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.

IEEE Future NETWORKS™

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.

IEEE INGR 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

IEEE

IEEE INGR

International Network Generations Roadmap

2022 Edition

Energy Efficiency

IEEE Future NETWORKS

An IEEE 5G and Beyond Technology Roadmap

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 2

2. Working Group Vision 3

2.1. Scope of Working Group Effort 3

2.2. Linkages and Stakeholders 4

2.2.1. Cross-Collaborative Activities Across INGR WGs 6

2.2.1.1. 2021 5G World Forum 6

3. Today's Landscape 6

3.1. Global Mobile Telecommunications Energy Footprint 8

3.1.1. EE System Design Best Practices 9

3.1.2. Global Metrics & Hierarchy for 5G&B 10

3.1.2.1. Defining a Universal Architecture & The Universal Currency 11

3.1.2.2. Defining Universal Metrics for 5G&B 12

3.1.2.2.1. KEY ANALYSIS: What is the true cost of 1 mW? 14

3.1.3. Articulating the Energy Risks of 5G&B 16

3.1.3.1. Relating Energy Risks of 5G&B to Financial Risks 17

3.1.3.2. Quantifying the Risks of 5G&B Deployments 18

3.1.4. Strict Payback Period Targets Driving Socioeconomic Disparity 19

3.2. Current State of Technology and Research 20

3.2.1. The Physics of RF Transmission 20

3.2.2. Requirements on Unwanted Emissions Must Be Satisfied 21

3.2.3. The Need to Address the Whole Ecosystem 22

3.3. Drivers and Technology Targets 22

3.3.1. 5G&B Applications Driving EE System Design Needs 22

3.3.2. The Impacts of a Virtualized World 24

3.3.3. 5G&B Business Drivers 25

3.3.4. Data Center Efficiencies to the Edge and Corresponding Data Processing Architecture 26

3.3.5. Network Energy Architecture 28

3.3.6. RF Base Stations Today 28

3.3.6.1. Renewable Energy-Enabled Cellular Networks 31

3.3.7. The Role of AI Deep Learning 31

3.3.8. Applications Deployment Optimization 31

3.3.9. AI Use for Network Optimization 32

4. Future State (2032) 33

4.1. Vision of Future Technology 33

4.1.1. Cell-free Architectures 34

4.1.2. Ubiquitous HetNets of Small Cells 34

4.1.3. Enabling/Deploying Energy-optimal Control Feedback Loop(s) 35

4.1.4. Model Complexity 36

4.1.5. Model Validation 37

4.2. Energy-Efficient Architectural Framework 38

4.2.1. Overview of Systems of Systems (SoS) 38

4.2.2. SoS Case Studies 43

4.2.2.1. Example 1: Cognizant, Real-time Power-grid Systems Management Under Variable Energy Resources Availability 43

4.2.2.2. Example 2: Estimation of Data Transmission Costs in a Fiber-Optic Connection 44

4.2.3. Systems-of-Systems (SoS) Tool Roadmap 45

4.2.4. SoS Tool architecture 45
5. Needs, Challenges, and Enablers and Potential Solutions 47
5.1. Summary 47
5.2. Network Efficiency - Need #1 48
5.2.1. Challenges 48
5.2.1.1. Inhibitors to EE System Design 48
5.2.1.2. Key Challenges at the Physical Layer 49
5.2.1.3. Large-scale Deployment of IoT Devices 51
5.2.2. Potential Solutions 52
5.2.2.1. Mitigating the Inhibitors to EE System Design 54
5.2.2.2. Efficient Physical Layer Operation in Active Mode Using Spatial Multiplexing 55
5.2.2.3. RF Hardware Evolution 57
5.2.2.4. Efficient Physical Layer Operation in Idle Mode 58
5.2.2.5. Wake-up Radio (WuR) for User Devices in Idle Mode 60
5.2.2.6. Energy Harvesting (EH) 60
5.2.2.7. Backscattering Communication 62
5.2.2.8. Wider Bandwidths and Visible Light Communication 62
5.3. Small Cell Migration - Need #2 64
5.3.1. Challenges 64
5.3.2. Potential Solutions 65
5.3.2.1. Characterizing Energy-Centric Coverage as "Carpeting" 65
5.3.2.2. Interference Management Within a Cell 68
5.3.2.3. Efficient Control Plane Transmission 68
5.3.2.4. Interference Management Between Cells 69
5.3.2.5. Cell-free Architecture 69
5.3.2.6. Coverage Improvements with Intelligent Reflecting Surfaces 71
5.4. Base Station Power – Need #3 73
5.4.1. Challenges 73
5.4.1.1. Challenges with Unwanted Emissions 73
5.4.1.2. RF Semiconductor Process Technologies Evolution and Application Fit 74
5.4.1.3. RF Semiconductor Challenges & Limitations for Massive MIMO and/or mmWave 75
5.4.2. Potential Solutions 77
5.4.2.1. RF Semiconductor Path to 6G 77
5.4.2.2. Power Electronics in 5G&B 77
5.4.2.3. Power Packaging 79
5.4.2.4. Thermal Mitigation 80
5.5. Economic Factors – Need #4 81
5.5.1. Challenges 82
5.5.1.1. Challenges in the Optimization of Energy Use and Environmental/Financial Impact of 5G&B Network Infrastructure 84
5.5.2. Potential Solutions 85
5.5.2.1. Solutions for the Optimization of Energy Use and Environmental/Financial Impact of 5G&B Network Infrastructure 86
5.6. Grid/Utility – Need #5 87
5.6.1. Challenges 88
5.6.1.1. The 5GEG & Overall Risk 5G&B Applications Pose to the Utility Grid (Smart or Otherwise) 88
5.6.1.2. The Role of the Utility Grid in 5G&B 90
5.6.1.3. Disaggregation of the Utility Grid 91
5.6.1.4. Energy Storage 91
5.6.2. Potential Solutions 93
5.6.2.1. Powering Options for 5G Infrastructure Equipment 93
5.6.2.2. Powering Opportunities 93
5.6.2.3. Applications of the Smart Grid 94

5.6.2.4. Network Power Integration 95
5.6.2.5. Case Study: A Smarter Grid 96
6. Standardization Landscape and Vision 99
6.1. Standardization Opportunities 99
6.1.1. Collaborative Opportunities 99
7. Conclusions and Recommendations 100
7.1. Summary of Conclusions 100
7.2. Working Group Recommendations 102
7.2.1. Future Work 103
8. Contributor Bios 104
9. References 112
10. Acronyms/abbreviations 120

Tables

Table 1. Overall, Major Need Categories Identified by the INGR EE WG 47
Table 2. Challenges Associated with "NEED #1 - Network Efficiency" 51
Table 3. Potential Solutions to Address "NEED #1 - Network Efficiency" 63
Table 4. Challenges Associated with "NEED #2 - Small Cell Migration" 65
Table 5. Potential Solutions to Address "NEED #2 - Small Cell Migration" 72
Table 6. Challenges Associated with "NEED #3 - Base Station Power" 76
Table 7. Potential Solutions to Address "NEED #3 - Base Station Power" 80
Table 8. Challenges Associated with "NEED #4 - Economic Factors" 83
Table 9. Potential Solutions to Address "NEED #4 - Economic Factors" 85
Table 10. Challenges Associated with "NEED #5 - Grid/Utility" 92
Table 11. Potential Solutions to Address "NEED #5 - Grid/Utility" 97

Figures

Figure 1. The IEEE INGR Cross-Cut Matrix for the EE WG 5
Figure 2. Outside forces affecting the infrastructure 7
Figure 3. The 5G System-of-Systems (SoS) Block Diagram 8
Figure 4. The Power Value Chain (PVC) from Network Edge to Power Plant 12
Figure 5. Attenuation of mmWave Transmission over the air [21] 21
Figure 6. [28] 29
Figure 7. The Systems-of-Systems (SoS) Block Analysis Template Model 40
Figure 8. The Systems-of-Systems (SoS) Power Value Chain (PVC) Chain Analysis (Static) Example Flow 40

Figure 9. The Systems-of-Systems (SoS) Network/System Optimization Chain Analysis (Dynamic) Example Flow 41

Figure 10. Management of Energy Sources as an additional input to sub-block level description 42

Figure 11. An example of Systems of Systems incorporating a RAN subsystem 43

Figure 12. The Power Grids form complex Systems of Systems 44

Figure 13. The energy consumption and energy efficiency of a base station depend on the traffic load. It is desirable to the energy consumption proportional to the load, to get a constantly high energy efficiency. 50

Figure 14. Sequential processing of data in a self-driving vehicle 52

Figure 15. Flow of data in a self-driven vehicle and trade-offs in energy optimization 53

Figure 16. Since the energy efficiency in active mode is the ratio between data throughput and energy consumption, there are three different ways that it can be improved. 56

Figure 17. Power consumption for a conventional 4x4 MIMO base station 58

Figure 18. The idle mode power consumption in comparable LTE and NR configurations, showing that the average energy consumption is substantially smaller in NR thanks to the new sleep mode features 60

Figure 19. Comparison of Base Station "Carpeting" at Various Power Levels and Frequencie 66

Figure 20. The propagation comparison for a specific case of 2.5GHz using the CRC model data for a Suburban configuration. While a 200W Macro Cell provides extensive coverage, the 1W Small Cell enjoys a large efficiency advantage because RF propagation is significantly more lossy than 1/r2. 67

Figure 21. The networks will gradually transition from the cellular architecture to the left to the cell-free architecture to the right. 70

Figure 22. A passive surface can be deployed to reflect signals from a base station towards shadowed areas. 71

Figure 23. A reconfigurable surface can be utilized to direct signals from base stations to shadowed locations in an adaptive manner. 72

Figure 24. Power Amplifiers Performance Survey 2000-Present [88].74

Figure 25. The NPI Model 96

Figure 26. The disaggregation of power, data communications, and communications about power 96

ABSTRACT

This 2021 Edition of the IEEE International Network Generations Roadmap (INGR) contains a new Chapter dedicated to Energy Efficiency, which builds upon the initial white paper released in April 2020 [1]. For this purpose, the Energy Efficiency Working Group developed an analysis of the energy efficiency constraints across the whole ecosystem of the Fifth Generation "5G" and following network infrastructure, which can be leveraged by all stakeholders to prioritize resources allocation and technology development to ensure that both technical and economic forecasts can be met. The complexity of the ecosystem and the traditionally siloed approach within the Industry has often prevented the adoption of a holistic approach to addressing the fundamental problem of energy, which is the ultimate constraint to any complex deployment. The proposed framework facilitates an assessment of bottlenecks and their implication on the network: it may be used by both academic and industry stakeholders to develop solutions that address the real issues and enable a healthy ecosystem.

After a comprehensive survey of the ecosystem and its challenges, the following key areas were selected for a more in-depth analysis:

- Network Efficiency
- Small Cell Migration
- Base Station Power
- Economic Factors
- Grid/Utility

This Chapter also identifies the need for a comprehensive "Systems-of-Systems" (SoS) analysis to address the complex inter-relations among the multiple layers, which the infrastructure leverages. An initial proposal describes how a model can be built to enable a comprehensive assessment of energy requirements across such a diverse ecosystem. A future step in the process will consolidate a proposal for standardization of this model, which can be utilized by all stakeholders for both analysis and forecasting of capabilities and return on investment.

Key words:

Energy Efficiency, 5G Energy Gap (5GEG), Power Value Chain (PVC), Power Cost Factor (PCF), Systems of Systems (SoS), Energy Harvesting (EH), Sustainable Power, Embodied Energy, 5G Economic Gap (5GEcG), 5G Equality Gap (5GEqG), 5G Derate Factor (5GDF), Assessment Framework

CONTRIBUTORS

Brian Zahnstecher, PowerRox (Co-chair)

Earl McCune, Eridan Communications (***IN MEMORIAM, RIP***)

Doug Kirkpatrick, Eridan Communications

Rick Booth, Eridan Communications

Kirk Bresniker, Hewlett Packard Enterprise

Lin Nease, Hewlett Packard Enterprise

Anirban Bandyopadhyay, Global Foundries

Bruce Nordman, Lawrence Berkeley National Laboratory

Francesco Carobolante, IoTissimo LLC (Co-chair)

Magnus Olsson, Huawei

Emil Björnson, KTH Royal Institute of Technology

Laurence McGarry, pSemi/Murata

Steve Allen, pSemi/Murata

Paul Draxler, Stonecrest Consulting

Frederica Darema, formerly of NSF and AFOSR

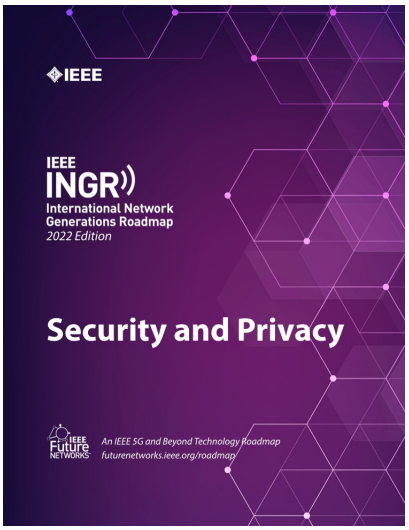
Mohamed-Slim Alouini, KAUST

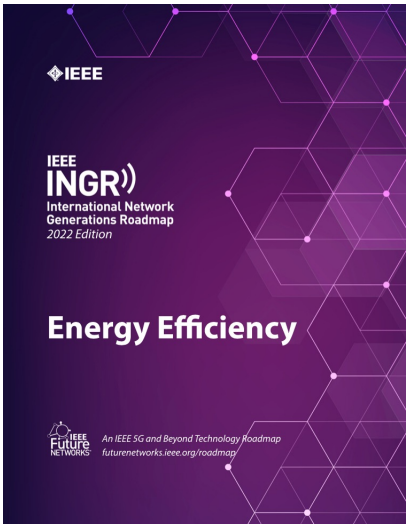
Want to read the full chapter?

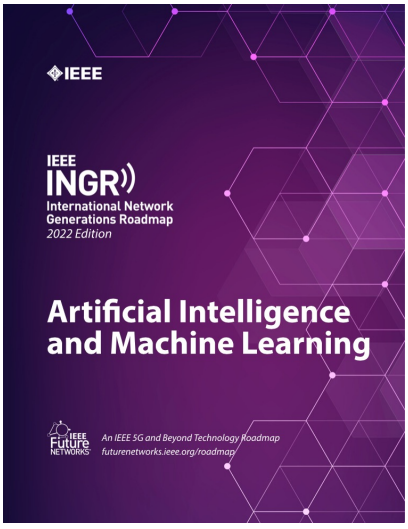
Accessing full INGR chapters is easy and affordable.

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!