Pre-Symposium Tutorial on NIST-Sponsored Roadmaps
5G/6G mmWave Materials and Electrical Test Technology (5G/6G MAESTRO)

Project Leader: Dr. Urmi Ray, iNEMI
IEEE Symposium on Heterogeneous Integration
February 22, 2023

Supported by: National Institute of Standards and Technology (NIST) Office of Advanced Manufacturing
NIST Advanced Manufacturing Technology (MFGTech) Roadmap Program
FEDERAL AWARD ID NUMBER: 70NANB22H050
https://www.inemi.org/maestro
Project
Introduction & Status

Email: urmi.ray@inemi.org
Project Duration: 1 May 2022 – 30 Sep 2023 (18 months)

Project Objective

Create a technology roadmap

- Develop a comprehensive 10-year hardware roadmap for mmWave materials development & electrical characterization and testing.

Develop a U.S.-focused implementation strategy

- Recommend a U.S.-centric, cross-supply-chain consortium to execute the vision of the roadmap, the foundations for a strong U.S. manufacturing ecosystem in RF materials and testing.
- Promote the growth of a strong and diverse U.S. workforce in RF communication technologies, by proposing a plan of university curricula development and training.
5G/6G MAESTRO: Technology Scope

Workforce Dev

Materials development

110GHz-170GHz (D-Band), 220-350GHz (G Band)

• mmWave frequency bands
• Roadmap materials to meet functional requirements on the loss tangent and dielectric constant
• Mechanical and thermal properties in scope
• Constraint: right cost-point & manufacturability at scale

Characterization

• Identify techniques for repeatable fast low-loss material characterization
• Address lack of standard reference materials (SRM)
• Propose cross-industry approaches, enabling cross-supplier comparisons

Electrical test

Mfg Scale-up proposal

5G/6G cellular & other applications

• Transition from contact testing to over-the-air testing, particularly with pervasive use of massive MIMO at mmWave frequencies
• Consider changes in RF front-end packaging, including emergence of antenna-in-package technology
• Scaling up from lab-level testing to high-volume manufacturing environments
Roadmap contributors are leaders in this field from industry, universities and research institutes.

For further information and to get involved, please contact Dr. Urmia Ray (urmi.ray@inemi.org)
iNEMI 5G/6G MAESTRO: Project Flow

5G/6G Maestro

- Market survey
- Design Analysis
- Materials Landscape
- E-Test Landscape

WP1: Tech & Market Assessment

WP2: Roadmap Generation
- Proof of concept white paper
- Location, Budget

WP3: Implementation Strategy

Dissemination: Webinar, Conferences, Technical Papers, Community college/University curricula

5G RF Cluster Manufacturing Institute
iNEMI 5G/6G mmWave Materials and Electrical Test Technology Roadmap (5G/6G MAESTRO): Project Structure

• Roadmap Creation is focused on:
  • Low Loss Materials Development
  • Materials Characterization
  • Electrical Test
• Project is divided into 4 Work packages

<table>
<thead>
<tr>
<th>WP Number</th>
<th>Work Package Title</th>
<th>WP Lead</th>
<th>Start Month</th>
<th>End month</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP1</td>
<td>Technology &amp; Market needs assessment</td>
<td>TechSearch</td>
<td>1</td>
<td>7</td>
<td>✓ Complete</td>
</tr>
<tr>
<td>WP2</td>
<td>Roadmap development</td>
<td>iNEMI</td>
<td>2-3</td>
<td>13</td>
<td>In flight, on track</td>
</tr>
<tr>
<td>WP3</td>
<td>Implementation strategy development</td>
<td>iNEMI</td>
<td>10</td>
<td>18</td>
<td>In flight</td>
</tr>
<tr>
<td>WP4</td>
<td>Operational Structure &amp; Program Management</td>
<td>iNEMI</td>
<td>1</td>
<td>18</td>
<td>In flight</td>
</tr>
</tbody>
</table>
# iNEMI 5G/6G MAESTRO: Overall Timeline

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP</td>
<td>Task</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP1</td>
<td>Market Survey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Design Analysis &amp; Trends</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Webinars &amp; Report (D1.1, D1.2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP2</td>
<td>Landscaping (D2.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roadmap content creation (D2.2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roadmap promotion (D2.3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP3</td>
<td>Develop Technical Definition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Develop Execution Detail Report (D3.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP4</td>
<td>Quarterly reporting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final report</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Complete</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**WP1 (Market assess.)**
- Market Survey
- Design Analysis & Trends
- Webinars & Report (D1.1, D1.2)

**WP2 (Roadmap)**
- Landscaping (D2.1)
- Roadmap content creation (D2.2)
- Roadmap promotion (D2.3)

**WP3 (Implement. strategy)**
- Develop Technical Definition
- Develop Execution Detail Report (D3.1)

**WP4 (Admin & gov.)**
- Quarterly reporting
- Final report

Quarterly reporting: Q D Q D Q D Q D Q D Q D Q D
• Continue the dissemination of the elements of the roadmap and workforce, educational training, conferences
• Georgia Institute of Technology and FIU will be incorporating suitable elements into course work and specialized seminar series.
• Explore with NIST and the Dept of Commerce where and how the RF manufacturing team (RF Cluster) can be formed. Propose the formation of a RF Cluster as either a new funded MFG USA or a satellite to a current MFG USA
• **COMPLETE**

• 3 reports completed and available in February
  
  • **Market Assessment Report** by *TechSearch International, Inc.*
  
  • **System Design Analysis** by *Florida International University*
  
  • **Identification of Next-Generation Dielectric Materials and Testing Needs** by *Georgia Institute of Technology*

• 1st Webinar/Workshop - Sep 2022

• 2\textsuperscript{nd} Webinar/Workshop - 9 Feb, 2023
Project Status – WP1


• **Key Requirements for Market Segments** identified through survey and 1:1 interviews

---

**Table of Contents**

- Table of Contents ................................................................. 2
- Introduction ........................................................................... 3
- Project Goals and Objectives ............................................... 3
  - WP1 Technology and Market Updates .................................... 4
- Overview of Market Assessment Report ................................. 5
- Mobile Phones ..................................................................... 7
- RF FEM ................................................................................. 7
- Power Amplifier ................................................................... 7
- Smartphone Antennas .......................................................... 7
- Infrastructure ........................................................................ 7
- Consumer Premises Equipment ............................................. 9
- Small Cells ............................................................................ 9
- Automotive Radar ............................................................... 10
- Defense ................................................................................. 10
- Antenna, Material, and Test Concerns ................................. 10
- Team Members and Contributors ........................................ 13
  - Contributors ....................................................................... 13
  - Maestro Team Members ...................................................... 13
- Acronyms/Abbreviations ....................................................... 13
- Acknowledgements ............................................................... 14
• WP1 System Design Analysis by Florida International University - Prof. Satheesh Venkatakrishnan, Prof Raj Pulugurtha, Prof. John Volakis

• Overview of System Design Hardware for mmWave Architecture

• Beamforming Architectures

• Package Integration Trends and Features
Project Status – WP1

- WP1 System Design Analysis by Florida International University
- Overview of System Design Hardware for mmWave Architecture
- Beamforming Architectures
- Package Integration Trends and Features
Research Areas in 5G, 6G, and Beyond

New Market Demands

- Amazingly Fast
- Great Service in a crowd
- Super Real-time & reliable communications
- Ubiquitous “things” Communicating

Areas of Research:

1) MIMO beamforming architectures
2) Advanced techniques to address spectrum coexistence and improve spectral efficiency and interference mitigation
3) Ultra-Wideband (UWB) systems
4) RF front ends: frequency agile, very small size, weight area, and power efficient (SWAP)
5) SMART Antennas
6) Millimeter-wave systems
7) RF-digital Transceivers
8) Integrating Machine Learning and Artificial Intelligence in RF design
9) Communication in contested environment
Reconfigurable Intelligent Surfaces – Assisted Joint Beamforming

Small wavelengths at 5G/6G mm-Wave frequencies are subject to path losses and multipath scattering leading to beam blockage.

Reconfigurable Intelligent Surfaces (RIS) supersede relay performance using large apertures with simple circuitry.

- Spectrally more efficient
- RIS reduce hardware complexity.

Goal: Beamforming and adaptive nulling using RIS via a very simple circuitry (in terms of SWAP-C)

Alternative Technology: Relays

- A dedicated power source per relay
- Reception and re-transmission circuitry
- Signal processing complexities.
Comparison of High Isolation Antennas

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Isolation</td>
<td>65 dB (sim)</td>
<td>37 dB (meas)</td>
<td>28 dB (meas)</td>
<td>35 dB (meas)</td>
<td>35 dB (sim)</td>
<td>50 dB (meas)</td>
</tr>
<tr>
<td>Frequency</td>
<td>1.6-2.7 GHz</td>
<td>0.8-2.7 GHz</td>
<td>2-5 GHz</td>
<td>1.6-3.3 GHz</td>
<td>2-18 GHz</td>
<td>1.6–3.2 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1.05 GHz (1.6:1)</td>
<td>1.9 GHz (3.3:1)</td>
<td>3 GHz (2.5:1)</td>
<td>1.7 GHz (2:1)</td>
<td>16 GHz (9:1)</td>
<td>1.6 GHz (2:1)</td>
</tr>
<tr>
<td>Tx/Rx Pattern</td>
<td>Omni</td>
<td>Omni</td>
<td>Directional</td>
<td>Directional</td>
<td>Directional</td>
<td>Omni</td>
</tr>
<tr>
<td>Patterns Similar</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Polarization</td>
<td>Tx Rx</td>
<td>H-pol V-pol</td>
<td>H-pol V-pol</td>
<td>LHCP RHCP</td>
<td>RHCP LHCP</td>
<td>Dual linear Dual</td>
</tr>
<tr>
<td>Scanning</td>
<td>Tx Rx</td>
<td>No No</td>
<td>No No</td>
<td>Yes Yes</td>
<td>Yes Yes</td>
<td>Yes No</td>
</tr>
</tbody>
</table>

- **Min Isolation**: 65 dB (sim) to 50 dB (meas)
- **Frequency**: 1.6-2.7 GHz to 1.6–3.2 GHz
- **Bandwidth**: 1.05 GHz (1.6:1) to 1.6 GHz (2:1)
- **Tx/Rx Pattern**: Omni, Directional, Omnidirectional
- **Patterns Similar**: No, Yes
- **Polarization**: H-pol V-pol, LHCP RHCP, Dual linear Dual
- **Scanning**: No Yes No Yes No No
ITU June Meeting on 6G Highlights and Key Points

- Efforts ongoing to understand 6G demands and requirements
- Expected speeds at Tbytes vs Gbytes.
- Insights into the 6G enabling technology requirements are still being hammered out.
- Japan: 600,000 stations to increase by 500x for 6G
- Countries including China, South Korea, and Japan, or regions such as North America and Europe have launched their own research groups.

Technology Enablers and Recommendations

- All players involved agree on the following Spectrum allocation:
  - New mid-spectrum at 7–20 GHz for urban capacity
  - New low spectrum/LTE at 470–694 MHz for extreme coverage
  - New THz spectrum beyond 90 GHz for the highest peak data (100Gbps) rates and sensing (proposed)

- **mmWave MIMO with beam-forming (at base stations)** to play a critical role toward 6G
- **RIS** critical for the urban environment
- **In-band full-duplex** is an enabling technology that will play a key role in building spectral coexistence within 6G.
WP1 Identification of Next-Generation Dielectric Materials and Testing Needs by Georgia Institute of Technology - Prof David Citrin

Looking ahead to the next 10-15 years

Materials options for packaging that are low-loss ($\tan \delta < 0.02$) above ~300 GHz

Dielectric characterization above ~300 GHz
Low-loss materials for terahertz packaging

- **Semiconductors**: (Si, Ge, III-V, SiO₂, sapphire) High-resistivity, high-purity materials can have very low loss below the *reststrahlen* band. E.g., Si 1 THz, \( \varepsilon' \sim 11.7 \) and \( \tan \delta \sim 0.00001 \). But losses mount quickly as carriers are introduced.

- **Ceramics**: Crystalline and amorphous. E.g., Al₂O₃ ceramic, Al₂O₃ crystal, AlN ceramic, Si₃N₄ ceramic, Dupont 9K7, and Ferro A6M have \( \tan \delta < 0.02 \) at 1 THz.

- **Glasses**: Ultrasmooth glasses with through-glass vias are of interest. Some glasses may be low-loss at 1 THz.

- **Fused Silica**: Mixed reports concerning low-loss at 1 THz.

- **Polymers**: Low-loss at 1 THz: Kapton, Cirlex polyimides, PTFE, HDPE, PS, COP, polynorbornene, polypropylene, PP, SU8, polycarbonate, LCP, and PMMA, the last three borderline.

- **Prepregs, Stackups, Composites**: Many choices, limited data at 1 THz.
• Proposed Chapters
  • Materials development
  • Materials Characterization
  • Electrical test
• Each Chapter has “small” working groups
• Materials Development TWG
  • Working document; ~70% completed
  • Multiple SME contributors; coalescing information together and pulling into cohesive flow is next step
• Materials Characterization TWG- background work and team from earlier iNEMI project
  • Complete: To be issued in March
• Electrical Test
  • Starting now
### Project Plans – WP2 (Roadmap Development)

**Example: Gaps and Challenges**

Table 5G-3: Materials Characterization Needs, Gaps, and Today’s Technology Status with Respect to Current and Future Needs

<table>
<thead>
<tr>
<th>ROADMAP TIMEFRAME</th>
<th>TODAY (2023)</th>
<th>3 YEARS (2026)</th>
<th>5 YEARS (2028)</th>
<th>10 YEARS (2033)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TECHNOLOGY ISSUE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency Range</td>
<td>28-110 GHz</td>
<td>110-170 GHz (D-Band)</td>
<td>220-350 GHz (G Band)</td>
<td>&gt;500 GHz</td>
</tr>
</tbody>
</table>

**In-table color + label key**

- **Solutions not known**: Solutions not known at this time
- **Solutions need optimization**: Current solutions need optimization
- **Solutions deployed or known**: Solutions deployed or known today
- **Not determined**: TBD

<table>
<thead>
<tr>
<th>CHARACTERIZATION FREQUENCY RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CURRENT TECHNOLOGY STATUS</strong></td>
</tr>
<tr>
<td><strong>GAP</strong></td>
</tr>
<tr>
<td><strong>CHALLENGE</strong></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

**CHALLENGE**

- High equipment cost
# Project Plans – WP2 (Roadmap Development)

Example: Potential Solutions

## Table 5G-4: Materials Characterization Potential Solutions

<table>
<thead>
<tr>
<th>TECHNOLOGY ISSUE</th>
<th>POTENTIAL SOLUTIONS</th>
<th>EXPECTED TRL LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TODAY (2023)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 YEARS (2026)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 YEARS (2028)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 YEARS (2033)</td>
</tr>
<tr>
<td>ANISOTROPIC MATERIAL CHARACTERIZATION</td>
<td>Develop new and disruptive methods for material characterization</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Converge on common sample geometry</td>
<td>3</td>
</tr>
<tr>
<td>SAMPLE THICKNESS VARIATION</td>
<td>“Cherry pick” samples</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Use of mechanical methods to modify existing samples to improve thickness uniformity</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Develop new methods with less sensitivity to thickness variation</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Color and Range of Technology Readiness Levels (TRL)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL: 1 to 4</td>
<td>Levels involving research</td>
</tr>
<tr>
<td>TRL: 5 to 7</td>
<td>Levels involving development</td>
</tr>
<tr>
<td>TRL: 8 to 9</td>
<td>Levels involving deployment</td>
</tr>
</tbody>
</table>
• Started Early due to the runway needed and the importance of forming partnerships and collaboration
• Currently working with ASIC coalition (www.asicoalition.org) a pre-competitive group of >100 entities (public, private companies, Universities etc)
• iNEMI leading the advanced SIP group and is putting together a proposal for a RF-SIP “demonstrator cluster” to address the majority of the challenges being identified in this roadmap
  • Team members: Georgia Tech, NGC, IBM, IPC, RPI, AMAT, Western Digital, Nantero, NEPES, Universal Instruments, ASPDL, UVM, Showa-Denko, 3DGS
Project Plans – WP4 (Governance and Communications)

- Teams site set up – all communications and collaborations on-line as much as possible
- TWG meetings focused on specific roadmap chapters
- Monthly meetings
- Additional roadmap/workshops planned
  - Workshop at IMAPS DPC 2023 [https://imaps.org/device_packaging_agenda.php](https://imaps.org/device_packaging_agenda.php)
    Tuesday, March 14: TA3: *INEMI INVITED SESSION: 5G/6G ROADMAP CREATION AND PACKAGING*
  - Workshop at International Microwave week, San Diego, CA (Jun 11-16, 2023)
  - Session IWWE6 on June 14, 2023: [https://ims-ieee.org/exhibition/microapps/industry-workshops?type=IWWE6&date=2023-06-14](https://ims-ieee.org/exhibition/microapps/industry-workshops?type=IWWE6&date=2023-06-14)

- More to come...Stay Tuned
Maestro Next Steps

- Mar 2023: Publish and propagate contents of Roadmap Chapter “Materials Characterization”
- April 2023: Complete NIST Semi-Annual Report #2
- May 2023: Complete Roadmap Materials Chapter
- 3Q 2023: Complete Implementation Strategy
Acknowledgement

MAESTRO Team
NIST Office of Advanced Manufacturing

https://www.inemi.org/maestro