ECE 693 – Special Topics:
AI for Radar System Design

Enabling (Hardware) Technologies for Cognitive Radar

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Needed Advancements

- Adaptable Antenna Technologies
- Wideband Adaptable RF Components
- High Performance Edge Computing Platforms
- Experimental Testing and Validation

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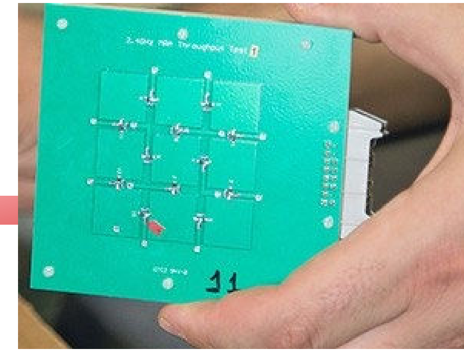
Adaptable Antenna Technologies

- Reconfigurable Antennas
  - Antenna capable of modifying dynamically its frequency and radiation properties in a controlled and reversible manner
  - To provide a dynamical response, reconfigurable antennas integrate an inner mechanism, such as RF switches, varactors, mechanical actuators or tunable materials, which enable the intentional redistribution of the RF currents over the antenna surface

Types of Antenna Reconfiguration

- Frequency Reconfiguration
  - Adjust dynamically the frequency of operation
- Radiation Pattern Reconfiguration
  - Modification of spherical distribution of radiation pattern
- Polarization Reconfiguration
  - Switching between different polarization modes
- Compound Reconfiguration
  - Capability of simultaneously tuning several different antenna parameters, e.g. frequency + radiation pattern

Multifuctional Reconfigurable Patch Antenna Example



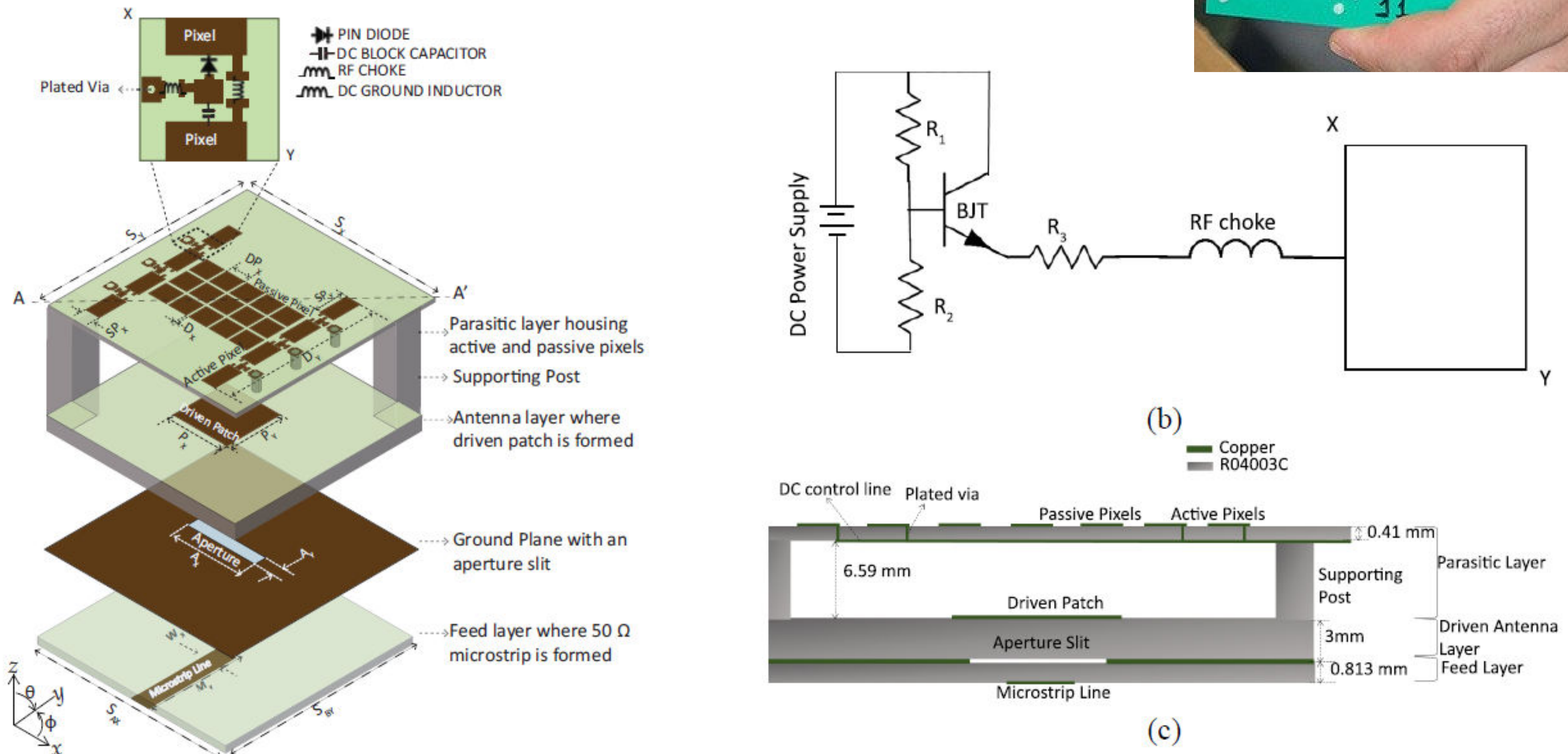


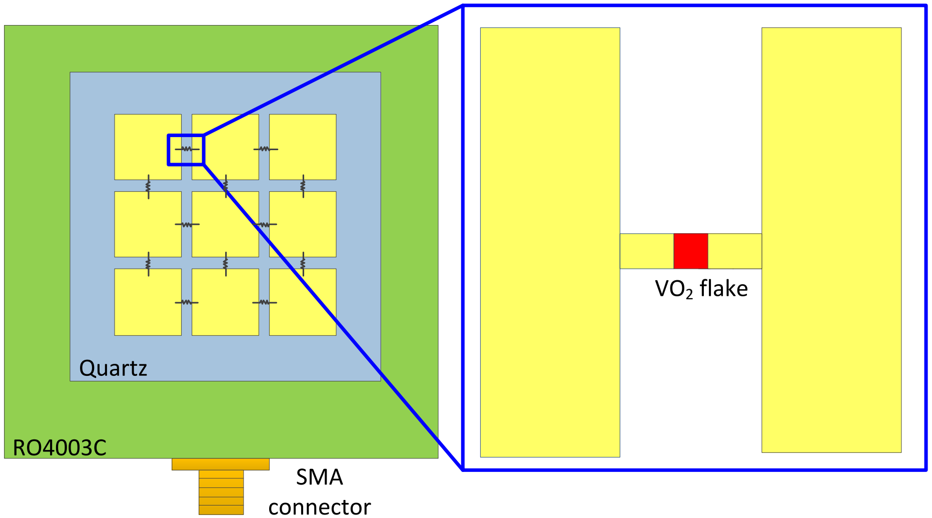
Fig. 1: (a) 3D exploded view of the RA, (b) DC biasing scheme of the PIN diode, and (c) AA' plane cross section of the RA

(Courtesy of Bedri Cetiner, Utah State University)

Number of Modes

- Number of possible antenna modes = (number of switch statates)$^{\text{(number of interconnections)}}$
  - 2^{24} (for 4x4 pixels, using binary switches)
  - 3^{24} (for 4x4 pixels, using three level of couplings)

How Does it Work?



- VO_2: grown using chemical vapor deposition techniques in the form of flakes
- Transferred on the pixel-antennas
- Resistivity tuning controlled via heating
- The resistivity changes at 65 °C:
  - ON state: $2.5 \times 10^{-6}\ \Omega$.m (conductor)
  - OFF state: $5 \times 10^{-2}\ \Omega$.m (insulator)

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MRA Example, cont.

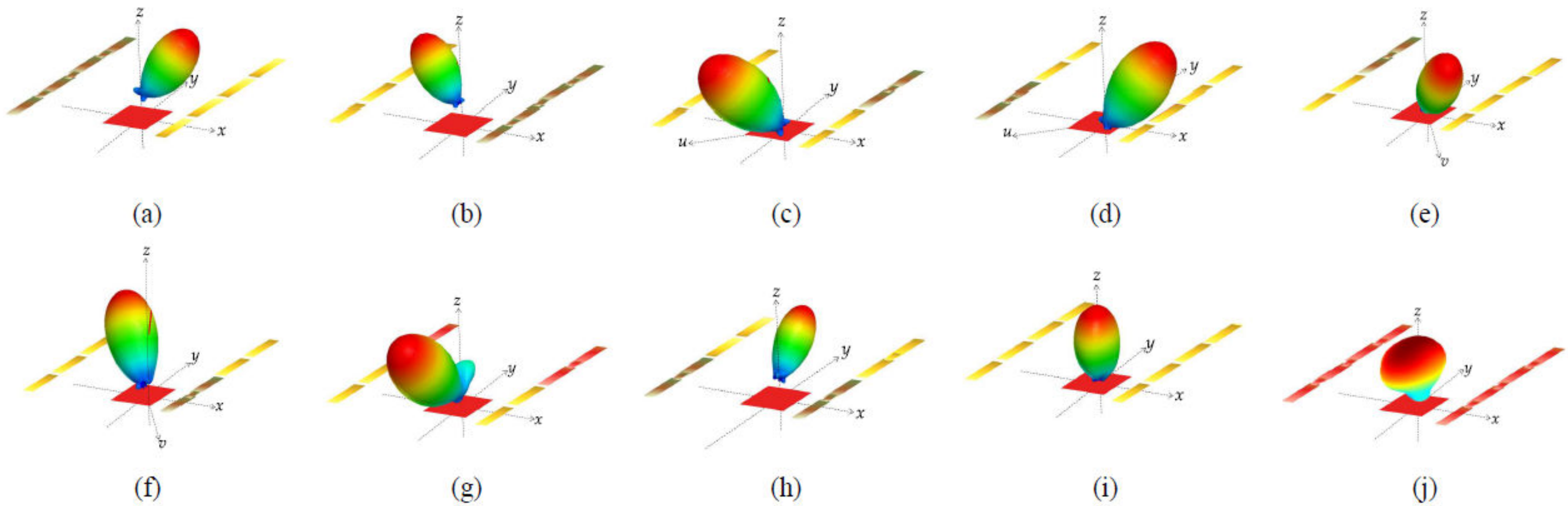
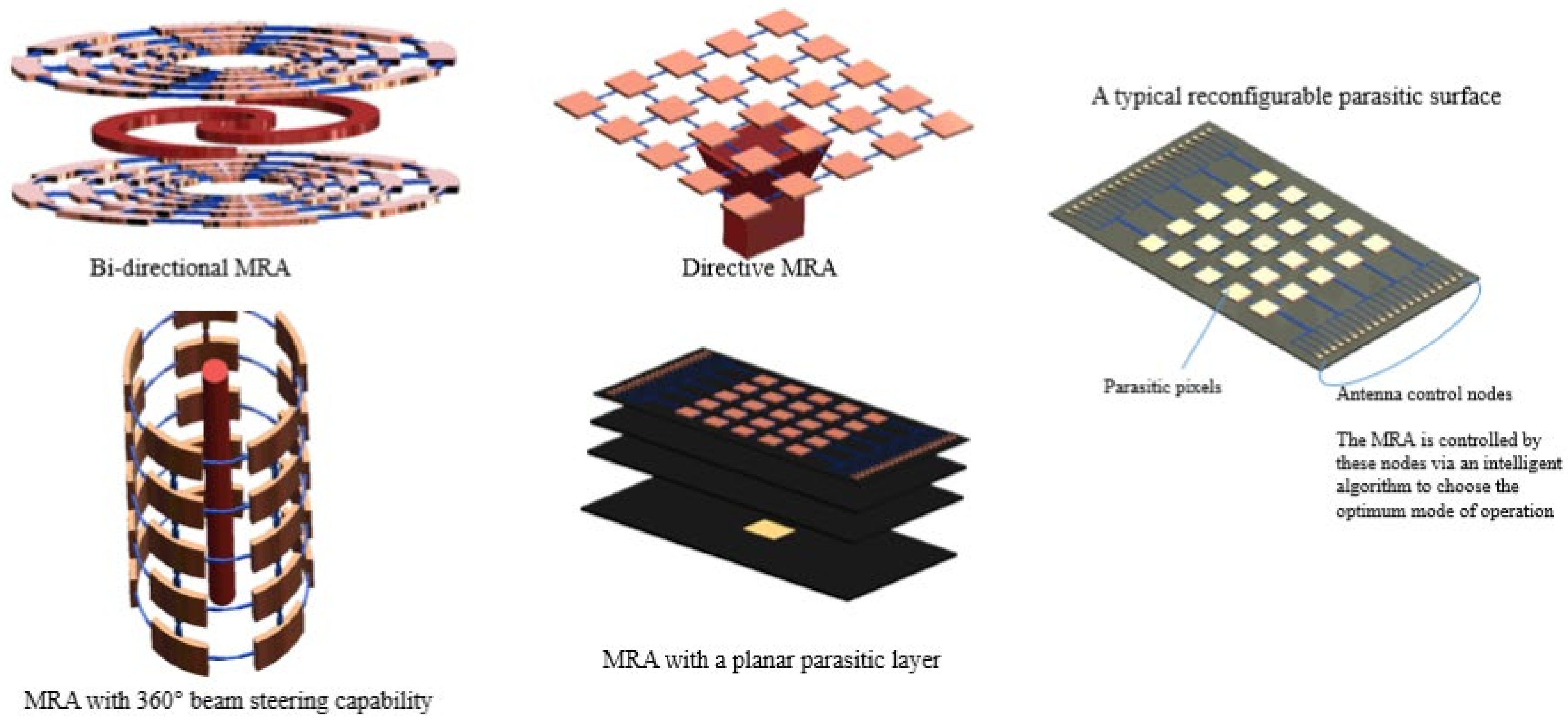


Fig. 4: Representative radiation patterns in dB scale for beam steering toward (a) $+x$ (b) $-x$ (c) $+u$ (d) $-u$ (e) $+v$ (f) $-v$ (g) $-y$ and (h)$+y$ direction, and (i) narrow and (j) broad beamwidth. Yellow colored pixels are disconnected and red colored pixels are connected.

Reconfigurable Parasitic Surfaces



Various active antenna and reconfigurable parasitic surfaces

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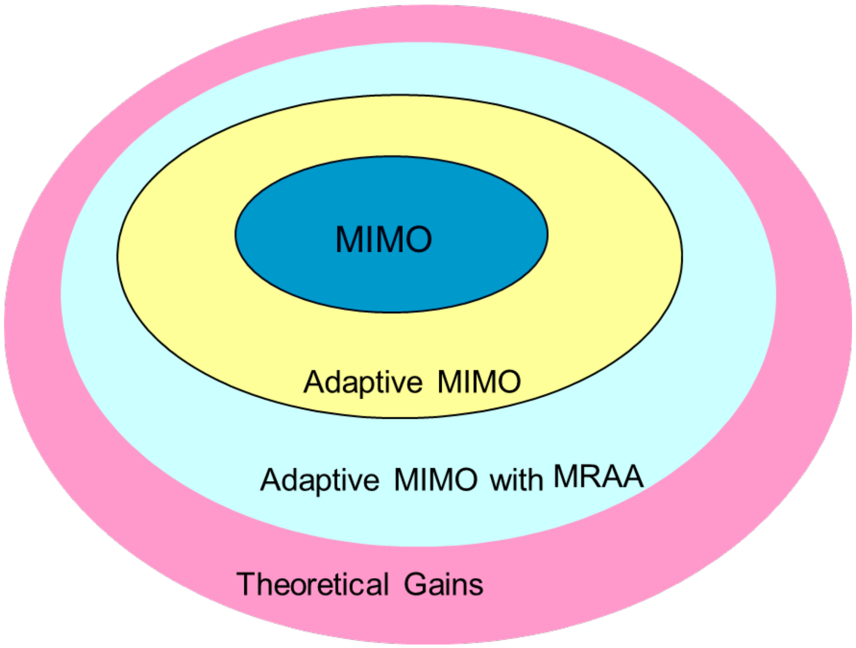
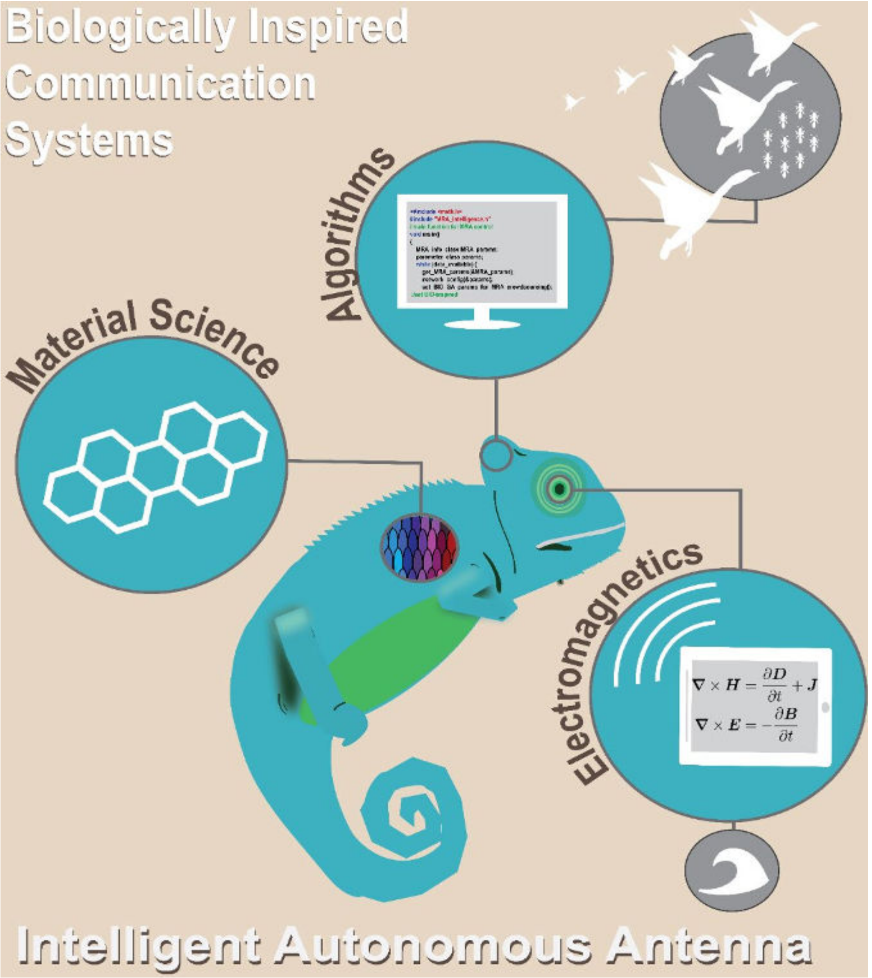
Comparison with Conventional Technology



- Cognitive Radio, i.e., Smart Antenna
  - Focus is on the Signal Processing algorithms
    - SM, TD, Beamforming w.r.t. channel variations
  - The properties of the antennas are fixed by initial design
    - Antennas are not smart
- Proposed MRA Systems
  - Joint optimization of MRA properties and signal
  - processing parameters w.r.t channel variations
    - Intelligent Algorithm development

R&D Vision



- A unified approach: Seamless integration
  - electromagnetics
  - intelligent algorithms
  - material sciences
- Establish intelligent autonomous antennas for next generation wireless communications systems

Adaptive Antenna Arrays

- Have a copy of desired signal *d*
- Error = difference between filter output and reference
- Vary weights to minimize m.s.e.

$$e(t) = d(t) - y(t) = d(t) - \mathbf{w}^H \mathbf{x}(t)$$

(Drop the time dependence for now)

$$E\left[|e|^2\right] = E\left[\left|d - \mathbf{w}^H \mathbf{x}\right|^2\right]$$

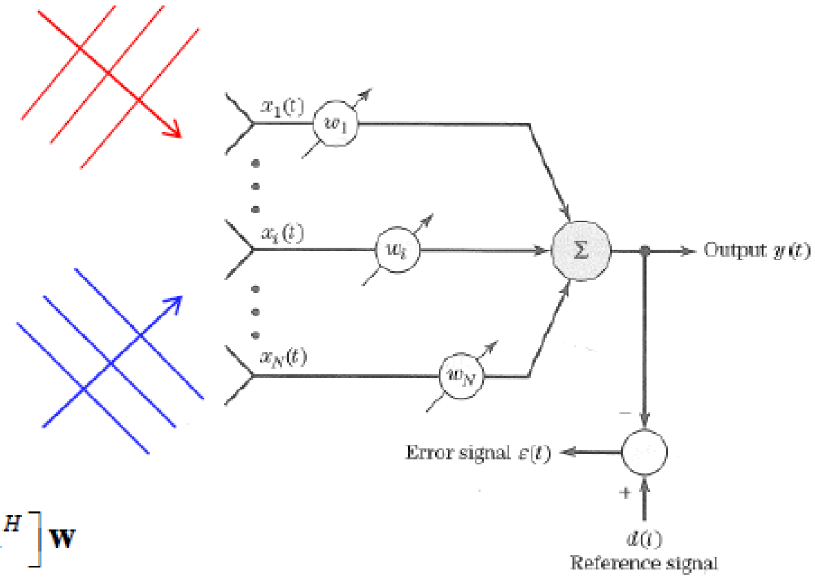
$$= |d|^2 - E\left[d^* \mathbf{w}^H \mathbf{x}\right] - E\left[d \mathbf{x}^H \mathbf{w}\right] + \mathbf{w}^H E\left[\mathbf{x}\mathbf{x}^H\right]\mathbf{w}$$

$$0 = \nabla_{\mathbf{w}} E\left[|e|^2\right] = -E\left[d^* \mathbf{x}\right] + E\left[\mathbf{x}\mathbf{x}^H\right]\mathbf{w}$$

$$0 = -\mathbf{r}_{xd} + \mathbf{R}_{xx}\mathbf{w}$$

$$\mathbf{w}_{opt} = \mathbf{R}_{xx}^{-1}\mathbf{r}_{xd}$$

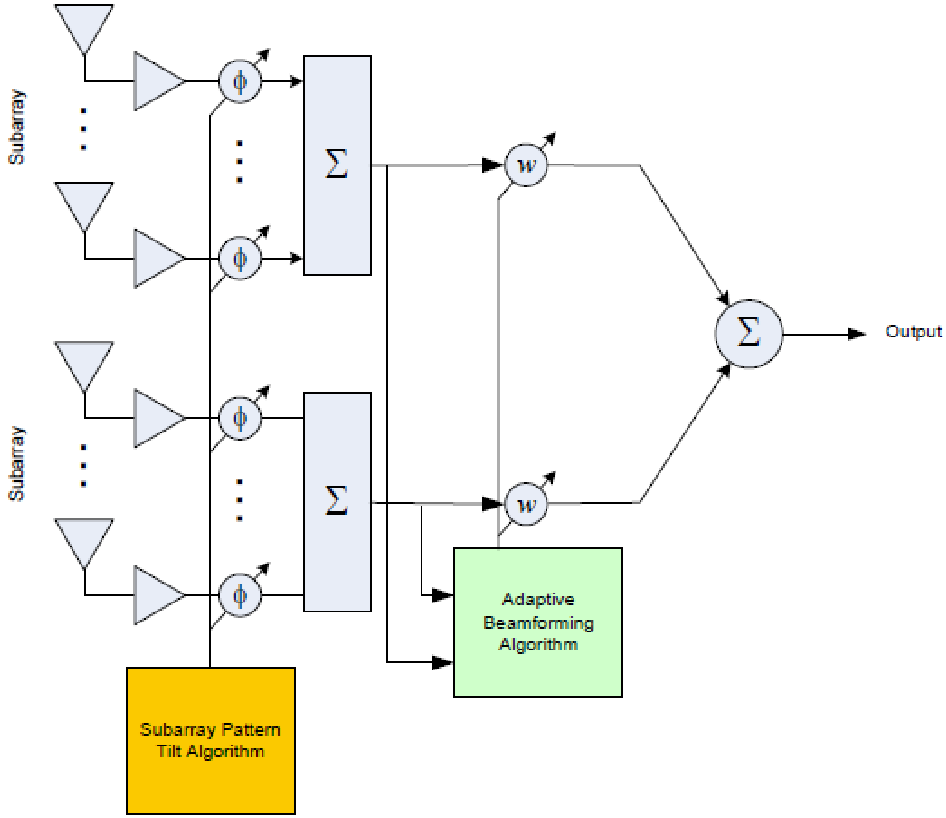
$$y(t) = \mathbf{w}_{opt}^H \mathbf{x}(t)$$



(Courtesy of Randy Haupt)

Adaptive Array of Steered Subarrays

- A simple type of partially adaptive array
  - Each adaptive element is a phased array
- Pros
  - Very low processing load
  - Retrofits to existing system
  - Provides nulling
- Con
  - Can suffer from grating lobes
- Will show an example later



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Array of MRAs (MRAAs)

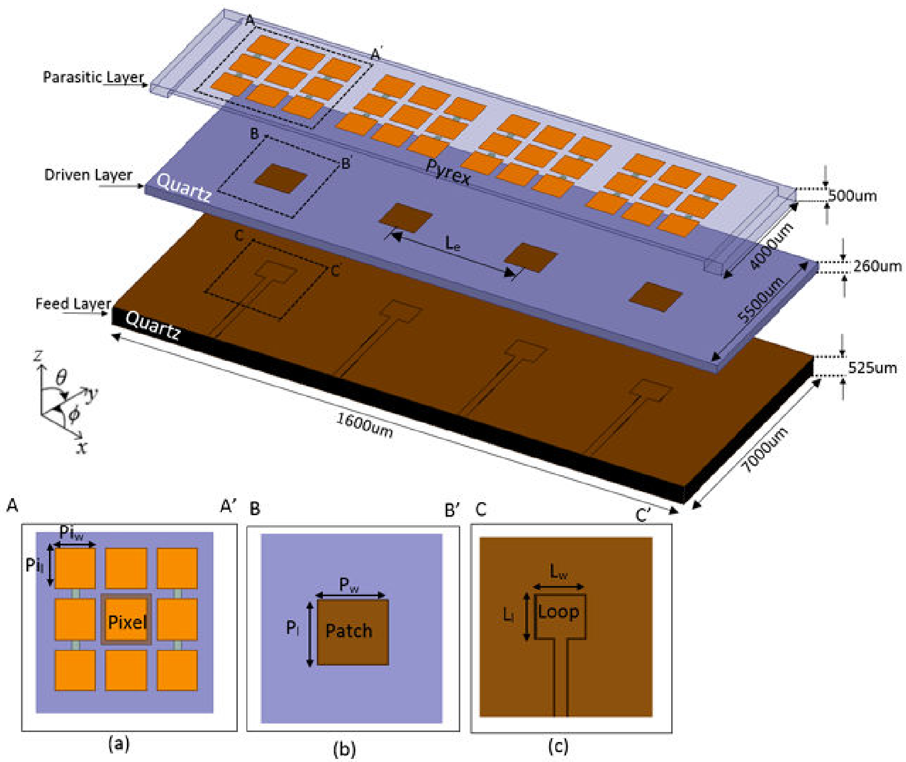
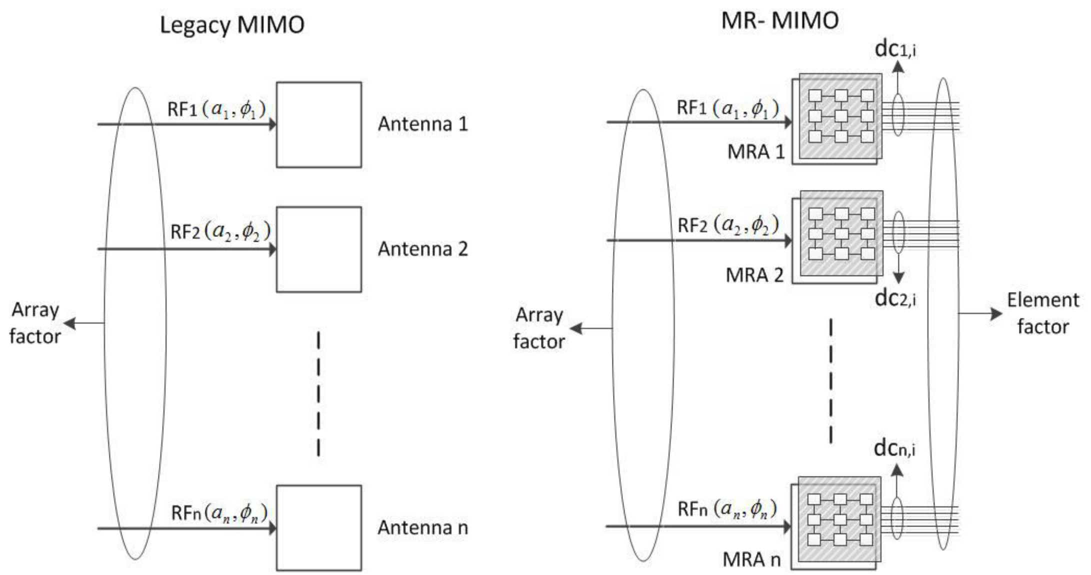


Fig. 6.1: Schematic of 3-D structure of 4×1 MRAA, (a) Enlarged A-A′, (b) Enlarged B-B′(c) Enlarged C-C′.

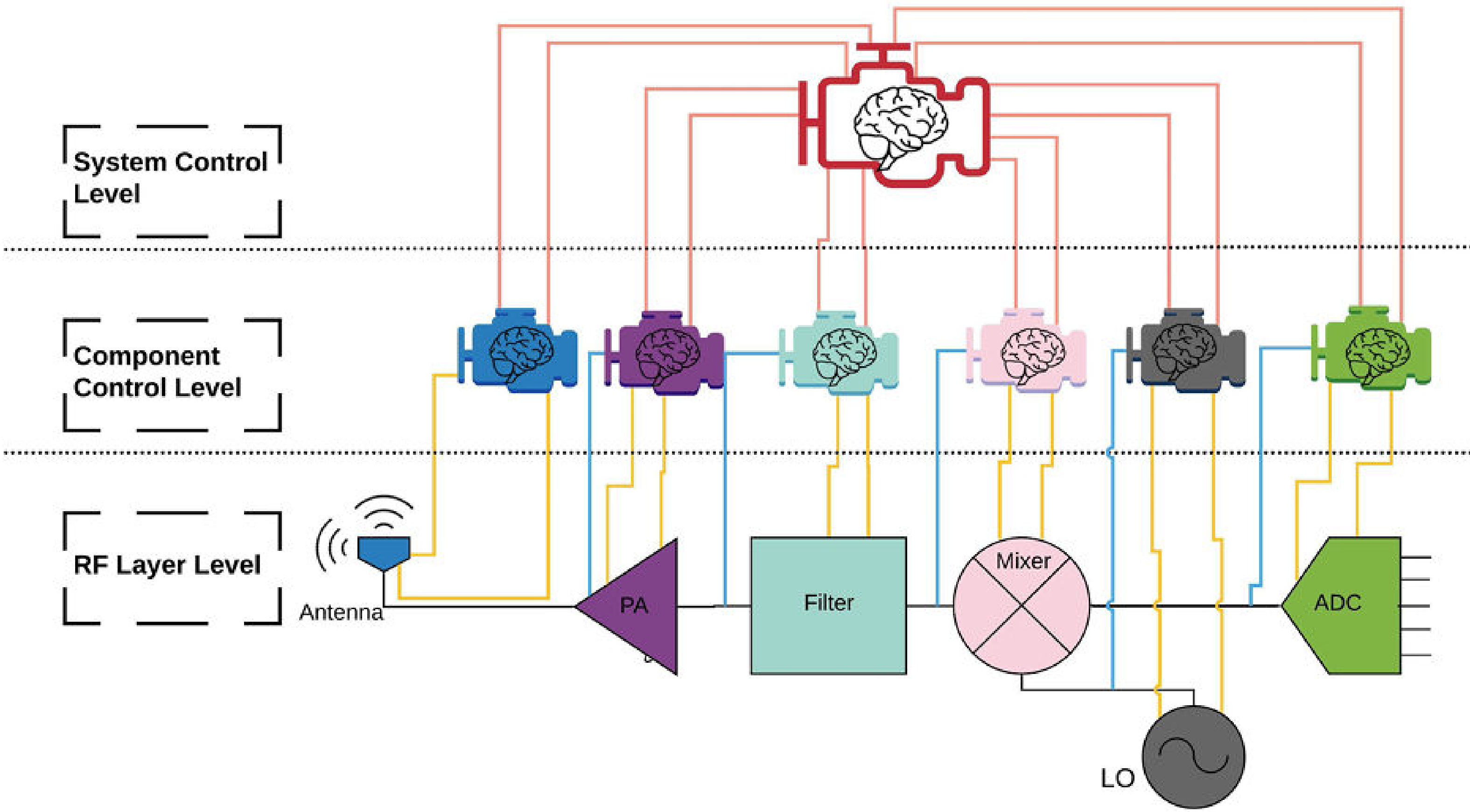
(Reconfigurable) RE-MIMO

Element Factor is changed intelligently in conjunction with array factor



Modifying the channel intelligently

CogRF: Cognitive RF System Design



CogRF: Tunable Elements

TABLE I
EXAMPLE RF CONTROLLABLE PARAMETERS

RF Component	Tunable Parameters
DAC/ADC	Sampling rate, number of bits per sample
LNA	Gain, current bias
LO	Oscillator frequency, drive level
Filter	Selectivity, operational frequency, bandwidth
Power amplifier	Voltage and current bias, antenna loading
Antennas	Excitation amplitude, phase, matching

AI for Circuit Reconfiguration

DEEPAK

- A. Egbert, A. Goad, C. Baylis, A. F. Martone, B. H. Kirk and R. J. M. Ii, "Continuous Real-Time Circuit Reconfiguration to Maximize Average Output Power in Cognitive Radar Transmitters," in IEEE Transactions on Aerospace and Electronic Systems.
- C. Baylis, R. J. Marks, A. Egbert and C. Latham, "Artificially Intelligent Power Amplifier Array (AIPAA): A New Paradigm in Reconfigurable Radar Transmission," 2021 IEEE Radar Conference (RadarConf21), 2021.

Cognitive Radar Experimental Workspace (CREW)

Fig. 2: The CREW: left, the main equipment rack, and right, a single pair of transmit and receive heads.

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CREW Specifications

TABLE I: OPERATING PARAMETERS OF THE CREW.

Parameter	Value
Max Tx power	25 dBm
Frequency range	92 - 96 Ghz
Pulse Width	1ns to 100 μs
PRF	Up to 30 kHz
Waveform	Programmable pulse to pulse
Number of transmitters	4
Antenna gain (Tx & Rx)	33 dB
Antenna beamwidth	2°
Number of receivers	4
A/D – Keysight M9703A	Four 3.2 Gs/s 12 bits channels
Waveform generation – Keysight M8190A	12/14 bit resolution at 8Gs/s (14 bit) or 12 Gs/s (12 bit) and an SFDR of 90 dBc
Baseband convertor	Input freqs: 0.3 – 1.3 GHz Output freq: 5 – 6 GHz Transmit gain, 20 dB and noise figure 19 dB Receive gain, 12 dB and noise figure 5 dB

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Cognitive Radar Framework for Target Detection and Tracking

EMRE

- How can we develop a Bayesian framework to determine the optimum PRF that maximizes our ability to track a target with a cognitive radar?
- Theory Paper:
  - K. L. Bell, C. J. Baker, G. E. Smith, J. T. Johnson and M. Rangaswamy, "Cognitive Radar Framework for Target Detection and Tracking," in IEEE Journal of Selected Topics in Signal Processing, vol. 9, no. 8, pp. 1427-1439, Dec. 2015.
- Experimental Validation:
  - G. E. Smith et al., "Experiments with cognitive radar," 2015 IEEE 6th International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP), 2015

Cognitive Tracking with MRAAs

SEAN

- A. C. Gurbuz, R. Mdrafi and B. A. Cetiner, "Cognitive Radar Target Detection and Tracking With Multifunctional Reconfigurable Antennas," in IEEE Aerospace and Electronic Systems Magazine, vol. 35, no. 6, pp. 64-76, 1 June 2020.

Cognitive Object, Detection, Identification, Ranging (CODIR)

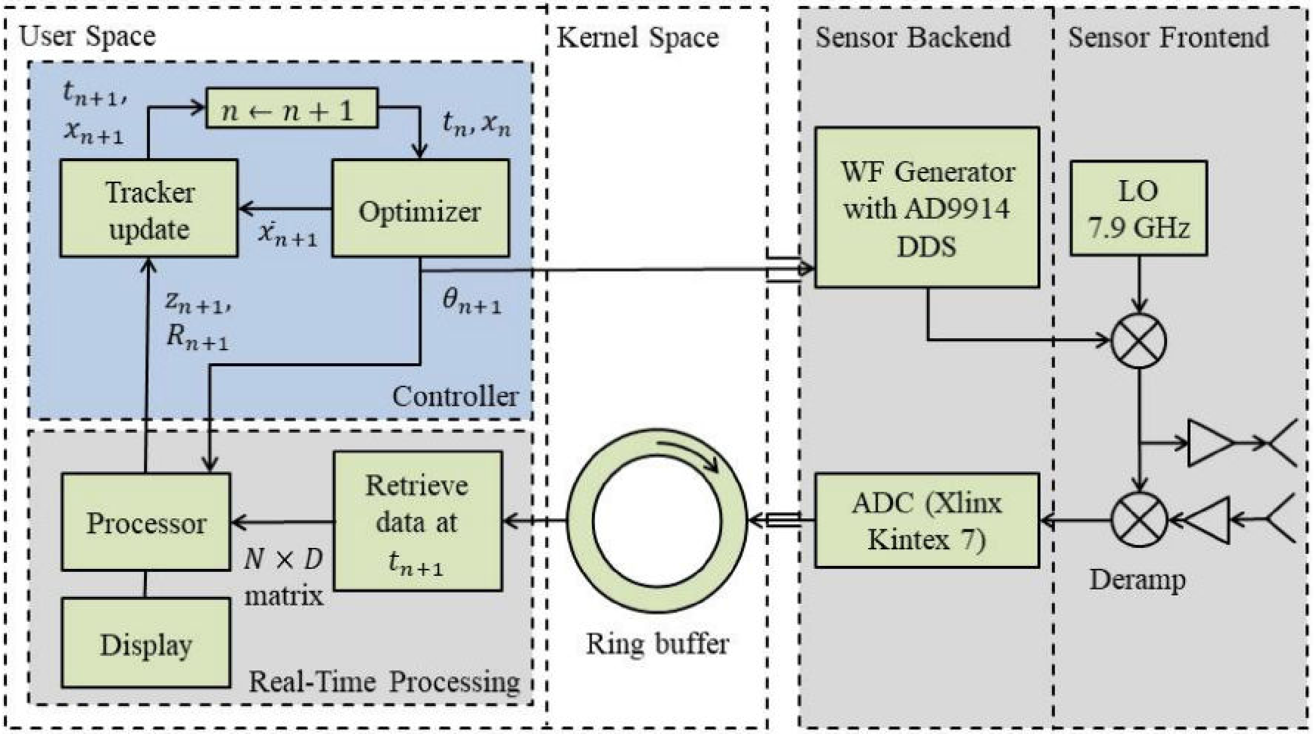

Figure 5-1: CODIR system functional block diagram. The system consists of the sensor and controller segment (colored in blue). The sensor is comprised of signal generator, HF frontend, AD conversion and data processor while controller (colored in blue) is comprised of the optimizer and the tracker. The black arrows represent the data flow and the scheduling of the cognitive feedback loop. The controller related quantities are explained in Sect. **

Cognitive Radar Experiments with CODIR

LADI

- R. Oechslin, U. Aulenbacher, K. Rech, S. Hinrichsen, S. Wieland and P. Wellig, "Cognitive radar experiments with CODIR," International Conference on Radar Systems (Radar 2017), 2017.
- R. Oechslin, P. Wellig, U. Aulenbacher, S. Wieland and S. Hinrichsen, "Cognitive Radar Performance Analysis with different Types of Targets," 2019 IEEE Radar Conference (RadarConf), 2019.

Canada's Efforts to Make a Large-Scale Radar System Cognitive

EDDIE

- Ponsford, A.; McKerracher, R.; Ding, Z.; Moo, P.; Yee, D. Towards a Cognitive Radar: Canada's Third-Generation High Frequency Surface Wave Radar (HFSWR) for Surveillance of the 200 Nautical Mile Exclusive Economic Zone. *Sensors* **2017**, *17*, 1588.

Challenges to T&E

- Requirements Definition
  - There are two approaches to cognitive optimization:
    - task-driven and
    - information-driven.
  - In the task-driven approach, performance quality of service (QoS) requirements are specified
    - They allow specification of multiple objectives in terms of tangible task requirements and/or mission requirements
  - In the information-driven approach, an information measure is optimized.
  - How can systems be evaluated when tasks and metrics depend on the waveform, which is dynamic?

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Challenges to T&E, cont.

- Robustness
  - Implications to electronic warfare
  - If you have a radar that learns, it can be deceived
  - How to know what is good data to learn from and what is deceitfully being presented by an enemy?
  - Can a radar unlearn bad habits? Misinformation?
- Implementation and Regulation
  - How to allocate dynamically changing spectrum usage
  - The dynamic reconfiguration of the spectrum portion to be used for transmitting is not always easily implementable due to out-of-band emissions

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Challenges to T&E, cont.

- Legal Issues
  - Who is responsible if a radar's AI goes rogue?
  - Makes a mistake, gets someone killed?
  - Autonomous vehicles have same challenge!
  - AI is currently not a legal entity ☺

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