IOWN Global Forum Member Meeting

Proposal of Probabilistic Digital-Twin

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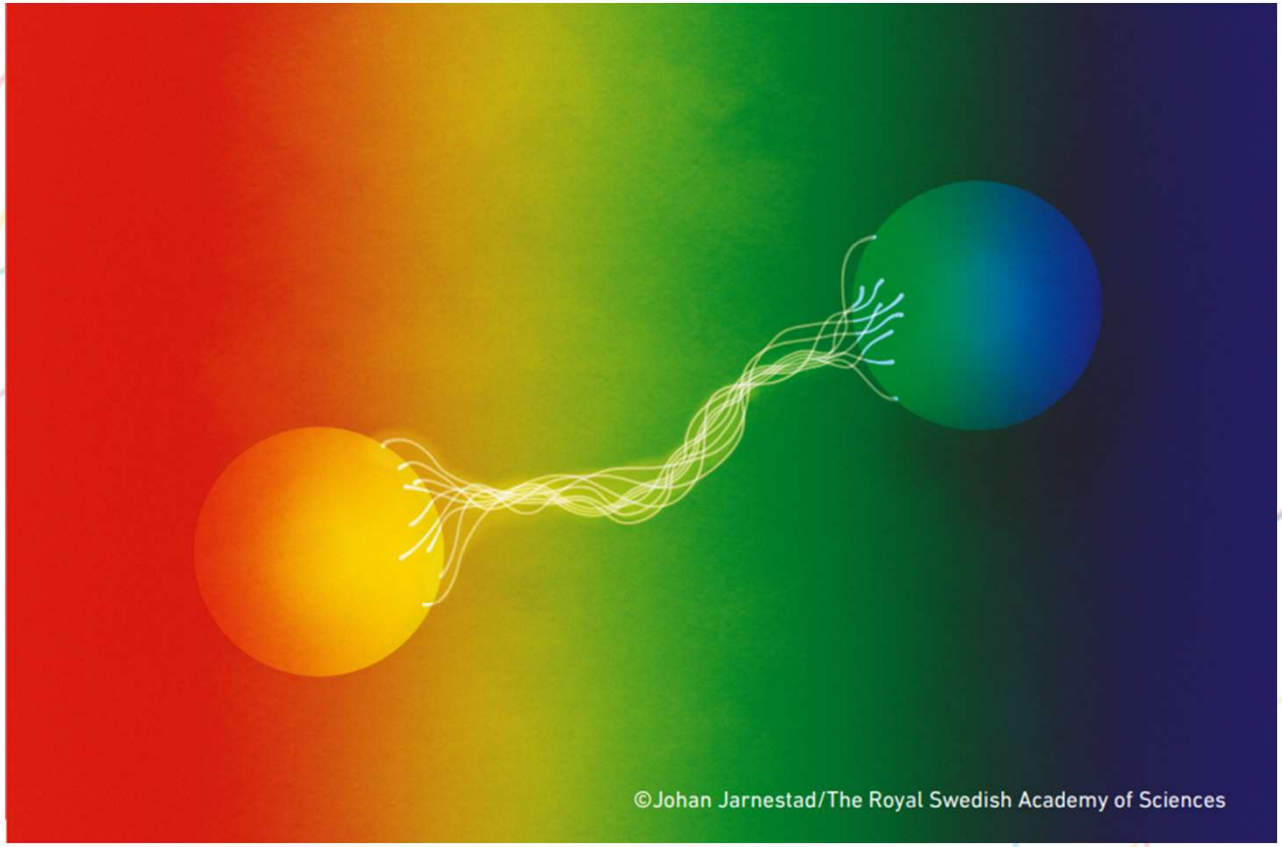
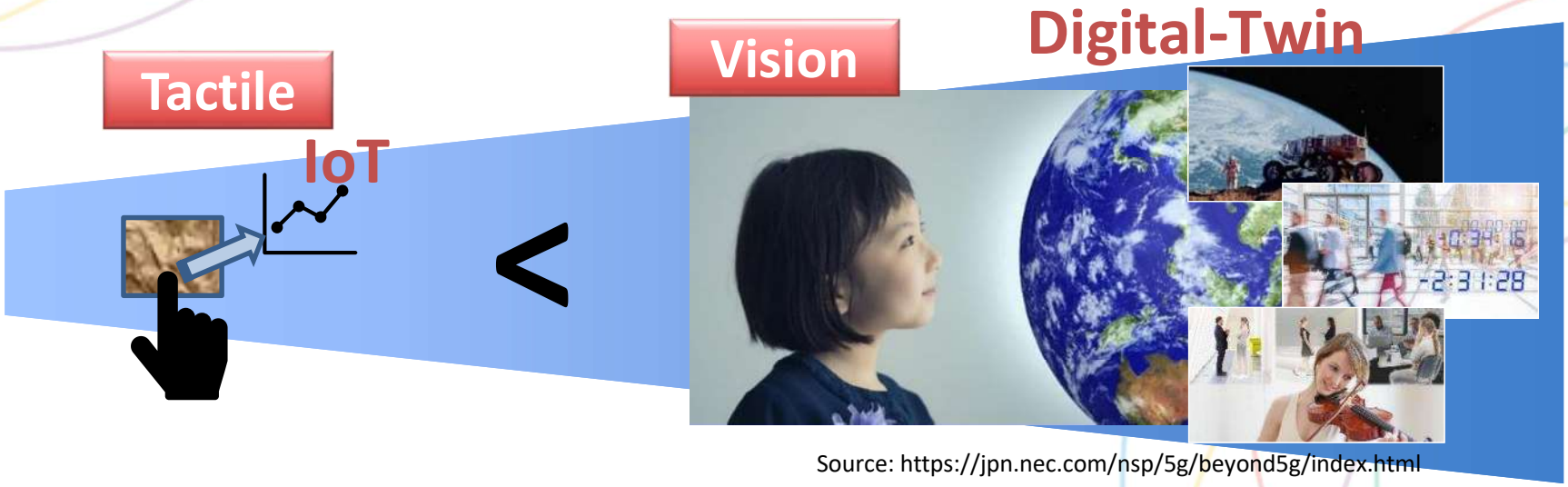


https://www.nobelprize.org/uploads/2022/10/press-physics2022-figure1.pdf

Expand IoT to Digital-Twin

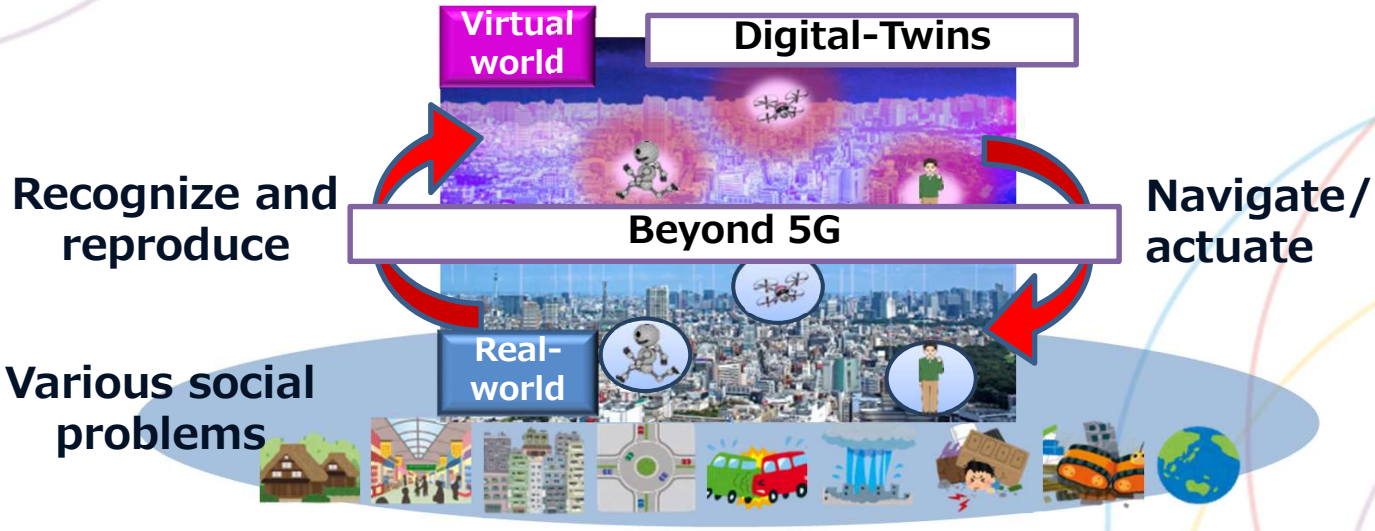
- **Digital-Twin as real-time and high-precision representation of the entire space**
- **Explosive Evolution of Telecommunications with Digital-Twin**
  - Organisms acquired eyes during the Cambrian explosion
  - ICT systems acquire “eyes” towards Beyond 5G/6G era



Source: https://jpn.nec.com/nsp/5g/beyond5g/index.html

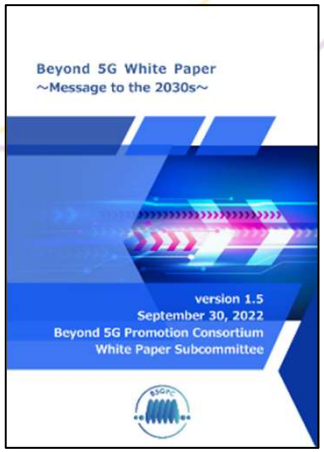
Digital-Twin (of our understanding)

- **Fusing real and virtual world to provide new value propositions to our society**
  - Digitalize the entire real-world in real-time, and reproduce them as a virtual world
  - Creating new services (such as future prediction and human-robot coexistence) by utilizing 4-dimensional (space + time) data structure in the digital-twin



Beyond 5G vision towards Digital-Twin

"Safety, security and peace of mind" would be a key driving force



Beyond 5G Promotion Consortium
Beyond 5G White Paper
https://b5g.jp/en/output.html

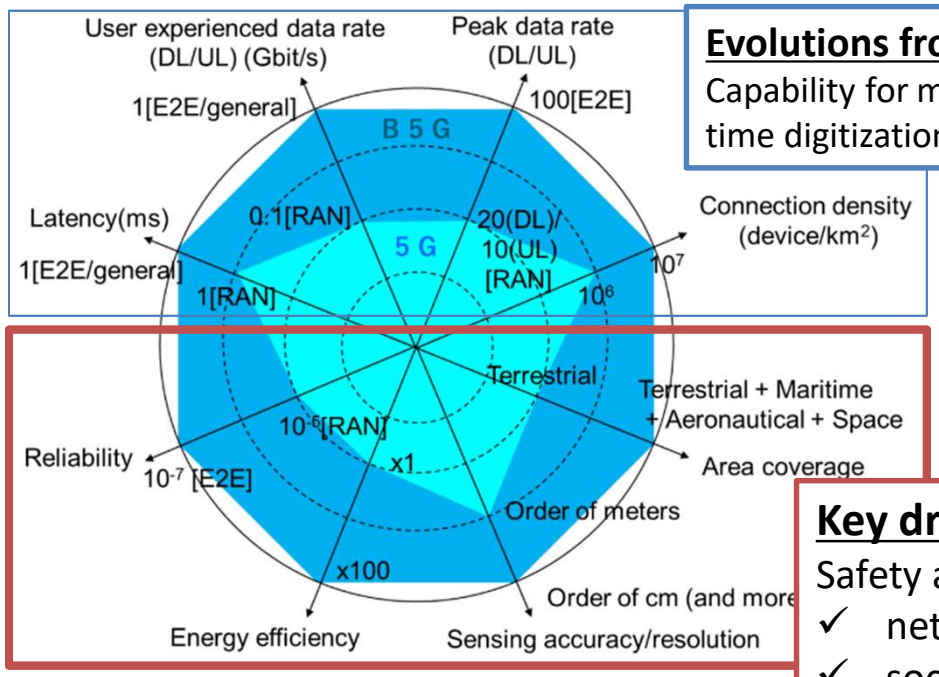


Figure 5.3-2 Target KPIs for Beyond 5G (Quantitative indicators)

Evolutions from 5G

Capability for massive and real-time digitization of the real-world

Key driving force towards B5G

Safety and security of both:

- ✓ network/ICT infrastructure, and
- ✓ social system and our daily life

“Deterministic” Digital-Twin

Constructing very precise copy of real-world to be safe and secure, with Beyond 5G and advance AI

- Robust ?
  - Uncertainty in network reliability and service quality
  - Uncertainty in recognition and control of real-world

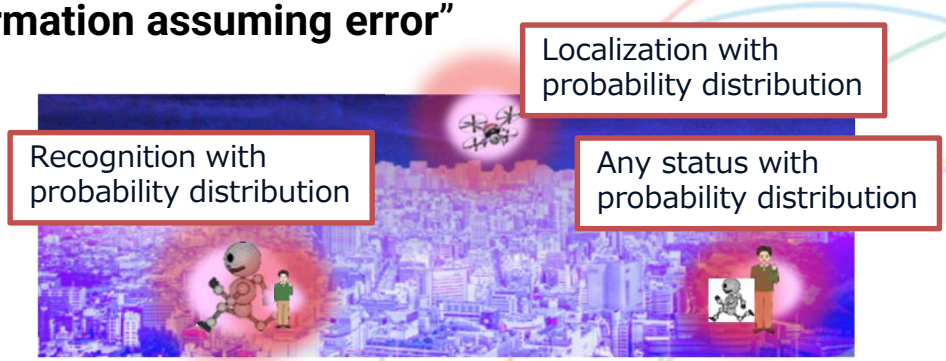
- Eco-friendly?
  - Huge traffic amount: very high-definition sensing data
  - Huge computation: very accurate recognition

“Probabilistic” Digital-Twin (1/2)

- **A digital twin that:**
  - **probabilistically infers real-world from uncertain observations,**
  - **non-deterministically predicts the future,**
  - **navigate human, actuate robots, and control things flexibly**

Real-world will tolerate sudden events and physical uncertainties by decision making based on ”**probabilistic information assuming error**”

Deterministic representation



Probabilistic representation

“Probabilistic” Digital-Twin (2/2)

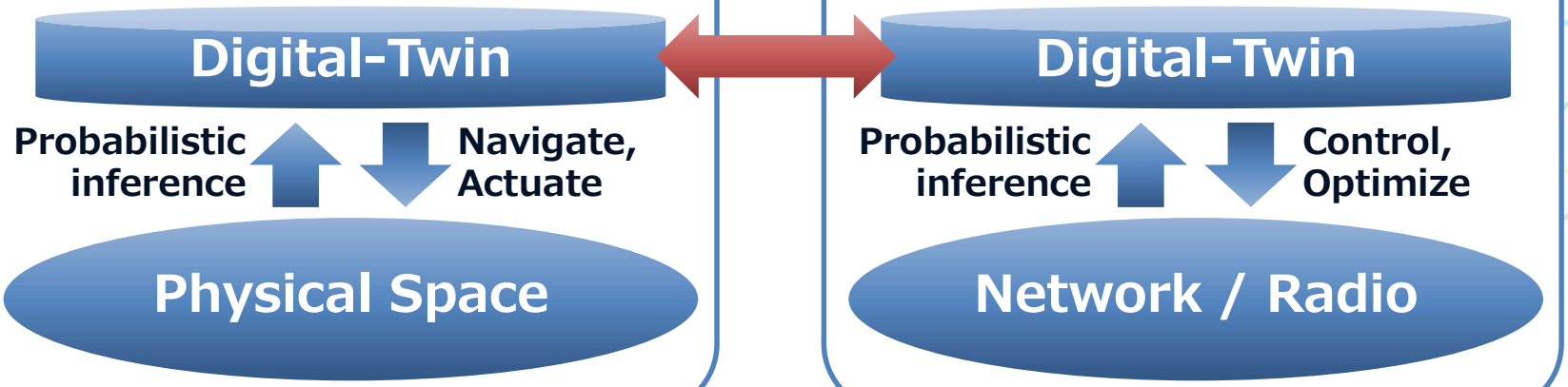
Digital-Twin with Beyond 5G

- Human/robot/car cooperation
- Industrial / smart city use cases

Digital-Twin for Beyond 5G

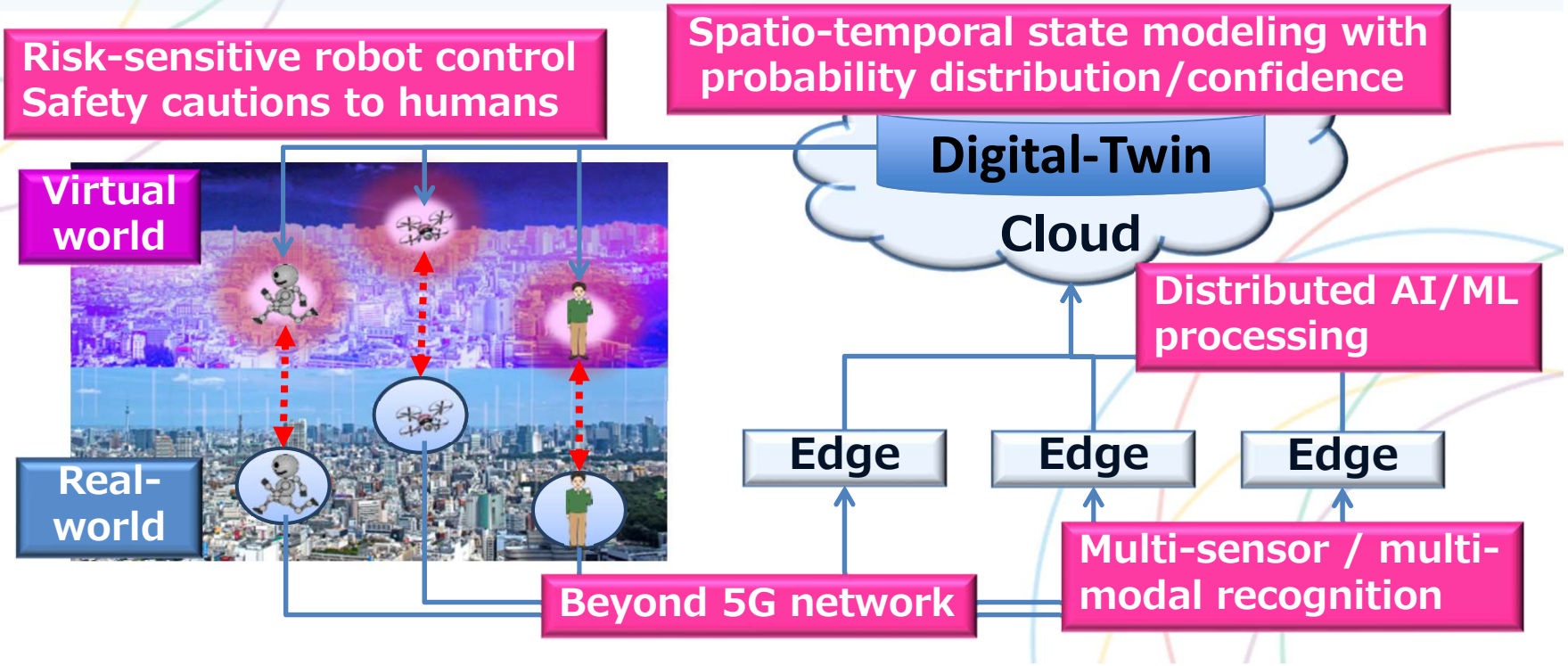
- Antenna control/selection
- Network and computing joint optimization
- Design and investment

Joint optimization via Digital-Twin Computing



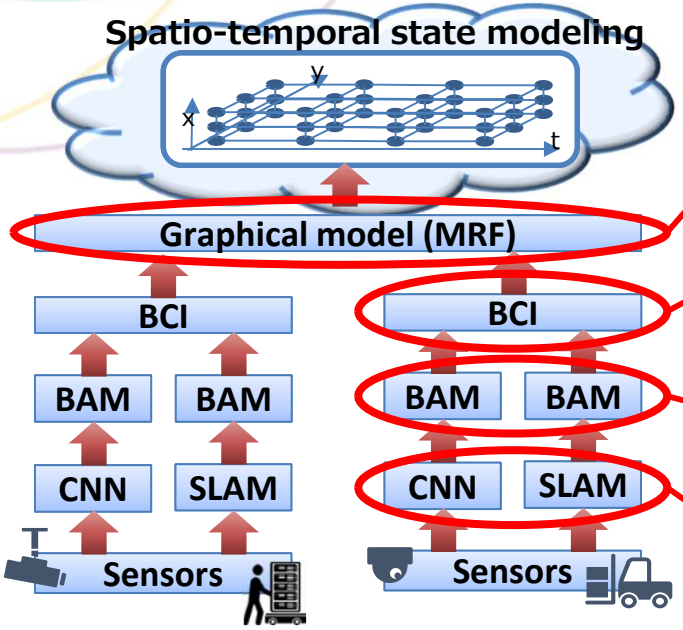
(1) Digital-Twin with Beyond 5G

Digital-Twin of human, robots, cars, cities, and things in physical space



(1) Digital-Twin with Beyond 5G
-Multimodal recognition (1/2)

- **Probabilistic recognition of various objects in physical space from noisy and unstable monitoring**
- **Mathematical model of the brain's stochastic perceptual function**



Cognitive decision making using graphical models
(most plausible interpretation of the entire real world)

Multimodal integration using Bayesian Causal Inference
(BCI = Causal inference by perceptual integration processing in the brain)

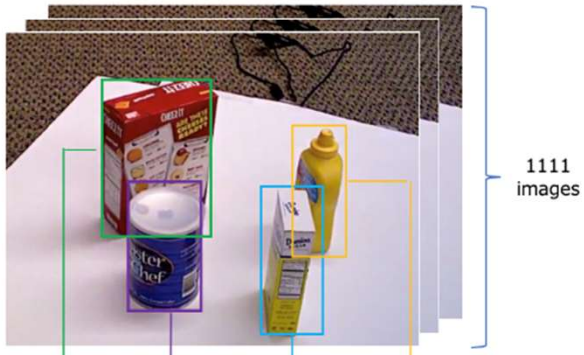
Unimodal object recognition using Bayesian Attractor Model
(BAM = cognitive models of the human brain to identify system states)

Feature extraction using CNN and other ML models

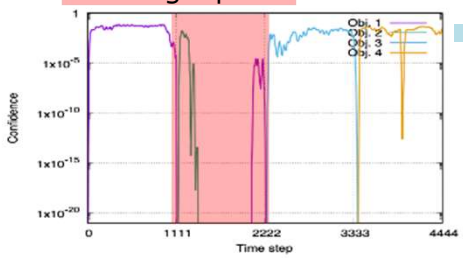
(1) Digital-Twin with Beyond 5G
-Multimodal recognition (2/2)

- **Multimodal complementation combines missing inputs to generate plausible cognitive decision making**

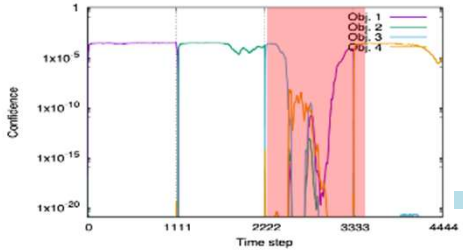
Video data (4444 frames)



Missing inputs



(a) 映像モダリティ

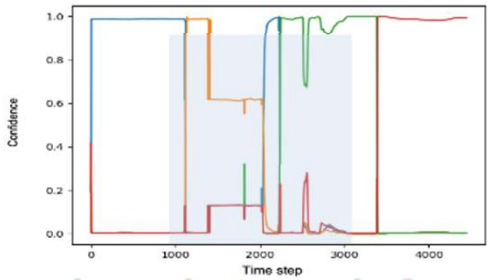


(b) 位置モダリティ

Mean accuracy

Video:79.41%

Video + Location:93.83%



Location: 81.66%

(1) Digital-Twin with Beyond 5G
-Risk sensitive robot control (collaboration with NEC)

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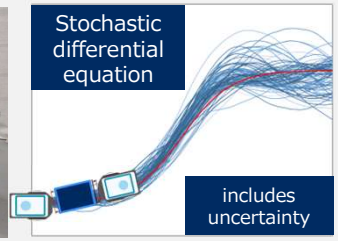
① Stochastic model of robot

Simulate a robot system by stochastic differential equation to describe physical disturbance and sensing noise

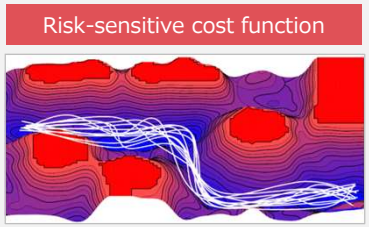
$$\underbrace{\mathrm{d}x}_{\text{State change}} = \underbrace{f(x,u)\mathrm{d}t}_{\text{Differential equation}} + \underbrace{\sigma(x,u)\mathrm{d}B_t}_{\text{Stochastic effect (uncertainty)}}$$



② Risk-sensitive cost function

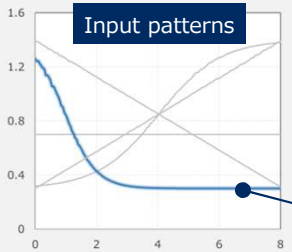
Cost function designed to be sensitive to collision, deviation, inefficiency, etc.

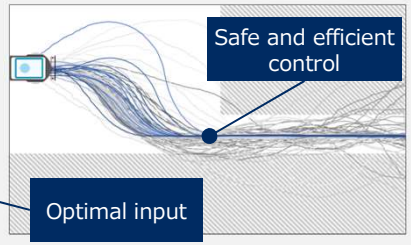
$$J = \frac{1}{\beta}\log\left\{\mathrm{E}\left[\exp\left(\beta S\right)\right]\right\}$$



③ Selection of optimal input

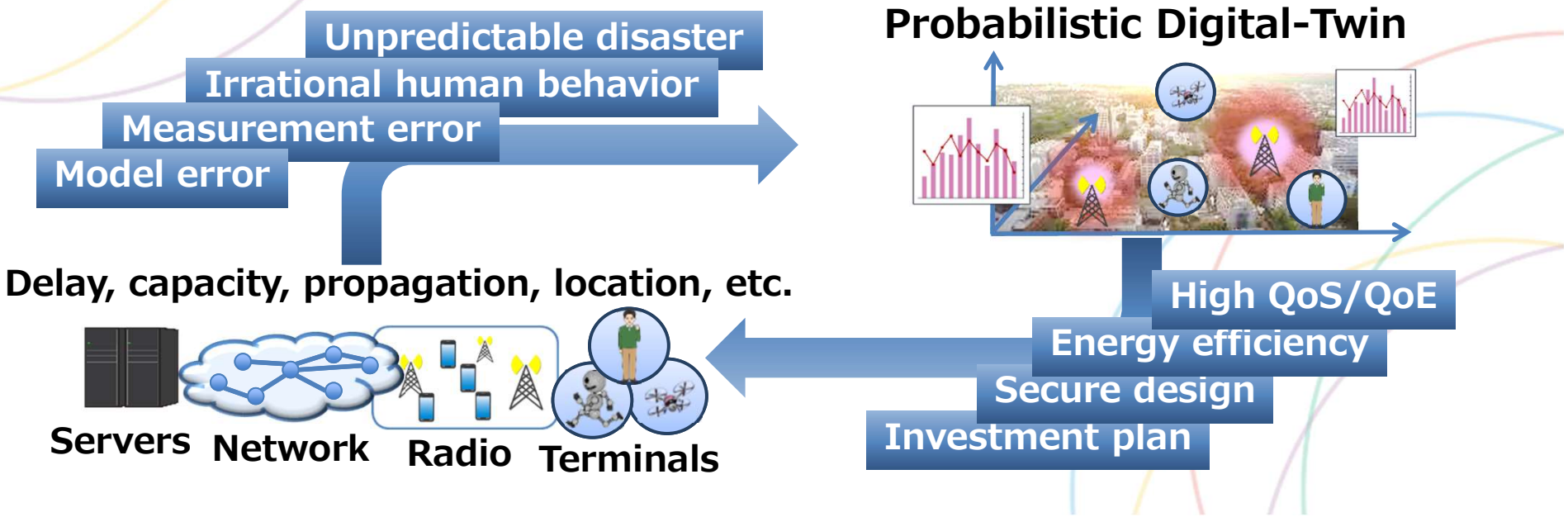
- Predict robot's behavior by solving stochastic differential equation with various inputs
- Select the input that minimizes the risk-sensitive cost function





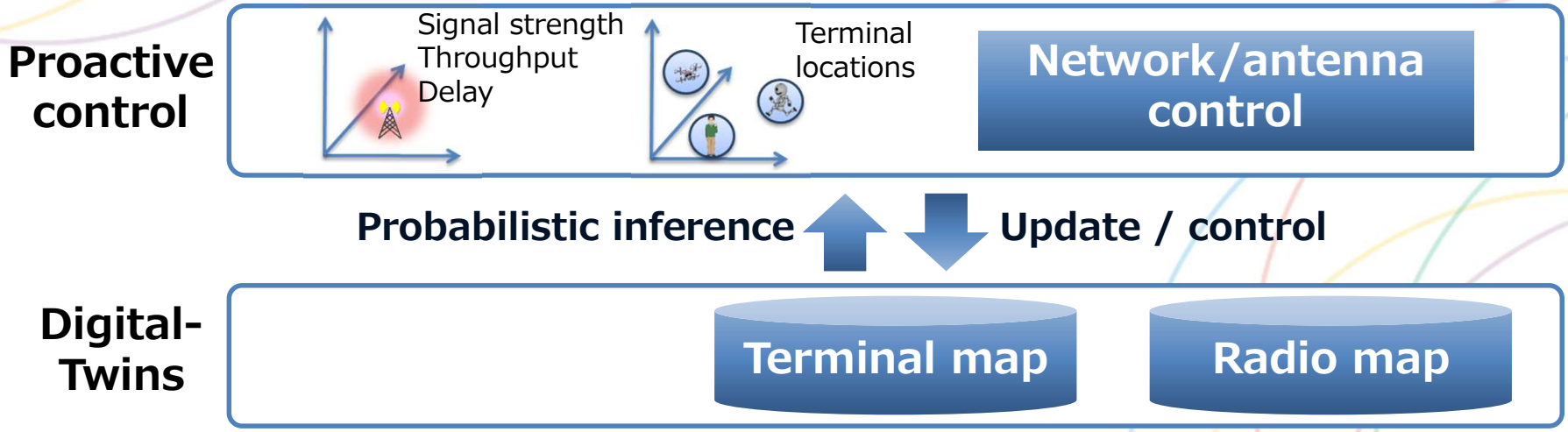
(2) Digital-Twin for Beyond 5G

- Robust network management for safety/security and efficiency
- Joint control of infrastructure and applications(robots/cars)



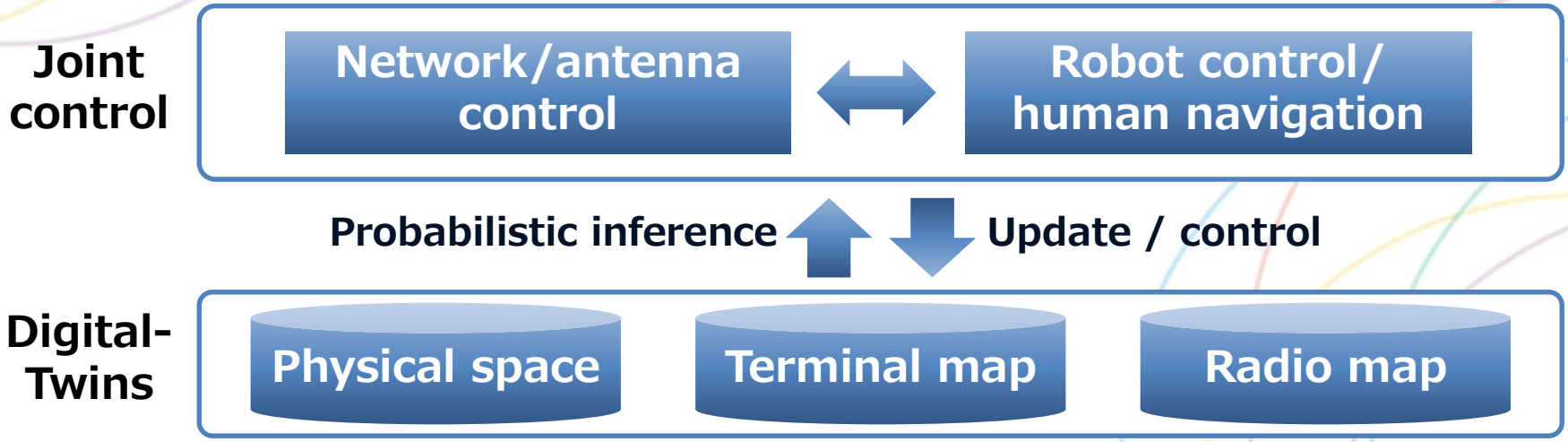
(2) Digital-Twin for Beyond 5G
-Radio communication map

- Practical use of higher frequency radio in mobile environment
- Controlling system and antennas using “Radio communication map”
  - Map mesh > Wavelength; deterministic representation would be hard
  - Probabilistic representation of signal strength/throughput/delay map



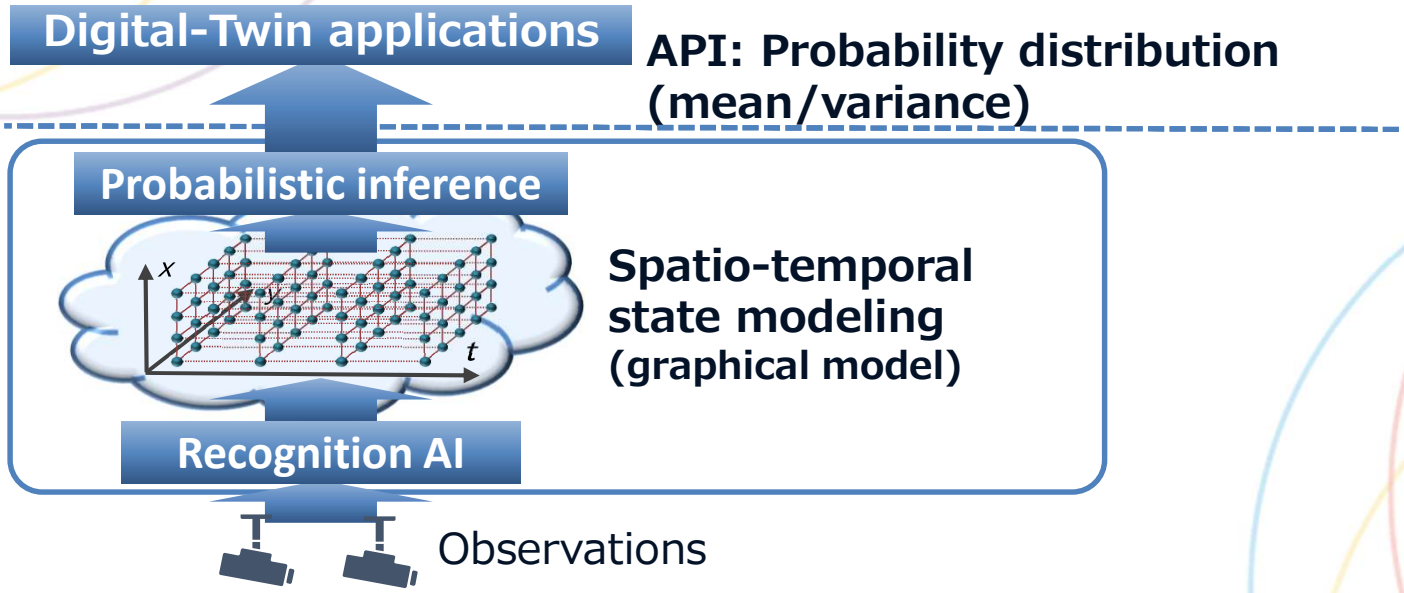
(2) Digital-Twin for Beyond 5G
-Radio and Robot Coordinated Control

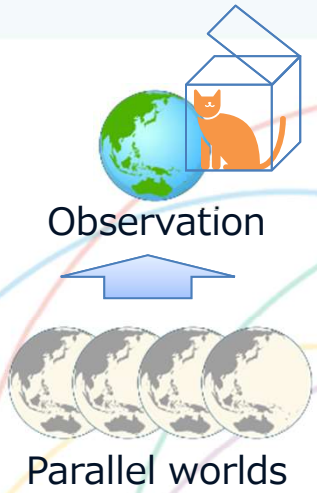
- Coordination of Digital-Twins of radio map and physical space
  ➔Maps them into common spatial axes
- Coordinated control of radio and robot
  - Robots take a path of good radio, and move cautiously otherwise
  - Network controls antenna beam targeting moving robots



Possible discussions: (Probabilistic) data structure and API

- Probabilistic internal data structure that allow for **<u>any parallel understanding of real world</u>**
- APIs that provide probabilistic information of **<u>maximum likelihood understanding of the moment</u>**





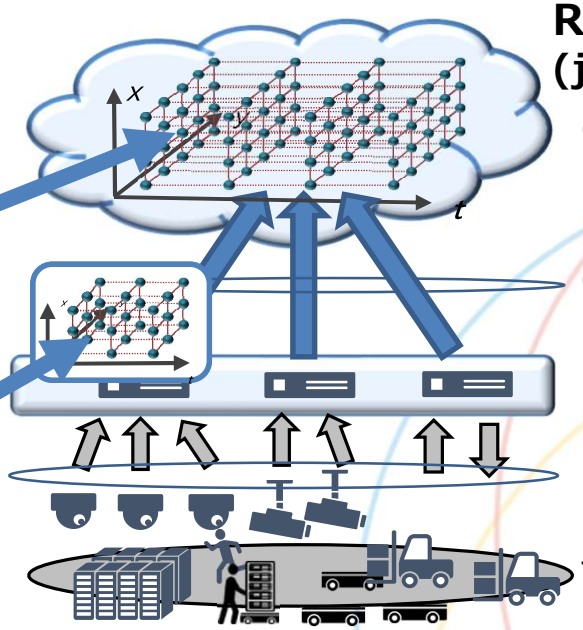
Possible discussions: Digital-twin computing platform

- Hierarchical edge-cloud data structure meeting space and time resolution requirements
- Integrated optimization of network and computing resources

Let us build campus-wide testbed as easy as possible.

Digital-twin (cloud)
Global and long-term data

Digital-twin (local)
Local data / real-time control



Resources
(jointly optimized)

Cloud servers

Optical/ radio

Edge servers

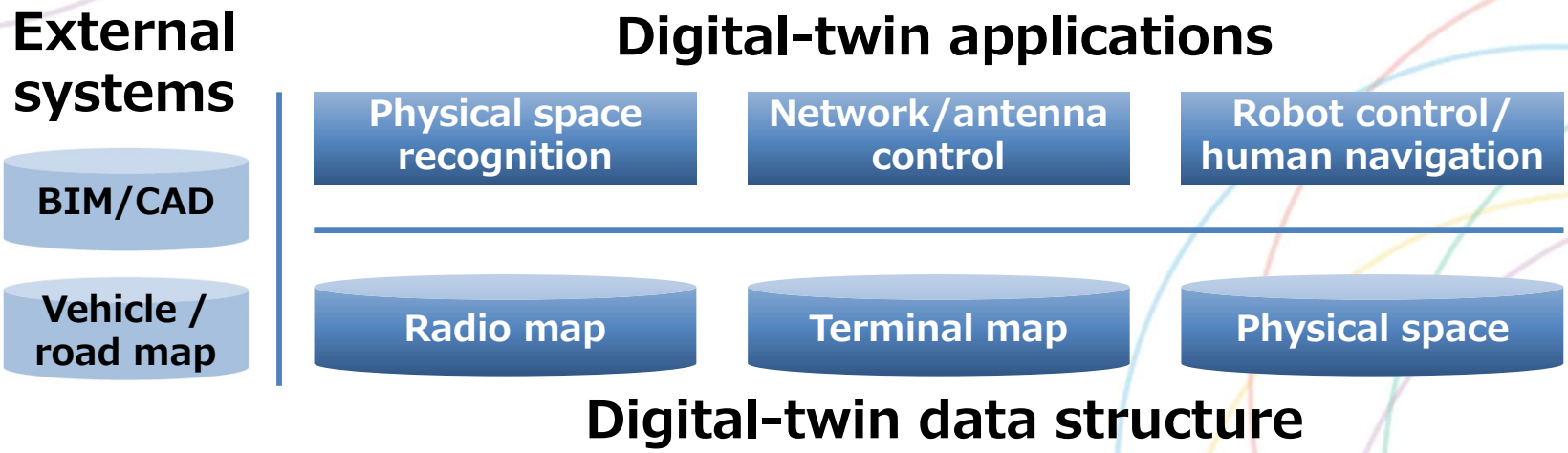
Local/private 5G

Terminal devices

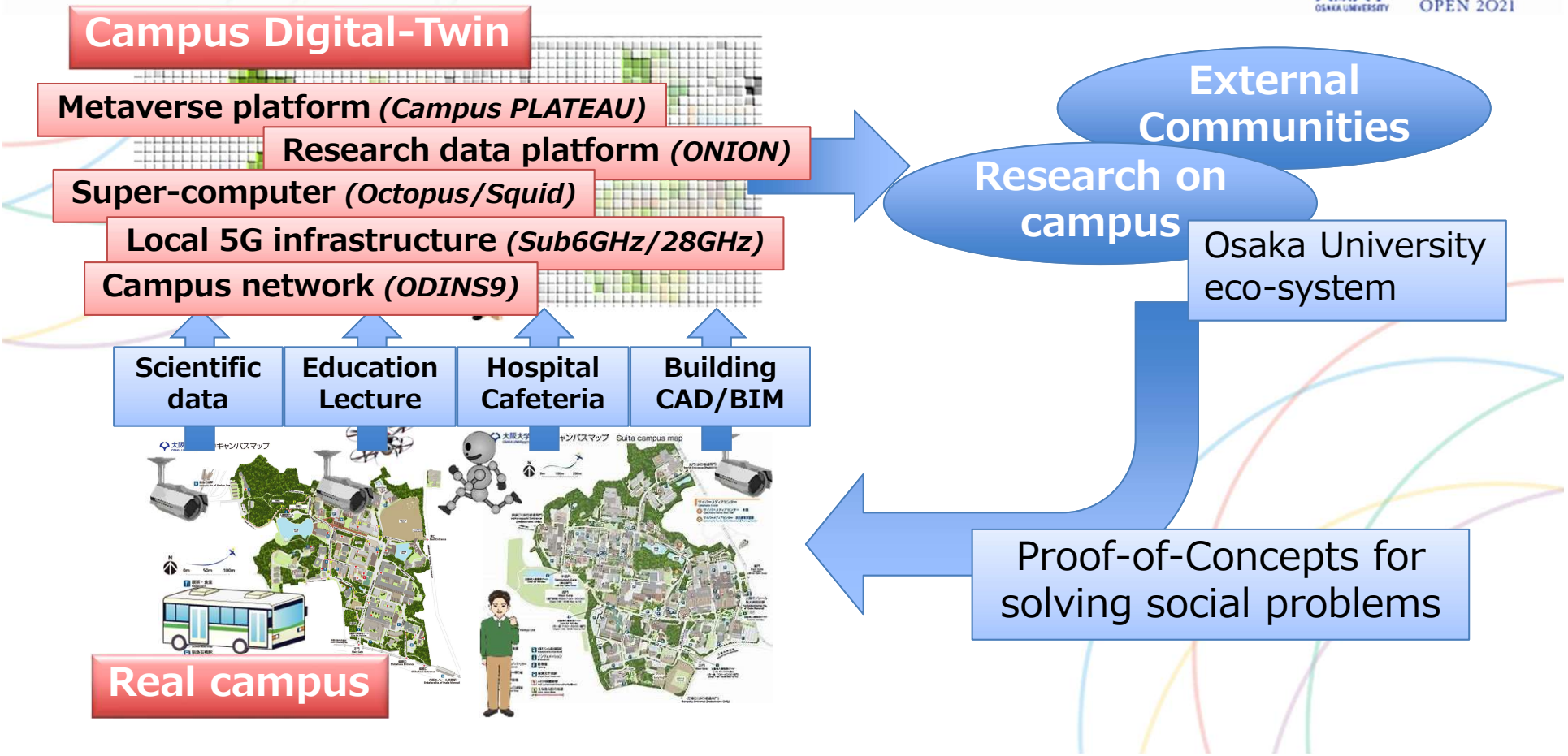
Possible discussions: Digital-twin computing framework

- Flexible data exchange with internal/external systems in real-time for Cyber Physical Systems (10-200msec)

Let our students write those experimental/PoC applications as easy as possible.

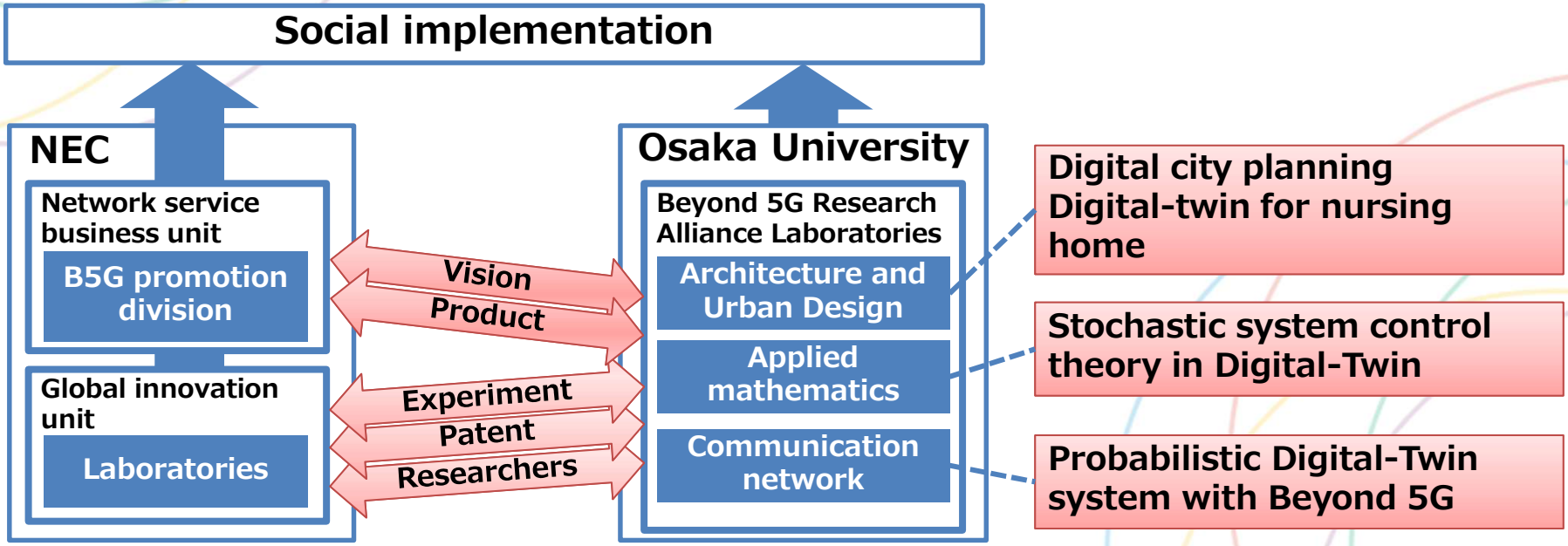


Campus Living-Lab vision



Industry-Academia Cocreation

- **<u>Osaka University, NEC Beyond 5G Research Alliance Laboratories</u>**
  - Beyond 5G/Digital Twin to expand human capabilities and realize a society where robots coexist with and accompany people



Summary

- Let us digitize probabilistically
  - Physical space
  - Network and radio
- Joint optimization / navigation
  - Network and radio
  - Human and things
- Possible discussions
  - Digital-Twin computing framework and platform
  - (Probabilistic) data structure and API

Acknowledgements

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