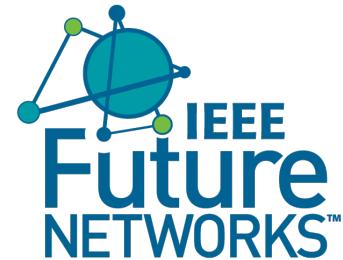


# This file is a free sample of this chapter.

The full chapter is available exclusively to signed-in participants of the IEEE Future Networks Community.



[Click here to join the Future Networks initiative](#) (free for any IEEE Society member, and low-cost for non-members), then return to the [INGR page](#) to download full chapters.



International Network Generations Roadmap

Would you like to join an INGR Working Group?

[Click here](#) for contact information for each group.

**Interested in booking a private session with INGR experts for your company? Contact an IEEE Account Manager to discuss an INGR Roadmap Virtual Private Event.**

+1 800 701 4333 (USA/Canada)  
+1 732 981 0060 (worldwide)

[onlinesupport@ieee.org](mailto:onlinesupport@ieee.org)





# IEEE INGR))

## International Network Generations Roadmap *2022 Edition*

# Massive MIMO



An IEEE 5G and Beyond Technology Roadmap  
[futurenetworks.ieee.org/roadmap](http://futurenetworks.ieee.org/roadmap)

Wi-Fi® and Wi-Fi Alliance® are registered trademarks of Wi-Fi Alliance.

The IEEE emblem is a trademark owned by the IEEE.

"IEEE", the IEEE logo, and other IEEE logos and titles (IEEE 802.11™, IEEE P1785™, IEEE P287™, IEEE P1770™, IEEE P149™, IEEE 1720™, etc.) are registered trademarks or service marks of The Institute of Electrical and Electronics Engineers, Incorporated. All other products, company names, or other marks appearing on these sites are the trademarks of their respective owners. Nothing contained in these sites should be construed as granting, by implication, estoppel, or otherwise, any license or right to use any trademark displayed on these sites without prior written permission of IEEE or other trademark owners.

Copyright © 2022

# Table of Contents

1.	Introduction .....	1
1.1.	2022 Edition Update .....	1
2.	Working Group Vision .....	1
2.1.	Scope of Working Group Effort.....	2
2.2.	Linkages and Stakeholders.....	2
3.	Today's Landscape.....	4
3.1.	2021 Massive MIMO Workshop.....	5
3.1.1.	Very Large Antenna Arrays.....	5
3.1.2.	Open Radio Access Network (Open RAN) .....	6
3.1.3.	Energy Efficiency, Security, and Deployment.....	6
3.1.4.	Architectural, Spectral, and Algorithmic Challenges .....	6
4.	Future State (2032).....	7
4.1.	mmWave Massive MIMO for HetNets .....	7
4.2.	MAC-PHY Cross-Layer Design for Massive MIMO in Future Wireless Systems.....	7
4.3.	Secure and private communications in Massive MIMO wireless systems.....	7
4.4.	The application of artificial intelligence and machine learning into Massive MIMO wireless systems .....	8
4.5.	Enabling massive connectivity with massive MIMO.....	8
4.6.	Autonomous Massive MIMO for a Variety of Applications.....	8
5.	Needs, Challenges, and Enablers and Potential Solutions .....	8
5.1.	Summary .....	8
5.2.	mmWave Massive MIMO for HetNet.....	8
5.2.1.	Cell Association and Mobility Management .....	9
5.2.2.	Big Data Management with QoS Constraints .....	9
5.2.3.	Low-Cost Channel State Information Acquisition and Beamforming.....	9
5.2.4.	Resource Management.....	9
5.3.	Channel Estimation .....	10
5.3.1.	Sparse Adaptive Filtering Algorithms for Channel Estimation in Massive MIMO Systems .....	10
6.	Networking Planning and Operation .....	10
6.1.	Guarantee of Coverage.....	10
6.2.	Real-Time Support.....	10
6.3.	Implementation Cost and Low Carbon Footprint.....	11
6.4.	Spectral Efficiency .....	11
6.5.	Network Integration .....	11
7.	MAC-PHY Cross-Layer Design for Massive MIMO in Future Wireless Systems .....	11
7.1.	Physical Design.....	11
7.2.	MAC protocol designs .....	12
7.3.	Fronthaul design.....	12
7.4.	Backhaul design .....	12
8.	Efficient Receiver Architecture Design.....	12
8.1.	Physical Layer Design.....	12

8.2.	MAC design .....	13
8.3.	Fronthaul and backhaul design.....	13
8.4.	Security in Cross-layer.....	13
9.	Secure and private communications in Massive MIMO wireless systems .....	13
9.1.	The design of precoding schemes .....	14
9.2.	Cooperative secure transmission & local processing/training.....	14
9.3.	Pilot contamination .....	14
9.4.	Hardware impairments .....	14
9.5.	Energy efficiency design.....	14
10.	Academia and Industry Engagement .....	15
10.1.	Efficient Design .....	15
10.2.	Relay and artificial noise aided techniques .....	15
10.3.	Blind channel estimation and precoding .....	15
10.4.	Hardware impairment.....	15
10.5.	Energy efficient signal processing .....	16
11.	The application of artificial intelligence and machine learning into Massive MIMO wireless systems.....	16
11.1.	Resource allocation based on machine learning.....	16
11.2.	Channel estimation based on machine learning .....	16
11.3.	Signal detection based on machine learning .....	16
11.4.	Interference management based on machine learning.....	17
11.5.	Physical layer design based on machine learning .....	17
11.6.	Detailed design considerations.....	17
11.7.	Overcome overfitting and underfitting.....	17
11.8.	System modeling.....	17
11.9.	Modeling of modulation and demodulation .....	17
12.	Enabling massive connectivity with massive MIMO .....	17
12.1.	Low complexity channel estimation.....	18
12.2.	Support for machine-type devices.....	18
12.3.	Hybrid precoding design .....	18
12.4.	Communication integration with M2M and cloud/edge network.....	18
12.5.	Interference coordination and management .....	18
13.	Challenges with Massive MIMO, Machine-Type, and Massive Connectivity .....	18
13.1.	A simple channel acquisition method .....	19
13.2.	New MAC protocols that support more users .....	19
13.3.	Diverse requirements from machine-type communications.....	19
13.4.	Hybrid precoding design .....	19
13.5.	Related standards .....	19
14.	Autonomous massive MIMO for a Variety of Applications.....	19
14.1.	Throughput optimized Massive MIMO .....	20
14.2.	Reliability and latency optimized Massive MIMO .....	20
14.3.	Extended coverage optimized Massive MIMO .....	20

14.4.	Autonomous Massive MIMO for various applications .....	20
15.	Internet-of-Things (IoT) / Machine-Type Communications .....	20
16.	Scalability .....	20
17.	Energy Efficiency and Low Carbon Footprint.....	21
18.	Signaling Efficiency .....	21
19.	Mobility .....	21
20.	Intelligent Edge Network.....	21
21.	Signal Processing and Massive MIMO.....	21
21.1.	Signal Processing for Single User Massive MIMO .....	23
21.1.1.	Single user massive MIMO (SU-MMIMO) .....	23
21.1.2.	Channel estimation .....	23
21.1.3.	Synchronization.....	23
21.1.4.	Beamforming.....	23
21.1.5.	mmWave Massive MIMO.....	23
21.1.6.	Efficiency .....	24
21.2.	Signal Processing for Multi-User Massive MIMO .....	24
21.3.	MU-MMIMO vs SU-MMIMO .....	24
22.	Intelligent Reflecting Surface .....	26
22.1.	Channel Estimation .....	26
22.2.	Channel Models and Spectrum .....	26
22.3.	Distributed IRS/RIS Communications .....	26
22.4.	Cooperative Beamforming in IRS/RIS Communications .....	27
22.5.	Machine Learning Aided IRS/RIS Communications .....	27
22.6.	Integrated Sensing and Communications Based on IRS/RIS and Massive MIMO.....	28
22.7.	Applications Enabled and Enhanced by IRS/RIS-Aided Massive MIMO Communications.....	28
23.	Massive MIMO Radar .....	28
23.1.	Introduction.....	28
23.2.	Definition .....	29
23.3.	Future Vision.....	29
24.	Cell-Free Massive MIMO.....	29
24.1.	Motivation.....	29
24.2.	Previous Research .....	30
24.3.	Cell-Free Approach.....	30
25.	Systems Design.....	30
26.	Regulatory & Compliance .....	30
27.	Safety .....	32
28.	Conclusions and Recommendations .....	33
28.1.	Summary of Conclusions .....	33
28.2.	Working Group Recommendations.....	34
29.	References .....	35
30.	Acronyms/abbreviations .....	37

31. Contributor Bios .....	40
----------------------------	----

## List of Figures

Figure 1. Massive MIMO Ecosystem .....	4
Figure 2. Massive MIMO array: Spatial multiplexing mode.....	22
Figure 3. Massive MIMO array: Beamforming mode .....	22
Figure 4. Constellation shaping.....	22
Figure 5. 3D transparent view of RIS-assisted mmWave communication with a realistic environment and human blockage ©Y. Huo .....	27

## Abstract

The use of a large number of antenna elements, known as Massive MIMO, is seen as a key enabling technology in the 5G and Beyond wireless ecosystem. The intelligent use of a multitude of antenna elements unleashes unprecedented flexibility and control on the physical channel of the wireless medium. Through Massive MIMO and other techniques, it is envisioned that the 5G and beyond wireless system will be able to support high throughput, high reliability (low bit-error-rate (BER)), high energy efficiency, low latency, and an Internet-scale number of connected devices.

Massive MIMO and related technologies will be deployed in the mid-band (sub 6 GHz) for coverage, all the way to mmWave bands to support large channel bandwidths. It is envisioned that Massive MIMO will be deployed in different environments: Frequency Division Duplex (FDD), (Time Division Duplex (TDD), indoor/outdoor, small cell, macro cell, and other heterogeneous networks (HetNet) configurations. Accurate and useful channel estimation remains a challenge in the efficient adoption of Massive MIMO techniques, and different performance-complexity tradeoffs may be supported by different Massive MIMO architectures such as digital, analog, and/or digital/analog hybrid. Carrier frequency offset (CFO), which arises due to the relative motion between the transmitter and receiver, is another important topic. Recently, maximum likelihood (ML) methods of CFO estimation have been proposed, that achieve very low root mean square (RMS) estimation errors, with a large scope for parallel processing and well suited for application with turbo codes.

Massive MIMO opens up a whole new dimension of parameters where the wireless applications or other network layers may control or influence the operation and performance of the physical wireless channel. To fully reap the benefits of such flexibility, the latest advances in artificial intelligence (AI) and machine learning (ML) techniques will be leveraged to monitor and optimize the Massive MIMO subsystem. As such, a cross-layer open interface can facilitate exposing the programmability of Massive MIMO through techniques such as network slicing (NS) and network function virtualization (NFV). Finally, security needs to be integrated into the design of the system so the new functionality and performance of Massive MIMO can be utilized in a reliable manner.

### **Keywords:**

5G, Massive MIMO, beamforming, mmWave, HetNet, energy efficiency, channel estimation, CFO estimation, hybrid architecture, beam optimization, average signal-to-noise ratio per bit.

## Contributors

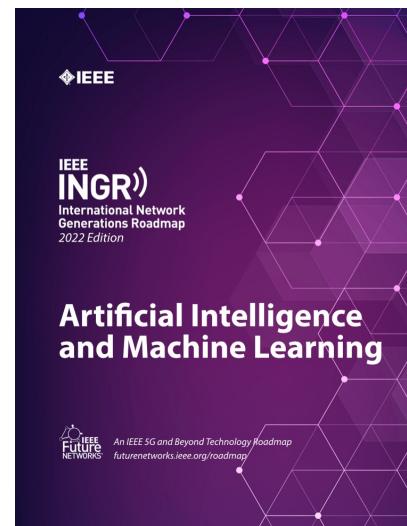
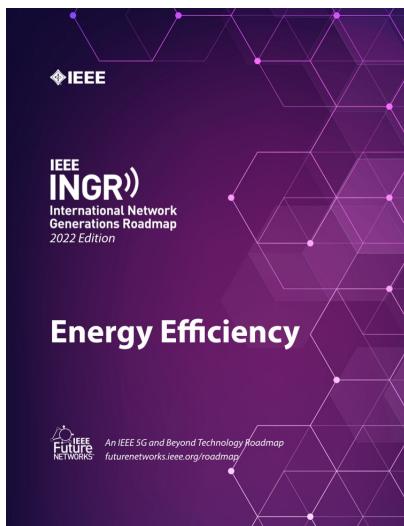
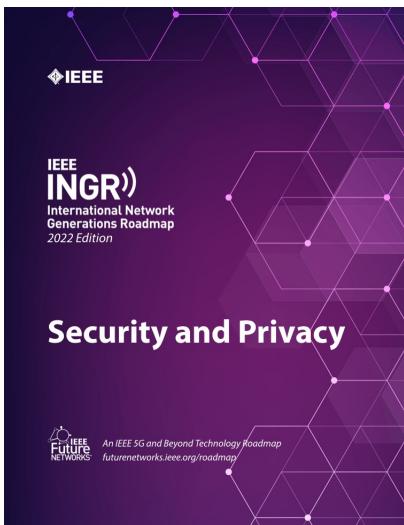
Haijian Sun	Department of Computer Science University of Wisconsin, Whitewater
Chris Ng	IEEE Future Networks Massive MIMO Working Group
Yiming Huo	University of Victoria
Rose Qingyang Hu	Utah State University
Ning Wang	Zhengzhou University
Chi-Ming Chen	AT&T, IEEE
Kasturi Vasudevan	IIT KANPUR
Jin Yang	Verizon Communications Inc.
Webert Montlouis	Johns Hopkins University
Dauda Ayanda	University of KwaZulu-Natal, South Africa
Kumar Vijay Mishra	United States CCDC Army Research Laboratory
Kürşat Tekbiyik	Department of Electronics and Communication Engineering Istanbul Technical University
Nasir Hussain	Samsung Electronics America
Harish Kumar Sahoo	Veer Surendra Sai University of Technology, India
Yang Miao	University of Twente, The Netherlands

# Want to read the full chapter?

Accessing full INGR chapters is easy and affordable.

**Step 1.** [Click here to join the Future Networks initiative](#) (free for any IEEE Society member, and low-cost for non-members)

**Step 2.** Return to the [INGR page](#) to download full chapters.



14 chapters  
available!