IEEE 802 Tutorial
Cognitive Radios – How close to reality?

Scott Seidel

John Polson

Tom Rondeau

David Maldonado

Communications as we know it is changing

- Past
  - Radio and TV signals
  - Handful of cell phones
  - Two to three access points (LANs)
- Present
  - Large number of cell phones multiple standards
  - Multiple LANs

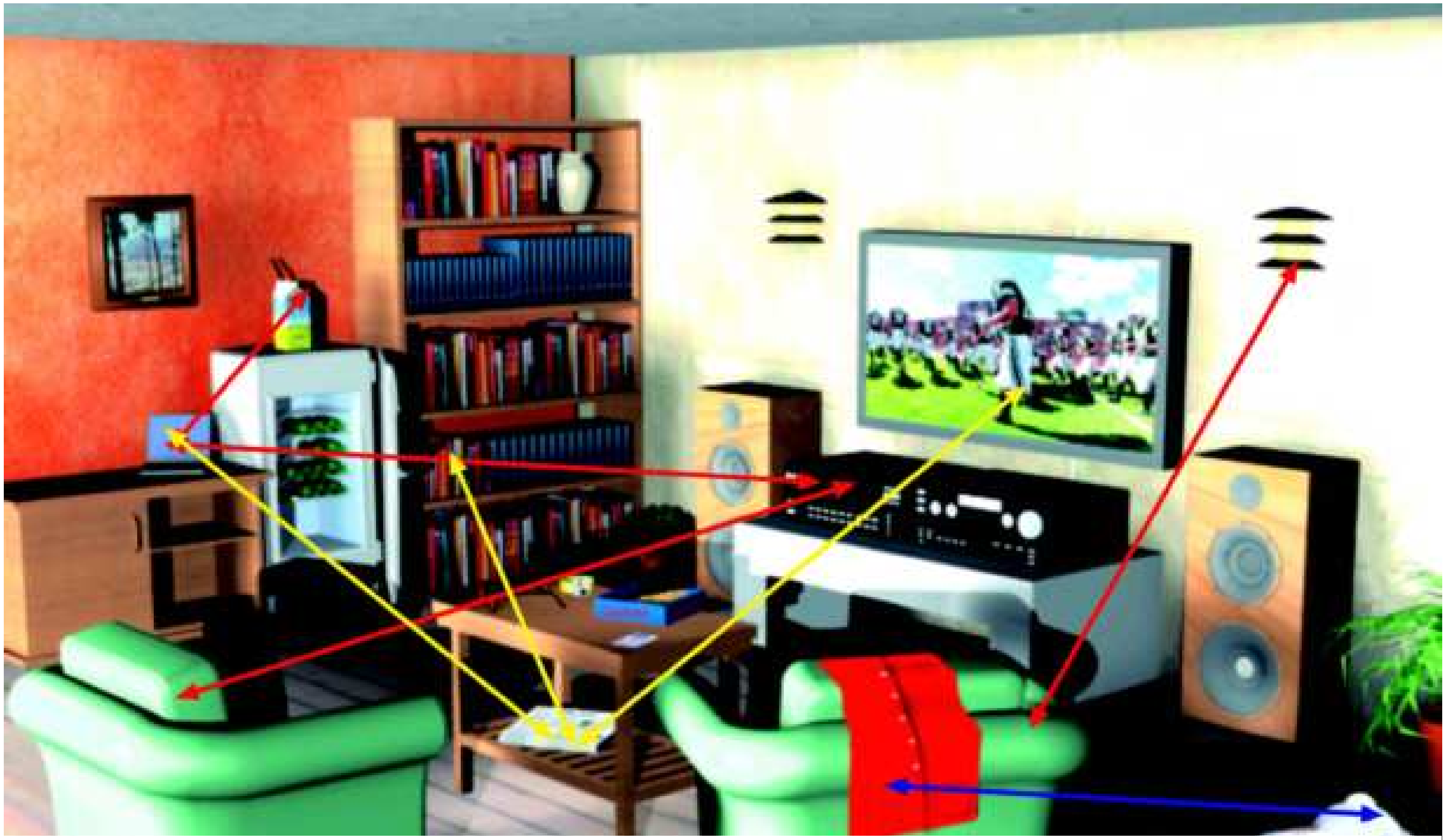
“I think it will be agreed from the outset that the use of the radio telephone for communication between single individuals as in the case of ordinary telephone is a perfectly hopeless notion”

Herbert Hoover, 1922

CORBIS

Secretary of Commerce Herbert Hoover.

Signal density at home…

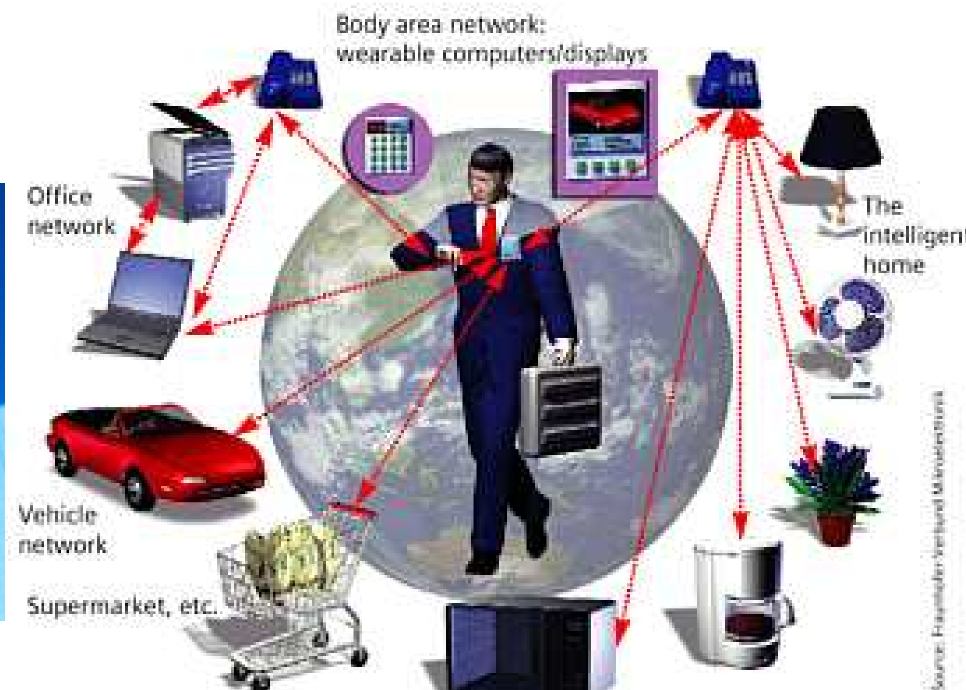


- Multiple devices per home or room

Source:http://w4.siemens.de/FuI/en/archiv/pof/heft2_02/artikel13/

Signal density per user…

- Multiple devices per person
- Complex waveforms

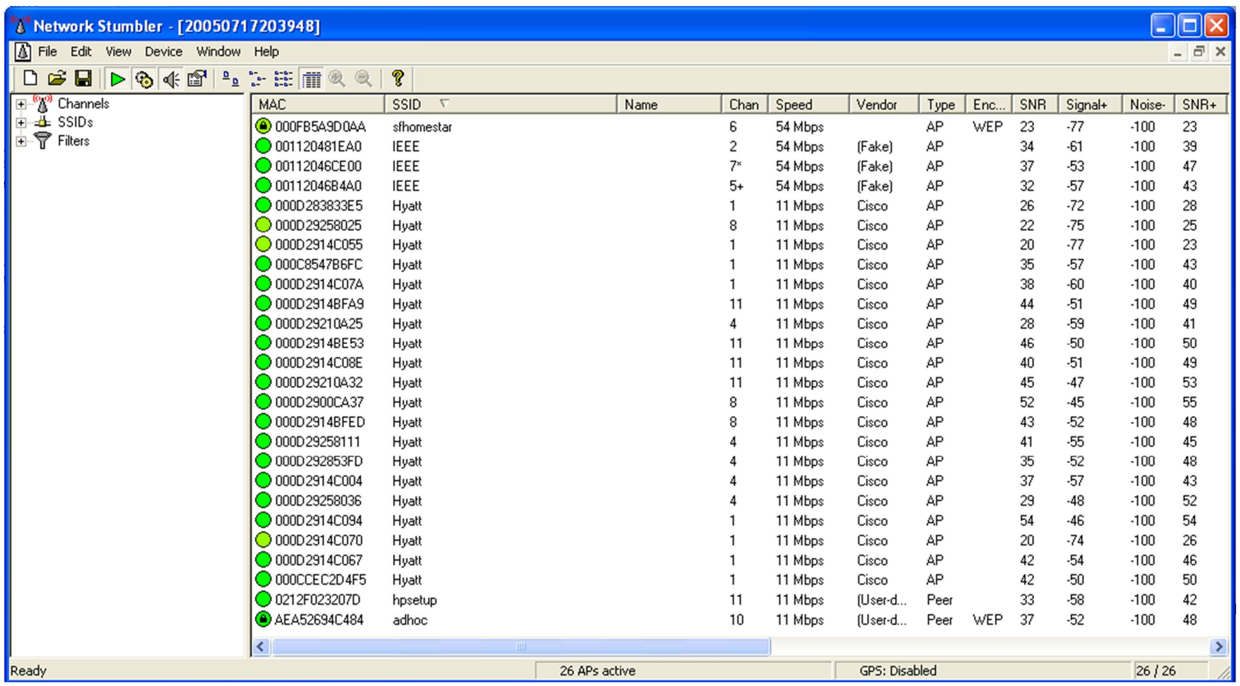


VirginiaTech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Demand for bandwidth will continue to grow for the foreseeable feature

- High data throughput applications (Freq. hunger)
- Multi-standard, multi-mode requirements

Opportunity for Cognitive Radios

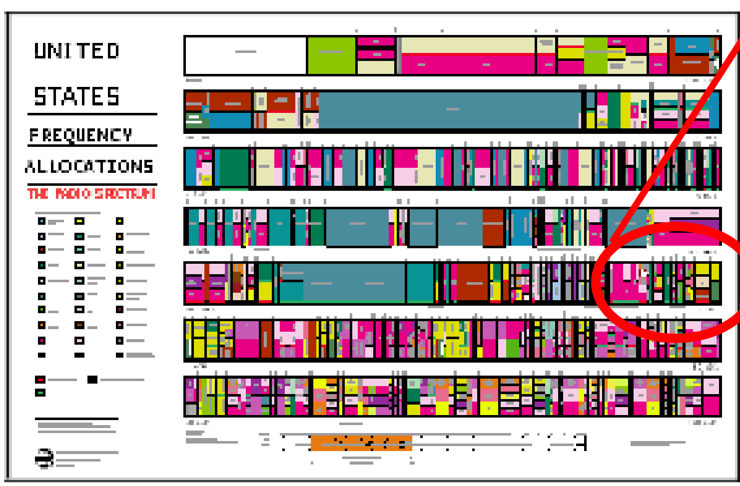


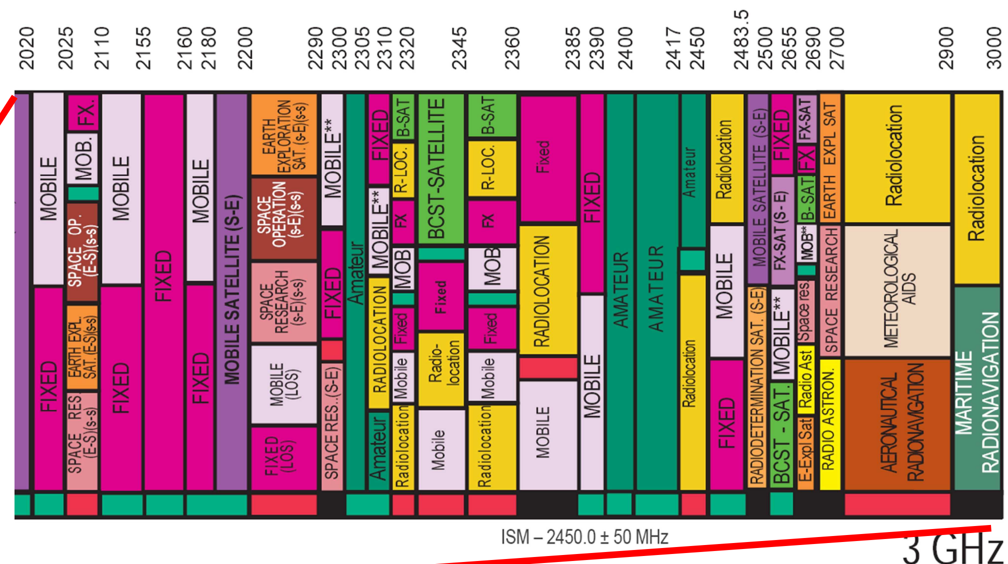
MAC	SSID	Name	Chan	Speed	Vendor	Type	Enc...	SNR	Signal+	Noise-	SNR+
000FB5A9D0AA	sfhomestar		6	54 Mbps		AP	WEP	23	-77	-100	23
001120481EA0	IEEE		2	54 Mbps	(Fake)	AP		34	-61	-100	39
00112046CE00	IEEE		7*	54 Mbps	(Fake)	AP		37	-53	-100	47
00112046B4A0	IEEE		5+	54 Mbps	(Fake)	AP		32	-57	-100	43
000D283833E5	Hyatt		1	11 Mbps	Cisco	AP		26	-72	-100	28
000D29258025	Hyatt		8	11 Mbps	Cisco	AP		22	-75	-100	25
000D2914C055	Hyatt		1	11 Mbps	Cisco	AP		20	-77	-100	23
000C8547B6FC	Hyatt		1	11 Mbps	Cisco	AP		35	-57	-100	43
000D2914C07A	Hyatt		1	11 Mbps	Cisco	AP		38	-60	-100	40
000D2914BFA9	Hyatt		11	11 Mbps	Cisco	AP		44	-51	-100	49
000D29210A25	Hyatt		4	11 Mbps	Cisco	AP		28	-59	-100	41
000D2914BE53	Hyatt		11	11 Mbps	Cisco	AP		46	-50	-100	50
000D2914C08E	Hyatt		11	11 Mbps	Cisco	AP		40	-51	-100	49
000D29210A32	Hyatt		11	11 Mbps	Cisco	AP		45	-47	-100	53
000D2900CA37	Hyatt		8	11 Mbps	Cisco	AP		52	-45	-100	55
000D2914BFED	Hyatt		8	11 Mbps	Cisco	AP		43	-52	-100	48
000D29258111	Hyatt		4	11 Mbps	Cisco	AP		41	-55	-100	45
000D292853FD	Hyatt		4	11 Mbps	Cisco	AP		35	-52	-100	48
000D2914C004	Hyatt		4	11 Mbps	Cisco	AP		37	-57	-100	43
000D29258036	Hyatt		4	11 Mbps	Cisco	AP		29	-48	-100	52
000D2914C094	Hyatt		1	11 Mbps	Cisco	AP		54	-46	-100	54
000D2914C070	Hyatt		1	11 Mbps	Cisco	AP		20	-74	-100	26
000D2914C067	Hyatt		1	11 Mbps	Cisco	AP		42	-54	-100	46
000CCEC2D4F5	Hyatt		1	11 Mbps	Cisco	AP		42	-50	-100	50
0212F023207D	hpsetup		11	11 Mbps	(User-d...	Peer		33	-58	-100	42
AEA52694C484	adhoc		10	11 Mbps	(User-d...	Peer	WEP	37	-52	-100	48

VirginiaTech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

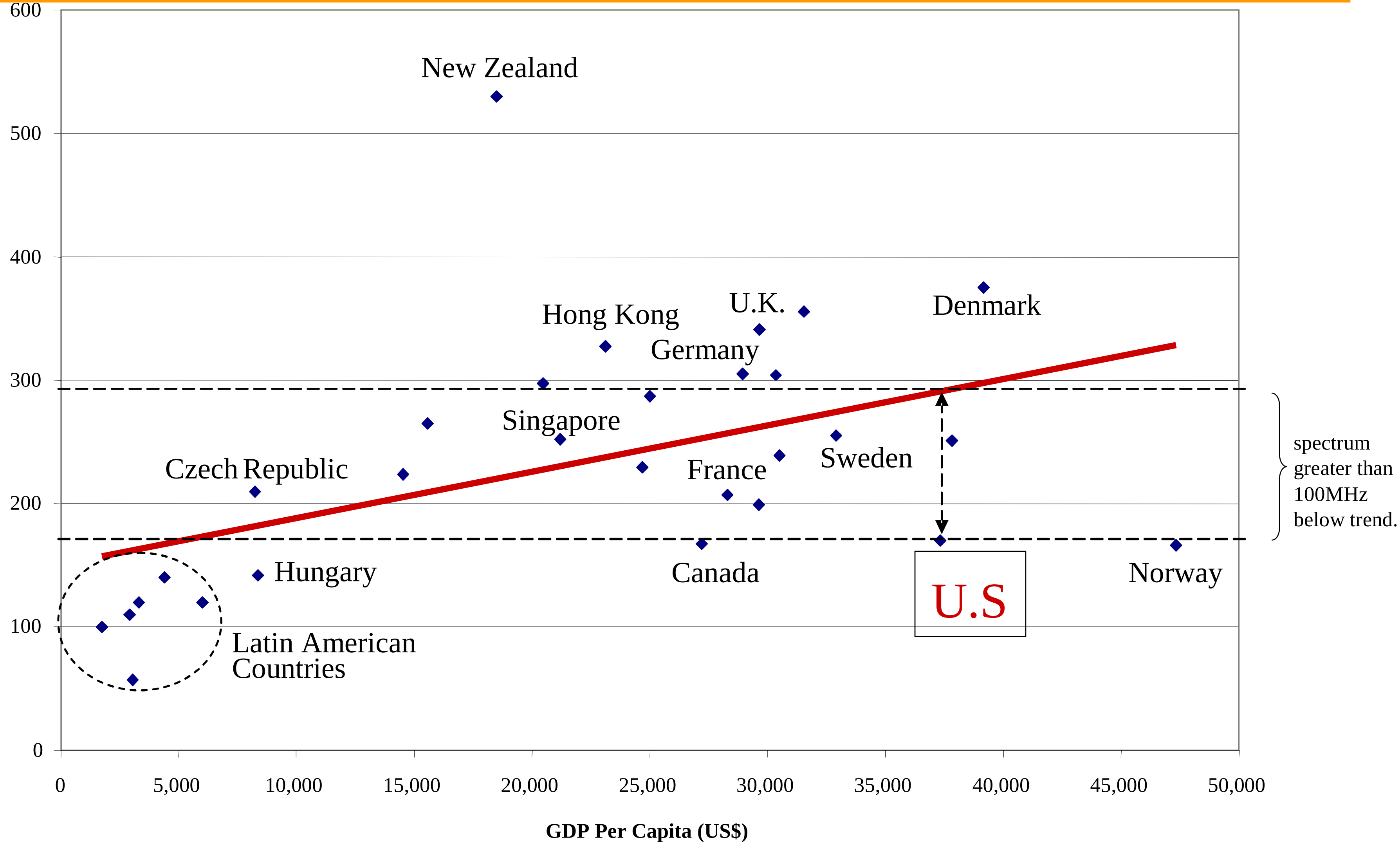
Wireless communications challenges

- Spectrum is already allocated
  - True spectrum scarcity on urban areas (ISM band)
- Existing standards





Spectrum v. Per Capita GDP



What does the future of wireless communications have to offer?

- Goal: Universal ubiquitous high speed device without spectrum restrictions
- Trend: Numerous high performance protocols will exist but most likely all be based on MIMO, OFDM, smart antennas, QoS based MACs, and an all IP network core.
- SDR/CR is a "transforming event"

  - Ed Thomas, former FCC's Chief Engineer

Cognitive radio questions

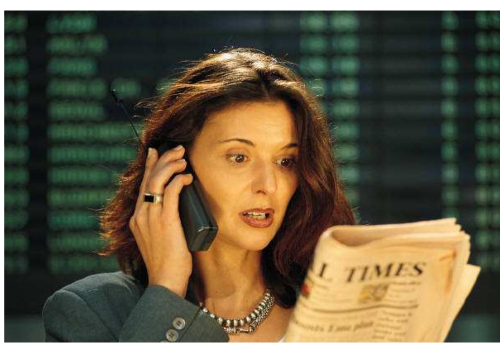
- How to embed cognition in a radio? – software package
- What cognitive model?
  - Evolutionary system, Neural networks, Fuzzy systems
- Which host radio architecture?
  - SDR or any agile radio
- Which radio layer?
  - Cross-layer - PHY, MAC, Network layer, etc.
- How to establish a cognitive wireless network?
  - centralized or distributed by network topologies
- What performance?

What are the regulatory trends and how will they affect CRs?

- Regulators are on our side
- Regulatory process can't keep up with technology
- Update regulatory regime to accommodate new technologies
  - Include proceedings
- Put engineers in front of lawyers for spectrum policy
- Regulatory trend: more sharing where co-existence is demonstrated (e.g. 5 GHz WLAN-Radar Sharing)
  - real time spectrum “transactions” like any other commodity asset
- International trend: get it done right at home; create global markets

Implications of CR to 802 community

- Spectrum efficiency
- Multi-Network selection
  - Public Safety
    - Proprietary and 802.11 networks
  - Consumer
    - Cellular and 802.11/.15 (Bluetooth)
    - Home entertainment



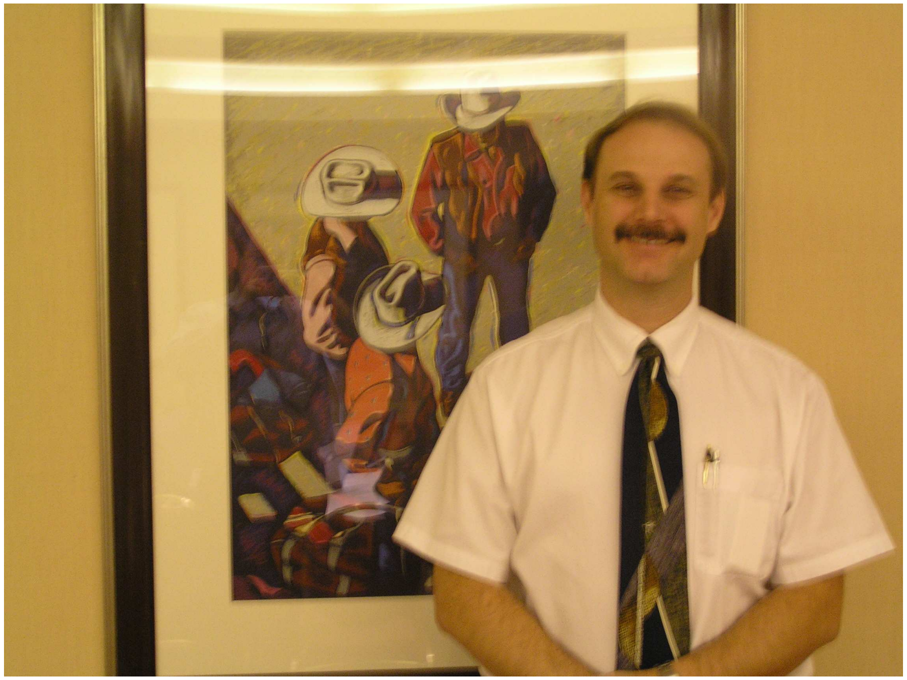
- Standards creation

Scott Seidel

Dr. Seidel has an extensive background developing leading-edge wireless communications technology and systems. He led Raytheon’s autonomous dynamic spectrum access algorithm and architecture development on DARPA's XG program. In 2003, Dr. Seidel received Raytheon's prestigious Excellence in Technology award for his work on the Future Combat System Communications Networking team. He received his Ph.D. in Electrical Engineering from Virginia Tech University. His research interests include design and analysis of dynamic spectrum sharing, adaptive communications, mesh networks, radiowave propagation, and cognitive radio. He is currently chair of the Cognitive Applications Special Interest Group of the SDR Forum.

John Polson

John Polson is a system engineer for the Communication Networks Division of General Dynamics C4S. He holds a Ph.D. in Electrical Engineering from New Mexico State University. His research interests are in software defined radio systems, systems architecture, and signal processing applications.



Thomas Rondeau

Tom Rondeau is a Ph.D. student with The Center for Wireless Telecommunications at Virginia Tech. He graduated summa cum laude in May of 2003 with a BS in E.E. and a minor in English literature. His current research is in cognitive radios to open access to spectrum and create robust communication links for disaster response and military response. He has been developing a cognitive radio engine, implementing new approaches to machine intelligence, and is researching the benefits of distributed intelligence to cognitive radio networks.

Tom is currently an IREAN Fellow at Virginia Tech.

David Maldonado

David Maldonado is a Ph.D. student with The Center for Wireless Telecommunications at Virginia Tech. He obtained his BS from the University of Puerto Rico, Mayaguez and a MS from Virginia Tech University. While working for both Ericsson and Anritsu companies, David was involved on the development of new wireless technologies. As part of the Cognitive Wireless Technology group, he is currently involved on the design and development of a CR for public safety use. In addition, he is responsible for the development and implementation of the policy engine.

David is currently an IREAN Fellow at Virginia Tech.

Intelligent Algorithms for Cognitive Radios

Thomas W. Rondeau

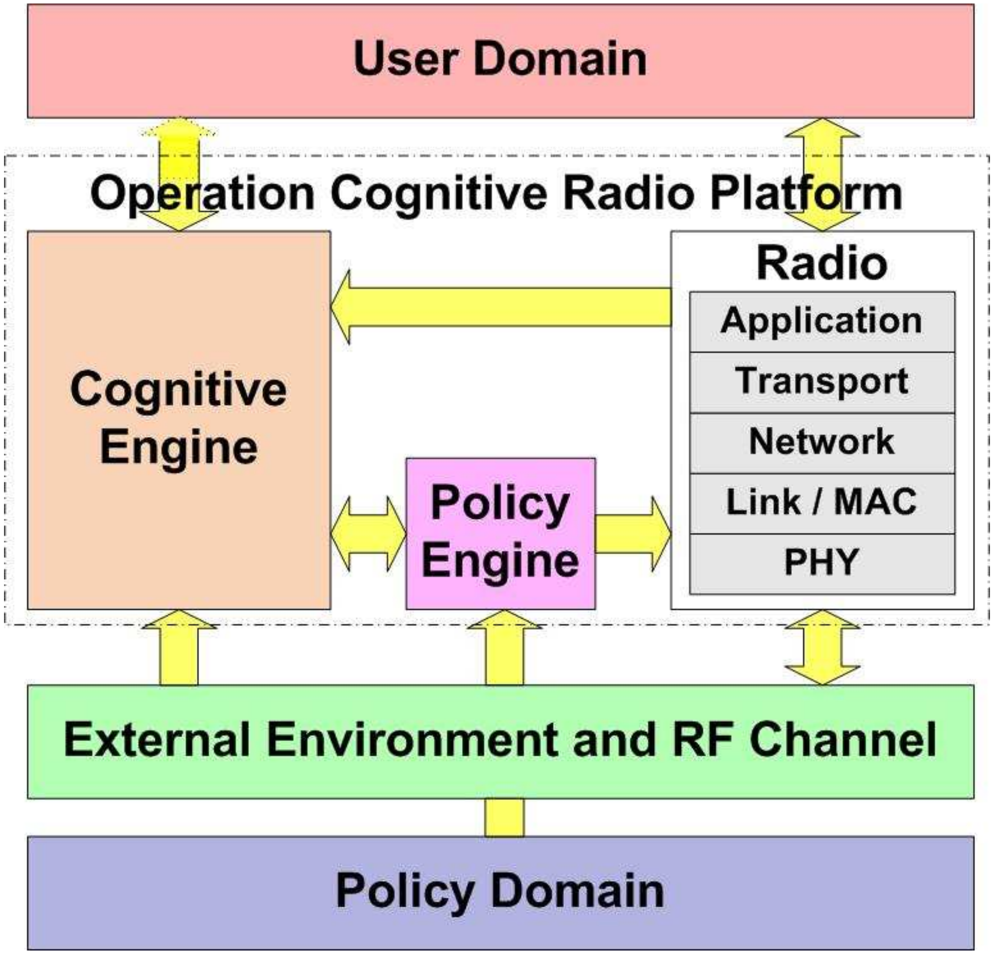
Center for Wireless Telecommunications (CWT)
Virginia Tech
Blacksburg, VA, 24061

The primary function of a cognitive radio is optimization.

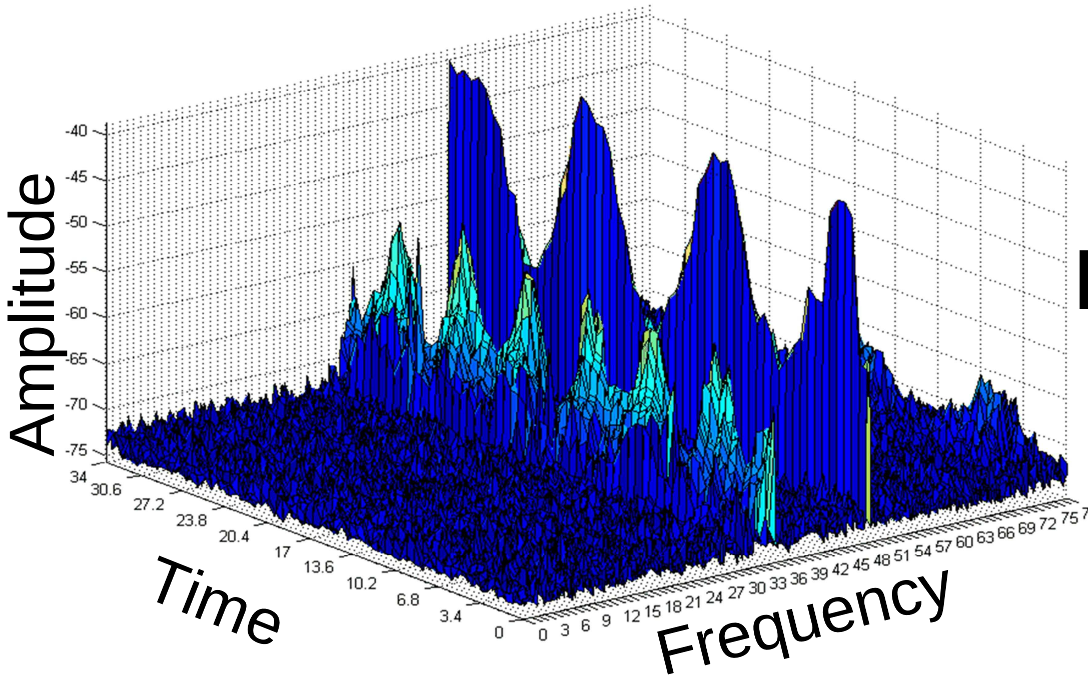
Optimization on all levels

And over multiple objective functions

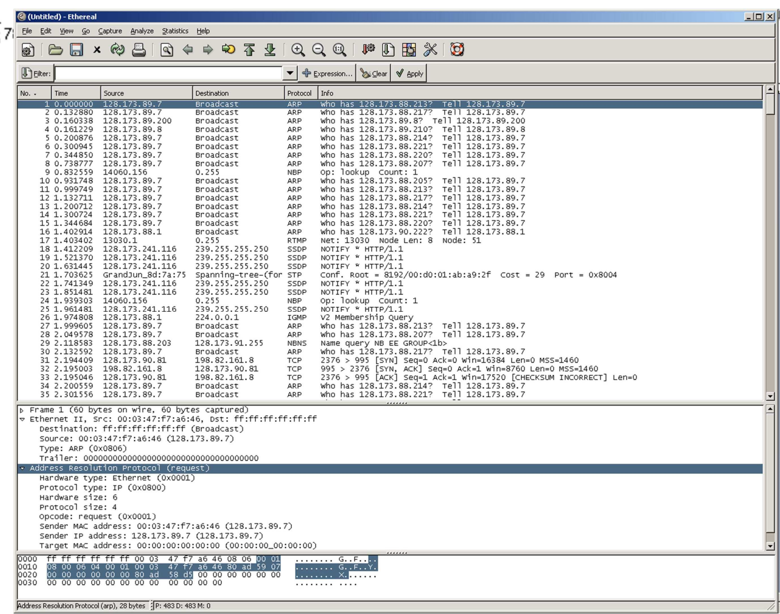
All other functions are necessary, but secondary



All systems associated with the cognitive radio provide important functionality.

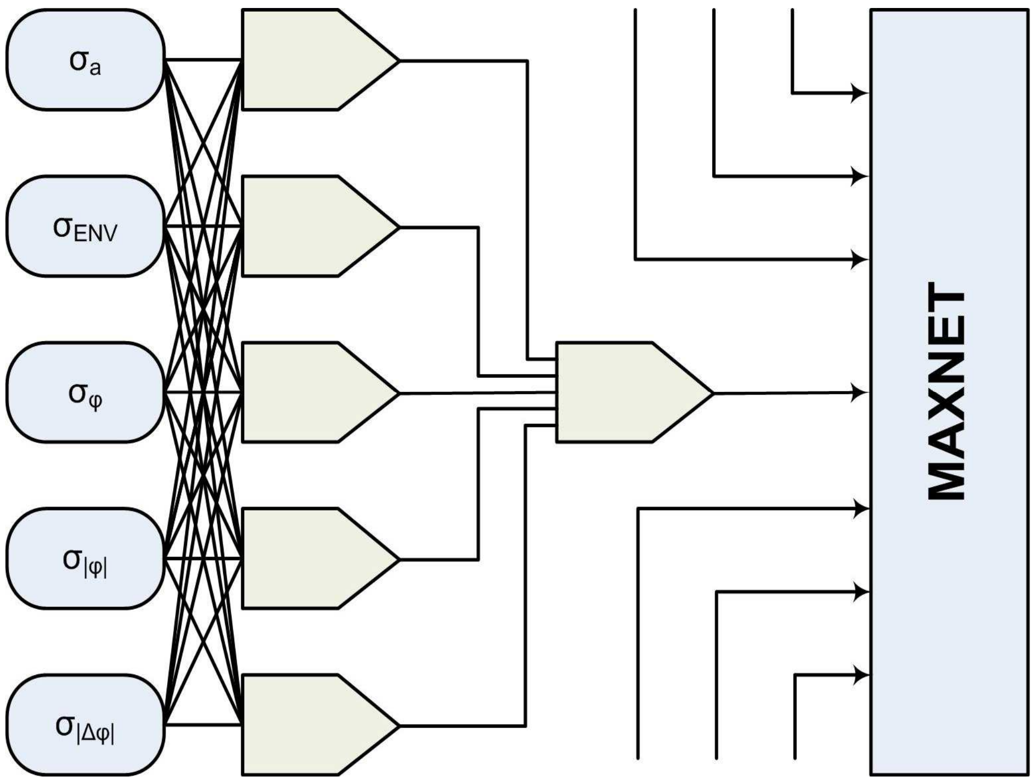


Environmental data



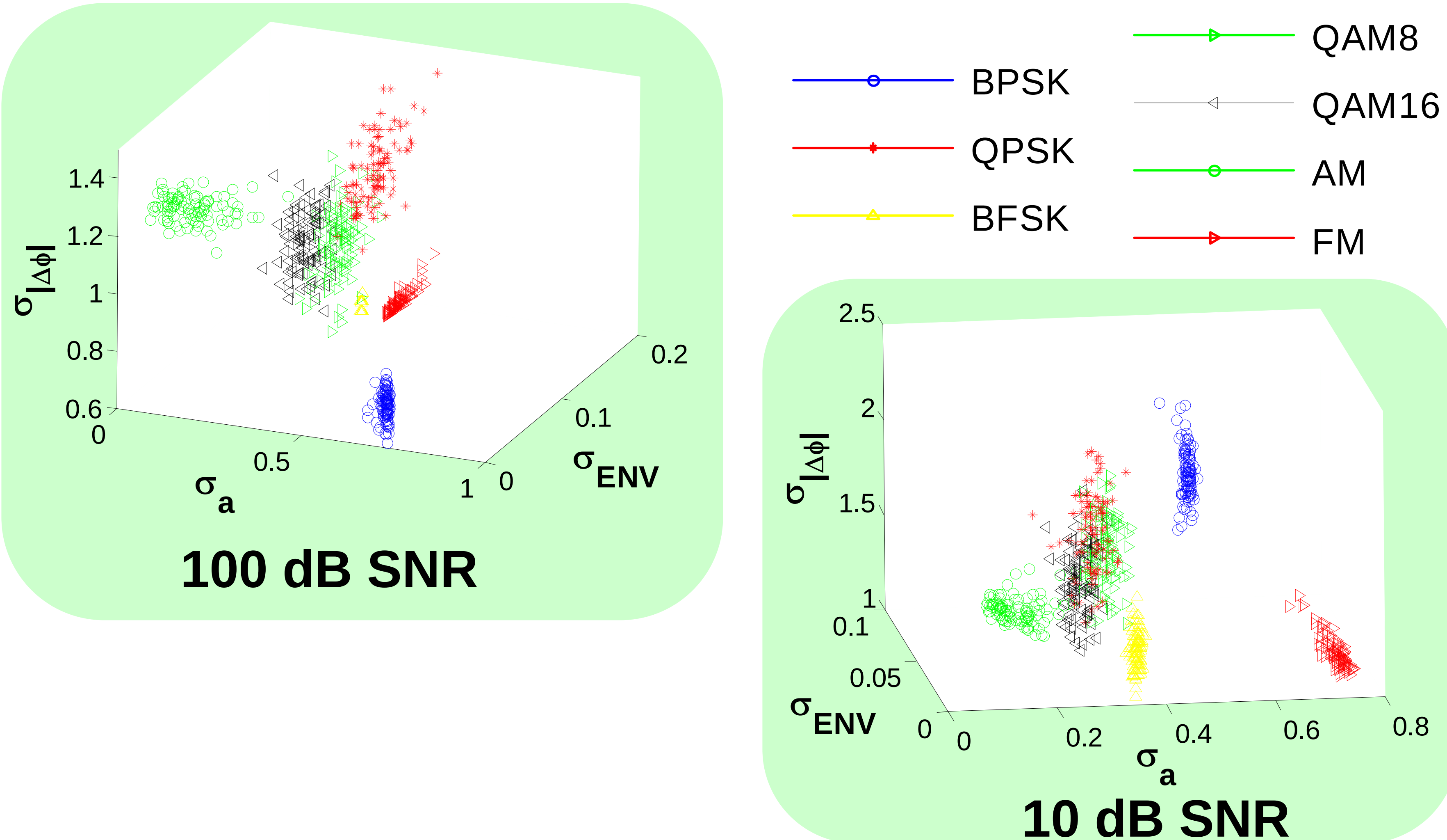
User/networking data

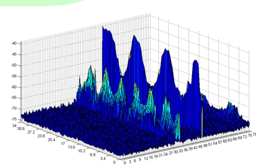
The external data provides environmental context to the solution.



Neural networks are great at pattern recognition

We have applied neural networks to modulation and signal classification.



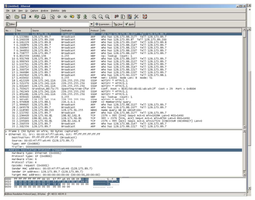


The user/networking model provides subjective needs from the solution.

IP Packet capture:

00	0f	1f	c0	42	6c	00	0c	41	80	a6	3a	08	00	45	00
05	dc	02	4e	40	00	2e	06	91	cf	c7	e8	29	0a	c0	a8
01	64	00	50	04	43	6b	21	3f	b7	50	b8	15	18	50	10
19	20	24	a4	00	00	09	09	09	3c	61	20	68	72	65	66
3d	22	6e	65	77	73	2e	68	74	6d	6c	22	3e	4d	6f	72
65	20	4e	65	77	73	2e	2e	2e	3c	2f	61	3e	0a	09	09
09	09	09	3c	2f	6c	69	3e	0a	0a	09	09	09	09	3c	2f
75	6c	3e	0a	0a	09	09	3c	2f	64	69	76	3e	0a	0a	09
09	3c	68	32	3e	49	6e	74	72	6f	64	75	63	74	69	6f
6e	3c	2f	68	32	3e	0a	0a	09	09	3c	70	3e	0a	09	09
09	47	4e	55	20	52	61	64	69	6f	20	69	73	20	61	20

Although it looks random, the patterns of protocol headers can be learned by a machine.



Application: Port 80 (HTTP)

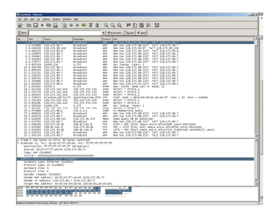
Transport Layer: TCP

Network Layer: IP

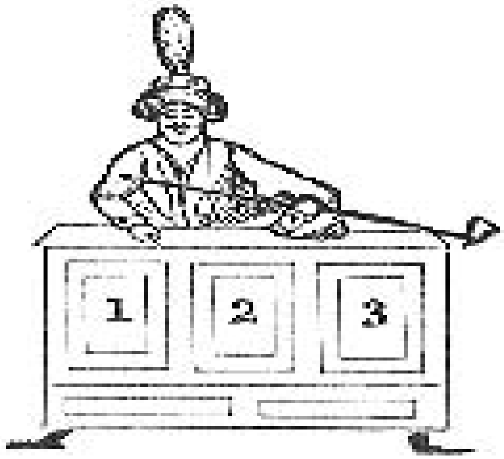
00	0f	1f	c0	42	6c	00	0c	41	80	a6	3a	08	00	45	00
05	dc	02	4e	40	00	2e	06	91	cf	c7	e8	29	0a	c0	a8
01	64	00	50	04	43	6b	21	3f	b7	50	b8	15	18	50	10
19	20	24	a4	00	00	09	09	09	3c	61	20	68	72	65	66
3d	22	6e	65	77	73	2e	68	74	6d	6c	22	3e	4d	6f	72
65	20	4e	65	77	73	2e	2e	2e	3c	2f	61	3e	0a	09	09
09	09	09	3c	2f	6c	69	3e	0a	0a	09	09	09	09	3c	2f
75	6c	3e	0a	0a	09	09	3c	2f	64	69	76	3e	0a	0a	09
09	3c	68	32	3e	49	6e	74	72	6f	64	75	63	74	69	6f
6e	3c	2f	68	32	3e	0a	0a	09	09	3c	70	3e	0a	09	09
09	47	4e	55	20	52	61	64	69	6f	20	69	73	20	61	20

Checksum and end of header

Data

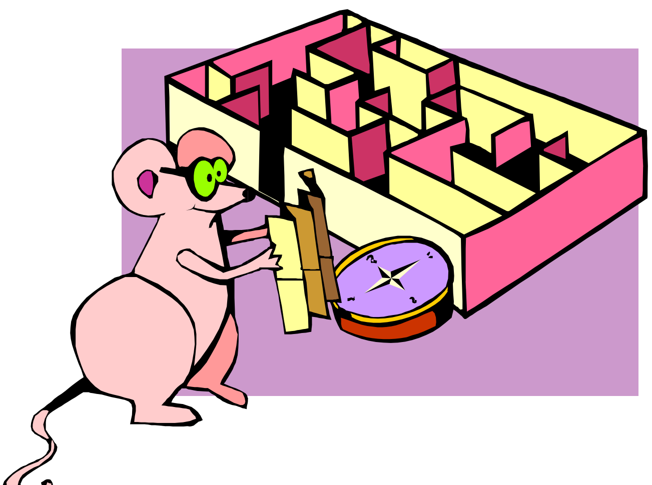


Optimization and feedback information aid in creating intelligent systems.



Multi-objective optimization

Feedback and memory



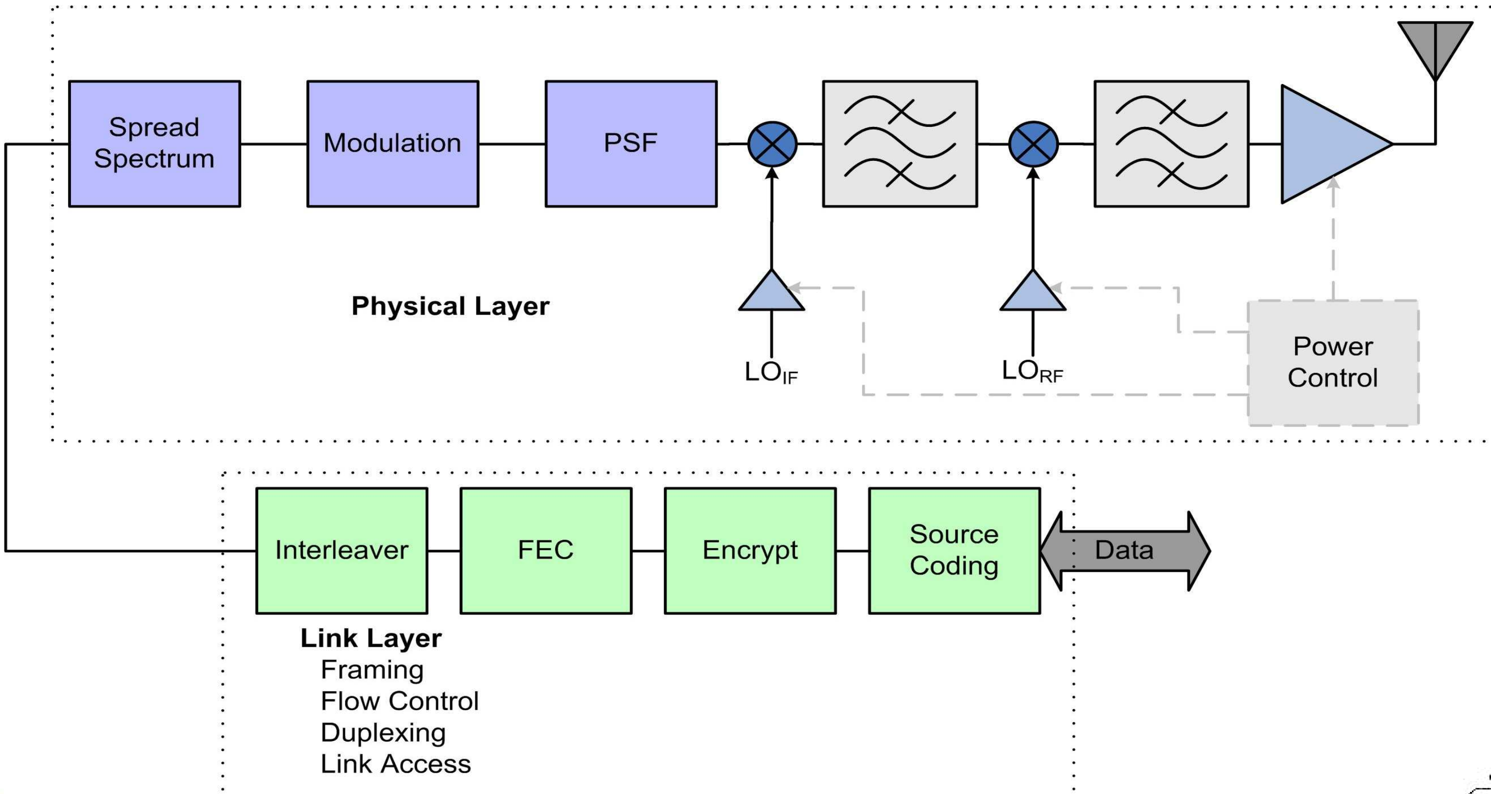
General learning concepts

Multi-objective optimization: learn to properly respond to situations

Adjust inputs: knobs

PHY Layer: power, frequency, symbol rate, modulation

MAC Layer: FEC, source coding, flow control, link access



Multi-objective optimization: learn to properly respond to situations

Produce desired outcomes: meters

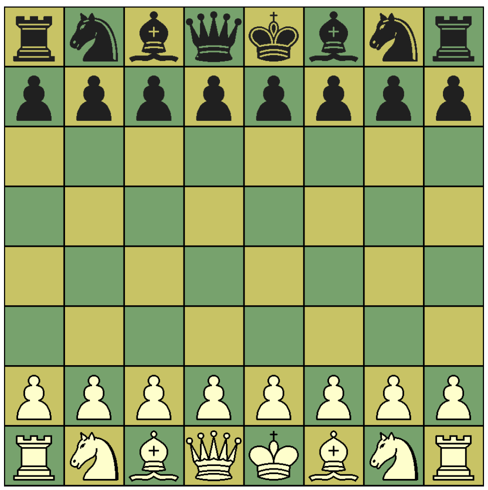
PHY Layer: BER, spectrum occupancy, SINR, symbol rate

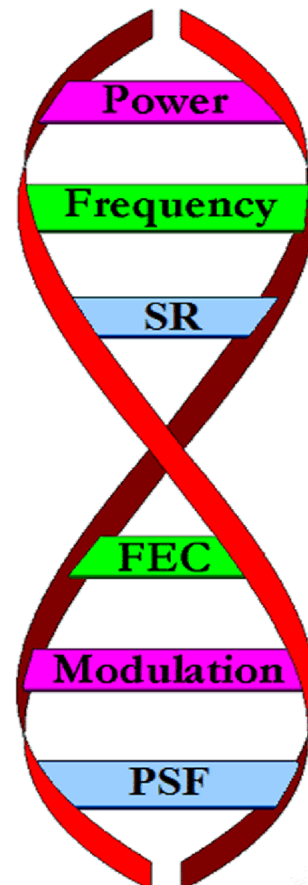
MAC Layer: FER, data rate, delay

General: computational complexity, power consumption

Biologically-inspired algorithms are highly adept at multi-objective optimization

Parallel analysis of solutions and dimensions



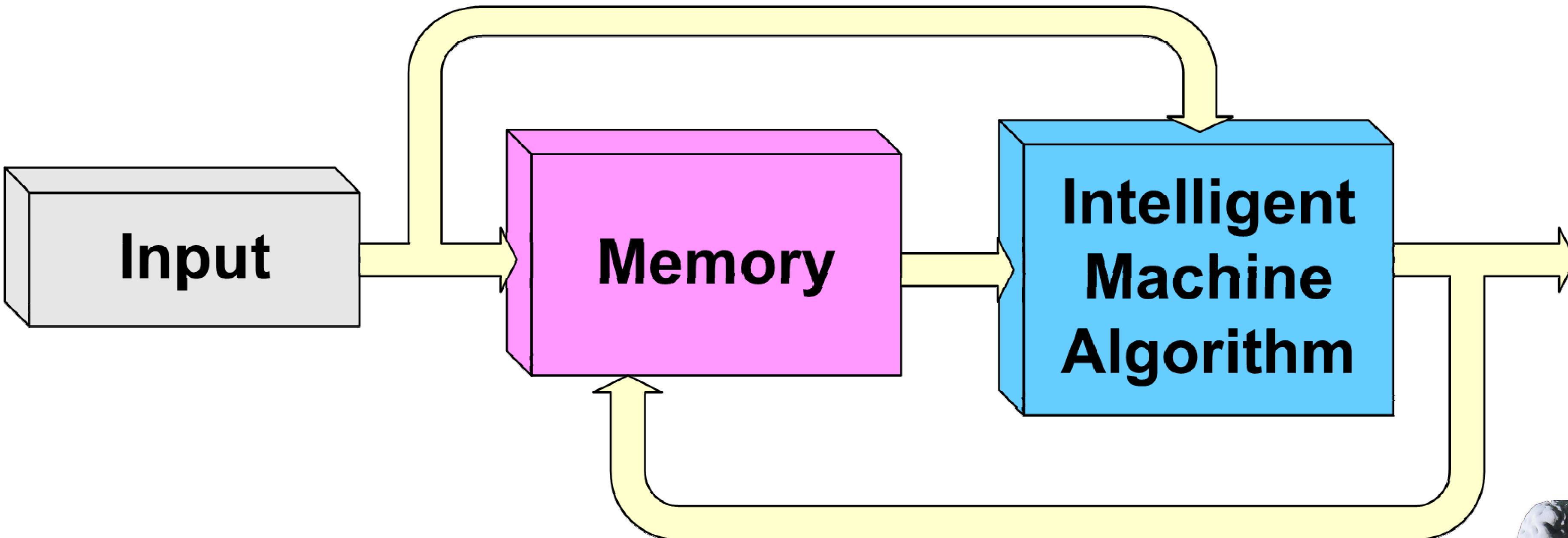


Creative solutions

Problems with long convergence times or suboptimal convergence

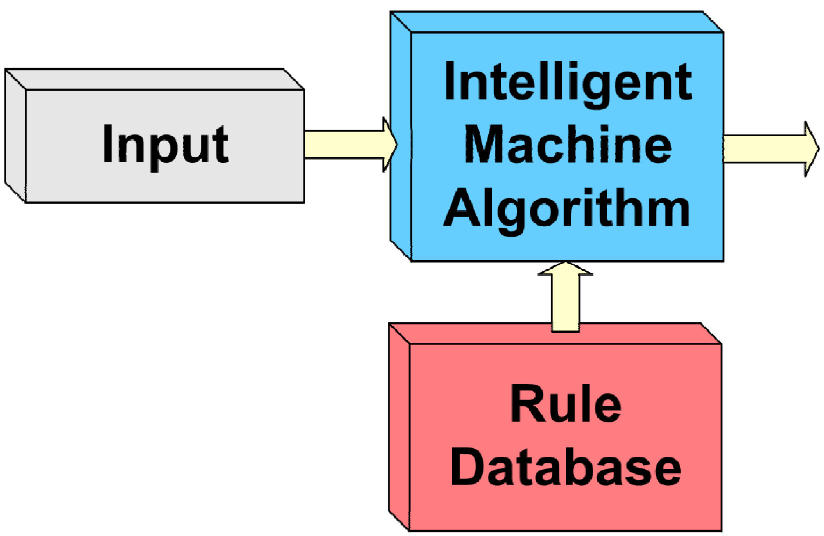
Feedback & memory improve performance by reapplication of knowledge.

Case-based systems feed information back to the algorithms to improve performance.



Feedback & memory improve performance by reapplication of knowledge.

Rule-based (expert) systems know things *a priori* for application immediately.

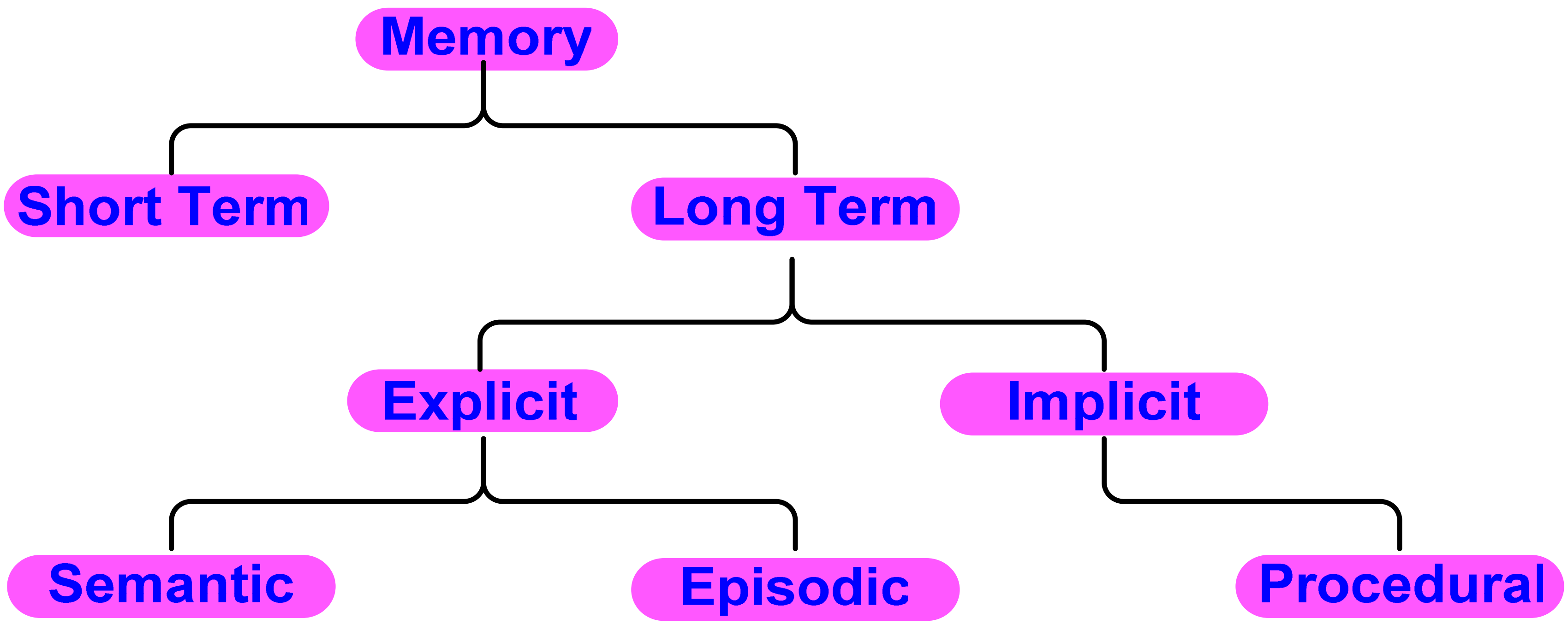


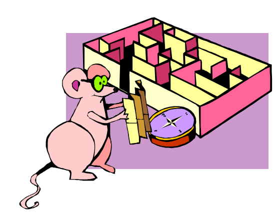
- Piece movement
- En passant
- When / how to castle
- When / how to draw
- Checks / check mates
- Relative value of each piece

General learning concepts: Everything is a trade-off

Supervised vs. unsupervised learning

Domain-specific knowledge vs. generalizations





The Dream…

The Renaissance Radio

The Reality (?) ...

The Enlightened Radio

Final Thoughts

Share and combine your knowledge

Bacon

Newton

Locke

We cannot forget that CR implementation has two parts to it

- Objectives
  - User requirements
    - User service preference, e.g. speed and WiFi
    - User security guarantee
    - User (local) access facilities
- Constraints
  - Hardware
  - Policy and regulations
    - Communication standards and protocols
    - Network (system) noise floor and dynamic range

Awareness and sensing

Self-awareness

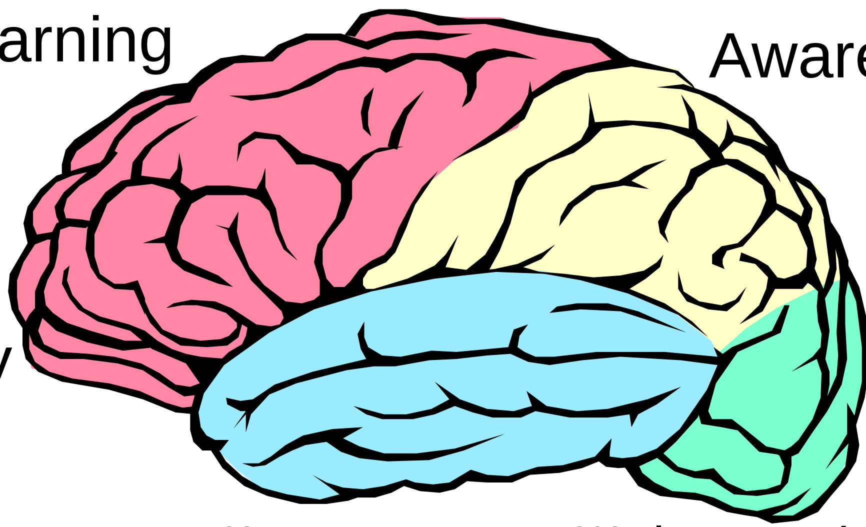
- Who am I?
  - Radio resource configuration
    - Analog/digital signal processing capacities
  - Self feature recognition, e.g. battery powered?
  - Standard and protocol recognition and handling
  - Service compatibility in hybrid network

External awareness

- What does the user wants?
- Where am I?
  - Environment learning and identification
  - Policy and regulations

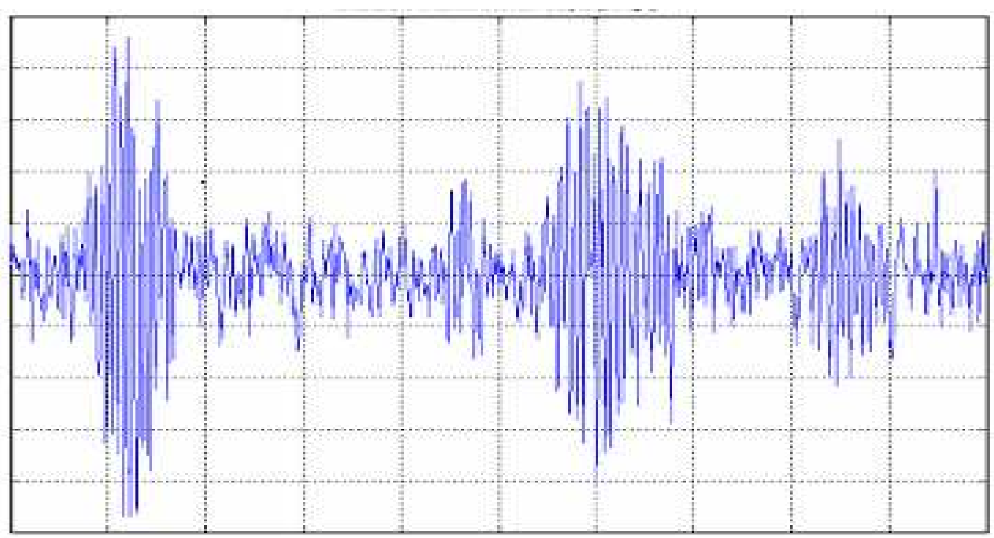
Cognitive Radio has an ugly side

- Pitfalls
  - Complexity
  - Computational power requirements
  - Carries all the existing standards' limitations
  - Cost



Things we need improvements on

- Standard way to quantify interference (IT)
- Signal/channel classification
- Cross layer optimization
- Hidden node problem
- Algorithm efficiency (DSP)
- Hardware Cost
- Intelligence!



Spectrum agility and/or efficiency is not the only dimension of CR's optimization

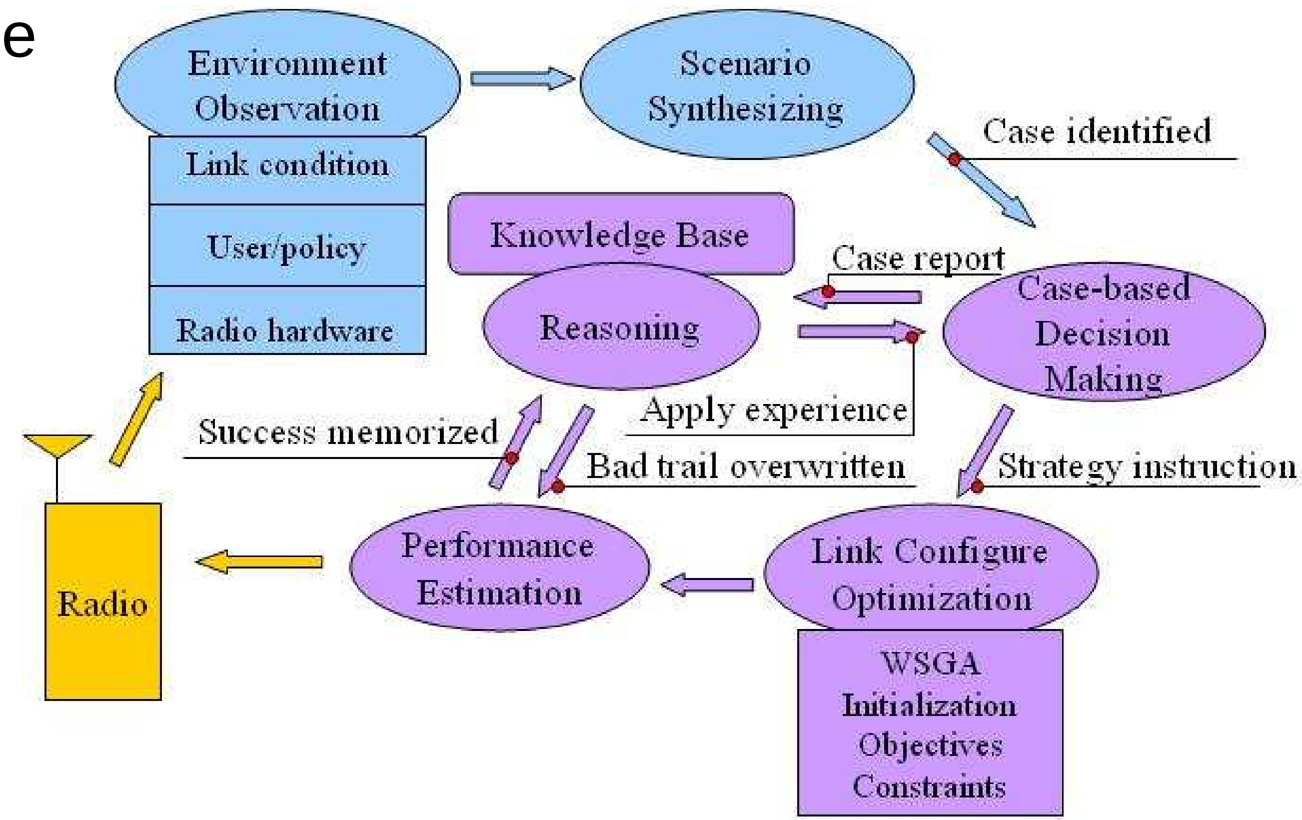
- Interoperability
- Personalized service
  - Learns from the user
  - Learns geographical patterns of signal strengths
- Multi-network selection

Can we make it hardware independent?

How much is too much?

- To have awareness
- Create Knowledge
- Make decisions
- Adapt

- Is it possible?



Time is not slowing down!

What metric could be use to compare cognitive radios?

- Measured performance with respect to an application
  - Spectral efficiency (BW), Data Rate (throughput), power, MIPS required for both waveform generation and algorithm convergence
- Intelligence – Radio IQ
  - The total amount of known usable information, the speed of decision making, the accuracy of decisions

Closing Thoughts

"It's dangerous to put limits on wireless."

-Guglielmo Marconi, 1897

(invented the wireless telegraph)

Thanks to…

This work was supported by the National Science Foundation under awards *9983463* and *DGE-9987586*.

Questions?