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6G-Enabled Digital Twin Framework for Real-Time Cyber-Physical Systems

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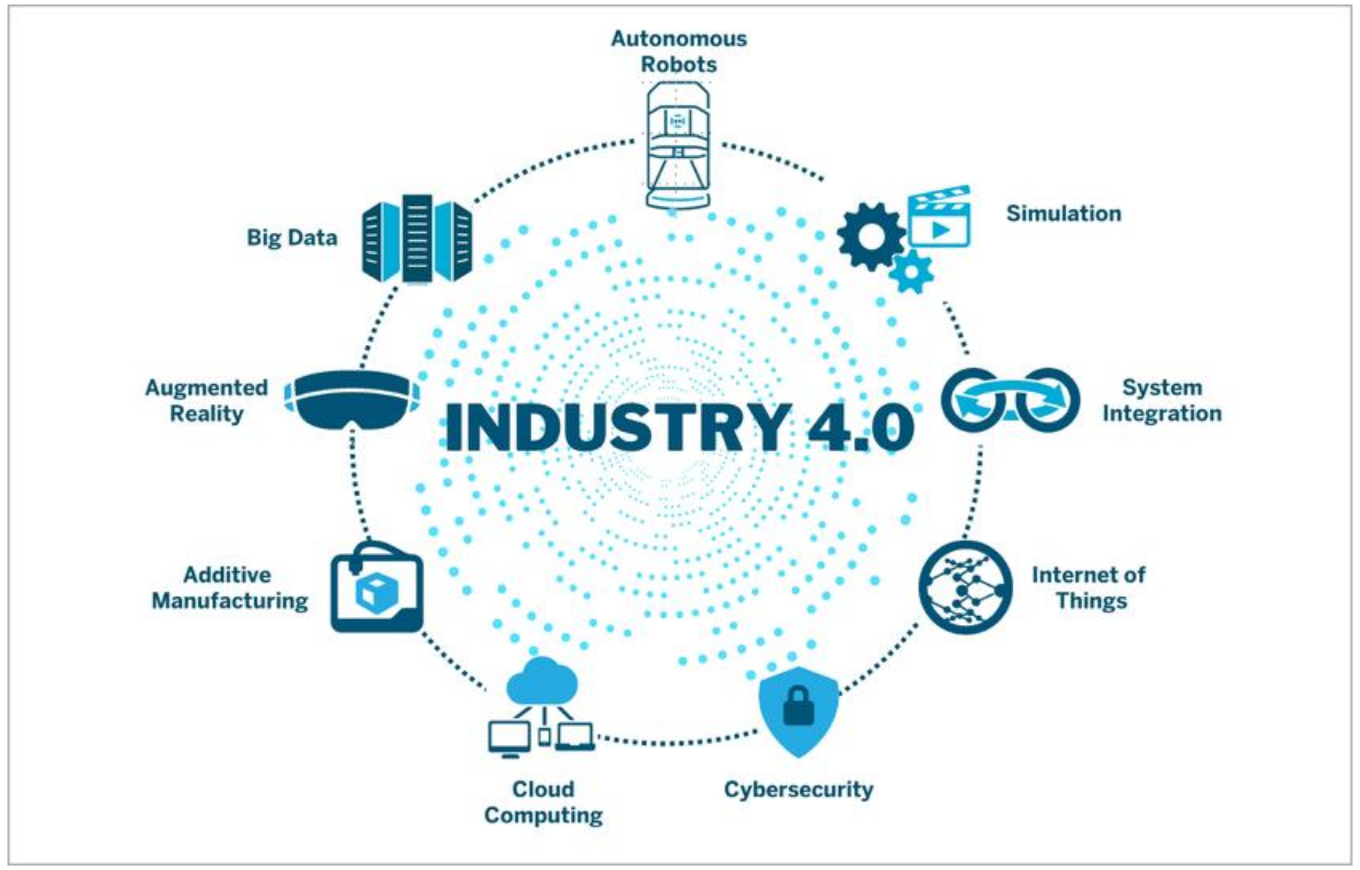
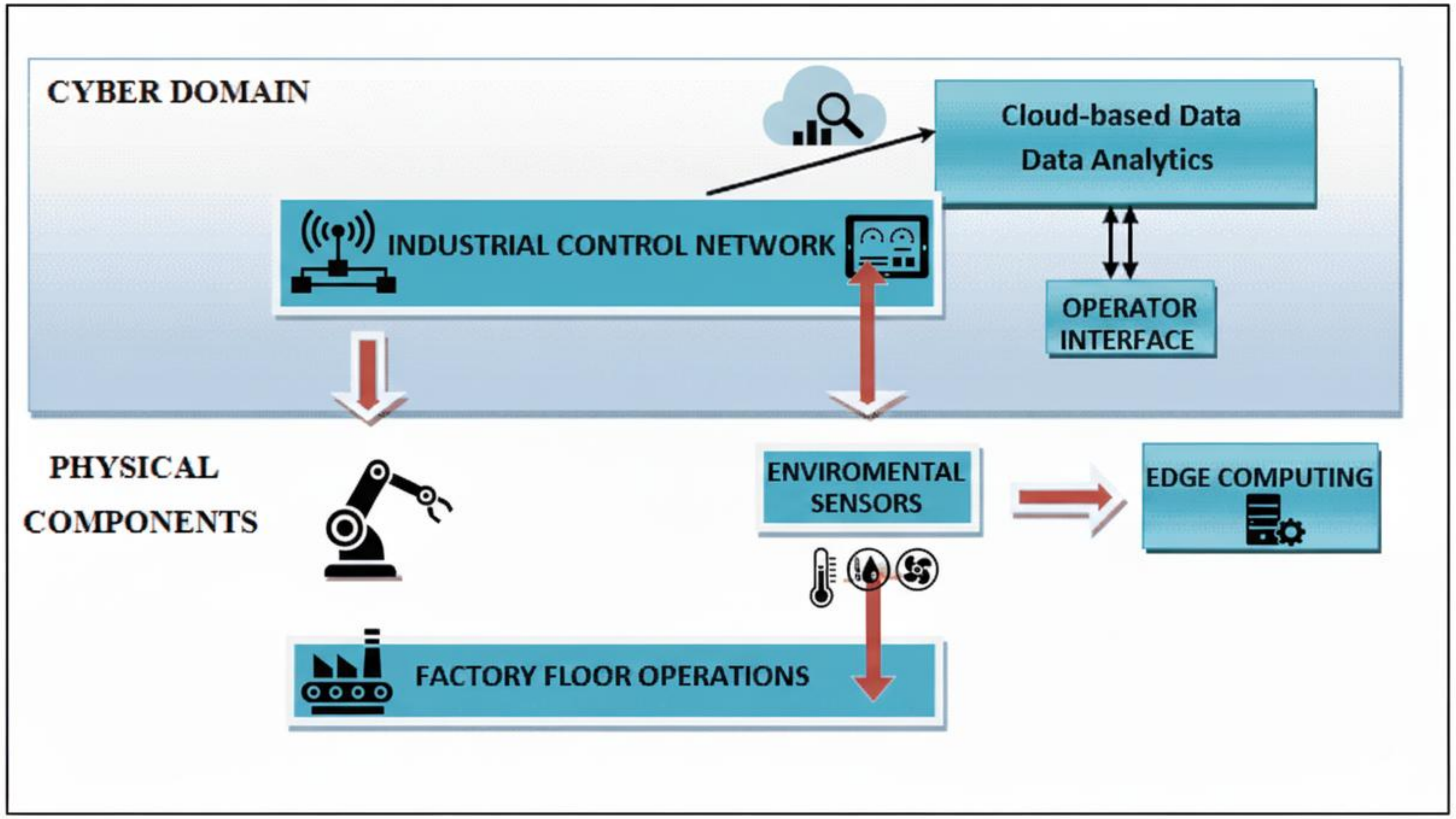
What is Cyber-Physical Systems (CPS)?

- CPS in simple terms:
  - It is a system where the physical world (machines, sensors, vehicles, medical devices, etc.) is tightly integrated with the cyber world (computation, networking, data, and control).
  - CPS enables real-time interaction between physical processes and computing/communication systems.





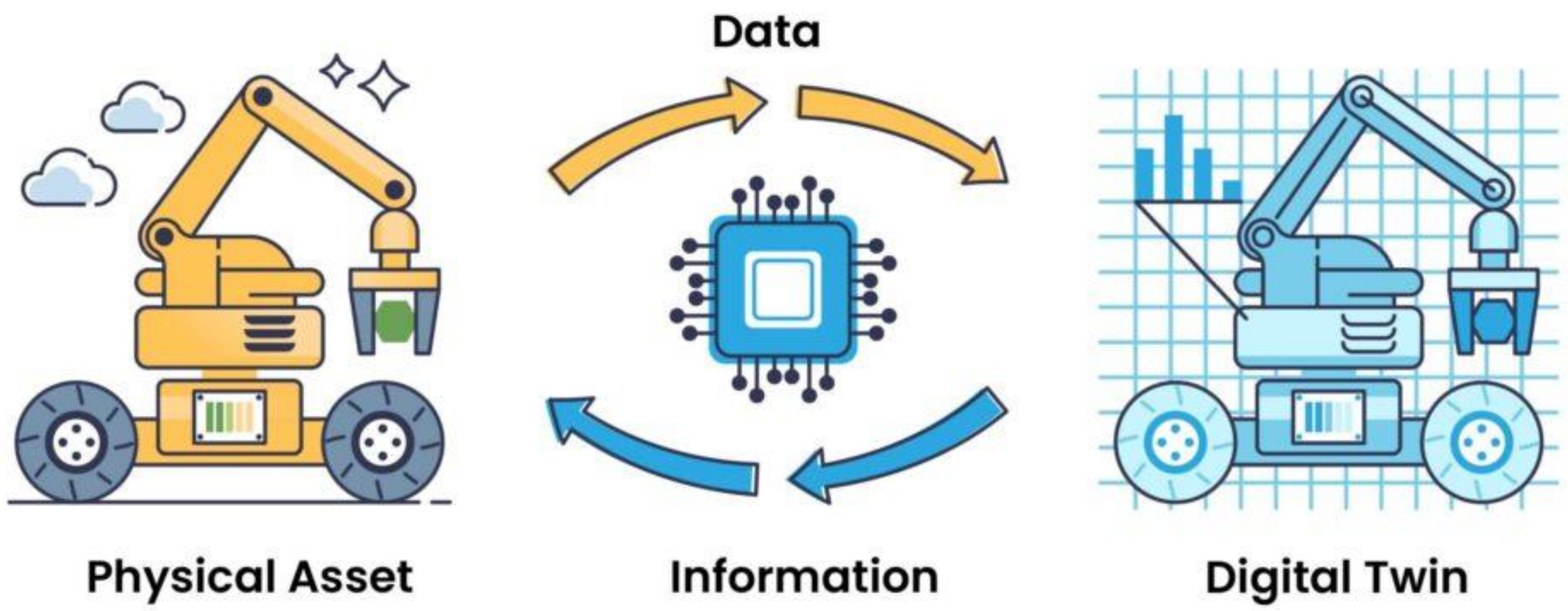
Essentially, CPS is the backbone of **Industry 4.0** and emerging smart infrastructure!!!

What is Digital Twin (DT)?

■ A Digital Twin (DT) is a virtual replica of a physical object, system, or process that stays connected to its real-world counterpart through real-time data.

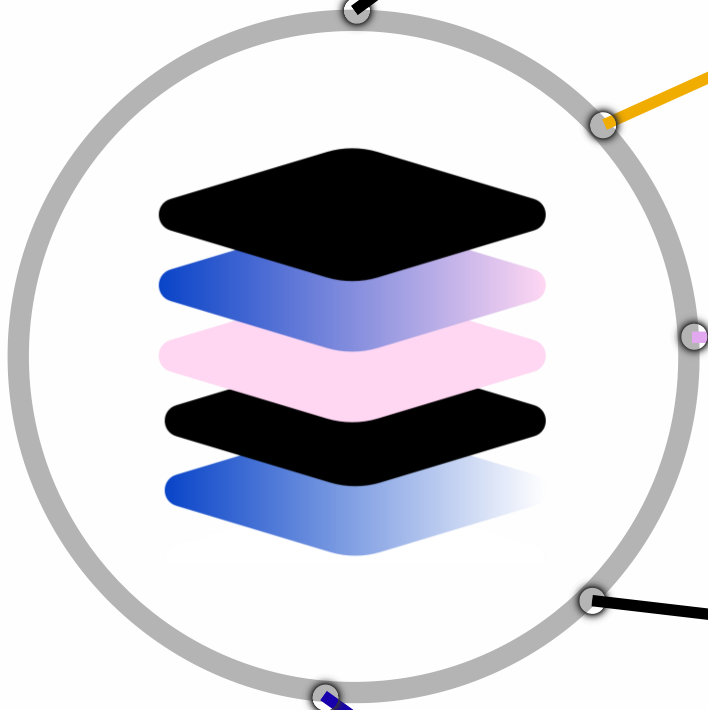
Key Points about Digital Twins (DTs)

- A DT mirrors the physical system using data from sensors, IoT devices, and networks.
- It allows real-time monitoring, simulation, and prediction of how the system behaves.
- DTs can test "what if" scenarios virtually before applying changes to the real system.
- They help with predictive maintenance, optimization, fault detection, and decision-making.



Proposed Framework

5-Layer Framework Architecture



CONTROL & FEEDBACK LAYER

5 — Optimized control signals, bidirectional feedback, adaptive control, continuous improvement

DIGITAL TWIN CORE

4 — High-fidelity simulations, real-time synchronization, predictive analytics, anomaly detection

EDGE INTELLIGENCE LAYER

3 — AI/ML models, predictive maintenance, federated learning, local processing

COMMUNICATION LAYER

2 — 6G THz communications, IRS technology, network slicing, ultra-low latency

DATA ACQUISITION LAYER

1 — IoT sensors, CPS devices, real-time data collection, preprocessing and normalization

Key Innovation: Seamless integration of 6G communication with edge intelligence for real-time bidirectional synchronization

System Model & Notation

NETWORK ARCHITECTURE

Physical CPS Nodes: $N = \{n_1, n_2, n_3, \dots\dots\dots, n_N\}$

Digital Twin Replicas: $D = \{d_1, d_2, d_3, \dots\dots\dots, d_N\}$

STATE SPACE REPRESENTATION

$x_p(t) \in R^n$ (Physical System State)

$x_d(t) \in R^n$ (Digital Twin State)

SYNCHRONIZATION ERROR

$$\varepsilon(t) = ||X_p(t) - X_d(t)||_2$$

Objective: Minimize $\varepsilon(t)$ subject to latency constraints

Data Acquisition Layer

SENSOR DATA COLLECTION MODEL

$$\mathcal{S}(t) = \{s_1(t), s_2(t), \ldots, s_m(t)\}$$

Where $s_i(t)$ represents the $\boldsymbol{i}$-th sensor reading at time $\boldsymbol{t}$

PREPROCESSING FUNCTION

$$\mathcal{S}'(t) = \phi(\mathcal{S}(t)) = [s'_1(t), s'_2(t), \ldots, s'_m(t)]^T$$

NORMALIZATION:

$$s'_i(t) = \frac{s_i(t) - \mu_i}{\sigma_i}$$

Where μ_i and σ_i are mean and standard deviation of sensor $\boldsymbol{i}$

Communication Layer

Terahertz (THz) Communication

Channel Capacity

$$C = B\log_2(1 + \text{SINR})$$

Bandwidth B in THz range: 0.1-10 THz

Path Loss Model

$$PL(f,d) = PL_0 + 10\alpha\log_{10}\left(\frac{d}{d_0}\right) + A(f,d)$$

Components:

f : frequency (THz)
d : distance (meters)
α : path loss exponent (2-4 for THz)
$A(f,d)$: molecular absorption loss

Molecular Absorption

$$A(f,d) = \alpha_{abs}(f)\cdot d$$

Intelligent Reflecting Surface (IRS)

Signal Model with IRS

$$y = (\mathbf{h}_d^H + \mathbf{h}_r^H\mathbf{\Phi}\mathbf{h}_t)x + n$$

Channel Components

- $\mathbf{h}_d$: Direct channel
- $\mathbf{h}_r$: BS-to-IRS channel
- $\mathbf{h}_t$: IRS-to-user channel
- n: AWGN noise

Phase Shift Matrix

$$\mathbf{\Phi} = \text{diag}(\beta_1 e^{j\theta_1}, \ldots, \beta_N e^{j\theta_N})$$

Optimization Problem

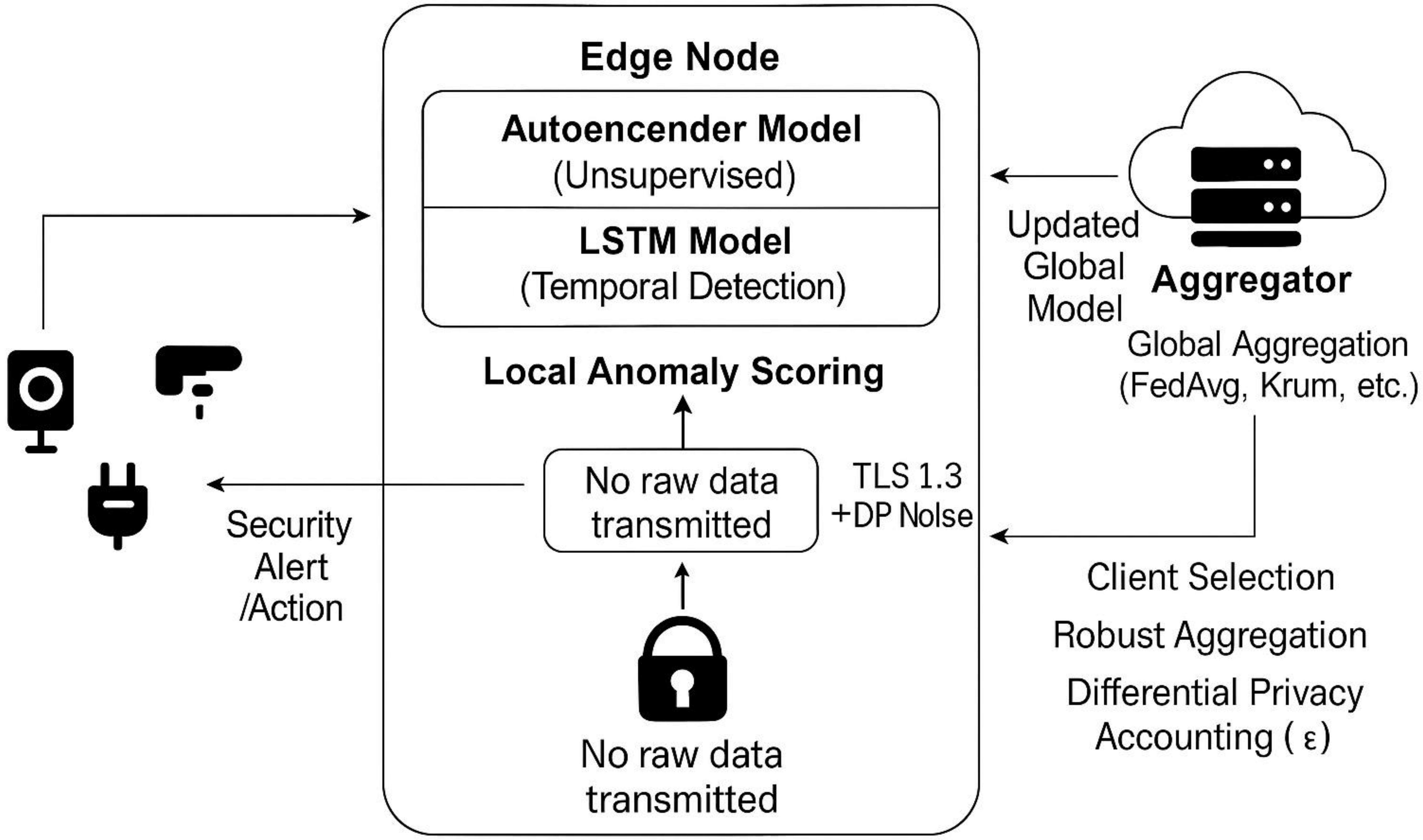
$$\max_{\mathbf{\Phi}} \quad R = \log_2\left(1 + \frac{|\mathbf{h}_d^H + \mathbf{h}_r^H\mathbf{\Phi}\mathbf{h}_t|^2}{\sigma^2}\right)$$

$$|\beta_i| \leq 1, \quad \theta_i \in [0, 2\pi], \quad \forall i$$

Total Latency Decomposition

$$T_{total} = T_{sensing} + T_{proc} + T_{comm} + T_{compute} + T_{feedback}$$

Edge Intelligence Layer



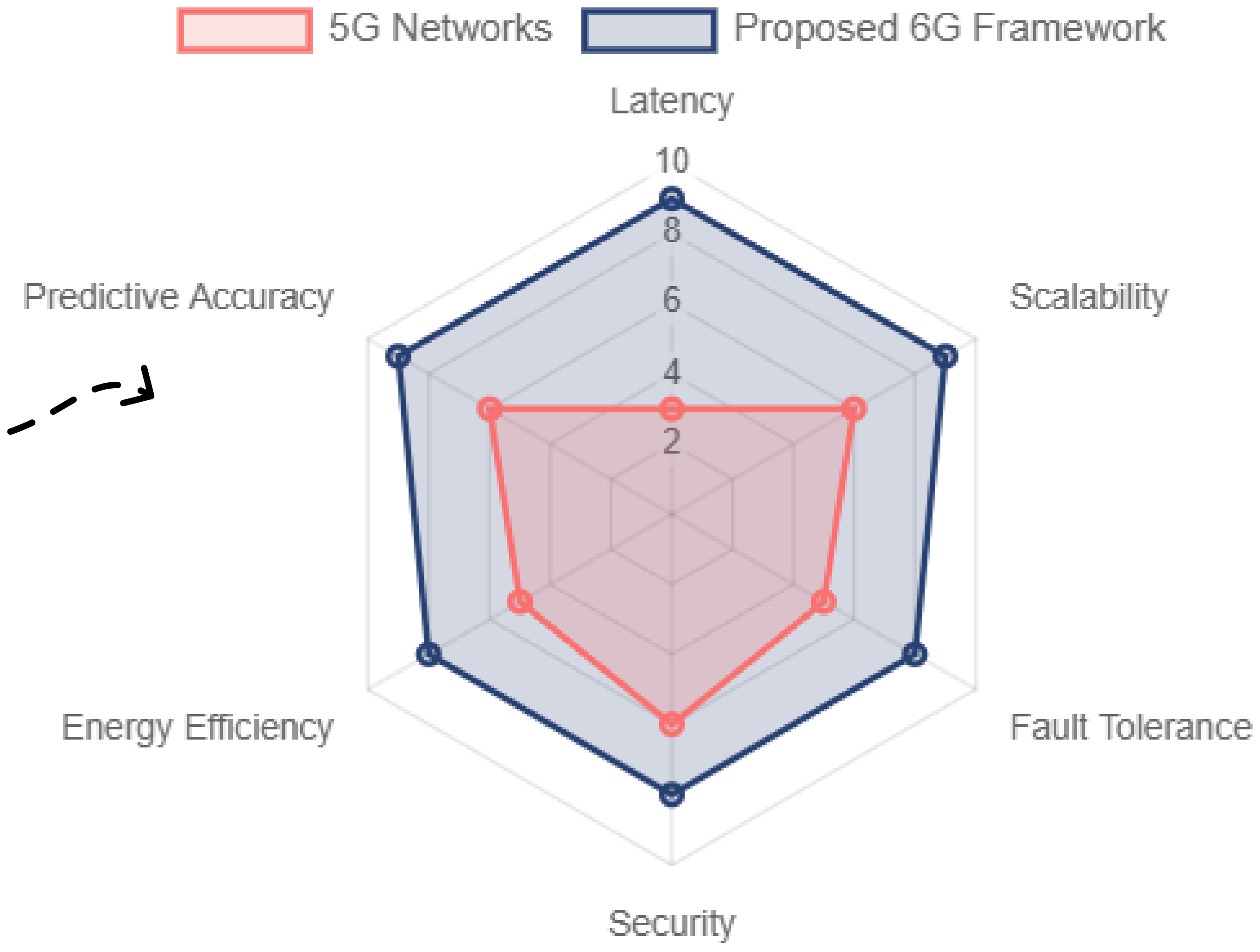
5G vs 6G Framework Comparison

Performance Metric	5G Networks	Proposed 6G Framework	Improvement
End-to-End Latency	~10 ms	~1 ms	90% Reduction
Data Processing	Centralized	Edge-based	Distributed
Synchronization	Periodic	Continuous	Real-time
Fault Recovery	Reactive	Proactive	Predictive
Learning Approach	Centralized ML	Federated Learning	Privacy-preserving
Scalability	Limited	Massive-scale	Enhanced

Smart Manufacturing Case Study Results

90% Latency Reduction (10ms → 1ms)	**20%** Downtime Reduction	**15%** Energy Savings	**✓** Production Efficiency

Performance Metrics Comparison



Key Achievement

THz spectrum and IRS-enabled links enable quick fault recovery with enhanced predictive accuracy compared to traditional CPS models

Application Domains

Smart Manufacturing
Predictive maintenance, quality control, process optimization, real-time monitoring

Intelligent Transportation
Autonomous vehicles, traffic management, safety systems, route optimization

Smart Cities
Urban planning, environmental monitoring, public services, resource management

Critical Infrastructure
Power grids, telecommunications, emergency systems, resource allocation

Healthcare Systems
Remote monitoring, surgical robotics, medical equipment synchronization

Thank You!

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