NIST Advanced Manufacturing Technology (MfgTech) Roadmap

5G/6G mmWave Materials and Electrical Test Technology (5G/6G MAESTRO)

March 14, 2023
IMAPS DPC 2023

Project Leader: Dr. Urmi Ray, iNEMI

Supported by: National Institute of Standards and Technology (NIST) Office of Advanced Manufacturing

FEDERAL AWARD ID NUMBER: 70NANB22H050

https://www.inemi.org/maestro

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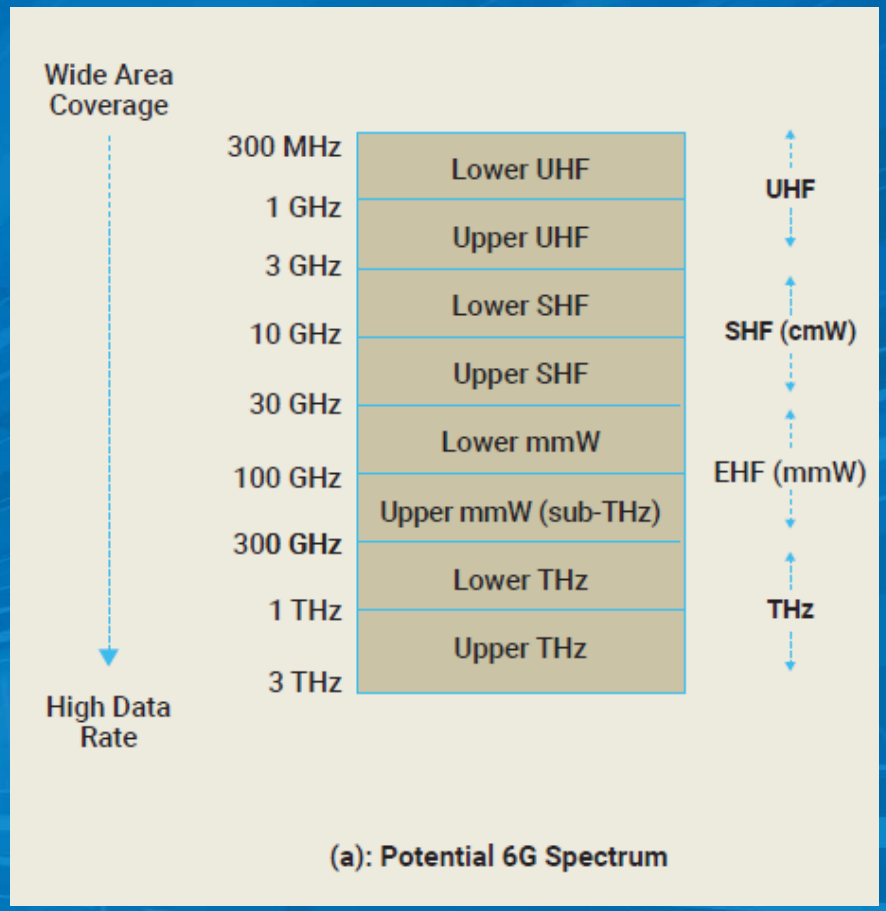
Project Introduction & Status



(a): Potential 6G Spectrum

Email: urmi.ray@inemi.org

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iNEMI: 5G/6G MAESTRO – Project Intro

Project Duration: 1 May 2022 – 30 Sep 2023 (18 months)

Project Objective

Create a technology roadmap

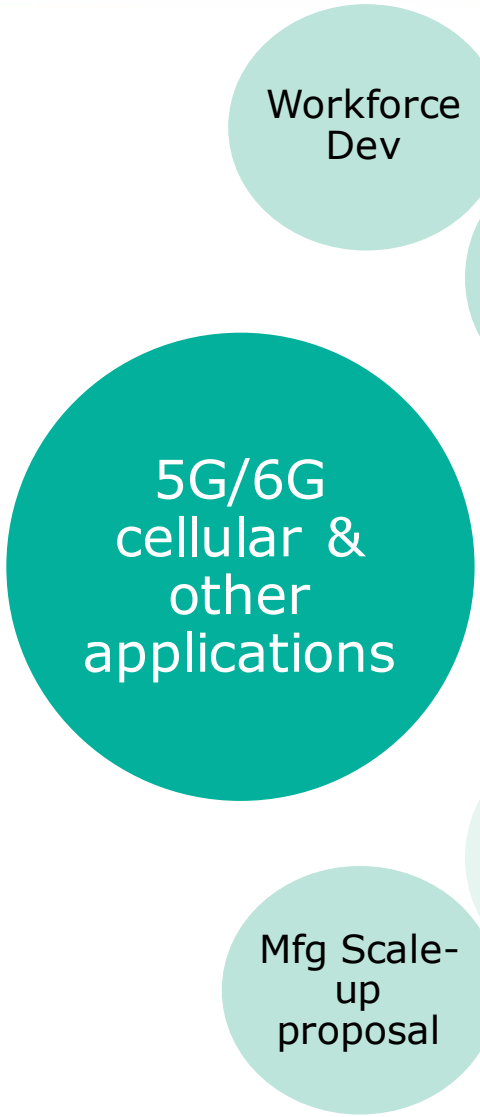
- Develop a comprehensive 10-year hardware roadmap for mmWave materials development & electrical characterization and testing.

Develop a U.S.-focused implementation strategy

- Recommend a 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

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

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

- 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

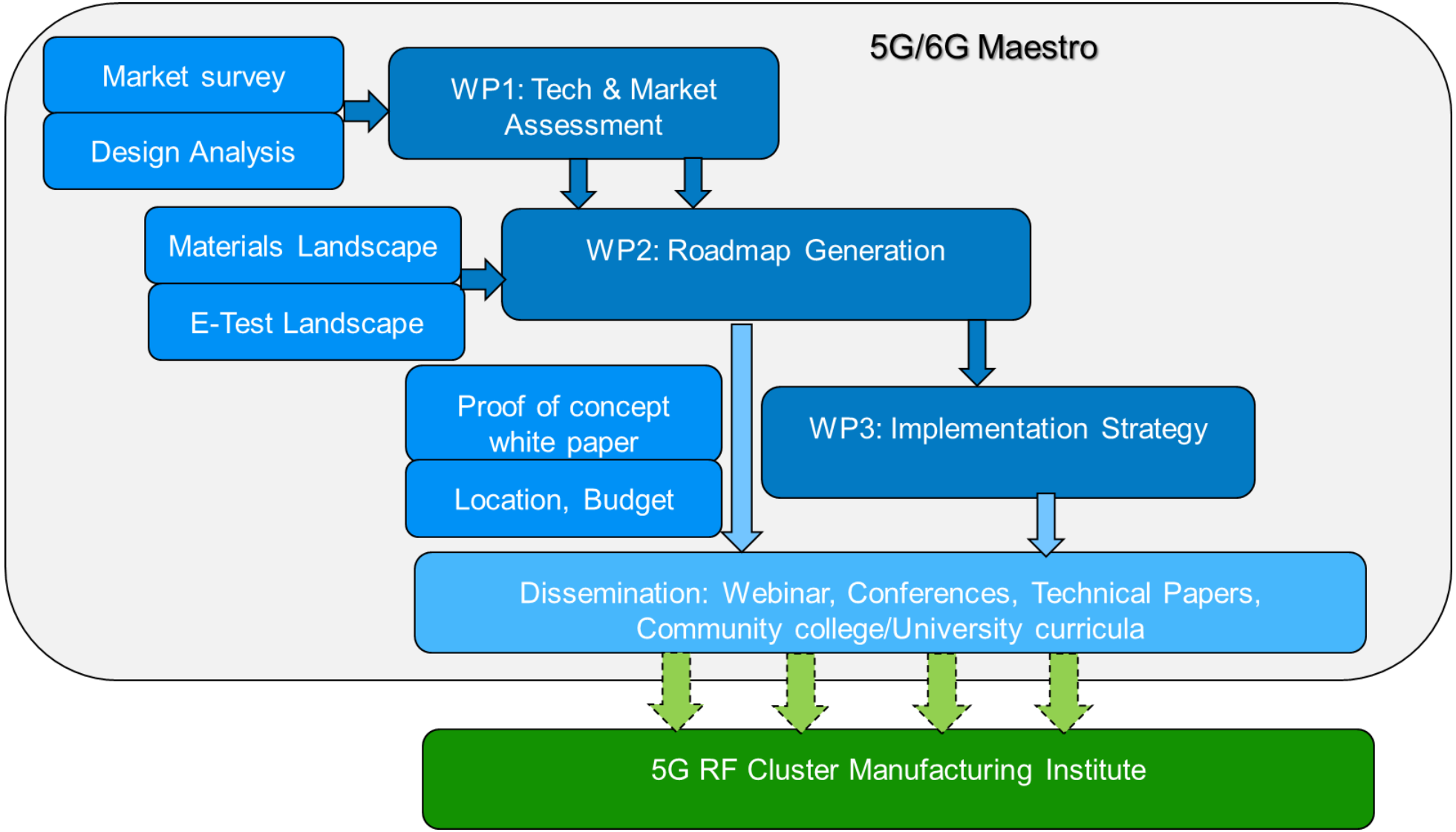
iNEMI 5G/6G MAESTRO: Partners

Roadmap contributors are leaders in this field
from industry, universities and research institutes

3DGS
3M
AMD
Applied Materials
Binghamton University
State University of New York
Dell
Dow
DuPont
Ectron Corporation
FIU Florida International University
Georgia Institute of Technology
IBM
intel
ITRI Industrial Technology Research Institute
Keysight Technologies
liloTree
Mosaic microsystems
Nantero
NIST RF Technology Center
Nokia
PennState
qorvo
QWED
TechSearch International

For further information and to get involved, please contact Dr. Urmi Ray (urmi.ray@inemi.org)

iNEMI 5G/6G MAESTRO: Project Flow



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

WP Number	Work Package Title	WP Lead	Start Month	End month	Status
WP1	Technology & Market needs assessment	TechSearch	1	7	✓ Complete
WP2	Roadmap development	iNEMI	2-3	13	In flight, on track
WP3	Implementation strategy development	iNEMI	10	18	In flight
WP4	Operational Structure & Program Management	iNEMI	1	18	In flight

iNEMI 5G/6G MAESTRO: Overall Timeline

Month		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
WP	**Task**																	
WP1 (Market assess.)	Market Survey	■	■	■	■	■												
	Design Analysis & Trends	■	■	■	■	■												
	Webinars & Report (D1.1, D1.2)				D	■	D	D										
WP2 (Road-map)	Landscaping (D2.1)						■	D										
	Roadmap content creation (D2.2)							■	■	■	■	■	D					
	Roadmap promotion (D2.3)												■	D				
WP3 (Implem. strategy)	Develop Technical Definition												■	■	■			
	Develop Execution Detail															■	■	■
	Report (D3.1)																	
WP4 (Admin & gov.)	Quarterly reporting	■	■	Q	D	■	Q	D	■	Q	D	■	Q	D	■	Q	D	■
	Final report																	■

Complete

iNEMI 5G/6G MAESTRO: Post Project Plans

- 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

Project Status – WP1 (Technology and Market Assessment)

- ***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
- 2nd Webinar/Workshop - 9 Feb, 2023

Project Status – WP1

- WP1 **Market Assessment Report** by *TechSearch International, Inc. –Jan Vardaman*
- *Key Requirements for Market Segments identified through survey and 1:1 interviews*

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Project Status – WP1

- 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*
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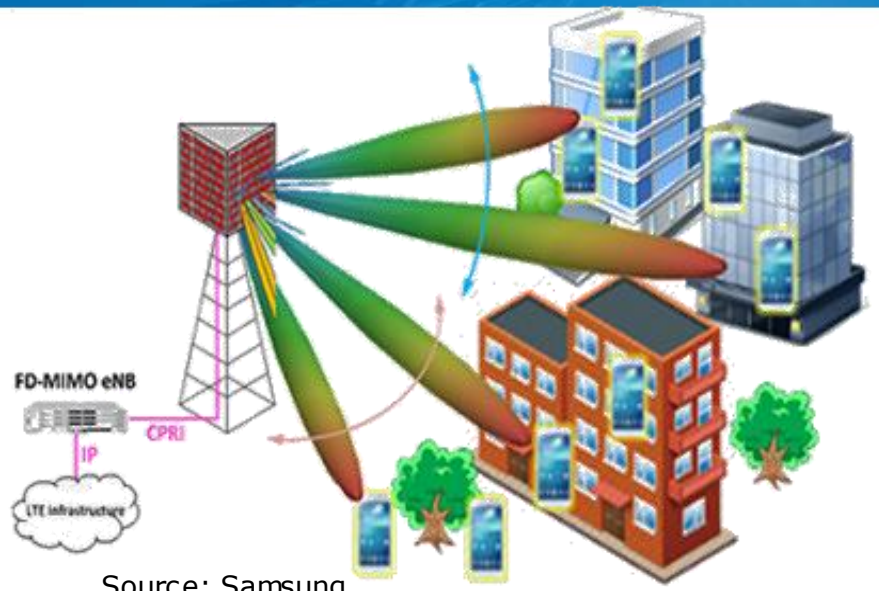
Tables

Research Areas in 5G, 6G, and Beyond



Source: Samsung

[1] https://www.extremetech.com/extreme/176093-v2v-what-are-vehicle-to-vehicle-communications-and-how-does-it-work

New Market Demands

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

Areas of Research:

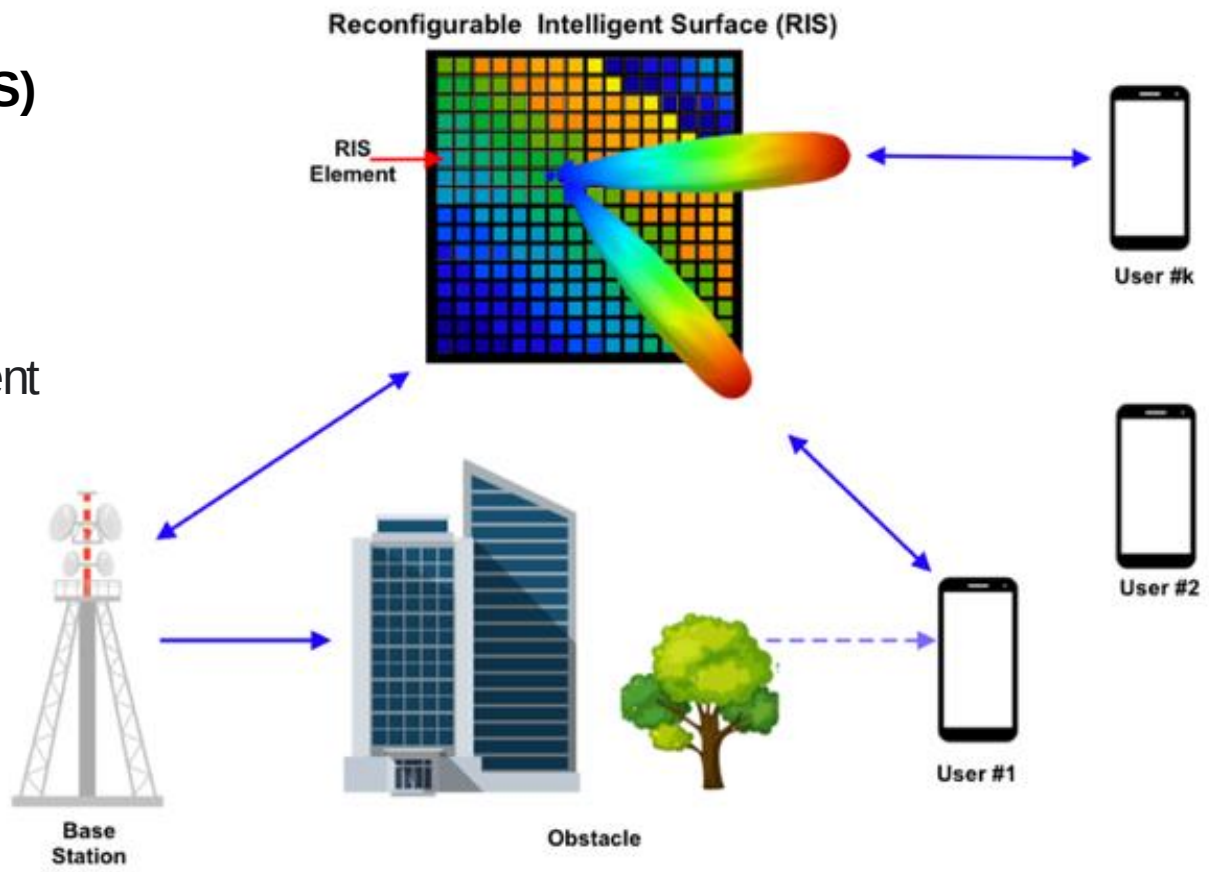
1) ***MIMO beamforming architectures***
2) ***Advanced techniques to address spectrum coexistence and improve spectral efficiency and interference mitigation***
3) Ultra-Wideband (UWB) systems
4) RF front ends: frequency agile, very small size, weight area, and power efficient (SWAP)
5) SMART Antennas
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.

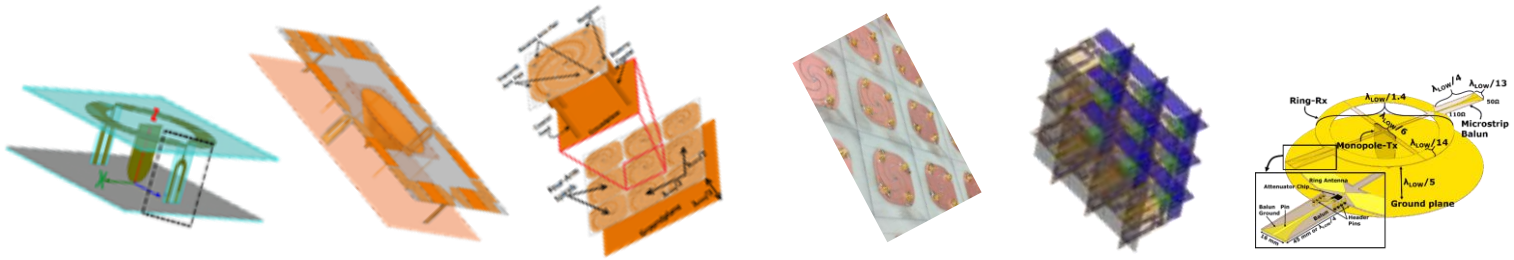


Alternative Technology: Relays

- × A dedicated power source per relay
- × Reception and re-transmission circuitry
- × Signal processing complexities.

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

Comparison of High Isolation Antennas



Year		2014/2018	2015	2017	2018	2019	2021
Min Isolation		**65 dB (sim)**	37 dB (meas)	28 dB (meas)	35 dB (meas)	35 dB (sim)	50 dB (meas)
Frequency		1.6-2.7 GHz	0.8-2.7 GHz	2-5 GHz	1.6-3.3 GHz	2-18 GHz	1.6–3.2 GHz
Bandwidth		1.05 GHz (1.6:1)	1.9 GHz (3.3:1)	3 GHz (2.5:1)	1.7 GHz (2:1)	16 GHz (9:1)	1.6 GHz (2:1)
Tx/Rx Pattern		Omni	Omni	Directional	Directional	Directional	Omni
Patterns Similar		No	No	Yes	Yes	Yes	No
Polarization	**Tx** **Rx**	H-pol V-pol	H-pol V-pol	LHCP RHCP	RHCP LHCP	Dual linear	Dual
Scanning	**Tx** **Rx**	No No	No No	Yes Yes	Yes Yes	Yes Yes	No No

WP1: System Design Analysis: Summary and Recommendations

https://www.google.com/search?q=5g+vision&rlz=1C1GCEA_enUS763US763&source=lnms&tbm=isch&sa=X&ved=0ahUKEwiQ27DKrYf7AhXLk1kKHdABAosQ_AUICygC&biw=1920&bih=1014#imgrc=_JkW5TnNe1OrIM:

ITU June Meeting on 6G Highlights and Key Points

- Efforts ongoing to understand 6G demands and requirements
- Expected speeds at Tbytes vs Gbyes.
- 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.

Project Status – WP1

- 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*

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Low-loss materials for terahertz packaging

- Semiconductors: (Si, Ge, III-V, SiO_2, 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., Al_2O_3 ceramic, Al_2O_3 crystal, AlN ceramic, Si_3N_4 ceramic, Dupont 9K7, and Ferro A6M have tan δ<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.

Project Plans – WP2 (Roadmap Development)

- 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

	ROADMAP TIMEFRAME			
TECHNOLOGY ISSUE	**TODAY (2023)**	**3 YEARS (2026)**	**5 YEARS (2028)**	**10 YEARS (2033)**
	Frequency Range= 28-110 GHz	**Frequency Range= 110-170 GHz (D-Band)**	**Frequency Range= 220-350 GHz (G Band)**	**Frequency Range= >500 GHz**
CHARACTERIZATION FREQUENCY RANGE				
NEED	Tools needed at 5G frequencies (28-39 GHz)	Tools needed at D-band (110-170 GHz)	Tools needed G-band (220-350 GHz)	Tools needed for >500 GHz
CURRENT TECHNOLOGY STATUS	**Solutions deployed or known**	**Solutions need optimization**	**Solutions not known**	
GAP	(NO GAP?)	Few tool options	Robustness and availability	
CHALLENGE	Limited tool availability for high frequencies	Supporting equipment is expensive (i.e., 100 GHz VNA)	Expensive supporting equipment	
CHALLENGE	High frequencies place burden on mechanical precision of equipment	Methods still in academic space		
CHALLENGE	High equipment cost			

In-table color + label key	Description of Technology Status
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

Project Plans – WP2 (Roadmap Development) Example: Potential Solutions

Table 5G-4 Materials Characterization Potential Solutions

		EXPECTED TRL LEVEL			
TECHNOLOGY ISSUE	**POTENTIAL SOLUTIONS**	**TODAY (2023)**	**3 YEARS (2026)**	**5 YEARS (2028)**	**10 YEARS (2033)**
ANISOTROPIC MATERIAL CHARACTERIZATION	Develop new and disruptive methods for material characterization	3	4	5	9
	Converge on common sample geometry	3	5	7	9
SAMPLE THICKNESS VARIATION	"Cherry pick" samples	9	9	9	9
	Use of mechanical methods to modify existing samples to improve thickness uniformity	4	4	4	4
	Develop new methods with less sensitivity to thickness variation	1	2	3	5

Color and Range of Technology Readiness Levels (TRL)	Description
TRL: 1 to 4	Levels involving **research**
TRL: 5 to 7	Levels involving **development**
TRL: 8 to 9	Levels involving **deployment**

Project Plans – WP3 (Implementation Strategy)

- 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, lBM, 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 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

- **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