Cognitive Radio –
An Overview and its Potential Benefits

ABSTRACT
The Cognitive Radio is a wireless communicator of the future that is able to survey its environment, understand the conditions and adaptively establish a communications call. Cognitive Radio in the tactical environment represents a new paradigm in operations that will lead to greater dynamic access capabilities, network throughput and reach, interoperability and assurance. Cognitive Radio represents the next frontier for radio systems/wireless devices as the world moves towards a more connected and content-rich society. This article presents an introduction to Cognitive Radio and its benefits, and the challenges towards realising this dream.

Liew Hui Ming
Lee Kwee Geak

Cognitive Radio –
An Overview and its Potential Benefits

INTRODUCTION

[Scenario 1 – Present Day]
An emergency has occurred at the Suntec Singapore International Convention and Exhibition Centre during a mega event where there are more than 50,000 delegates and visitors present. There is chaos and panic. Anxious citizens frantically attempt to use their mobile phones to contact their loved ones but the lines are jammed. The entire homeland security force, including the police and the military, quickly converges on the scene. Command Posts are set up immediately in the vicinity. Attempts to establish clear lines of communication for the various units from the homeland security force have been frustrating, as the communication devices are either not interoperable or are jamming one another. It is a nightmarish situation, since without any means to communicate, the entire command and control hierarchy is rendered ineffective. The scene is one of total anarchy. The situation stabilises only after a long delay during which the authorities establish communication lines via careful spectrum management and network access regulation.

[Scenario 2 – The Future]
An emergency has occurred at the Suntec Singapore International Convention and Exhibition Centre during a mega event where there are more than 50,000 delegates and visitors present. There is initial chaos and panic. The entire homeland security force, including the police and the military, quickly converges on the scene. Command Posts are set up immediately in the vicinity. Inside the centre, anxious citizens use their cognitive-enabled mobile phones to contact their loved ones, and despite the heavy call traffic, there is good call quality and coverage. Outside the centre, various security units use their cognitive software-defined handheld radios to establish clear lines of communication to their command post and to one another. The situation stabilises quickly, as the homeland security force's entire command and control hierarchy is firmly put in place. The citizens inside the centre wait confidently for the situation to be taken care of, with access to real-time public news via their 4G video mobile phones.

WHAT IS A COGNITIVE RADIO?

Rene Descartes famously proclaimed "Cogito, ergo sum"[1] or "I think, therefore I am", thereby convincing himself of his own existence. Likewise, cognition is the cornerstone of a Cognitive Radio (CR).

CR is usually discussed in the same breath as Software Defined Radio (SDR)[2], simply because the best brain is helpless unless there is a body for it to act with. The SDR is the body which the CR acts with to sense the world around it and influence its position in the world. The CR can thus be viewed as the next quantum step beyond Software Radio.

CR is a smart radio that possesses self-awareness, environmental / contextual awareness, and adapts itself accordingly. The term Cognitive Radio was coined by Joseph Mitola III in his PhD dissertation at the Royal Institute of Technology, Sweden, and encapsulated the radio ideal – a flexible, multipurpose device which offers communication everywhere, anywhere, anytime.

Like any thinking organism[3] the CR has to go through a thought process to lead to changes in its internal model (learning) and its actions (adaptation). The CR's cognition cycle is shown in Figure 1.

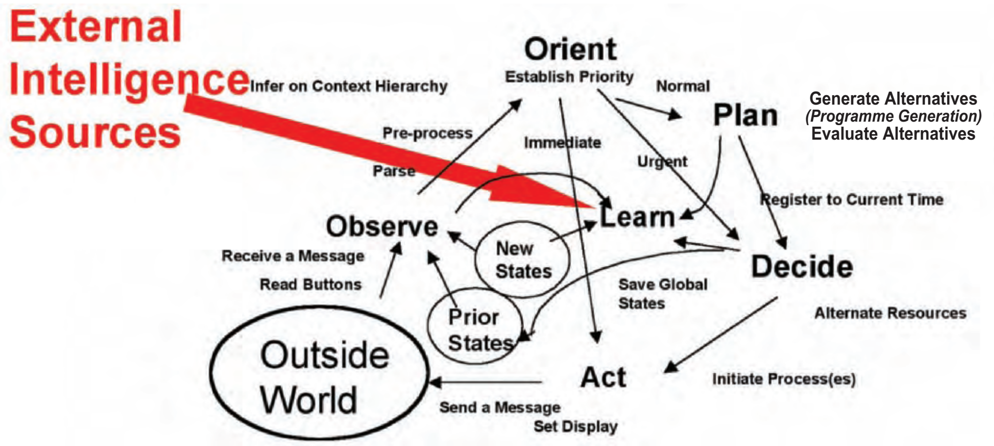

Figure 1. Cognition Cycle (Mitola, 1999)

Cognition cycle behaviour can be generalised into two main tracks:

• Reaction Loop (External loop in Figure 1) – The envisioned CR observes the outside world, orients itself in the context of this world, and either plans, decides, or acts immediately, depending on the urgency of the situation.

• Learning Loop (Internal loop in Figure 1) – The CR observes the outside world and applies the external stimulus to its knowledge base with artificial intelligence.

Joseph Mitola classified the tasks to be performed into nine levels based on the level of cognition required (Table 1).

Until recently, the radio has been a "dumb" piece of equipment that could only function as it had been pre-programmed to, and adapt in a very limited manner when the operator manually controlled the mode change. This was in a very large part due to the radio's dependence on specific hardware, resulting in incompatible systems which could only interoperate with each other via implementing specific gateways for each pair of radio types that needed to communicate with each other. The gateway was thus the single point of failure in connecting two different radio nets, and was a critical weakness in force intra-connectivity. In addition, implementing a different gateway for each pair of radio types would be expensive and laborious for forces with many different radio types. This is because the number of gateways increases dramatically as the number of radio types increases.

In the late 1990s, the US embarked on the Joint Tactical Radio Systems (JTRS) programme to solve its blue force intra-operability problem. The JTRS would replace legacy radios with "a family of interoperable, digital, modular, software-defined radios that operate as nodes in a network to ensure secure wireless communications and networking services for mobile and fixed forces" (Joint Program Executive Office, 2006). This ambitious goal was to be realised by the SDR, which by decoupling the radio from its hardware, was a radio that could be reconfigured via software to perform different functions. This would result in a flexible system and break the then stovepiped development of radio systems.

Thus, the SDR marked the first evolutionary step towards the fully adaptive radio idealised by the CR.

Cognition Level	Capability	Task Characteristics
0	Pre-programmed	Radio has no model-based reasoning capability
1	Goal-driven	Goal-driven choice of frequency band, air interface, and protocol
2	Context Awareness	Infers external communications context with minimum user involvement
3	Radio Aware	Flexible reasoning about internal and network architectures
4	Capable of Planning	Reasons over goals as a function of time, space and context
5	Conducts Negotiations	Expresses arguments for plans / alternatives to users, peers, and networks
6	Learns Fluents	Autonomously determines the structure of the environment
7	Adapts Plans	Autonomously alters plans as learned fluents change
8	Adapts Protocols	Autonomously proposes and negotiates new protocols

Table 1. Cognition Tasks (Mitola, 2000)

WHY IS COGNITIVE RADIO VIEWED AS A DISRUPTIVE TECHNOLOGY[4]

The SDR can be described as today's front-runner in radio research and technology, and yet, cannot truly claim to have attained cognition level 1. The SDR, for all its flexibility, is still dependent on manual reconfiguration (Over The Air or otherwise) and is not able to adapt in goal-driven scenarios without substantial operator/man-in-the-loop intervention.

In contrast, the CR is ideally able to perform high-level cognition tasks autonomously. Taken to extremes, the CR is able to propose and negotiate protocols (Level 9) with minimal user intervention. This is akin to two humans who speak different languages being able to communicate with each other (after a learning period) without outside help.

In truth, the CR need not attain Level 8 to push radio communications to a new frontier. With context awareness (Level 2), self-awareness (Level 3), planning capability (Level 4), and negotiation capability (Level 5), the CR would already have relieved radio operators of much of the frequency preplanning and other tasks required for blue force communications.

Figure 2 shows the suite of functions which may be required in order to unleash the full potential of a cognitive radio. The radio must sense the external environment, know its own position in this context (hence the need for positioning), and be able to access multiple bands and networks.

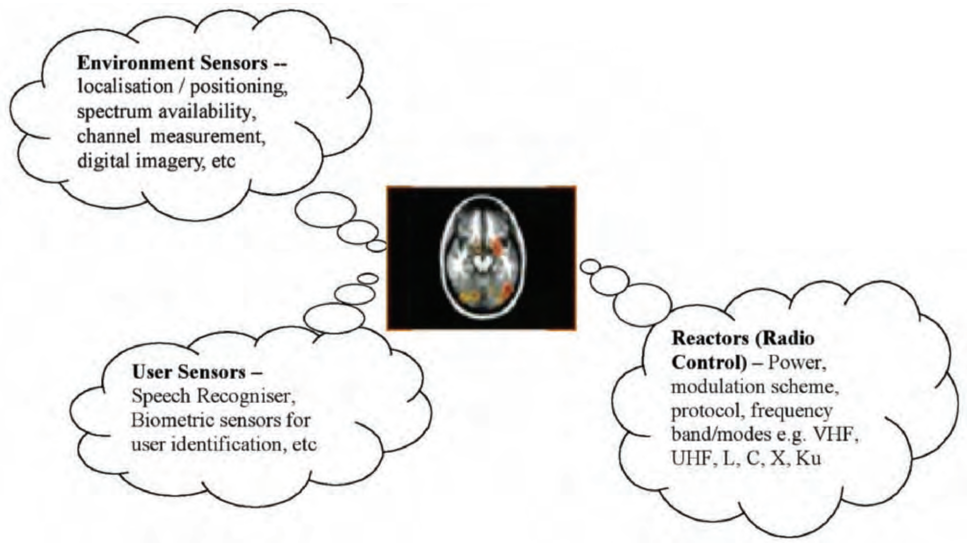

Figure 2. Potential required functionalities of a cognitive radio[5]

POTENTIAL BENEFITS

Dynamic Spectrum Access

A major motivation for the development of CR today is its promise of opportunistic and dynamic spectrum access. Today, licensed spectrum is a scarce and costly resource. However, studies conducted in the US indicate that at any one time, in any one location, the actual spectrum usage is only 5-10%.

The CR senses spectrum usage by licensed users and uses the unused spectrum, giving way to licensed users when it detects that the licensed user is transmitting a message. This application brings tremendous benefits to the commercial telecommunications industry, and is currently a major driver in CR research.

In the military context, dynamic spectrum access does away with much of the laborious frequency preplanning and coordination required before deployment. Blue force interoperability is also enabled since two mutually interfering equipment in close proximity would adapt to each other in such a way that interference is reduced.

Increased Network Throughput and Reach

In a normal scenario, a sender who desires to transmit a message would need to sense if the desired spectrum is currently occupied by a sender. If it was, many current network protocols required the second sender to back off. In contrast, CR offers the potential for both senders to transmit simultaneously. Using an algorithm similar to dirty paper coding, the second sender could encode his transmission such in a way that the interference presented by the second sender to the first receiver was transparent to the first receiver. A priori knowledge of the first sender's transmission by the second sender is required; this would be obtained by the CR via its spectrum sensing methods.

Alternatively, an idle CR that detected a transmission from another node in its network could aid the transmission by transmitting a copy of the same message, thus increasing the reach and achievable data rate of the transmission. Collaborative sending would need to be balanced against each node's own need for transmission. Network coding techniques, with which a node in reach of both the sender and receiver nodes encodes the messages between them smartly to reduce the total number of messages sent between the two communicating nodes, could also be applied in an adaptive / cognitive radio network with greater ease than a non-adaptive network[6].

In a non-collaborative scenario, the CR would increase data rates and reach by sensing the interference within its context, and adapting to it when the need arises by tweaking its own radio parameters e.g. transmitted power, modulation scheme, or even antenna directivity.

Interoperability

Due to the congested nature of the electromagnetic spectrum, it is common for multiple emitters to share the same frequency band. Thus, interference mitigation is unavoidable for blue force interoperability. CR's dynamic spectrum access functionality goes a long way towards mitigating much of the mutual interference. Smart transmission encoding by secondary users of the spectrum as described above would also mitigate the interference experienced by receivers. In addition to frequency access and encoding techniques, CRs equipped with smart directional antennas and power control would also focus their transmission only in the direction of the intended receivers at an appropriate power level to minimise potential interference to other receivers.

Interoperability between different systems has been a major concern for many military forces. As noted earlier, the US was motivated to drive SDR development simply because they had difficulties communicating across their different radio systems (Joint Program Executive Office, 2006)! A high-level CR would mitigate this problem by negotiating and proposing new protocols. Essentially, two Level 8 CRs would be able to communicate by autonomously proposing new protocols between themselves.

On a less ambitious note, a Level 3 CR would learn about the existing radios in its proximity and depending on a priori knowledge, switch to the appropriate protocol to communicate with its desired receiver nodes. This does away with the need to carry multiple radio equipment or to implement a gateway for each pair of radio types.

Communications Assurance

All users of wireless communicators such as mobile phone users have had the experience of a call being interrupted by noise or even suddenly terminated as they moved from location to location. A CR would sense the changes in the external environment and adapt based on the user's requirements. For example, in an especially noisy area, the CR could sacrifice data rate for low bit error rates by changing its modulation, or by simply changing the frequency band. Over time, the CR would learn the combination of parameters that works best in each environment e.g. foliage vs. urban terrains, and adapt by adopting the optimal set of actions for each environment. Examples of observed parameters ("meters") and the possible reaction parameters ("knobs") are shown in Table 2.

CHALLENGES

The challenges to realising a CR in the military context are manifold, ranging from physical considerations to policy development.

Software Challenges

CR has the ambitious goal of incorporating and implementing the learning capacity and flexibility of a human brain into a machine. The tasks associated with this goal are staggeringly complex. These range from basic cognitive functions such as data collection from the environment and user sensing, to medium-level functions such as performing dynamic

Layer	Meters (Observable parameters)	Knobs (Writable parameters)
MAC	Frame error rate Data rate	Source coding Channel coding rate and type Frame size and type Interleaving details Channel / slot / code allocation Duplexing Multiple access Encryption
PHY	Bit error rate Received signal power Noise power Interference power Power consumption Fading statistics Doppler spread Delay spread Angle of arrival	Transmitter power Spreading type and code Modulation type and order Pulse shaping Symbol rate Carrier frequency Automatic gain control Antenna directivity
Other	Computational power Battery life	CPU frequency scaling

Table 2. Examples of Meters and Knobs[7]

resource allocation and radio parametric adaptation in real time, and high-level functions such as collaborating and negotiating with ever expanding ad hoc networks and applications. In addition, the military operational scenario is unpredictable and ad hoc, requiring communications any time and anywhere, presenting a problem that is not easily bounded or predictable. The artificial intelligence skill set required to tie the CR together is a key challenge that needs to be overcome to realise this dream.

Radio "Hardware" Challenges

The CR needs a "hardware" platform, very much like how a Microsoft Windows Operating System needs a PC with which to influence its position in the world. Although SDR technology has progressed significantly since the inception of the JTRS programme as well as other non-US programmes, coupled with the maturity of the common Software Communications Architecture (SCA)[8], a few finer details remain to be worked out. One of these finer details is the adoption of common security hardware requirements for the SCA-compliant SDR platform.

The CR's hardware requirements are not trivial. For example, in order to dynamically access spectrum without interfering with primary users, the CR would need -- (a) to have a receiver much more sensitive than that of the expected receivers in the area; (b) to filter the multitude of incoming signals and decide which are the valid signals from existing users; (c) to locate the existing users; and (d) to adapt in real time its own transmission behaviour in terms of power, direction, frequency band, modulation, etc. The challenge for CR hardware is to fit all of these requirements into a single cost-effective and portable platform[9].

Regulatory Challenges

In order for CR to interoperate on a large scale, rules of behaviour need to be set out and adhered to. For example, in the commercial context, in the case of dynamic spectrum access, the interests of licensed spectrum users need to be protected. Unfortunately, the current technology is not sufficiently mature in providing the necessary level of assurance to existing primary users to reduce their resistance against the deregulation of spectrum access. In the military context, etiquette would dictate the behaviour of "secondary" users who want to operate in the same spectrum and locality where other military "primary" users are already operating. Such rules of behaviour could help to mitigate the mutual interference effects of emitters and receivers located on the same platform[10].

Policy development for CR is a necessary but delicate and painstaking process involving various stakeholders ranging from regulatory bodies to industry and R&D players who would influence the policy trends with their technology.

Security Challenges

Over-the-air reconfiguration of a SDR offers an operational flexibility that is currently unheard of. However, a highly-evolved CR that is able to negotiate with other radios and modify its own protocols would be even more vulnerable to malicious software attacks.

Hence, there are security implications associated with the SDR/CR downloading, installing and using software that could reconfigure the radio behaviour such as frequency, power, and modulation. Unauthorised modifications to the SDR/CR, for example, could result in system overload, violation of power control profile, unauthorised access to content, impersonation and spoofing behaviour. In the military context, the security implications cannot be underestimated.

Security issues include the identification of the authority to control the reconfiguration, protection of the reconfiguration signal, accuracy of the reconfiguration information, secure download of the reconfiguration software, and conformance requirements of the hardware (Cook, 2004 and NTIA, 2005)[11].

CONCLUSION

With the trend towards network-centricity both in the commercial and military arenas, the use of wireless communications technologies and devices is becoming more prevalent everyday. The solution to meeting this insatiable appetite for connectivity, in the face of limited frequency spectrum and rigid regulatory policy rules, while not increasing costs (operator or man-in-the-loop), lies in the spirit of CR.

This dream is not beyond reach. The Defense Advanced Research Projects Agency's Next Generation (XG) programme is developing the technology and system concepts to dynamically access the radio spectrum. The first in a series of field demonstrations of XG integrated tests was recently conducted and showed that XG could operate without interfering with existing radios in the area[12].

REFERENCES

1. P. Cook, Wireless Software Download Security, SDR Forum Document No. SDRF-04-I-0069-V0.00, June 2004

2. N. Devroye, P. Mitran, V. Tarokh, Achievable Rates in Cognitive Radio Channels, IEEE Transactions on Information Theory, vol. 52, No. 5, May 2006

3. S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard, J. Crowcroft, XORs in the Air: Practical Wireless Network Coding, SIGCOMM 2006

4. M. McHenry, Presentation to FCC Workshop on Cognitive Radios, 2003

5. J. Mitola III, Cognitive Radio for Flexible Mobile Multimedia Communications, IEEE Mobile Multimedia Conference, 1999

6. J. Mitola III, Cognitive Radio -- An Integrated Agent Architecture for Software Defined Radio, Doctor of Technology Dissertation, Royal Institute of Technology (KTH), 8 May 2000

7. National Telecommunications and Information Administration Comments ET Docket No. 03-108

8. J. Reed, C.W. Bostian, Understanding the Issues in Software Defined Cognitive Radio, Mobile and Portable Radio Research Group, Virginia Polytechnic Institute and State University, U.S.A

9. T.W. Rondeau, B. Le, D. Maldonado, D. Scaperoth, C.W. Bostian, Cognitive Radio Formulation and Implementation, Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM) 2006

10. Joint Program Executive Office, JTRS Overview Brief, 2006

ENDNOTES

1. This is the Latin rendition of Descartes' original statement "Je pense, donc je suis" in 1637.

2. A SDR is a radio whose channel modulation and demodulation waveforms are defined in software. As the purpose of a SDR is to allow re-programmability simply via loading new software, the SDR performs much of its signal processing on re-configurable electronics such as general purpose processors.

3. Many cognitive radio researchers perceive the Cognitive Radio as a biological organism due to its ability to learn and adapt to external stimuli.

4. Disruptive technology is a term coined by Harvard Business School professor Clayton M. Christensen to describe a new technology that unexpectedly displaces an established technology.

5. Adapted from Joseph Mitola's Doctor of Technology Dissertation, 2000.

6. MIT CSAIL and University of Cambridge (Ref [3]) have worked on a new forwarding architecture for wireless mesh networks called COPE. COPE's advantage can be seen in the simple scenario of two nodes, X1 and X2, communicating across an intermediate relay node. In most network architectures, a total of four transmissions would be required for X1 and X2 to communicate. Under COPE, the relay node stores the data from X1 and X2 and transmits an XOR of these two data packets. X1 can then recover X2's data by performing an XOR of its own data with the data from the relay node. The same applies to X2. The total number of transmissions required is reduced to three. Experimental results indicate that the network throughput gain varies from a few percent to several times depending on traffic patterns, protocol, congestion levels.

7. Courtesy of Centre for Wireless Technology, Virginia Polytechnic Institute and State University.

8. The latest released SCA version is SCA v2.2.2. Note: SCA v2.2 is most commonly adopted by industry players.

9. The authors note that the signal detection threshold is higher than the receiver sensitivity in order to reduce false alarms. Thus, the CR may not detect an existing signal that is very weak even if the signal level is above its receiver sensitivity and transmit, causing an increase in interference to the existing user.

10. Today, the conflicts between emitter(s) and receiver(s) on the same platform are resolved via sending blanking signals to the affected Systems when the emitter wishes to transmit.

11. Please see Ref [1] & [7].

12. Please refer to Shared Spectrum Company's 18 September 2006 press release at: http://www.sharedspectrum.com/content/press/XG_Demo_News_Release_060918.pdf

BIOGRAPHY

Liew Hui Ming is Programme Manager (Directorate of R&D). He is responsible for developing and charting out the Long Term Defence Technology Plan for Advanced Communications as part of the IKC2 R&D portfolio. Hui Ming led the team which received the DSTA Excellence Award in 2003 for the Tactical ONE Network Experimentation. He was also part of the team which received the DSTA Team Excellence Award in 2006 for the Battlefield Instrumentation System. Hui Ming holds a Bachelor of Engineering (Information Systems Engineering) (Honours) from the Imperial College, London, where he also received the Imperial College Psion Prize for Best Final Year Project in Adaptive Filtering. He also holds a Master of Science (Electrical Engineering) from the National University of Singapore.

Lee Kwee Geak is Project Manager (Directorate of R&D). Her work focuses on new Wireless Communications R&D initiatives such as the Software Defined Radio. She was previously in the Sensor Systems Division, and worked on Surveillance Radars. Kwee Geak graduated with a Bachelor of Science (Electrical Engineering) summa cum laude with honours from Cornell University, US, under the Defence Technology Training Award. She also holds a Master of Engineering (Electrical) from Cornell University. Kwee Geak received the Harvard Prize Book in Economics in 1997.