Vertically Integrated Millimeter-Wave Systems: A Bridge Between Antennas and AI

Alberto Valdes-Garcia
IBM T. J. Watson Research Center
A Set of Factors Creating a Key Opportunity

Availability of complex, silicon-based, mmWave multi-antenna systems

Growth in demand and infrastructure for ubiquitous communications and sensing

Growth in capabilities of AI technology

Vertically integrated “Antennas to AI” systems for communications and sensing
Examples of AI Applied to RF Systems


From Antennas … to AI

Our key interface to the EM spectrum

Driven by data sets, high-level programming interfaces, requires fast iterations….

Goal: Learning-driven recognition, classification, adaptability….
Vertically integrated hardware + software platforms enabling data set creation, data labeling, and algorithm development in real-world environments.
Outline

1. Software-defined phased array (SDPAR)
   ▪ Enables millimeter-wave directional comms. data collection, application development and beamforming algorithms research

2. Multi-spectral imaging platform ‘Hyperimager’
   ▪ Enables multi-spectral (millimeter-wave radar, IR, and visible) data collection and image composition

3. Real-time 3D radar imaging platform ‘Hyperimager F’
   ▪ Enables AI-based event classification
5G Era Directional Communications Challenge: Beam Finding, Pointing, & Tracking

- Directional (mmWave) 5G presents an extremely complex spatio-spectral allocation challenge
- Opportunities exist for network throughput optimization, small cell deployment planning, and new applications
Software Defined Phased Array Radio (SDPAR): Concept and Prototype

SDPAR:
- SDR + Phased Array + API
- Single SW interface
- Air interface (antenna array)
- Arbitrary spatial filter

- Radio parameters (freq., gain, BW)
- Signaling parameters (constellation size, coding)
- Radiation pattern control (beam direction + shape AND gain + phase per element)
- Data link input/output
- Data link quality metrics (EVM, BER)

B. Sadhu et al., IMS 2018
Hardware-Software Vertical Integration: From antennas to API

- Configurability of radio and radiation pattern functions from high-level API
- Reduced control latency and synchronization between radio and beamforming functions
- Small form factor

A. Valdes-Garcia et al, VLSI 2020
Features Suitable for SDPAR

- Multi-function module
- Creates 8 simultaneous 16-element beams in TX or RX
- Creates 2 simultaneous 64-element beams in TX or RX
- Dual polarization with independent data support
- Antenna gain uniformity
  - No calibration required
- Orthogonal & fast beam controls
  - No calibration required

B. Sadhu et al., ISSCC 2017, JSSC 2017
X. Gu et al., IMS 2017
Example Application: Study Fixed Wireless Access

SDPAR 1
configured as TX
Inside building

SDPAR 2
configured as RX
Outdoors

Beam-pointing angle sweep

T. J. Watson Research Center

B. Sadhu et al., IMS 2018
28-GHz Link EVM Measurements Across 60° Solid Angle Using SDPARs

- TX inside Building (14dBm EIRP)
- RX

Good EVM (RX main lobe points at TX)
28-GHz Link EVM Measurements Across 60° Solid Angle Using SDPARs

TX inside Building (14dBm EIRP)

RX

Poor EVM (RX points away from TX)

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28-GHz Link EVM Measurements Across 60° Solid Angle Using SDPARs

2400 EVM measurements at different angles in <30 seconds
Example Application: Indoor 28-GHz Access with Interferer

SDPAR configured as interferer

SDPAR configured as TX

Beam-pointing angle sweep

SDPAR configured as RX

VIDEO DEMO
Opportunity: 3D sensing with reflected OFDM 5G communication signals

J. Guan et al, IEEE RFIC 2020, T-MTT 2021
3D Imaging Results Using OFDM Signals

- Range resolution: 15cm
- Angular resolution: 1 deg.

J. Guan et al, IEEE RFIC 2020, T-MTT 2021
Outlook

• System level challenges of mmWave 5G can be solved using SDPARs
  – Agile 5G directional channel sounding
  – Development of new beam pointing and beam forming algorithms
  – Development of ML-driven adaptable directional communication systems

• We expect SDPARs will be the new backbone of networking research in the 5G/6G era
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Si-based Sensors Operating Across the EM Spectrum

- 3-D distance
- see through fog, smoke, dust,
- material properties
- polarization effects
- Electronic steering

- Molecule detection
- 3-D distance
- Imaging

- Temperature
- 3-D distance

- scene
- colors
- Low-cost

- <1% of the EM spectrum is accessible through human vision and conventional cameras
- Compact, Si-based sensors for accessing other wavelengths are emerging

A. Valdes-Garcia et al., IEDM 2020
Increasing Relevance of EM Sensors Beyond Visible-Domain Cameras

“In a post-quarantine world, **heat sensors** could help spot sick people with elevated temperatures as they enter public places. But it’s not that simple.”

“**The Californian company** is using **millimeter wave** technology, best known for being used for 5G connections, that will allow radars to detect and measure a body, so it can tell the difference between adults and children.”
https://www.thetimes.co.uk/article/tesla-sensors-will-protect-children-in-hot-cars-lttbqn527

“In one of the first studies of its kind, researchers installed a **depth and thermal sensor** inside the bedroom and observed 1,690 activities during 1 month. A convolutional neural network was 86% accurate at detecting assistance…. **Although visual sensors** are promising, they **raise privacy concerns** in some environments”
https://www.nature.com/articles/s41586-020-2669-y
Multi-spectral Imaging: To look at a scene at multiple different wavelengths and obtain new information and insights about objects and situations.

A. Valdes-Garcia et al., IEDM 2020
A phased array with transmit (TX) and receive (RX) functions can electronically steer a beam across a field of view (FOV).

When coupled to radar signal processing, the phased array can obtain radar imaging information (distance and reflectivity from the scene) in each TX/RX beam direction.

# Multi-Spectral Imaging Platform ‘Hyperimager’

<table>
<thead>
<tr>
<th>Sensors</th>
<th>mmWave (60 GHz) 3D radar</th>
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<tbody>
<tr>
<td></td>
<td>IR camera</td>
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<tr>
<td></td>
<td>visible-domain camera</td>
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</table>

| Radar imaging performance | FOV: +/- 35deg. (H&V), Number of pixels: >441, 15cm range resolution |

| HW platform integration   | 3 sensors and tablet in a single chassis |
|                          | Separate laptop for control and network interface |

| App features              | Combined visualization of radar imaging, IR camera image, visible-domain image |
|                          | 3D radar imaging visualization |

| Cloud features            | Sensor data access and sensor control through remote tablet |
The platform enables the creation of multi-spectral image data sets and the exploration of new AI-based solutions for non-visible information.
Hyperimager Platform: What is in the Box?

Scene

60-GHz Phased Array

COTS High-speed ADC (signal acquisition)

COTS PRBS generator and RF coupling components

Laptop or mini-PC: radar algorithm computation, beam direction control, network interface

Tablet with camera running app

Beam direction control

Wireless connection between app, radar interface, and additional viewer app through cloud server

User interface of primary app or viewer app at remote location

What's Behind the Paper?
Multi-Spectral Images Captured with Hyperimager

mmWave radar imaging (reflectivity @ 2m) + camera (with edge detection):
2 separate square objects behind paper (monitors)

IR camera + visible-domain camera (with edge detection):
Left object has IR emissivity (left monitor is on)
mmWave 3D Radar Imaging Visualization

Room corner
Object behind ceiling
Metallic chassis
Ceiling corner
Corner reflector
Monitor
Test Case Scenario: Road with Obstacles in Close Proximity

- Visible domain image
- Visible domain image w/ edge detection
Test case scenario: Road with obstacles in close proximity

*Joint visualization of three spectral domains*

- Visible domain image w/edge detection + IR in radiometric scale + mmWave reflectivity @ 4.8m
- Visible domain image w/edge detection + IR in radiometric scale + mmWave reflectivity @ 8.4m
Test case scenario: Road with obstacles in close proximity

*Vertical + horizontal obstacle separation with 3D radar*

- **Visible domain image**
- **3D radar image (perspective 1)**
- **3D radar image (perspective 2)**
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3. Real-time 3D radar imaging platform ‘Hyperimager F’
   ▪ Platform concept and implementation
   ▪ AI-based hands gestures classification
   ▪ AI-based concealed object detection
3D Event Recognition with mmWave Radar:

- **Fast** (100s of frames/sec) scanning of a scene enables the creation of a series of 3D data
- An AI-based algorithm can extract temporal and volumetric features from such 3D data stream enabling automatic event recognition

A. Tzadok et al, IEEE IMS 2020
Hyperimager F Platform: Enabling 3D Radar Imaging at 100s of Frames/sec

- Every 1500ns, RX and TX beams are steered in a new beam direction and a radar waveform is sent and captured.
- This architecture enables the realization of fast 3D radar functionality using a phased array TRX with I/Q BB interface designed for comms.
<table>
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<tbody>
<tr>
<td><strong>Range resolution, range, BW</strong></td>
<td>15cm, 18.6M, 1GHz (1.4GHz is possible)</td>
<td>15cm, 27M/13.5M (Saw/Tri), 1GHz (1.4GHz is possible)</td>
</tr>
<tr>
<td><strong>Transmit beamwidth</strong></td>
<td>16 element phased array (20 degrees)</td>
<td></td>
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<tr>
<td><strong>Radar repetition frequency</strong></td>
<td>10 kHz</td>
<td>66.6666kHz</td>
</tr>
<tr>
<td><strong>Number of beam directions</strong></td>
<td>Configurable up to 8x4</td>
<td>Configurable up to 21x21</td>
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<tr>
<td><strong>Angular resolution</strong></td>
<td>3 degrees</td>
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<tr>
<td><strong>FMCW ramp</strong></td>
<td>Sawtooth</td>
<td>Sawtooth and triangular</td>
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<tr>
<td><strong>Preprocessing</strong></td>
<td>Batch FFT</td>
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<tr>
<td><strong>Output</strong></td>
<td>Temporal volumetric response (3D tensor), amplitude &amp; phase</td>
<td>Temporal volumetric response (3D tensor), amplitude &amp; phase for both positive/negative ramp</td>
</tr>
</tbody>
</table>
Each vertical beam direction row contains 15 depth range bars, each with 15cm range resolution

FFT mag. is mapped to colors

Video Demo: 60-GHz 3D Radar (21x21 Directions)
Video Demo: 60-GHz 3D Radar (21x21 Directions)

441 directions/frame, 150 frames/sec, 15 depth positions/direction, 6.6K voxels/frame
Radar frames are down-sampled to match video rate at 30fps.
Raw radar response is shown with no averaging/de-noising
Data set description:

- 4 one-hand gestures: back and forth (A), left-top-right-bottom (B), left-bottom-right-top (C), waving (H).
- 4 two-hand gestures: resize depth (D), resize width (E), rotate (F), rotate and hold (G)
- Each gesture was continuously repeated and captured for 30 seconds, using our 1250 radar readouts/sec system and 5x5 directions, providing 1500 frames
DNN Architecture to Extract Temporal and Volumetric Features from 3D Radar Frames

**Input Tensor:**
- 30 Frames
- 5x5 directions
- 7 range cells

**Filter Size:**
- 3D Filter Shape (2,2,2)

**Max 3D Pooling:**
- Temporal pooling by a factor of 2

**Tensor Reshape:**
- 6x1x1x256 to 6x256

**Dropout:**
- 80% dropout to avoid training overfit

**# of Filters:**
- 128 3D Convolution Filters

**Deep 3D Convolution:**
- Temporal, horizontal and vertical convolution

**Max 3D Pooling:**
- Temporal pooling by a factor of 2

**Tensor Reshape:**
- 6x1x1x256 to 6x256

**Dropout:**
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**Fully Connected Neural Net:**
- Final classification layer, from features to class id

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**Temporal and Volumetric Features**

**Temporal Signatures**

**Classifier**

**Temporal Convolution:**
- 32 convolution filters, 6 cells wide to extract temporal features based inter-frames trend
9 volunteers were asked to perform the gestures
Each volunteer performed 12 data captures for each gesture
Each data capture consists of a ~30 sec clip where the gesture is being repeated
Complete data separation was enforced between training and testing
- 10x8x9x30 sec (~1e6 frames) for training
- 2x8x9x30 sec (216e3 frames) for testing
All gestures are classified with >93% accuracy using only 30 3D radar frames

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A. Tzadok et al, IEEE IMS 2020
Second Use Case: Concealed Object Detection

No concealed object

Concealed iPad

Concealed tools

Concealed bolts
DNN Architecture and Classification Results

- The DDN training can be optimized for inferencing with a specific number of frames
- Each trained DNN can be applied/tested with any number of input frames
- The DNN optimized for 135 input frames achieves 95% accuracy
Visualization of 3D-radar inference results over time

- Test data includes videos and 3D radar data sets that were captured simultaneously.
- Using only the 3D radar data (i.e. video data is only for visual reference), the inferencing engine determines if one of 3 possible concealed objects (Bolts, Tools, iPad) or none (no concealed objects) are present in the scene.
Summary and conclusions

- We envision a future where the application space of millimeter-wave systems enters new domains as the capabilities of such systems are fully realized by AI-driven adaptation and data interpretation.

- Vertical hardware-software co-integration key to leverage other technology trends such as cloud/edge computing, image processing and visualization, and ultimately AI.
  - A 28-GHz SDPAR prototype has been demonstrated by performing directional EVM measurements on more than 20,000 independent directions.
  - A multi-spectral imaging platform “hyperimager” consisting of sensors, an App, and cloud infrastructure has been demonstrated by capturing multi-spectral images with 3D radar, IR, and visible-domain information.
  - The automatic recognition of events using AI and a high-speed 3D radar data acquisition system has been demonstrated for two use cases (1) hand gestures classification, and (2) classification of concealed objects in motion.
References

• B. Sadhu et al, “A 28-GHz 32-Element TRX Phased-Array IC With Concurrent Dual-Polarized Operation and Orthogonal Phase and Gain Control for 5G Communications”, IEEE JSSC, Vol. 52, pp. 3373-3391, December 2017
• J. Guan, A. Paidimarri, A. Valdes-Garcia, and Bodhisatwa Sadhu, “3D Imaging using mmWave 5G Signals” IEEE RFIC, pp. 147-150, August 2020
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