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Fraunhofer Institute for Reliability and Microintegration IZM

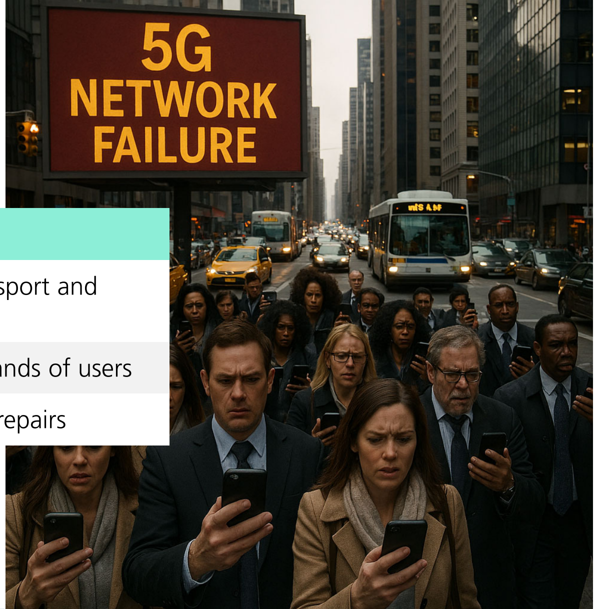
Electronic Packaging Days 2025

Dr. Johannes Jaeschke

Design for Reliability of Advanced Packages for 5G and 6G Wireless Infrastructure

What happens if your 5G Infrastructure fails during rush hour?

ASPECT	IMPACT
Urban Connectivity	Disruption of public transport and emergency services
User Experience	Loss of service for thousands of users
Operational Costs	High cost of emergency repairs



Reliability assurance of 5G/6G infrastructure starts long before deployment - at package-level design

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Challenges in Design

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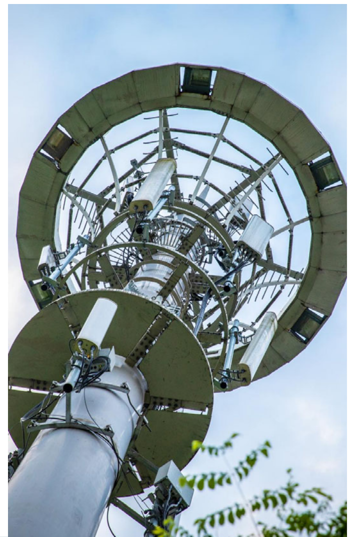
Uncertain or Unknown Stress Conditions

Requirements

- Design for Reliability: Ensure functionality over lifetime under **specified stresses**
- 5G/6G packages: Global use in **complex systems** under **diverse, harsh environments**
- Standard-based qualification and technical specifications
  (e.g. ETSI EN 300 019: environmental conditions and tests; 3GPP 38-series: conformance testing)

Uncertain Operational Profiles and Stress Conditions

- Global climate conditions (e.g. temperature, humidity, vibration) usually known for specific deployment sites – but usage worldwide
- Local usage conditions (e.g. duty cycles, sleep modes, system interactions) often uncertain or unknown



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Gap between Package and System Validation

Multiple Scale Interaction: <u>System</u> – Board – <u>Package</u> – Chip

Challenges in Package Design Validation

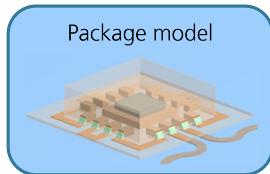
- Package manufacturers use detailed multiphysics simulation techniques (e.g. FEM) but lack real field condition data

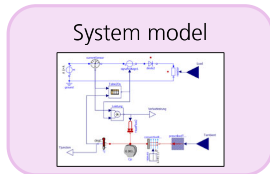
System Integration Limitations & Intellectual Property (IP)

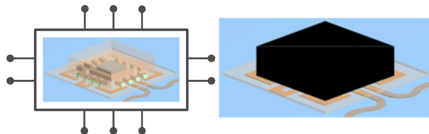
- System integrators simulate system dynamics and interactions but lack access to detailed package designs due to IP protection

Bridging the Gap between Package & System Knowledge Transfer

- IP-secure digital twins and mission profiling enable virtual validation







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Digital Twins

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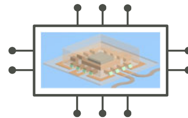
Solution: Digital Twins and Compact Models

Digital Twin
- **Virtual representation** of real objects or connected systems
- Linking physical and digital worlds **for a specific purpose or business case**

Compact Models
- Reduced-complexity, physics-based component models
- Provide fast and accurate simulation with IP protection



How Compact Models enable Digital Twins
- Serve as secure, modular building blocks within digital twin architectures
- Allow system-level modeling without exposing sensitive design details

Use Cases in Electronics (e.g.)
- **Virtual qualification** and testing during the design-phase
- **Real-time condition monitoring** and predictive maintenance during operation

Main Reliability Challenges

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Why Design for Reliability (DfR) is Critical for Advanced 5G/6G Packaging

Advanced Packaging Technologies

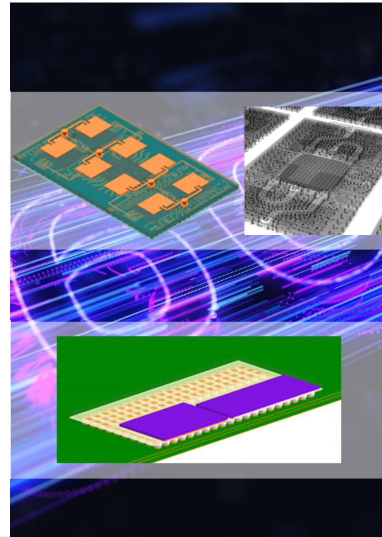
- Antenna-in-Package (AiP), System-in-Package (SiP), chiplets and 2.5D/3D integration are key technologies enabling high-performance RF systems

Challenges in 5G to 6G Transition

- Higher frequencies and new packaging technologies increase thermal, mechanical, and electrical stresses

Critical Role of Packaging

- Packaging becomes the key vulnerability for system reliability due to dense integration



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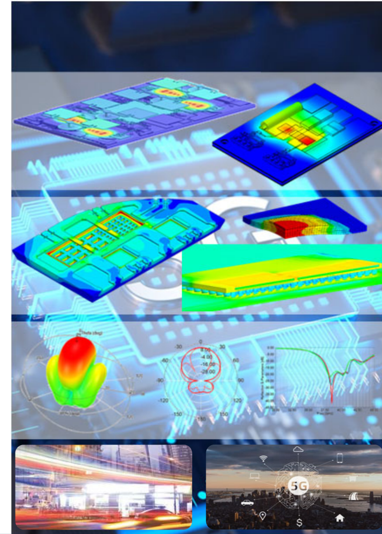
Top Reliability Drivers for 5G/6G Packages



Thermal and Signal Integrity Issues

- High-frequency and power interactions create signal and power integrity constraints causing significant thermal loads and hotspots

Material Mismatches and Thermo-Mechanical Stresses

- Differences in thermal expansion coefficients (CTE) in heterogeneous stacks cause warpage and mechanical stress

Material and RF Performance

- Inappropriate materials cause dielectric losses, detuning, and signal distortion affecting RF performance

Environmental Stressors

- Temperature, humidity, and power cycling accelerate degradation

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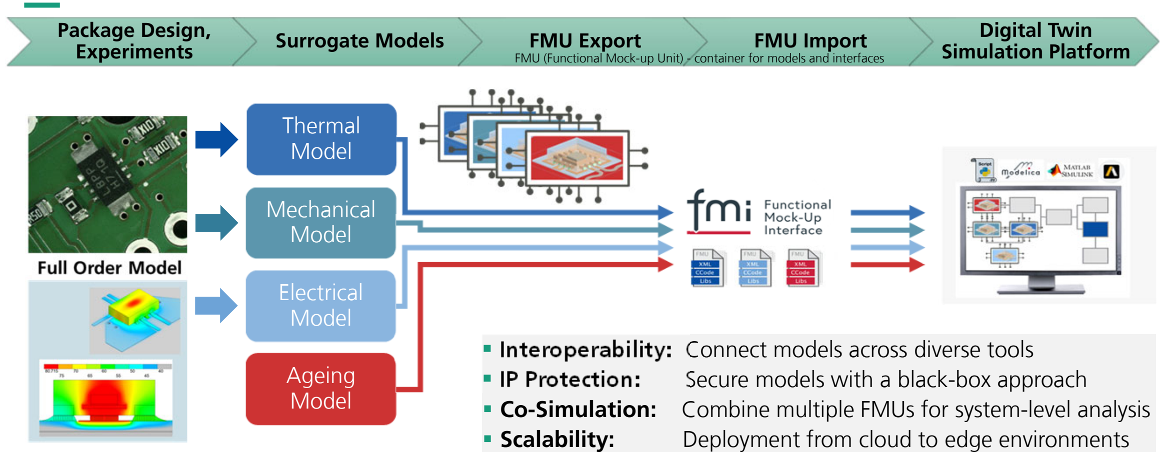
Digital Twin Framework with Standardized, Open-Source Interface



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Project Implementation, Examples

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Example: mmWave Antenna-in-Package

gan-on-**S**ilicon **E**fficient mm-wave eu**R**opean syst**E**m i**N**tegration pl**A**tform

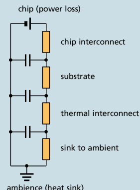
The SERENA project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 779305.

Advanced 5G Package Integration

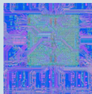
- Integration of GaN power amplifiers with SiGe beamformer ICs in a hybrid Antenna-in-Package module
- PCB embedding enables short, controlled-impedance interconnects for better signal integrity and compact design

Thermal Management and Integrity Analysis

Thermal RC network (Cauer/Foster)

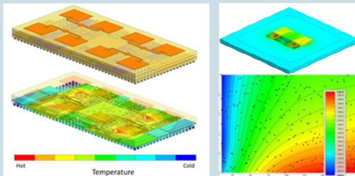


Circuit Design

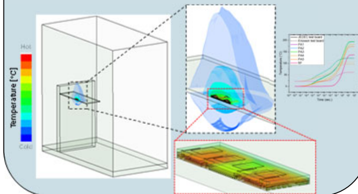


e.g. ODB++, Gerber

Detailed **package & interconnect sub-modeling** and optimization based on circuit design



Analysis of **system dynamics**, reduced complexity



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Example: Condition Monitoring with Grey-Box Modeling (AI & Digital Twins)

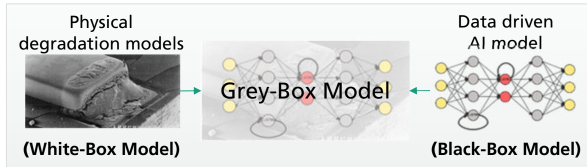
Predictive Maintenance

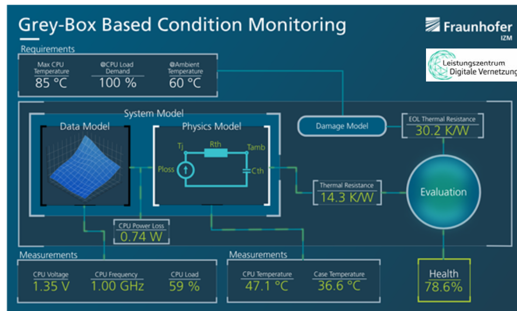
Challenges

- AI-based predictions are not explainable (**Black-Box**) → low acceptance in industrial environments
- Physics of Failure approaches (PoF, **White-Box**) are hardly applicable for complex systems and load profiles

Solution: Hybrid Modeling Approaches

- **Grey-Box** modeling (**White-Box + Black-Box**)
  → Decision processes of the Grey-Box are physically justified and thus explainable





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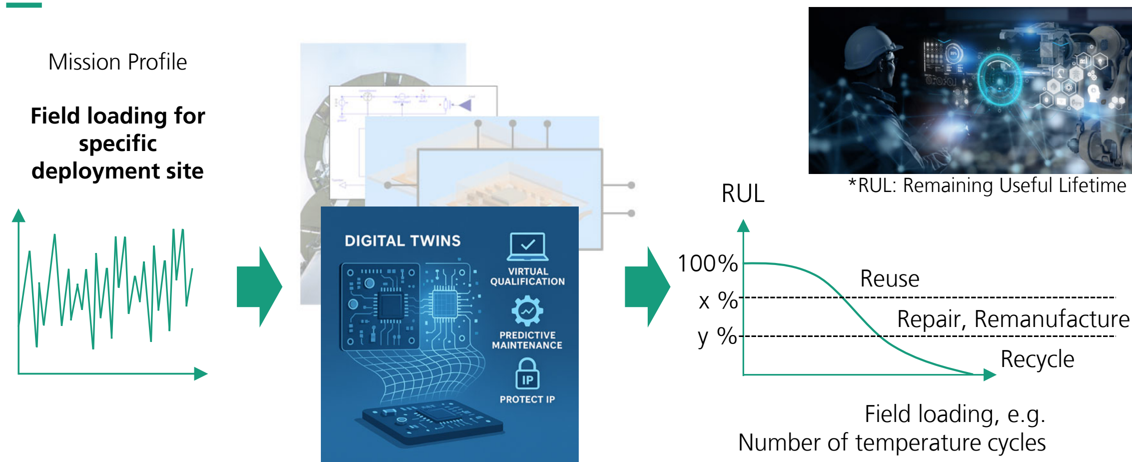
Example: Utilizing Digital Twins for Ecodesign Requirements

Support for Circular Economy



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Key Takeaways

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Summary and Vision

Key Takeaways

- Digital twins and compact models enable virtual qualification and real-time monitoring
- Data trust frameworks secure sensitive information exchange across company boundaries

Main Barriers

- Lack of standardized data formats & frameworks
- Data alignment & validation
- IP protection & model synchronization

Vision

- **Interconnected digital twins** spanning design, manufacturing, packaging, testing and operation

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