications Technology (NICT), Yokosuka, Japan, have characterized SDR and cognitive radio from technical [26], [27] and regulatory [28] perspectives. Ofcom, the regulatory body of the United Kingdom, remains appropriately skeptical of the economics of dynamic spectrum [29]. On the other hand, the Commission for Communications Regulation, Ireland, imposes constraints [30] but also encourages innovation such as by allocating over 100 MHz of spectrum for experiments and demonstrations during the IEEE Dynamic Spectrum (DySPAN) Conference in 2007 in Dublin. Guatemala[6] employs Titulos de Usurfrucato de Frecuencias, specifying spectrum use parameters in great detail, which establishes a strong reference point for the liberalization of spectrum allocation towards dynamics [31]. In Europe, countries including Austria, Sweden, and the United Kingdom apparently have sanctioned de facto transfers of spectrum rights among spectrum licensees, while a recent EU Framework Directive empowers all European Commission countries to introduce secondary trading of spectrum usage rights [18].

The SDR Forum's CR working group (CRWG) and the inclusion of CR in its annual academic challenge promotes the global interchange among academic research and industry development of cognitive radio in SDR.[7] DARPA's XG program [32], [33] put substantial emphasis on the near-term potential of smart radios to share the radio spectrum dynamically, leading, among other things, to the success of the IEEE Dynamic Spectrum (DySPAN) conferences in 2005 and 2007, where XG research results were demonstrated [34]. XG simplified the ideal cognitive radio architecture (iCRA [35]) to a simple rule-engine that controls the radio's air interfaces to conform to spectrum use policies expressed in a rule-based policy language. This yields a simple, flexible, near-term dynamic spectrum access (DSA) architecture clearly articulated by Haykin [36].

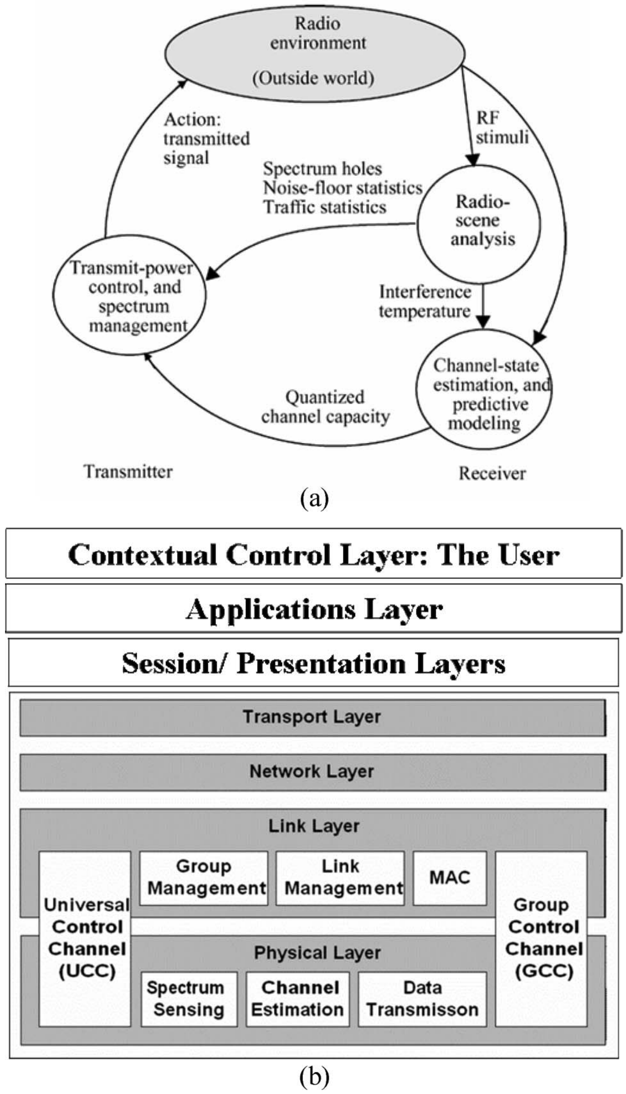

Fig. 3. *Haykin DSA architecture. (a) DSA architecture and (b) implications.*

B. The Haykin Dynamic Spectrum Access (DSA) Architecture

The ubiquity of wireless today is more of a fact than a goal even in many developing economies. In most developed economies, evolved GSM and CDMA networks are both competing and cooperating with an Internet gone wireless for the revenue from voice and Internet traffic, with voice over Internet Protocol (VoIP) growing.

Integral to this evolution is the potential for some adjustment to the protocol stack. As illustrated in Fig. 3(a), Haykin's DSA emphasizes the need for cognitive radio to be aware of the many occupants of a radio environment by analyzing the radio scene to avoid interference, to operate in spectrum holes, and to provide channel state information that enhances the transmission. One implication for the protocol stack is the integration of cognitive nodes into cognitive networks via the universal control channel of some sort, as shown in Fig. 3(b), supplemented by group control channels. Spectrum sensing emerges in this architecture as the key enabler for greater agility in the use of spectrum for best possible QoS. Such a cognitive radio can quantify channel occupancy and identify opportunities for RF chip set selection, signal in space transmission control [37], and other high-performance spectrum management features in the physical layer such as MIMO operation.

[5] See www.cantor.com/sales_trading.
[6] http://www.itu.int/osg/spu/ni/spectrum/.
[7] www.sdrforum.org.

C. The ideal CRA (iCRA)

Self-awareness, user awareness, and machine learning differentiate what has become known as the ideal cognitive radio architecture [2] from the DSA. The cognition cycle developed for the research prototype cognitive radio CR1 [2] is shown in Fig. 4. This cycle implements the full embedded agent and sensory perception capabilities required of an iCR, differentiating proactive planning from reactive behaviors and learning. Sensory stimuli enter the cycle via sensory perception (e.g., RF, location, motion, temperature, vision, speech, etc.). Object-level change detection initiates the cognition cycle.

Such an iCR continually observes (senses and perceives) the environment; orients itself; creates plans; makes decisions on its own and in conjunction with the user and external networks; and then acts. Actions may be physical, such as transmitting a signal, or virtual, such as associating a user's action with the current situation. The iCR may observe user actions (e.g., via keystroke capture) to form a macrosequence to be applied in similar situations, such as searching for wireless business card when introductions are detected via voice in some future setting. Actions of intelligent agents include movement in the environment in order to improve the likelihood of achieving a goal. Early planning systems used rule bases to solve simple planning problems like the monkey and the bananas [38], stimulating the development of an entire subculture of planning technologies now integrated into a broad range of applications from factory automation to autonomous vehicles [39] and RoboCup Soccer [40], integrating learning with planning [41]. These planning technologies apply to radio domains for further architecture evolution.

The processes illustrated in the figure are called the wake epoch because the reasoning components react to changes in the environment. The iCR might analyze speech or text of radio broadcasts, e.g., checking the weather channel, stock ticker tapes, etc., for changes of interest to the user. Any RF-LAN or other short-range wireless broadcasts that provide environment awareness information may be also analyzed for relevance to the user's needs inferred by the iCR via machine learning, e.g., assisted via a library of behavior stereotypes. In the observation phase, a CR also reads location, temperature, light level sensors, etc., to infer the user's communications context. Since the iCRA was based on agent technology, it leverages the continuing advances in Agent Communications Language, the Java Agent Development Environment,[8] and multiagent systems [42]. During the wake epoch, the detection of a significant change such as the presence of a new radio network in the RF domain or of a new physical object in a visual scene, or the detection of a topic in the speech domain, initiates a new cognition cycle. For example, IMEC Belgium developed low-power burst signal detection and presynchronization techniques to characterize changes in the RF scene [43].

Sleep epochs allow for computationally intensive pattern analyses, self-organization, and autonomous learning. A prayer epoch during sleep provides autonomous interaction with higher authorities such as cognitive networks and regulatory authorities for constraints, advice, and solutions to problems unavailable locally.

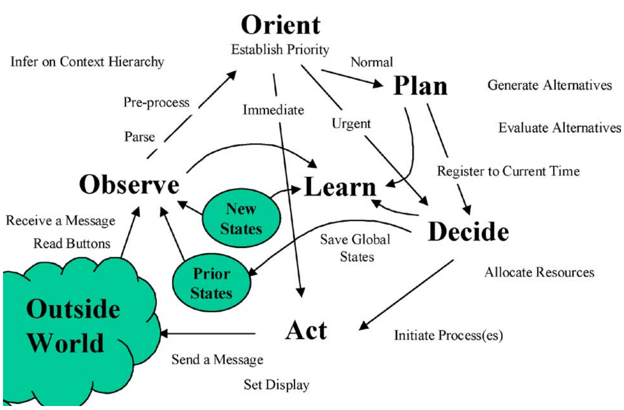

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Fig. 4. ***Ideal cognition cycle: Observe-Orient-Plan-Decide-Act-Learn (OOPDAL) of the iCRA embeds self-awareness, user awareness, and RF awareness for QoS and QoI.***

D. Networking and CRA Evolution

Unfortunately, neither the DSA nor the iCRA provide a comprehensive architecture for cognitive wireless networks (CWNs).[9] At the Dagstuhl workshop in 2003, a consensus emerged that CWN significantly expands the research framework and architecture evolution possibilities to a mix of ad hoc and fixed wireless networks with self-awareness and greater spectrum efficiency; to mobile device awareness; to substantial memory-in-the-network [44]; and to distributed machine learning [45]. The DSA and iCRA per se do not provide such a rich research and development framework for legacy and cognitive devices and heterogeneous networks with regulatory policy constraints. In addition, without a supportive distributed network architecture, policy language, and methods of payment, short-term real-time spectrum auctions over small geographic areas seem unlikely to emerge, in spite of much research (e.g., [36], [46]) and position papers before regulatory bodies [47].

Fitzek (Aalborg University) and Katz (Samsung) bring together ideas for CWN CRA characterized by cooperation among intelligent entities [3]. Cooperation results from not just game theoretic considerations [48] but also from considerations of power optimization [49], [49]; relays [51] and ad-hoc discovery and routing [52]; diversity [53]; cross-layer optimization [54]; stability and security [55], [56]; and spectrum efficiency considerations [44]. Distributed

[8] Avalon.tilab.com.

[9] Mahonen formulated this concept at the Dagstuhl Workshop.

antennas [57], [58], cooperative header compression [59] and coding [60], and distributed spatial channel control [61], among others, result from such a focus on cooperation in cognitive wireless networks.

Mahmoud (Canada), similarly, brings together ideas for CRA migration towards self-awareness [62]. In this context, researchers at Osaka University, Japan, point out that biological systems from molecular processes and immune systems and from social insects to predator–prey relationships exhibit robustness in the face of catastrophe, a property desired in communications networks. Architectural properties of such biological systems include (group) membership perception, network awareness, buffer management (pheromone decay), and message filtering [63]. Also in this context, Strassner and his group in Waterford, Ireland, report a refined autonomic network architecture, in some sense a distributed networked version of the iCRA [64]. Strassner makes a strong case for cognitive network architecture to address network semantics more completely, using the Border Gateway Protocol[10] as a motivating example. There is no lingua franca for networking that bridges vendor-specific syntax and semantics, modalities, functions, and side-effects, as Strassner dramatically illustrates. He shows the potential contributions of autonomic networking in future cognitive networks via a framework of (user) experience and (wireless and wire line) connectivity architectures with FOCALE [65]. Although there have been many research investigations into the role of semantic Web technologies in CRA evolution [66], [67], none as yet appears to address Strassner's key issues in a sufficiently intuitive, computationally feasible, compact, and efficient way as to have become widely adopted. In part because of the shortfalls of the XML and semantic Web technologies alone, the IEEE 802.21 and P1900.5 standards committees are pursuing behavior modeling of cognitive radio nodes and networks in their policy language deliberations [68].

In addition, Manoj *et al.*'s cognition plane organizes cross-layer reasoning of a joint layer optimization module by placing cognition and control modules in the PHY, MAC, network, transport, and applications layers. The cross-layer cognition bus applies the Observe, Orient, Decide, and Act loop of the iCRA with get/set access to the networks to bypass intervening layers, such as direct linkage from the application to the MAC, e.g., analyzing the MAC layer to avoid default wireless channels during congestion. This CogNet AP can, for example, identify a preferred channel based on expected traffic during any hour of the weekday. They analyze Neel's game-theoretic treatment of cognitive networks [69] to characterize challenges of sustaining Nash equilibriums in myopic, s-modular games and potential games, showing how potential games may be realized in practice. In spite of such promising work, apparently as yet there is no widely accepted comprehensive architecture (functions, components, and design rules) within which the potential for fair, stable dynamic spectrum (potentially including microscale space-time-RF auctions) is being realized in the marketplace in spite of positive regulatory rule making. A deeper understanding of the related technical, social, and economic factors seems to be an important open metalevel issue for CRA evolution.

[10] www.ietf.org/rfc/rfc1772.txt.

Clearly, the Haykin DSA, cooperative and self-aware networks research, and cross-layer cognition provide crucial foundations for cognitive radio architecture evolution. Where power management remains important, simplifications of the DSA bring cognitive behavior in the RF domain closer to practice. The pace with which systems evolve from the practical focus of the current architectures to address the larger issues may be driven by evolved use cases.

IV. ARCHITECTURE EVOLUTION AND USE CASE EVOLUTION

Commercial wireless use cases continue to evolve. The use cases that have captured market share and propelled radio engineering to its current levels of success have been based on the proliferation of cellular wireless networks on the one hand and the affordability of fiber-optic core networks and short-range WLAN of the Internet on the other. Ubiquity has brought with it a shift of use case from mere ubiquity towards affordable differentiated multimedia services in purely commercial markets as well as greater integration of historically distinct market segments such as commercial and public safety wireless, e.g., Block D in the U.S. 700 MHz wireless auctions. Block D challenges have been characterized by the SDR Forum [70] as "meeting the divergent needs of commercial and public safety users, coverage, shared operational control, robustness, adaptability, and spectrum use in the absence of network buildout." Such public commentary reflects an evolution of use case that drives wireless architectures from the relatively monolithic cellular radio networks with gateways to the PSTN towards greater integration with the Internet, as characterized in Table 1.

The lines of Table 1 without italics have been well established during the past few years and thus need little elaboration, but set the stage for the more speculative use case projections in italics.

1) Product Differentiation: With ubiquity in developed economies, wireless service providers have suffered profit erosion and are beginning to compete for multimedia services integration across the broad domains of personal information (voice, text, personal games, Internet access, and e-mail) and entertainment (digital radio and TV broadcast, network games, and Internet broadcast modalities like YouTube and MySpace), with many forms of infotainment taking shape. Wireless has been both a

Table 1 Wireless Use Case Parameters Drive Radio Architecture Evolution

Use Case Parameters	Foundation era (1990-2005)	Evolution era (2005-2020)
Core wireless use cases	Towards ubiquitous access	Towards integrated services
Profit margins	High (handsets-infrastructure) then handset profits declining	Low (handsets-infrastructure) to high for differentiated services
Value proposition	***QoS (Connectivity, data rate)***	***QoI (User is the 8th OSI layer)***
PSTN integration	SS7[81], SDH[82]	IP-SIP [83], Mobile IP, or IPv6[84]
Reconfigurable HW	***Not worth the cost vs chipset***	***Transitioning to mainstream?***
Location awareness	Niche applications	Ubiquitous
Multimedia	***Infeasible to feasible***	***Strong differentiator***
Spectrum awareness	Within allocated band	Across multiple bands
Spectrum Auctions	***Large blocks for long term***	***Small space-time holes short term***
Public safety	Distinct markets	Integration with agility
Data rate framework	***Stationary, walking, vehicle***	***Hot spot, traveling, emergency***
Sentient Spaces	***Video surveillance markets***	***Elder care and home robotics***

perpetrator and a beneficiary of the infotainment megatrends. To remain relevant, cognitive radio architectures must make it easier (and more affordable) for the service provider to deliver highly user-specific (differentiated) services whether at home, at work, traveling, or on holiday. This need, along with other factors, tends to drive the CRA from today's DSA's towards greater use of technical parameter profiles that are tailored to each particular user's infotainment practices, e.g., learned by a recommender system embedded in the radio [75]. In fact, semantic Web technologies[11] are making it increasingly easy to represent computationally and reason with ever more subtle and sophisticated aspects of the needs, habits, and preferences of individual users. This leads one to postulate an emerging value proposition founded on QoS, but expanded to reflect ubiquitously high QoS across service providers with QoI as an increasingly central driver of wireless architecture evolution.

2) Protocol Stacks: Although asynchronous transfer mode [76] established transport efficiency with predictable QoS for its high value in core networks of the foundational era, IP seems to be the ultimate beneficiary of efficiency and QoS in the era of network convergence. This applies both in the current transitional patchwork of IP with network address translation (NAT), VoIP via session initiation protocol, and, in the longer term, towards IPv6 perhaps. This expectation sets some characteristics of the networking layers of the protocol stacks of handsets, vehicular radios, and radio access network infrastructure, and thus of CRA evolution as well.

3) OA&M: Self-awareness is not evident in the DSA, but the costs of operations, administration, and maintenance are moving self-awareness for autonomous configuration management towards center stage in the EC's End to End Efficiency (E3) wireless initiative [77], [78]. Self-awareness and self-examination properties of agent-based evolved CRAs may help address the challenges of configuring software stacks for mobile device and infrastructure releases, as well as offer additional protection from inadvertent misconfiguration. The iCRA incorporates the necessary self-awareness, and its mathematical theory [11] draws on Gödel theory to establish the basis in computability for the self-referential but computationally stable self-examination. Thus, the DSA provides an appropriately simplified transitional architecture that is now beginning to evolve towards the iCRA's promise of autonomous OA&M.

4) Location Awareness: A microcosm of evolution from QoS to QoI has occurred in location-based services. During the early foundational era, location seemed to be potentially useful, but did not rise to the status of "killer app" on its own. Government mandates for ~150 m accurate location information for the delivery of emergency services to cell phone users helped to transition location awareness from niche to mainstream. But at the same time, inventions for routing as a function of location [79] and services like GEOPRIV [80], [81] made it possible to customize access to knowledge about personal location, so the role of location information in wireless architectures continued to grow. Today, wireless location-based services are differentiated based on ease of use (e.g., Google Maps versus MapQuest) and QoI parameters [2] rather than on mere availability (a QoS parameter) or time delay of the results (another QoS parameter). Multimedia services may also undergo such a transition from QoS to QoI as wireless multimedia coverage continues to expand, soon becoming expected even in developing economies. Thus, the ability of cognitive radio architectures to enhance multimedia in terms of both cost of availability (cost of a QoS service level agreement) via spectrum efficiency with QoI as a mobile user value proposition may propel cognition for either or both purposes into a more central role in architecture evolution.

5) Spectrum Awareness: Spectrum awareness now too is beginning to move to center stage, as suggested in Table 1. Historically, a commercial wireless device had to be aware

[11]www.ontolog.cim3.net.

of the network, but not much else. The network told the radio what to do and that was that. Today's handsets, PDAs, and even some laptops are armed with multiple chip sets capable of accessing GSM (ideal for global roaming) and CDMA (e.g., for medium data rates in a larger coverage area) as well as for accessing 54 Mbps WiFi hot spots. Today's user puts up with the tedium of picking the WiFi network, with whatever security risks that entails, while host cellular networks deal with most of the other choices of radio band and mode for the user. However, regulatory rulings on dynamic spectrum and the commercial success of Internet alternatives to cellular wireless and the PSTN (e.g., Skype over WiFi) render the autonomous mediation of radio bands and modes into an opportunity for CRA evolution. As something like the U.S. 700 MHz Block D rules emerge, it will become useful for wireless devices of the future to autonomously recognize prototypical emergency situations without being told to by a network that is inoperative because of the emergency. This raises the performance bar for DSA and places the autonomous determination of the user's situation at center stage: is the user a victim who has priority for assistance; or a first responder authorized to assist in the emergency; or a bystander who should yield spectrum to those who need it most? Integration of diverse sensor modalities may be needed to effectively address such situations [2].

6) Spectrum Auctions: In the foundation era, radio spectrum has been allocated in relatively large blocks—the lanes in the road—that raise substantial government revenue. Within the past few years, private enterprise has offered Web-based tools and services for incumbent spectrum licensees to anonymously cross-license relatively small slices of spectrum for relatively short periods of time—notionally, a few megahertz for a few months at a time [82]. As Jondral's group at TU Karlsruhe has characterized in some detail [83], the sale of chunks of primary spectrum as small as 5 s in duration for prices as low as a few cents per chunk for enhanced e-mail services and Web browsing could provide an increase in spectrum utilization of between 15 and 25%. Thus, CRA could improve secondary markets from today's megahertz-months towards the more efficient kilobits/second-seconds, although just where the revenue breakpoints might be is yet to be determined. Doyle's group at Trinity College, Ireland, has shown that what is feasible still appears to be orders of magnitude from theory [84]. Indeed, the government of Ireland dedicated more than 100 MHz of spectrum to the experimental characterization of the potential for IEEE DySPAN 2007. To characterize performance in spectrum overcrowding, DySPAN 2008 has intentionally smaller spectrum allocations [85].

7) User Expectations: The way users value QoS parameters like coverage (probability of mobile dial tone) and data rate may also change with the agility of spectrum access. Users readily recognize that megabit per second data rates are available in WiFi hot spots, but not in remote areas, so they adjust their expectations and plans for the use of a flexible PDA accordingly. Today, mobile data rates are expressed in a framework that reflects the mobility of the user within fully built-out and relatively monolithic cellular infrastructure: stationary users have a higher data rate than users who are walking, and they have higher data rates than those in moving vehicles. 3G recognizes data rate differentiation indoors, reflecting additional nonhomogeneity of the networks. During the next few years, most homes and businesses could become multimegabit/second wireless hot spots, potentially via B3G femtocells or Internet WLANs or both, accelerating CRA evolution.

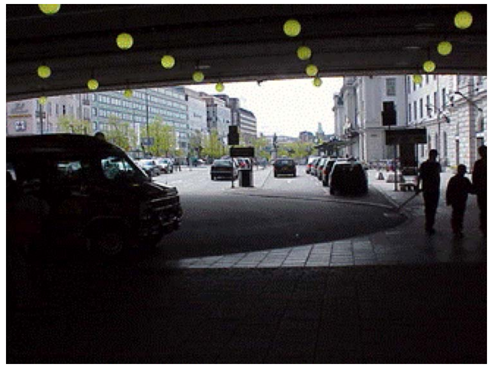


Fig. 5. *SAS Royal Viking facing street.*

The identification of a specific hot spot may be based in part on GPS, but in complicated urban settings, other sensor modalities like computer vision, speech, and other human language technologies may play a role [2]. For example, Fig. 5 shows the entrance to the Royal Viking Hotel in Stockholm facing from a revolving door towards the street. The glass foyer provides great GPS and GSM coverage, but the GPS does not establish whether the radio is inside or outside of the hotel. In addition, GSM fades deeply when one traverses the entrance, and most cell phones lose a call in progress here. If instead of merely reacting to a deep fade the cell phone were aware of the user's precise location and direction, then a more aggressive adaptive equalizer could be invoked for the transit through the tunnel so that the call is not lost.

Generally, it is impractical to operate a GSM network-handset pair with the high-performance equalizer and network compensation that would be required to transit such a tunnel. That is, you cannot operate a network profitably if constantly configured for such worst case situations. However, if the cell phone autonomously detects the lobby and reliably predicts the tunnel transit, it may employ expensive measures autonomously (its high-performance equalizer), coordinating with the network to maintain connectivity affordably. The resulting perception of never dropping a call (exceptional QoS via multisensory CRA) could be a market differentiator. Although consumers are not likely to wear a cell phone camera to gain such a minor advantage, the information prosthetic value of such a camera might create market value. A first responder might wear such a camera phone to transmit images to the incident commander. Location fine structure includes altitude, trajectory, indoors/outdoors, weather, and other characteristics of location. Thus, a CRA that enables higher radio performance by the opportunistic exploitation of larger situation information (such as the visual cues to the transit of the tunnel) may facilitate smoother transition to higher QoS for emerging applications, like the commingling of public safety and commercial services in the recent 700 MHz spectrum auctions in the United States.

B. First Responder Situation Awareness

Public safety and military users refer to the detailed knowledge of physical state as situation awareness [86], [87]. With DSA, a cognitive radio bases its actions on little more than GPS and instantaneous fade data. However, by taking advantage of the video surveillance streams that public safety incident commanders are employing in increasing numbers to manage major incidents, the cognitive radio of the future may be able to optimize its use of radio resources to reflect finer grain aspects of the user's situation: specific location, surroundings (e.g., in dense smoke), movement (e.g., trapped), and, potentially, intent (trying to rescue a victim versus trying to escape a cleared area). The value to the radio of greater awareness of the user's physical setting in space and time may reduce uncertainty and promote better situation-based radio resource management, such as which of the first responders gets MIMO resources for video to assist rescue versus, perhaps, location-only low-power low-data-rate radio resources, e.g., when on standby in an assembly area. Historically, such needs have not been met with corresponding financial resources, but governments around the world may be more inclined to invest for the evolution era of Table 1 than they were during the foundation era.

C. Commercial Sentient Spaces

Spatial spectrum confluence domains may be defined as the radio environments that are created (usually unintentionally) where a wide diversity of commercial and other wireless products, services, and networks are brought together in a single location such as a home, business, apartment building, factory, or other social space, becoming the venue for a variety of broadcast (e.g., HDTV, DBS), WLAN (e.g., 802.11a/b/g, WiFi, HomeRF/Zigbee, Bluetooth, UWB), cellular (e.g., 3G femtocells), and broadband radio resources (e.g., WiMAX). Confluence domains create a combinatorially explosive set of opportunities for interference, as is often true today, or for cognitive load balancing and cooperative power management [88] as architectures evolve.

Elder care may be an emerging market where such tight integration of space, time, and RF makes economic sense during the evolution era of Table 1. The sentient home of the future may include video cameras and voice interaction to assist elderly residents in remembering whether they took their prescription drugs, removing a shoe from the stairs, turning off the stove, and performing other tasks that promote health and avoid accidents [89]. Other sentient space applications include child care [2], infotainment, and interactive games, where the wireless devices situated in the sentient space enhance the interactive experience. Usually in the United States, there is a wireless point of sale terminal to check-in your rental car at the airport. Although the parking lot with only such devices falls short of the sentient space vision, the application shows how wireless technologies move sensors and data entry from a desk, where it is convenient for the administrator, to the parking lot, where it is convenient for the user. The iCR architecture's emphasis on the user enables more aggressive redeployment of sensing, such as cognitive replacement of data entry and fiducials with machine vision to reduce costs and enhance commercial customer experience. Wireless networks meet several needs in commercial spaces, including low-cost deployment and removal, high mobility for the users, and modular evolution of the sentient space as medical and wireless technologies continue to advance.

In part in response to industry interest in sentient spaces for elder care and agricultural robotics [90], the Object Management Group (OMG) has developed specifications that facilitate the deployment of embedded intelligence. So far the OMG has released specifications for smart transducers and superdistributed objects, logical representations of hardware/software components that perform well-known functionality and services.[12] The architecture appears to rely on autonomy and cooperation among a massive number of such objects, where the very number of interacting objects reduces the effectiveness of conventional plug and play technologies. Superdistributed objects may include wireless devices, software modules for radios, transducers, video cameras, servers, smart light bulbs and switches, electric motors, and other massively distributed components. In such applications, radio is a means for distributed control among hardware–software artifacts, and the need for trustable wireless connectivity is substantial. Although it is far too early to tell, there may be a transition during the evolution period of Table 1 where the majority user of wireless becomes IPv6-enabled devices instead of people. The potential disruption could be significant in an evolution to autonomous networked devices as the primary wireless user. People may interact with a house full of smart devices via ubiquitous computer vision and HLT, both spoken and written. These technologies may proliferate for the commercialization of sentient

[12]See www.omg.org.

spaces apart from radio applications, but the information about the user's situation that results could be used by cognitive radios to autonomously adjust radio resource priorities to changing needs.

V. SENSORY PERCEPTION IN THE EVOLVING CRA

Characterizing the potential for evolution towards commercially viable sentient spaces requires a brief review of computer vision and human language technologies. Each of these technologies is so broad that there is no hope of providing even a survey of the state of the art in this brief treatment. The intent instead is to identify important aspects of these technologies for future cognitive radios to interact with users, peer radios, and external sensory-perception networks (such as a cognitive video surveillance network), including speaker identification via voice biometrics, context-aware voice commands, and keyword extraction from e-mail to detect stereotypical situations for proactive wireless services synthesis.

A. Computer Vision

Computer vision includes video analytics[13] that reliably identify people and objects in complex scenes and that reliably detect events of interest such as an illegal turn via a traffic camera. Cognitive vision [91] systems continuously observe a video scene in order to perform such event detection tasks. Video analytics applications programmer interfaces (APIs) have evolved for video surveillance[14] and for Internet retrieval,[15] among others.

Video analytics products offer few open-architecture standards suited for CRA evolution, but as video object APIs and interface standards emerge, CRs may interact with cognitive video systems, such as a surveillance network in a snowy, deserted parking lot where the user has a serious fall after hours, injured and unable to call for aid. In this use case, autonomous collaboration between the users' CR and the wireless video surveillance network could yield an accurate diagnosis of the user's state and timely emergency response for enhanced QoI as the cognitive PDA acts as an agent for the injured user [92]. An important cognitive vision/cognitive radio API research issue is the rapid characterization of visual scenes with fidelity (granularity and accuracy) appropriate to radio use cases. The video scene API should assist the CR in connecting with a data rate and priority appropriate to the user's situation and larger context of others contending for spectrum access. For example, radio access may be expedited for a small number of users in and near a traffic accident until first responders arrive, but such simple priority schemes may be counterproductive in a tsunami-class event. Thus, the exchange of situation information with CWNs seems to be important in the evolution towards interdisciplinary integration with cognitive vision towards the sentient networked CRA.

B. Human Language and Machine Translation

Computer processing of human language includes both real-time speech recognition and high-performance text processing, as well as machine translation. During the evolution period of Table 1 CRs may perceive spoken and written human language (HL) with sufficient reliability to detect, characterize, and respond appropriately to stereotypical situations, unburdening the user from the counterproductive tedium of identifying the situation for the radio. Machine translation in the cell phone may assist global travelers with greetings, hailing a taxi, understanding directions to the restaurant, etc. Such information prosthetics may augment today's native language facilities. With ubiquity of coverage behind, CRA evolves towards more accurately characterizing the user's information needs, e.g., via speech recognition and synthesis to interact with wearable wireless medical instruments, opening new dimensions of QoI.

1) Computer Speech: Computer speech technology offers opportunities for machine perception of content in well-structured audio channels such as 800 directory assistance.[16] Although deployed with all Windows XP laptops, speech recognition does not appear to be in wide use for interaction with personal electronics or for machine dictation. However, the technology now is mature enough to transcribe carefully spoken speech in benign acoustic environments, such as a (quiet) home office,[17] with 3–10% raw word error rates, reduced in structured utterances such as dictation to less than 2%. In situations where the speech is emotional, disfluent, heavily accented, or focused on a rare topic, the word error rates increase to about 25%. But even with these high word error rates, topic spotting for geographical topics can yield 14.7% precision, improved by an order of magnitude during the past five years [93].

Speaker identification technology [94] has equal error rates (equal probability of false dismissal and false alarm) of $<10\%$ for relatively small collections of speakers (<100). Such algorithms are influenced (usually corrupted) by acoustic backgrounds that distort the speaker models. Speaker recognition may be termed a soft biometric since it could be used to estimate a degree of belief that the current speaker is authorized to access private data. Such speaker modeling could contribute to multi-factor biometrics to deter the theft of personal information from wireless devices.

[13] www.iscwest.com.

[14] http://www.nedstat.co.uk/web/nedstatuk.nsf/pages/analytics_stream_sense; www.agentvi.com/.

[15] http://www.developer.truveo.com/.

[16] For example, TellMe 800 directory assistance.

[17] Dragon Systems.

2) Text Understanding: Business intelligence markets are deploying text understanding technology that typically focuses on the quantitative assessment of metrics of text documents, e.g., to assess and predict the performance of a business organization. Quantitative analyses of databases and spreadsheets often do not clearly establish the causal relationships needed for related business decision making. Causal cues typically are evident in the unstructured text of business documents like customer contact reports, but the extraction of those relationships historically has been excessively labor intensive. Therefore businesses, law enforcement, and government organizations are employing text analytics to enhance their use of unstructured text for business intelligence [95], with a rapidly growing markets. These products mix word sense disambiguation, named entity detection, and sentence structure analysis with business rules for more accurate business metrics than is practicable using purely statistical text-mining approaches on relatively small text corpora. Google depends on the laws of very large numbers, but medium to large businesses may generate only hundreds to thousands of customer contact reports in a time interval of interest. For example, IBM's Unstructured Information Management Architecture (UIMA)[18] text analytics analyzes small samples of text in ways potentially relevant to cognitive radio architecture evolution such as product defect detection.

In addition, Google's recent release of the Android open handset alliance software[19] suggests a mix of statistical machine learning with at least shallow analyses of user input (e.g., for intent in the Android tool box). Google has become a popular benchmark for text processing. For example, a query tool based on Artificial Linguistic Internet Computer Entity (ALICE) is reported to improve on Google by 22% (increasing proportion of finding answers from 46% to 68%) in interactive question answering with a small sample of 21 users. Of the half of users expressing a preference, 40% preferred the ALICE-based tool (FAQchat) while only 10% preferred Google [96]. This is not to disparage the planet's most commercially successful search engine but to show how the commercial success of text retrieval stimulates research and productization in directions increasingly relevant to cognitive radio architecture evolution. Unstructured comments in wireless network service and maintenance records, for example, can yield early insight into product defects and service issues before they become widespread, for quicker resolution and lower after-market service and recall costs. Communities of cognitive radios might analyze their own maintenance records to discover operations, administration, and maintenance issues with less human oversight [97], enhancing the cost-effectiveness of cognitive devices and infrastructure compared to conventionally maintained wireless products and networks and complementing current research in functional description languages (FDL) such as the E3 FDL [38], [98].

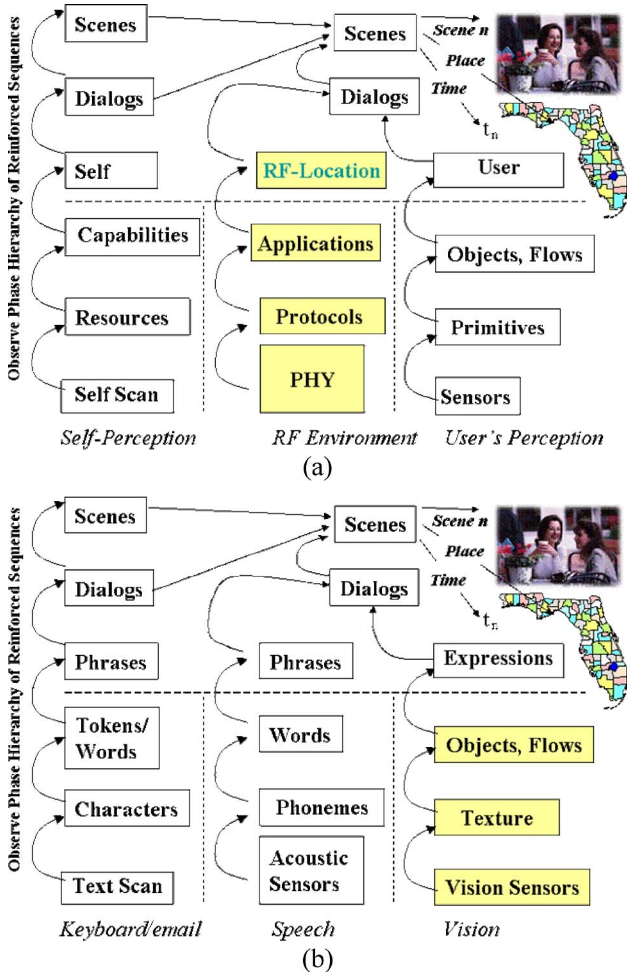


Fig. 6. ***Comprehensive situation perception architecture. [adapted with permission from J. Mitola, III, Cognitive Radio Architecture (New York: Wiley 2006)]. (a) Self-, RF, and user perception and (b) media stream contributions.***

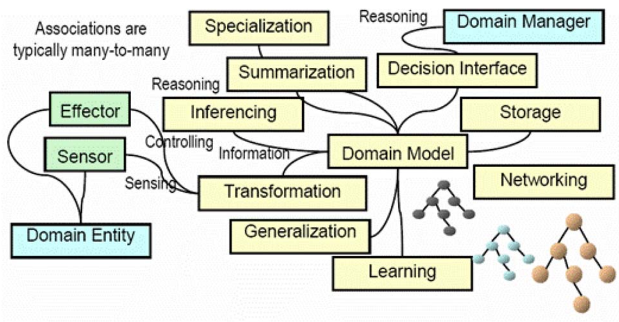
Global mobility of the foundation era of Table 1 spurred the creation of world-phones such as GSM mobile phones that work around the world. During the evolution era, text analytics, real-time speech translation [99], text translation [100], image translation [101], and automatic identification of objects in images [102] will propel CRA evolution.

C. Situation Perception Architectures

With a set of APIs for cognitive vision, video analytics, speech recognition and synthesis, and text analytics, individual cognitive radios and CWNs may evolve towards the organization of machine perception illustrated in Fig. 6.

Perception of the self and the user in a specific situation may be aided by the recognition of stereotypical interchanges between the user and the wireless networks

[18] http://www-306.ibm.com/software/data/enterprise-search/omnifind-enterprise/uima.html.
[19] www.code.google.com/android/.



(c) 1998–2006 Mitola's STATISfaction, reprinted with permission

Fig. 7. ***The complexity of situation assessment.***

in which the user employs the radio more or less directly, as is the case today while the cognitive agent observes the dialog. In addition, text, speech, or visual cues to situation changes may be reinforced in one of the other domains. Different participants perceive such situations differently as a function of role and information need [103], as illustrated in Fig. 7.

The complexity of such situations must be fully addressed with the user as the eighth layer of the protocol stack—fully characterized in machine readable form—to reach the next level of QoI.

VI. QUALITY OF INFORMATION

QoS concerns the availability, data rate, and timing of bitstreams, addressing user needs at the physical through network layer of the protocol stack. QoI concerns the information that meets a specific user's need at a specific time, place, physical location, and social setting, climbing the protocol stack through the applications layer to a postulated user layer, the eighth layer of the protocol stack. QoI may augment QoS to help guide the evolution of radio architecture from SDR and DSA towards the iCRA. One expression for the QoI metric [2] is as follows:

$$\mathbf{QoI} = \mathbf{Quantity} * \mathbf{Precision} * \mathbf{Recall} * \mathbf{Accuracy} * \mathbf{Detail} * \mathbf{Timeliness} * \mathbf{Validity}.$$

There are many possible valid forms for each of the parameters of this equation. The only requirements for the purposes of characterizing QoI are the following.

a) Each parameter is real, occurring in the range [1.0, 0].
b) Each parameter reflects the best QoI at its maximum of 1.0.
c) Parameters monotonically approach zero in proportion to degradation of QoI.

The parameters need not be linear. Given the product form, any term that reaches zero reduces net QoI to zero, so the forms most helpful in decision support would retain nonzero value in all terms where potentially useful information is provided. Each term is briefly discussed.

A. Quantity

The quantity term represents the information displayed or provided by the wireless device or network via the device to the user. If the device has no information for a given situation, then quantity is zero. Information provided to a user in response to a need does not have to be provided in real time but may be made available from cache or a priori knowledge. Thus, while QoS measures the quality of a connection, QoI measures the service provided to the user in terms that matter to the user. QoS metrics do not ascribe value to cached data, but QoI ascribes value to autonomous caching of data that the CR infers might be helpful at some point in time (and for which space is available). Users know that if the most current information is not available, then older information may be better than nothing and may be as good as real-time information if it has not changed. Maps, for example, may be safely cached for relatively long periods of time since roadways change relatively infrequently. As CRs learn user preference, the ability to cache relevant data may increase, and if that is the case, then QoI characterizes the value to the user of such proactive caching.

Proactive management of quantity may shape network traffic as well. A cognitive radio that displays a cached street map, advises the network of the date of its cached map, and thus avoids downloading a megabyte of data has provided the user with accurate information nearly instantaneously and has offloaded a megabyte of traffic from a potentially busy network. In the foundation era, when revenue was based to a first-order approximation on increasing the use of the network, this might not be such a smart thing for a profit-making network to do. However, in the evolution era, when revenue is based on market share through product differentiation, instantaneously accurate information valued by the consumer might capture market share without burdening the network. Thus, the quantity term in the QoI metric expresses value not just in terms of connectivity and data rate but also in terms of information made available without using the network unnecessarily. On the other hand, suppose sufficient information is present, so that Quantity = 1.0. Precision, recall, and accuracy further characterize the quality of the quantity provided.

B. Precision and Recall

Precision and recall reflect the degree to which the information corresponds to the user's need. In information retrieval, recall is the fraction of relevant documents retrieved from a corpus by a query. Precision is the fraction of documents retrieved that are relevant. Recall of 1.0 indicates that all relevant documents are retrieved, while precision of 1.0 indicates that no irrelevant documents have been retrieved. Adapting this well-known metric to

QoI, one may apply precision and recall to items provided to a user by a wireless device, with or without the assistance of one or more networks and with or without prior caching. Users may provide feedback by obtaining more items or rejecting or not using the items retrieved.

C. Accuracy

Accuracy characterizes the quantitative aspects of the information provided. Accuracy is reduced by errors such as lack of factual correctness (e.g., spelling the president's name wrong). Numerical accuracy in QoI reflects any numerical error, whether from the original source, via transmission, or via misformatting the results. Numerical precision may limit accuracy. If the accuracy required by the user is met, then accuracy $= 1.0$. The rate of degradation of the accuracy metric from 1.0 may depend on the situation and may take any form (linear, quadratic, exponential, fractal, defined by table lookup, etc.).

D. Timeliness

Timeliness is defined in terms of the user's timeline along which the information is to be employed. If the information is needed immediately, then the quality may be characterized as inversely proportional to excessive time delay. To avoid division by zero, one may consider timeliness to be 1.0 if the information is available before a minimum delivery time

$$\mathbf{Tmin}(\mathbf{time}, \mathbf{place}, \mathbf{social\text{-}setting}, \mathbf{topic}).$$

Situations include time, place, and social setting, such as shopping or needing medical attention. Suppose the shortest time delay in such a setting is *varepsilon* so the maximum contribution of timeliness to QoI would be $1/\varepsilon$. If timeliness is normalized by *varepsilon*, then maximum timeliness would be 1.0. In medical situations, there typically is a window after which the information is of marginal value, if any, so the timeliness parameter may fall off sharply after such a window. Similarly, in some situations, timeliness may be decremented from 1.0 if the delivery time is less than *varepsilon*. There is value in meeting users' exact timelines in the same sense that a wakeup call should be delivered when requested, and a user is not happy if the wakeup call is 15 minutes early.

E. Validity

Validity is 1.0 if the information provided is true and approaches zero if false with fuzzy set membership, for validity values in [1.0, 0.0].

F. Detail

Lastly, if sufficient detail is provided that the user regards the information provided as complete, then Detail $= 1.0$, gradually dropping towards zero if insufficient elaborating detail is provided.

The representation of the user as the eighth layer of the protocol stack becomes a computational reality in what may be called the value plane [104] to the degree that the user's preferences in the QoI dimensions are made computationally accessible via semantic Web, computational ontology, user modeling, and other languages for expressing user needs. QoI has cross-layer implications. Given the intermittent connectivity of wireless devices, QoI can guide a cognitive radio in its choice among a collection of candidate wireless access points. User preference modeling guides the CR in proactive caching when connectivity and data rate are available, particularly in a future where there is no additional cost to such caching (such as from WiFi and the Internet service provider at home). To the degree that a cognitive radio can independently estimate user state or can infer that state from a CWN or a collaborating network, such as a wireless video surveillance network, the embedded cognitive agent may be able to manage radio resources so as to maximize the QoI for its own user whose needs and preferences it has learned.

VII. CHALLENGES AND OPPORTUNITIES

There are many challenges and opportunities in cognitive radio architecture evolution. For example, many spectrum measurements reported in the literature do not fully caveat the feasibility of spectrum sharing. Measurements that show 5% occupied spectrum often do not account for GPS and other navigation aids that cannot be detected via spectrum scanning, but require cross-correlation receivers. Other measurements do not reflect the duty cycles of the radar bands where a pulsed radar listens for most of its duty cycle, contributing 0.1% to spectrum occupancy but 100% to airport surveillance. Pulsed radar spectrum therefore may not be shareable in a meaningful way, but often radar bands are included in the spectrum scan statistics without clear caveats. Space communications typically require high gain receiving antennas—some 60 ft across-and the signals from the spacecraft are not detected in the spectrum scans either. Ad hoc networking in the apparently unoccupied downlink band would raise havoc with space systems. Important counterexamples to the unintentional oversimplification of spectrum occupancy characterization include the rigorous spectrum sensing campaigns of Tuttlebee's Virtual Center of Excellence (VCE) conducted by Beach's group at the University of Bristol, U.K.,[20] [105] and the data sets of the Crawdad site.[21] Lastly, even in the evolution era of Table 1, emergency channels simply must be kept clear for the relatively infrequent emergency communications to experience maximum SNR, so they should in fact show no occupancy most of the time. Analog AM voice is audible 6 dB below the 0 dB tangential noise floor because of the sinusoidal

[20]www.mobilevce.com.

[21]http://www.crawdad.cs.dartmouth.edu.

nature of voice, but if that emergency broadcast channel is full of ad hoc network traffic, then the safety officer may not hear "Mayday."

The business implications of overstating the case for spectrum sharing ultimately cause problems for the dynamic spectrum community. The opportunity, then, is to include in the evolving CRA sufficient computational intelligence about navigation aids, radar, and emergency communications that cognitive radios know how to listen to legacy communications as a function of band type and know how to avoid jamming location services, creating hot clutter in radar tracks, and generating other spectrum artifacts that detract from the trust of the evolving cognitive radio architectures.

Radio propagation is notoriously ragged in its spatial extent, even in the sweet spot between 300 MHz and 3 GHz because of multipath, knife edge diffraction, Fresnel zones, and other well-known phenomena. Yet the potential contributions of communities of cognitive radios to space-time fine structure of the radio spectrum may not be fully realized until the CRAs come to include high-performance spatial knowledge. A technical paper on the compact representation of such spatial knowledge was deemed best paper at DySPAN 07, for example [106].

There have been several proposals for general spectrum auction frameworks [107], [108] and many technical papers on this topic (e.g., [109]), with at least one commercial Web site that offers anonymous rental of underused spectrum today [42]. Yet at present, there is no technical architecture deployed for real-time small space-time-RF spectrum auctions.

VIII. CONCLUSION

Radio engineering is undergoing exciting transformations. The introduction of SDR indeed has put greater demands on analog devices to access spectrum in increasingly larger chunks, to generate increasingly pure transmissions with increasingly efficient power conversion. The technologies, products, networks, and related systems are increasing in complexity to meet rising expectations. Cognitive radio architecture provides an evolving series of frameworks for research, development, and product deployment. As users transition from the question of "Can you hear me now?" to "What have you done for me lately?" the radio engineering community may transition from QoS as the coin of the realm towards metrics more like QoI and QoS∗QoI. Architectures will evolve greater QoI for lower cost via interdisciplinary information integration, where radio engineers will be better able to leverage information about the user's location, preferences, and current situation to deliver multimedia infotainment in one instant and emergency response in the next. High value-added and profitability is needed to transition smoothly to continue to balance market needs and public interest. During this evolution, the radio research community will continue to lead the way with mathematical foundations, focused use cases, sensory-perception integration, and radio engineering evolution, towards ultimate realizations of the cognitive radio value proposition: better use of radio spectrum for the user. ■

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ABOUT THE AUTHOR

Joseph Mitola, III (Senior Member, IEEE) received the B.S. degree in electrical engineering from Northeastern University, Boston, MA, in 1971, the M.S.E. degree from The Johns Hopkins University, Baltimore, MD, in 1974, and the Licentiate (1999) and doctorate degrees in teleinformatics from KTH, The Royal Institute of Technology, Stockholm, Sweden, in 1999 and 2000, respectively.

He is a Distinguished Professor in the School of Engineering and Science and the School of Systems and Enterprises, Stevens Institute of Technology, Hoboken, NJ, where his research interests include trustable cognitive systems. Previously, he was the Chief Scientist of the U.S. Department of Defense (DoD) Federally Funded Research and Development Center, The MITRE Corporation; Special Assistant to the Director of the Defense Advanced Research Projects Agency (DARPA); DARPA Program Manager; Special Advisor to the Executive Office of the President of the United States; and Technical Director of Modeling and Simulation for DoD. He has also held positions of technical leadership with E-Systems, Harris Corporation, Advanced Decision Systems, and ITT Corporation. He began his career as an engineering student assistant with DoD in 1967.