Second Edition

COGNITIVE RADIO TECHNOLOGY

Bruce A. Fette
Editor

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Cognitive Radio Technology

Preface

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This preface[1] takes a visionary look at ideal cognitive radios (iCRs) that integrate advanced software-defined radios (SDRs) with CR techniques to arrive at radios that learn to help their user using computer vision, high-performance speech understanding, GPS navigation, sophisticated adaptive networking, adaptive physical layer radio waveforms, and a wide range of machine learning processes.

CRS KNOW RADIO LIKE TELLME KNOWS 800 NUMBERS

When you dial 1-800-555-1212, a speech synthesis algorithm may say, "Toll Free Directory Assistance powered by TellMe®. Please say the name of the listing you want." If you mumble, it says, "OK, United Airlines. If that is not what you wanted press 9, otherwise wait while I look up the number." Reportedly, some 99 percent of the time TellMe gets it right, replacing the equivalent of thousands of directory assistance operators of yore. TellMe, a speech-understanding system, achieves a high degree of success by its focus on just one task: finding a toll-free telephone number. Narrow task focus is one key to algorithm successes.

The cognitive radio architecture (CRA) is the building block from which to build cognitive wireless networks (CWN), the wireless mobile offspring of TellMe. CRs and networks are emerging as practical, real-time, highly focused applications of computational intelligence technology. CRs differ from the more general artificial intelligence (AI) based services (e.g., intelligent agents, computer speech, and computer vision) in degree of focus. Like TellMe, ideal cognitive radios (iCRs) focus on very narrow tasks. For iCRs, the task is to adapt radio-enabled information services to the specific needs of a specific user. TellMe, a network service, requires substantial network computing resources to serve thousands of users at once. CWNs, on the other hand, may start with a radio in your purse or on your belt—a cell phone on steroids—focused on the narrow task of creating from myriad available wireless information networks and resources just what is needed by one user: you. Each CR fanatically serves the needs and protects the personal information of just one owner via the CRA using its audio and visual sensory perception and autonomous machine learning.

[1]Adapted from J. Mitola III, *Cognitive Radio Architecture: The Engineering Foundations of Radio XML*, Wiley, 2006.

TellMe is here and now, while iCRs are emerging in global wireless research centers and industry forums such as the Software-Defined Radio Forum and Wireless World Research Forum (WWRF). This book introduces the technologies to evolve SDR to dynamic spectrum access (DSA) and towards iCR systems. It introduces technical challenges and approaches, emphasizing DSA and iCR as a technology enabler for rapidly emerging commercial CWN services.

FUTURE ICRS SEE WHAT YOU SEE, DISCOVERING RF USES, NEEDS, AND PREFERENCES

Although the common cell phone may have a camera, it lacks vision algorithms, so it does not see what it is imaging. It can send a video clip, but it has no perception of the visual scene in the clip. With vision processing algorithms, it could perceive and categorize the visual scene to cue more effective radio behavior. It could tell whether it were at home, in the car, at work, shopping, or driving up the driveway at home. If vision algorithms show you are entering your driveway in your car, an iCR could learn to open the garage door for you wirelessly. Thus, you would not need to fish for the garage door opener, yet another wireless gadget. In fact, you would not need a garage door opener anymore, once CRs enter the market. To open the car door, you will not need a key fob either. As you approach your car, your iCR perceives this common scene and, as trained, synthesizes the fob radio frequency (RF) transmission to open the car door for you.

CRs do not attempt everything. They learn about your radio use patterns leveraging a-priori knowledge of radio, generic users, and legitimate uses of radios expressed in a behavioral policy language. Such iCRs detect opportunities to assist you with your use of the radio spectrum, accurately delivering that assistance with minimum tedium.

Products realizing the visual perception of this vignette are demonstrated on laptop computers today. Reinforcement learning (RL) and case-based reasoning (CBR) are mature machine learning technologies with radio network applications now being demonstrated in academic and industrial research settings as technology pathfinders for iCR[2] and CWN.[3] Two or three Moore's law cycles, or three to five years from now, these vision and learning algorithms will fit into your cell phone. In the interim, CWNs will begin to offer such services, presenting consumers with new trade-offs between privacy and ultrapersonalized convenience.

CRS HEAR WHAT YOU HEAR, AUGMENTING YOUR PERSONAL SKILLS

The cell phone you carry is deaf. Although this device has a microphone, it lacks embedded speech-understanding technology, so it does not perceive what it hears. It can let you talk to your daughter, but it has no perception of your daughter, nor of your

[2]J. Mitola III, *Cognitive Radio Architecture*, 2006.

[3]M. Katz and S. Fitzek, *Cooperation in Wireless Networks*, Elsevier, 2007.

conversation's content. If it had speech-understanding technology, it could perceive your dialog. It could detect that you and your daughter are talking about a common subjects such as a favorite song. With iCR, speech algorithms detect your daughter telling you by cell phone that your favorite song is now playing on WDUV. As an SDR, not just a cell phone, your iCR determines that she and you both are in the WDUV broadcast footprint and tunes its broadcast receiver chipset to FM 105.5 so that you can hear "The Rose." With your iCR, you no longer need a transistor radio in your pocket, purse, or backpack. In fact, you may not need an MP3 player, electronic game, and similar products as high-end CR's enter the market (the CR may become the single pocket pal instead). While today's personal electronics value propositions entail product optimization, iCR's value proposition is service integration to simplify and streamline your daily life. The iCR learns your radio listening and information use patterns, accessing songs, downloading games, snipping broadcast news, sports, and stock quotes you like as the CR reprograms its internal SDR to better serve your needs and preferences. Combining vision and speech perception, as you approach your car, your iCR perceives this common scene and, as you had the morning before, tunes the car radio to WTOP for your favorite "traffic and weather together on the eights."

For effective machine learning, iCRs save speech, RF, and visual cues, all of which may be recalled by the radio or the user, acting as an information prosthetic to expand the user's ability to remember details of conversations, and snapshots of scenes, augmenting the skills of the ⟨Owner/⟩.[4] Because of the brittleness of speech and vision technologies, CRs may also try to "remember everything" like a continuously running camcorder. Since CRs detect content (e.g., speakers' names and keywords such as "radio" and "song"), they may retrieve content requested by the user, expanding the user's memory in a sense. CRs thus could enhance the personal skills of their users (e.g., memory for detail).

IDEAL CRS LEARN TO DIFFERENTIATE SPEAKERS TO REDUCE CONFUSION

To further limit combinatorial explosion in speech, CR may form speaker models—statistical summaries of speech patterns—particularly of the ⟨Owner/⟩. Speaker modeling is particularly reliable when the ⟨Owner/⟩ uses the iCR as a cell phone to place a call. Contemporary speaker classification algorithms differentiate male from female

[4]Semantic Web: Researchers formulate CRs as sufficiently speech-capable to answer questions about ⟨Self/⟩ and the ⟨Self/⟩ use of ⟨Radio/⟩ in support of its ⟨Owner/⟩. When an ordinary concept, such as "owner," has been translated into a comprehensive ontological structure of computational primitives (e.g., via Semantic Web technology), the concept becomes a computational primitive for autonomous reasoning and information exchange. Radio XML, an emerging CR derivative of the eXtensible Markup Language (XML) offers to standardize such radio-scene perception primitives. They are highlighted in this brief treatment by ⟨Angle-brackets/⟩. All CR have a ⟨Self/⟩, a ⟨Name/⟩, and an ⟨Owner/⟩. The ⟨Self/⟩ has capabilities such as ⟨GSM/⟩ and ⟨SDR/⟩, a self-referential computing architecture, which is guaranteed to crash unless its computing ability is limited to real-time response tasks; this is appropriate for a CR but may be too limiting for general-purpose computing.

speakers with a high level of accuracy. With a few different speakers to be recognized (i.e., fewer than 10 in a family) and with reliable side information (e.g., the speaker's telephone number), today's state-of-the-art algorithms recognize individual speakers with better than 95 percent accuracy.

Over time, each iCR can learn the speech patterns of its ⟨Owner/⟩ in order to learn from the ⟨Owner/⟩ and not be confused by other speakers. The iCR may thus leverage experience incrementally to achieve increasingly sophisticated dialogs. Today, a 3-GHz laptop supports this level of speech understanding and dialog synthesis in real time, making it likely to be available in a cell phone in 3 to 5 years.

The CR must both know a lot about radio and learn a lot about you, the ⟨Owner/⟩, recording and analyzing personal information, and the related aggregation of personal information places a premium on trustworthy privacy technologies. Therefore, the CRA incorporates ⟨Owner/⟩ speaker recognition as one of multiple soft biometrics in a biometric cryptology framework to protect the ⟨Owner/⟩'s personal information with greater assurance and convenience than password protection.

MORE FLEXIBLE SECONDARY USE OF THE RADIO SPECTRUM

In 2008, the US Federal Communications Commission (FCC) issued its second Report and Order (R&O) that radio spectrum allocated to TV, but unused in a particular broadcast market (e.g., because of the transition from analog to digital TV) could be used by CRs as secondary users under Part 15 rules for low-power devices—for example, to create ad hoc networks. SDR Forum member companies have demonstrated CR products with these elementary spectrum-perception and use capabilities. Wireless products, both military and commercial, already implement the FCC vignettes.

Integrated visual- and speech-perception capabilities needed to evolve the DSA CR to the situation-aware iCR are not many years distant. Productization is underway. Thus, many chapters of Bruce's outstanding book emphasize CR spectrum agility, suggesting pathways toward enhanced perception technologies, with new long-term growth paths for the wireless industry. Those who have contributed to this book hope that it will help you understand and create new opportunities for CR technologies.

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