DT-BAN Design from a Modeling Perspective: A Use Case-Driven Approach

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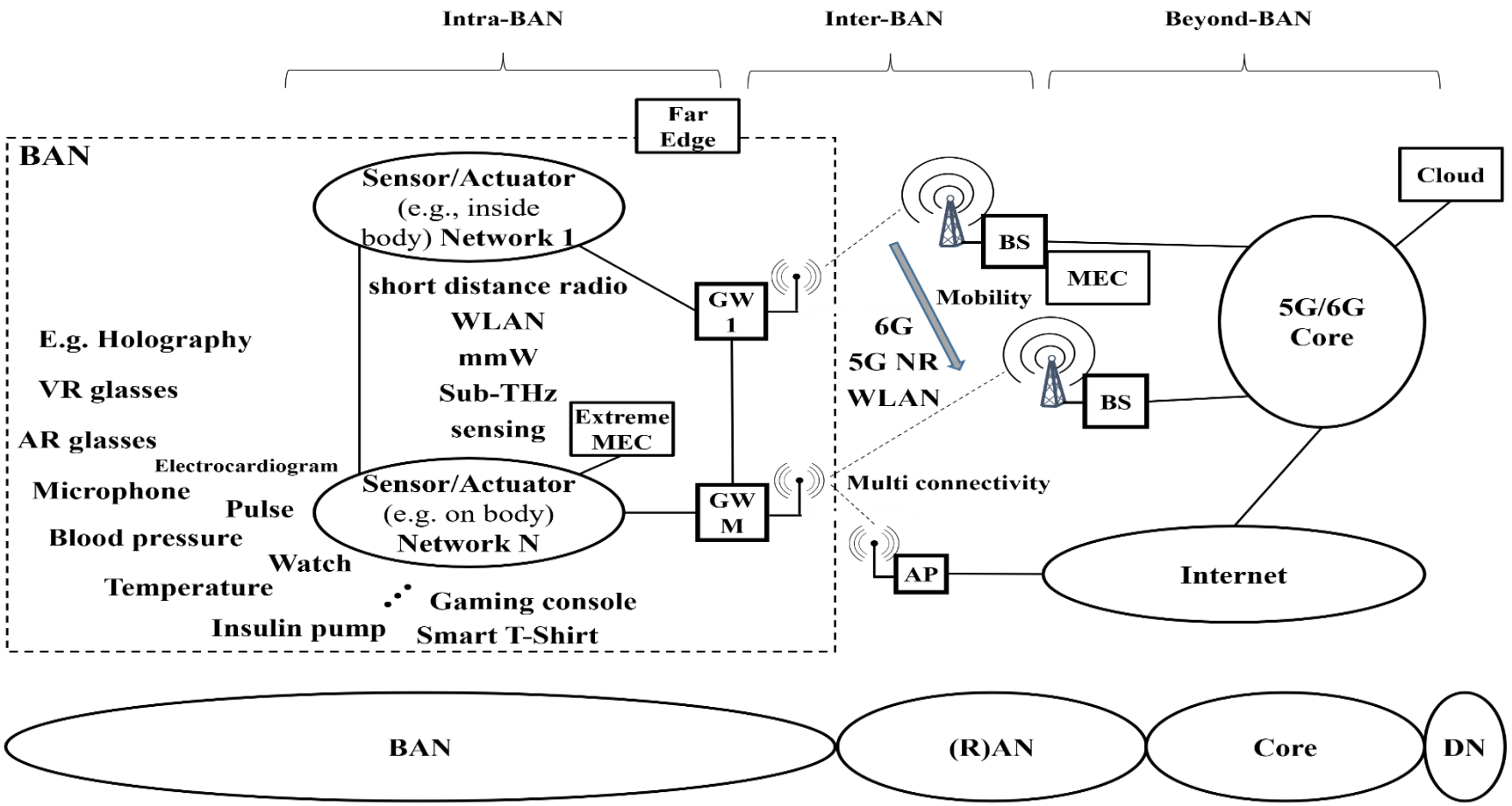
HAW Hessen

Forschungsgruppe für
Tele-
kommunikationsnetze

Agenda

- **Motivation**
- **BAN & DTN Requirements**
- **Process Flow for DT-BAN Design & Implementation**
- **Use Case-Driven Modeling**
- **Conclusion & Future Directions**

Motivation



AP: Access Point
GW: Gateway
(R)AN: (Radio) Access Network

BS: Base Station
MEC: Multi-Access Edge Computing

DN: Data Network
NR: New Radio

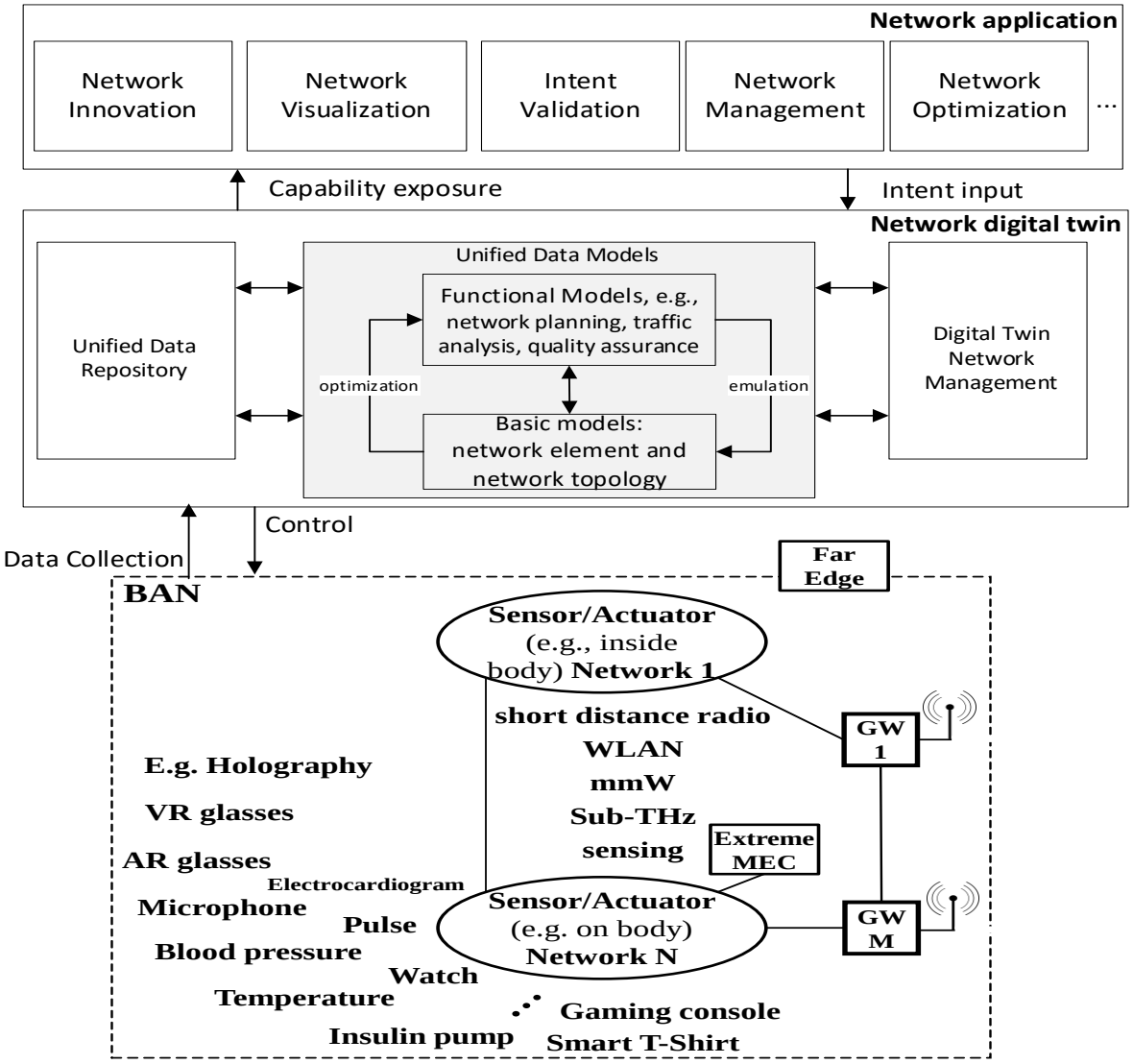
Motivation

- A Digital Twin creates a virtual replica of a physical system to enable real-time monitoring, analysis, and control.

- Extending this concept to networks, a Digital Twin Network (DTN) creates a virtual representation of a physical network.

- DTNs enable:
  - Accurate simulations of network behavior
  - Improved testing and validation of configurations
  - Efficient troubleshooting and proactive diagnosis
  - Optimized control and operation of real-world networks
  - And more…

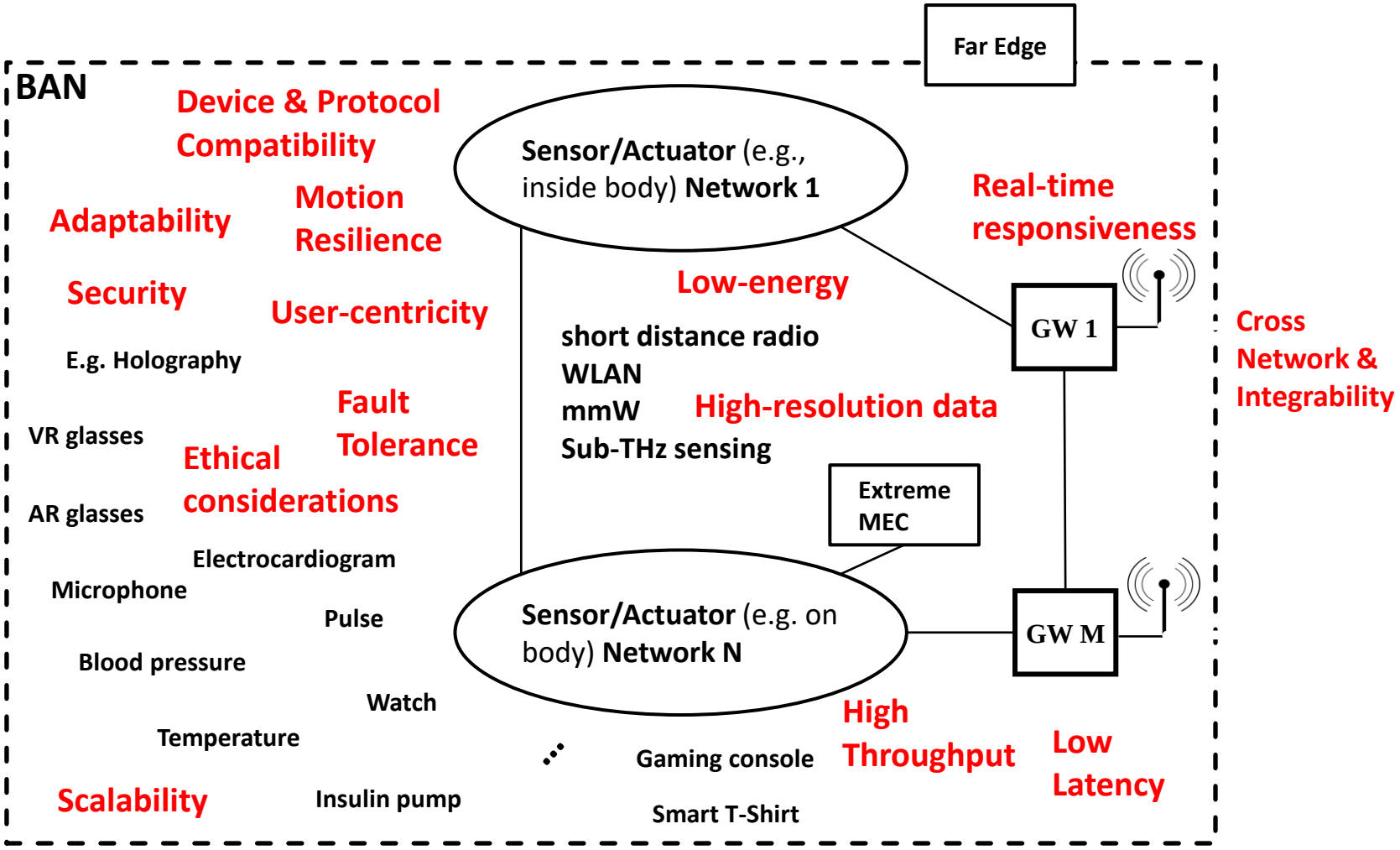
Motivation


Network application
Network Innovation
Network Visualization
Intent Validation
Network Management
Network Optimization
...
Capability exposure
Intent input
Network digital twin
Unified Data Repository
Unified Data Models
Functional Models, e.g., network planning, traffic analysis, quality assurance
optimization
emulation
Basic models: network element and network topology
Digital Twin Network Management
Control
Data Collection
Far Edge
BAN
Sensor/Actuator (e.g., inside body) Network 1
short distance radio
WLAN
mmW
Sub-THz
sensing
GW 1
E.g. Holography
VR glasses
AR glasses
Extreme MEC
Electrocardiogram
Microphone
Pulse
Blood pressure
Watch
Temperature
Insulin pump
Sensor/Actuator (e.g. on body) Network N
GW M
Gaming console
Smart T-Shirt

Motivation

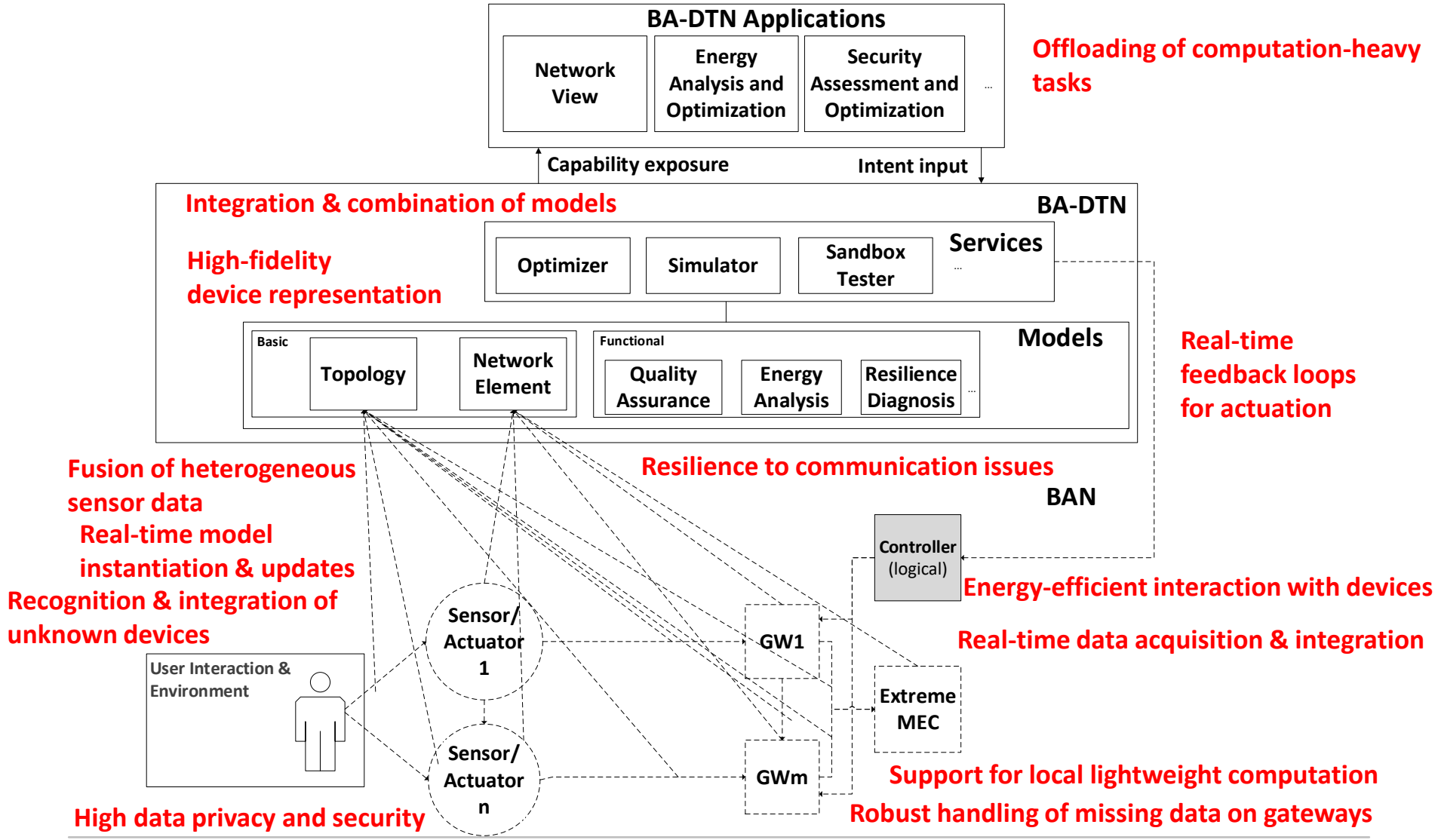
- However, gaps remain:
  - Lack of comprehensive design methodologies
  - Limited consideration of network-specific constraints
  - Missing a comprehensive definition of DTN models and their representation methods
  - Missing integration of diverse modeling approaches

BAN Requirements

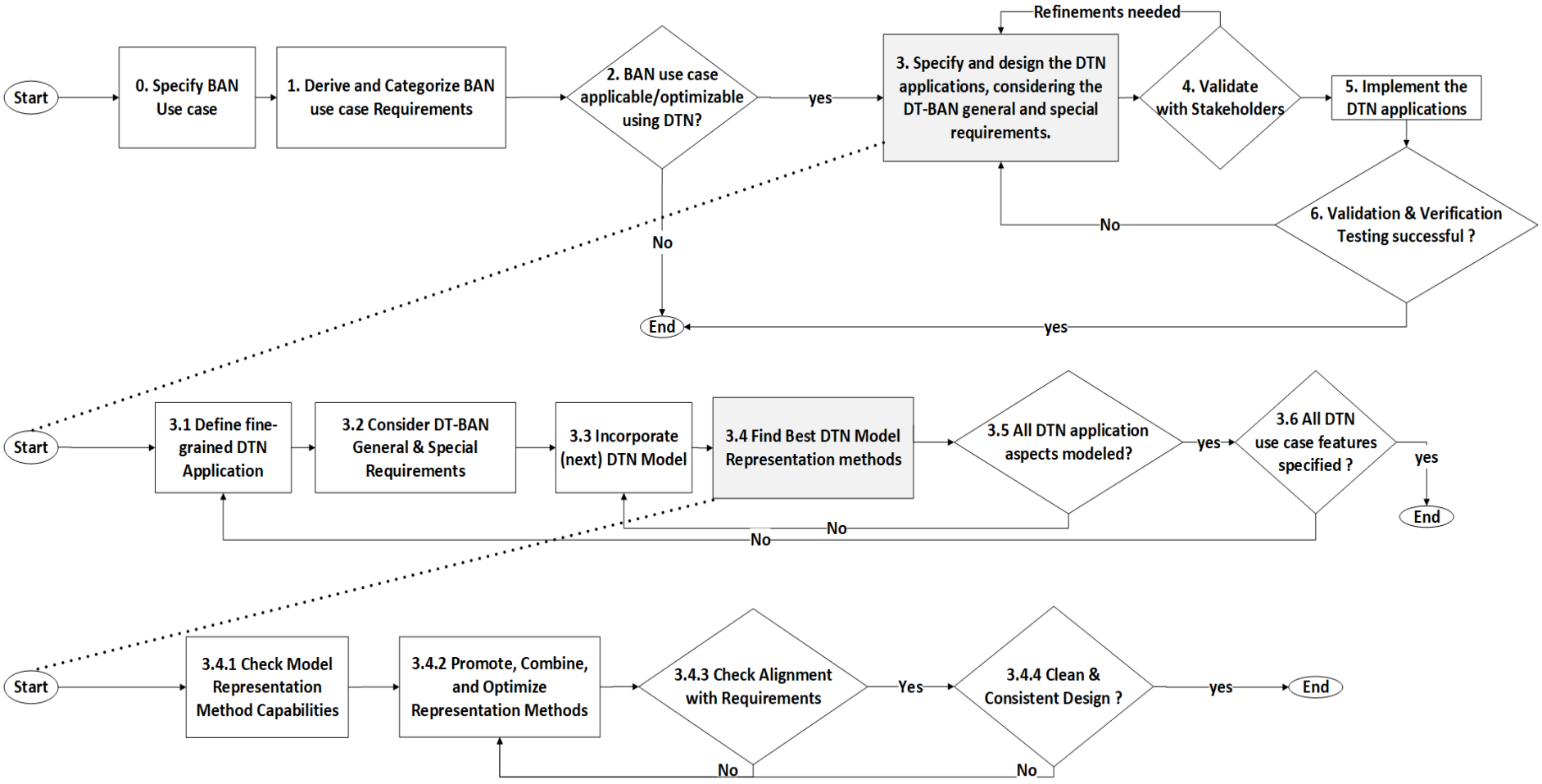


→ **Digital Twin for BANs must be designed to address a tailored subset of these requirements based on application-specific needs.**

DT-BAN Requirements



Process Flow for DT-BAN Design & Implementation



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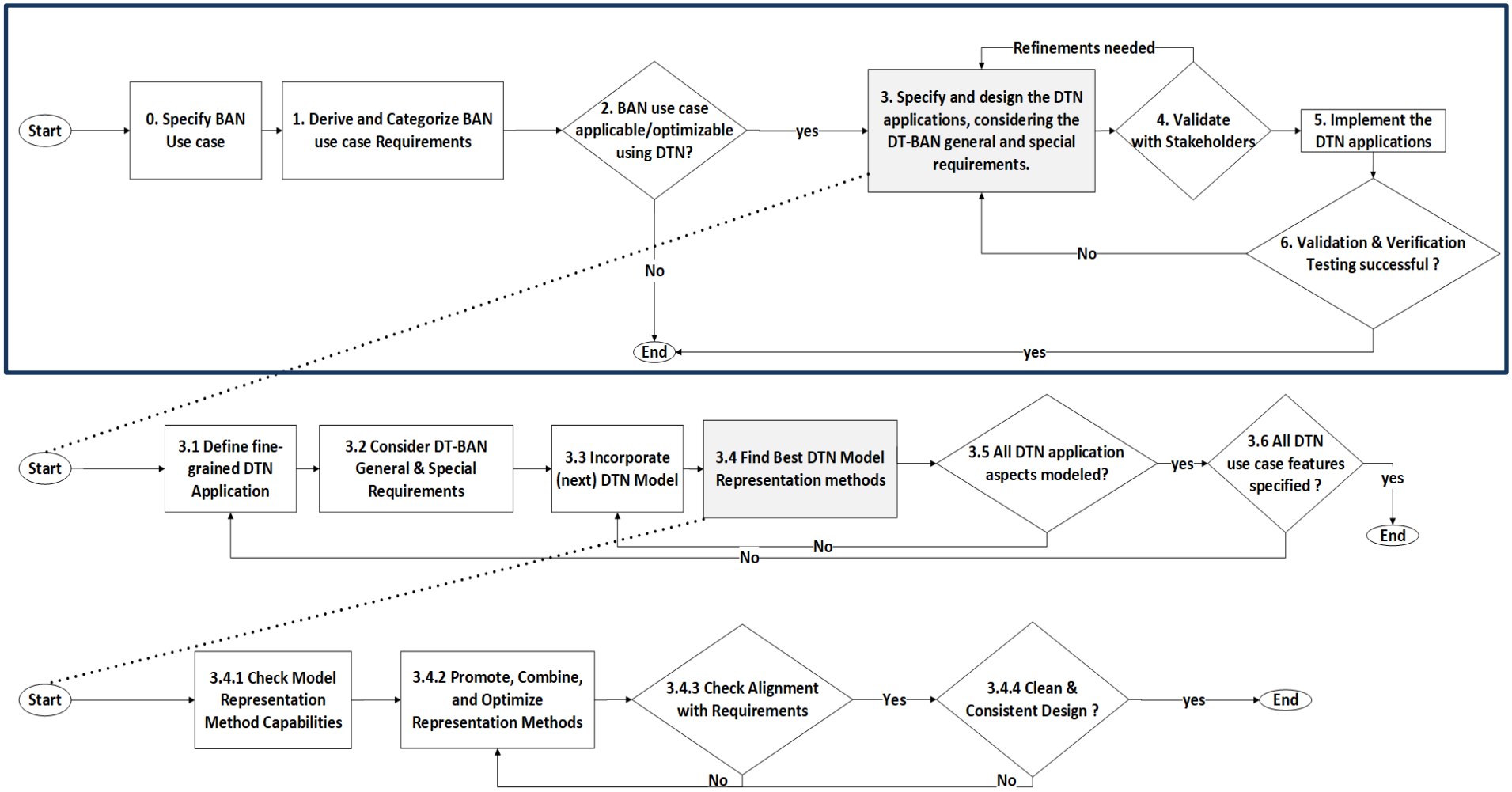

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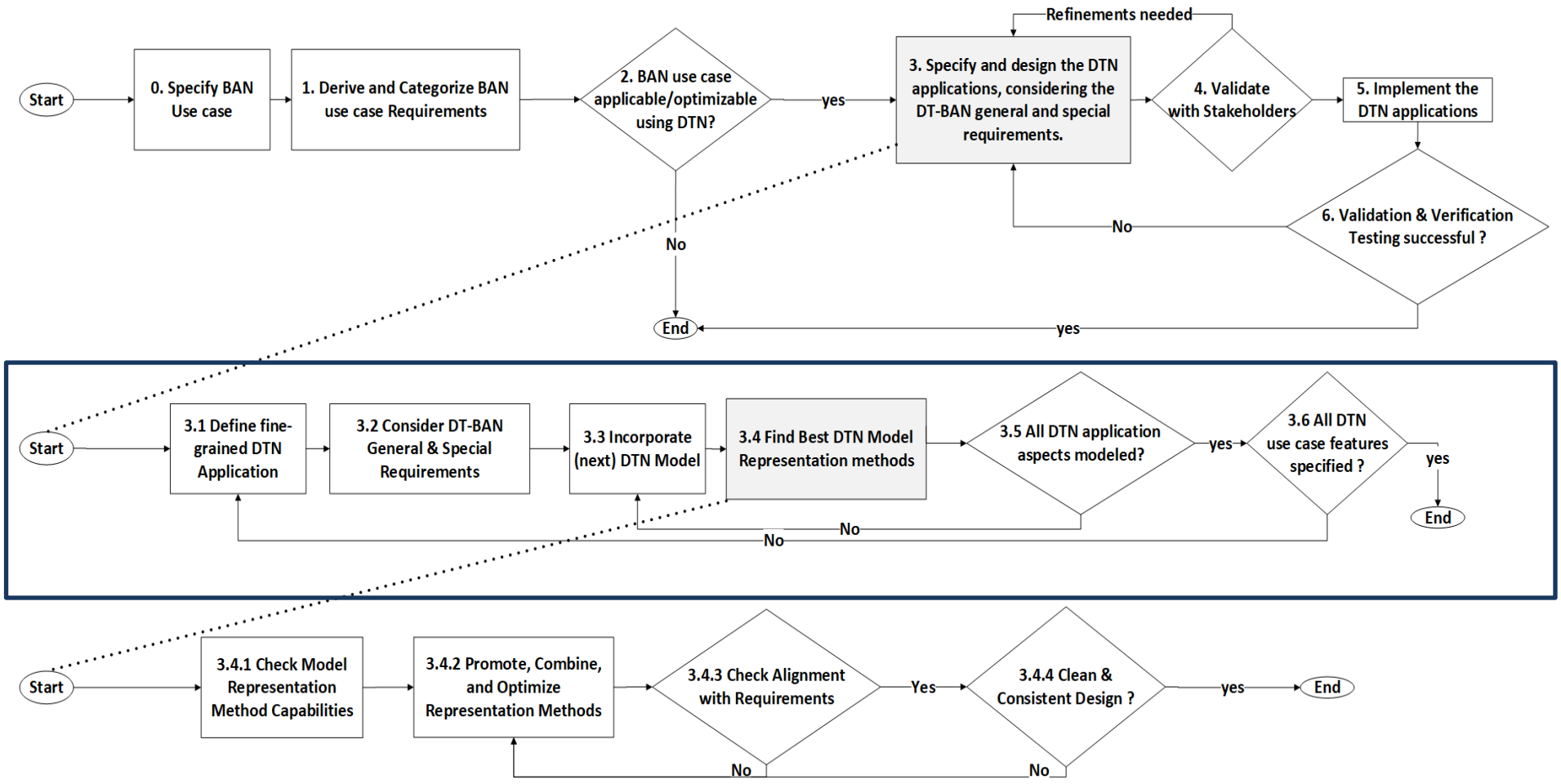
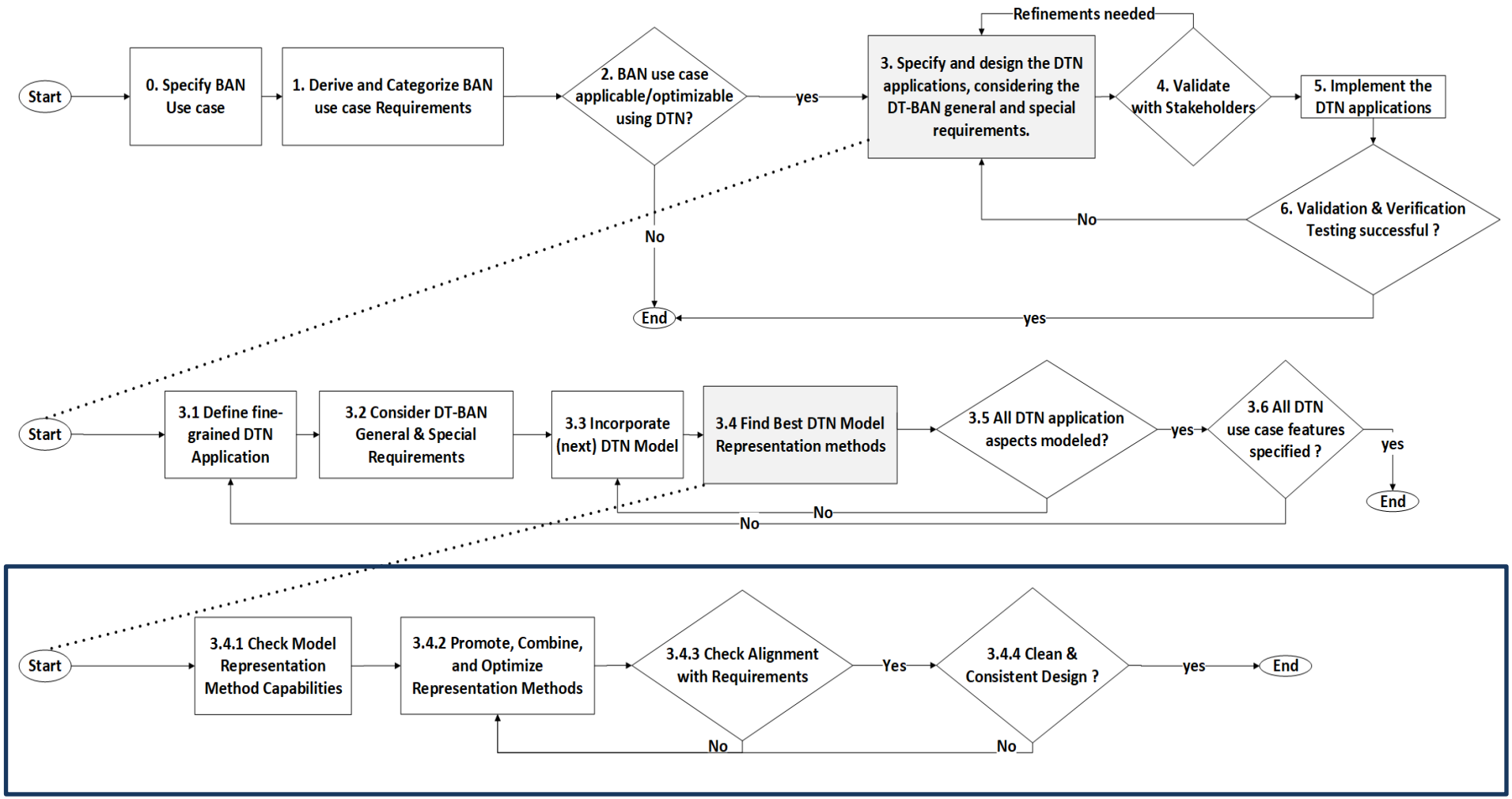


Process Flow for DT-BAN Design & Implementation



Use Case-Driven Modeling

- Stakeholders (e.g., doctors, researchers, responders, gamers) have diverse objectives and application needs.
- A structured use case template is essential for consistency, clarity, and reusability.
- It defines key components for modeling and implementing DT-BAN use cases:

Use-Case Template
<Stakeholders>
<Main User Story>
<Requirements>
<Benefits of DT-BAN>

<DT-BAN Applications>
• <Application1>
  • <Special Req.>
  • <Models/Methods>
• <ApplicationN>

Demo Use Case: Proactive Quality Assurance & Optimization for BAN Operations

- **Stakeholders:** Doctors, Researchers, First Responders, etc.
- **Main BAN Scenario / User Story:**
  - BAN adapts to changing network conditions.
  - Continuous optimization of: Performance, Safety, Energy efficiency, and Security.
- **Requirements**:
  - Real-time monitoring of network state
  - Dynamic adaptation to changing conditions
  - Optimization (e.g., performance, safety, energy, security)
  - Energy-aware operations to extend device lifespan

Use-Case Template
<Stakeholders>
<Main User Story>
<Requirements>
<Benefits of DT-BAN>

<DT-BAN Applications>
• **<Application1>**
  • **<Special Req.>**
  • **<Models/Methods>**
• **<ApplicationN>**

Demo Use Case: Proactive Quality Assurance & Optimization for BAN Operations

- **Benefits of DT-BAN Deployment:**
  - Continuous monitoring and real-time insights
  - Intelligent, automated adaptation & multi-dimensional optimization
  - Enhanced resilience and fault tolerance
  - Improved energy efficiency and device longevity
  - Strengthened security and privacy assurance

- **Applications:**
  - Network View
  - Network Resilience Evaluation & Optimization
  - Energy Analysis
  - Network Security Assessment & Optimization

Use-Case Template
<Stakeholders>
<Main User Story>
<Requirements>
<Benefits of DT-BAN>

<DT-BAN Applications>
• **<Application1>**
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  • **<Models/Methods>**
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Demo Use Case: Proactive Quality Assurance & Optimization for BAN Operations

DTN Application	Special Requirements	Models & Representation Methods
Network View	• Real-time model updates • High-fidelity representation of devices • Extreme energy-efficient interactions • Integration of multi-modal sensor interfaces • Fusion of heterogeneous sensor data • High data privacy and security	• Network element: Structured data (e.g., JSON, YANG data model) and data lakes for structured, semi-structured, unstructured data • Network topology: Graphs
Network Resilience Evaluation & Optimization	• Network view requirements + • Computation-heavy task offloading • Local lightweight computation support • Real-time feedback loops for actuation	• Network element & topology • Quality assurance optimization: Graphs, optimization problems, AI/ML • Resilience diagnosis model: Graphs, equations, rule-based systems, simulations, emulations, physical device integration

Demo Use Case: Proactive Quality Assurance & Optimization for BAN Operations

DTN Application	Special Requirements	Models & Representation Methods
Energy Analysis	• Network view requirements + • Energy-aware device orchestration • Computation-heavy task offloading • Local lightweight computation support	• Network element & topology • Energy diagnosis: Graphs, equations, first-order logic, AI/ML, physical device integration • Energy optimization model: Markov chains, optimization problems, rule-based methods, physical device integration
Network Security Assessment & Optimization	• Network view requirements + • Advanced data privacy and security	• Network element & topology • Security drill: AI/ML, physical device integration • Security optimization model: Simulations, emulations, AI/ML, physical device integration

Conclusion & Future Directions

- **Key Contributions**
  - Identified BAN requirements
  - Defined DT-BAN-specific requirements
  - Proposed a systematic process flow for DT-BAN development
  - Presented a structured template to support use case-driven modeling
  - Demonstrated the approach through a multi-domain use case
- **Future Directions**
  - Validate the generalizability of the proposed methodology in additional domains
  - Create an intent-driven DTN design framework that autonomously synthesizes DTN applications, models, and suitable representation methods from high-level user intents
  - Design a detailed, scalable, and secure DT-BAN architecture

Q&A

THANK YOU FOR YOUR ATTENTION!