

Smart Internet of Things: A Cyber Physical Social System Perspective



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10th International Conference on Sensor Networks
SENSORNETS 2021

February 10th, 2021





Internet of ...

Internet of Things

Social Internet of Things

Internet of Social Things

Internet of Everything

Industrial Internet of Things

Internet of Military Things

Internet of Nano Things

Internet of Mobile Things

Internet of Mission-Critical Things



Internet of Things Definitions (1/2)

The Internet of Things represents a vision in which the Internet extends into the real world embracing everyday objects. **Physical** items are no longer disconnected from the **virtual** world, but can be controlled remotely and can act as physical access points to Internet **services**. [Mattern and Floerkemeier 2010]

Or

A world where **physical** objects are seamlessly integrated into the **information** network, and where the physical objects can become active participants in **business processes**. Services are available to interact with these “**smart objects**„ over the Internet, query their state and any information associated with them, taking into account security and privacy issues [Haller et al. 2008]

Or ...



Internet of Things Definitions (2/2)

Cluster of European research projects on the IoT domain characterizes Internet of Things (IoT) as an integrated part of Future Internet and could be defined as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual “things” have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network

Or

United States department of commerce defines that IoT or smart devices refers to any object or device that is connected to the Internet. This rapidly expanding set of “things,” which can send and receive data, includes cars, appliances, smartwatches, lighting, home assistants, home security, and more

Or ...



IoT Opportunities

IoT opens up opportunities across multiple verticals





From Cyber-Physical-Systems (CPS) to Networked Cyber-Physical-Social-Systems (Net-CPSS)

- **CPS (Cyber-Physical-Systems):** Technological systems where physical and cyber components are tightly integrated
 - **Examples:** smart phones, smart sensors, smart homes, smart cars, smart power grids, smart manufacturing, smart transportation systems, human robotic teams, ...
- **Most of modern CPS are actually networked:** via the Internet or the cloud, or via special logical or physical networks → **Networked Cyber-Physical-Systems (Net-CPS)**
 - **Examples:** modern factories, heterogeneous wireless networks, sensor networks, social networks over the Internet, Industrial Internet of Things (IIoT) ...
- **Net-CPSS (Networked Cyber-Physical-Social-Systems) :** incorporation of humans in Net-CPS, as system components from the beginning (during the design)



Sensing, measuring; event capture and filtering for timely response



linkage of objects, people, process, and systems



Deep discovery and analysis for optimization and forecasting



Networked Cyber-Physical Systems are Ubiquitous

Communication,
infrastructure,
technological
networks

Designed and/or
engineered

Social and
economical
networks

Human initiated,
but spontaneous
growth

Biological
networks

Spontaneous
evolution



Internet of Things: Conceptual Layered Architectures

3-layered architecture which consists of:

Perception Layer: contains all those devices which can interact with the physical world such as (sensors, actuators, tags, etc.)

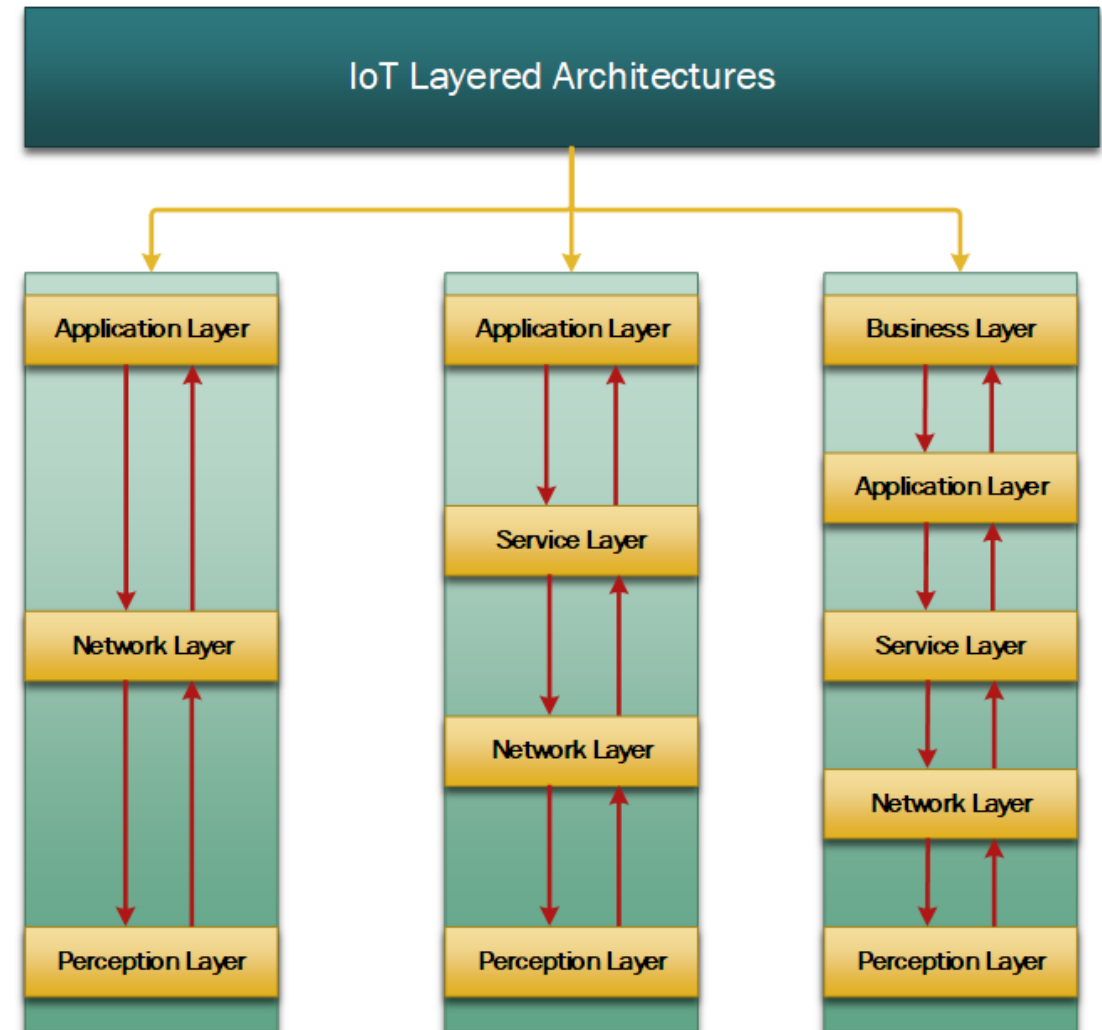
Network Layer: This layer is responsible for the unhindered transmission of the data from the perception layer and the physical devices to the application layer and vice versa

Application Layer: This layer receives the data from the network layer and performs specific objectives such as storage, data analysis, data visualization, etc.

4-layers and 5-layers architectures which also contain:

Service layer can be integrated between network layer and application layer so to provide supporting services for the application layer

Business layer manages the overall IoT system both activities and services

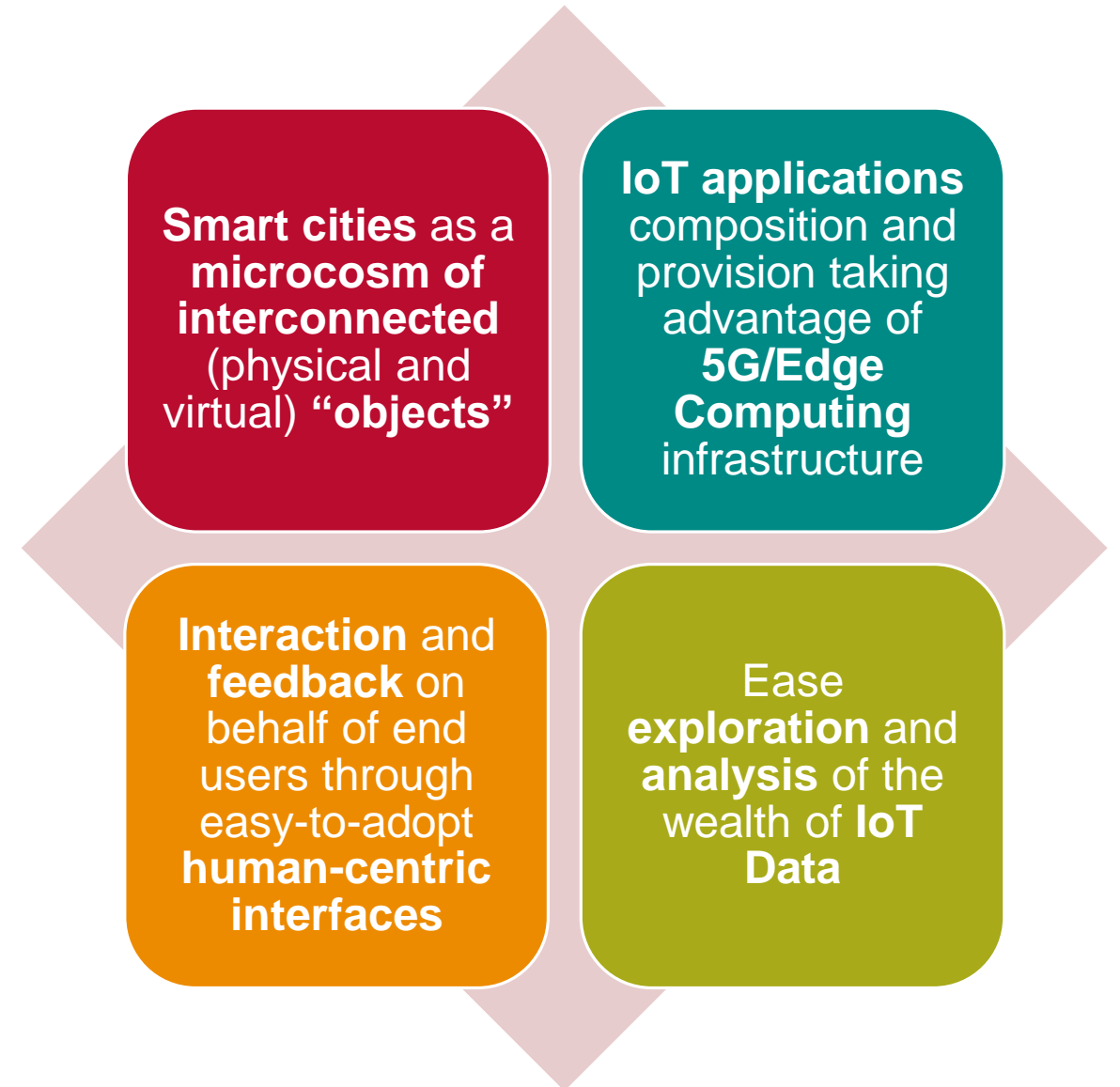




IoT is enabler for the Smart Cities of the Future

Supports the vision of end-to-end ecosystem to enable a fully mobile and connected society

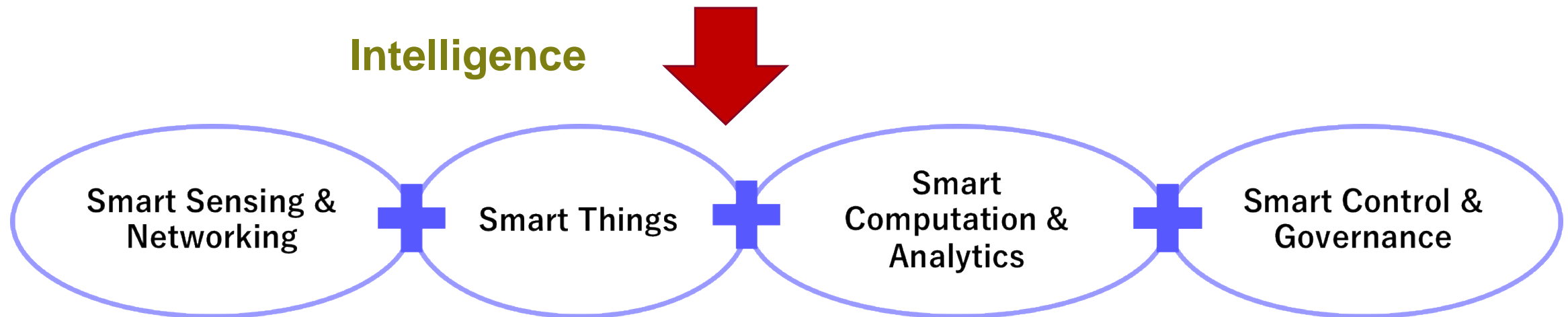
Part of **Future Internet**, representing a **network of networks**,” i.e., a heterogeneous system comprising a variety of air interfaces, protocols, frequency bands, access node classes, and network types





Smart IoT Characteristics and Trends

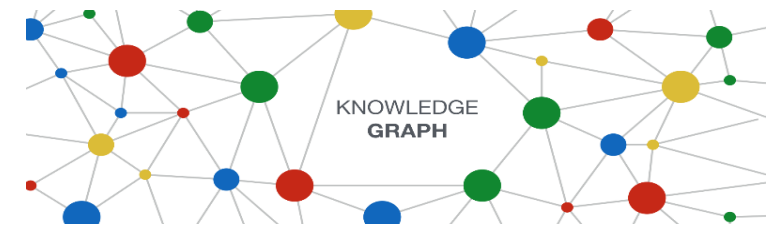
- Increase in the heterogeneity of the IoT technologies in terms of
 - the production of different types of intelligent IoT devices,
 - the support of various communication protocols,
- Release of IoT platforms tackling deployments in various parts of the available infrastructure (e.g. edge, cloud)
- Tackling of diverse requirements stemming from various use cases
- Conceptualization of various information models for semantically representing entities





Challenges and Enabling Technologies

- **Convergence** of IoT technologies (heterogeneity, interoperability, openness)
- Emergence of **5G and beyond-5G networks**: provision of high-data rates, dense deployments, accurate localization
- **5G/Edge Computing orchestration platforms** for efficient, reliable and secure applications provisioning
- **Intelligence and automation** in the edge and cloud part through **Machine Learning (ML)** techniques
- IoT Data storage, representation and management through IoT **Data Lakes** and **Knowledge Graphs**
- **Internet of Skills** evolution by involving the human in the decision-making loop





IoT & 5G: Growth and Characteristics

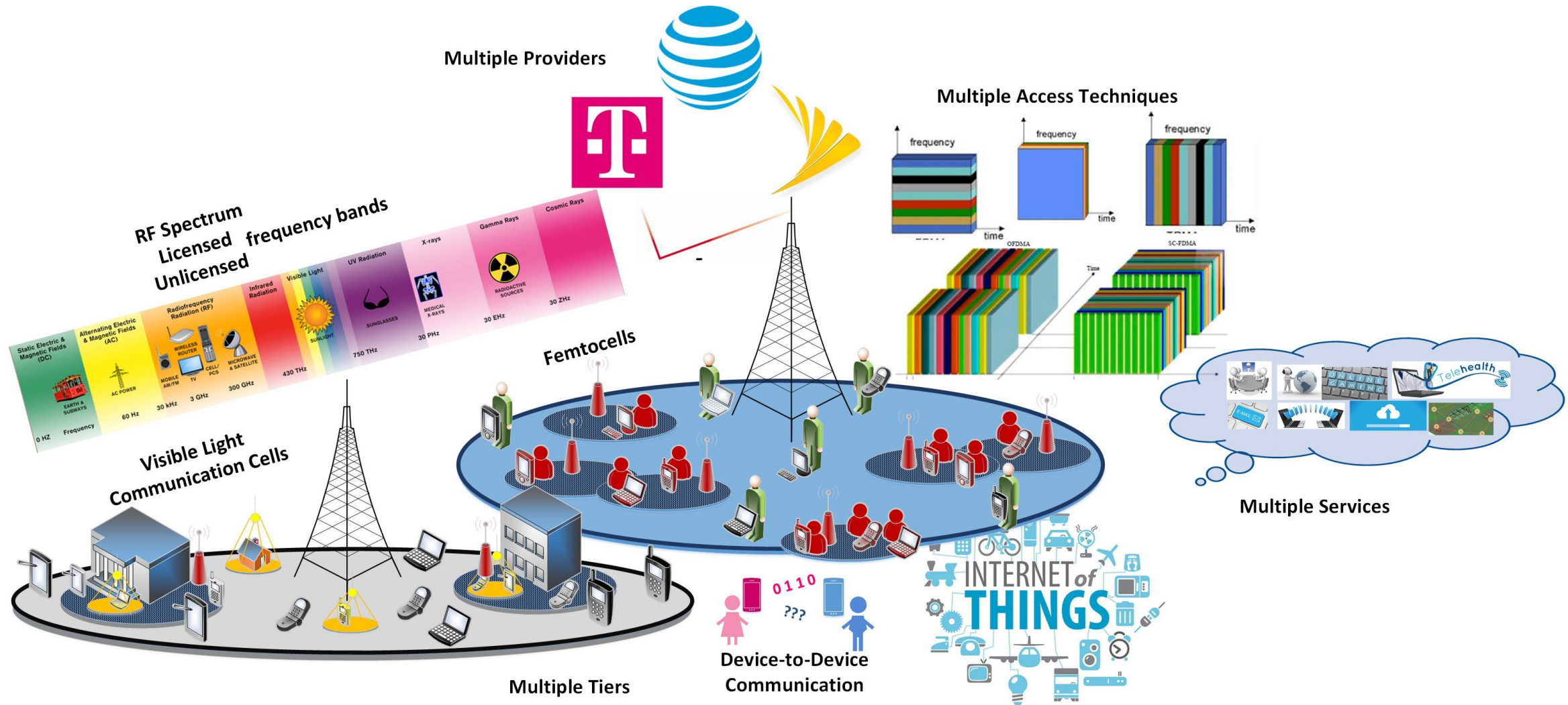
Massive growth of IoT

IoT Market Size 2025 - IDC \$7.1T	Connected Devices 2025 50B
IoT Market Growth 2025 - IDC 28.1% CAGR	IoT Data Growth 2015 -> 2025 49x

5G	
Capacity 1000x more traffic 10-100x more devices	Latency 1 millisecond
Data rates 10 Gbit/s @peak	Coverage 100 Mbit/s wherever
Bandwidth & latency demands	

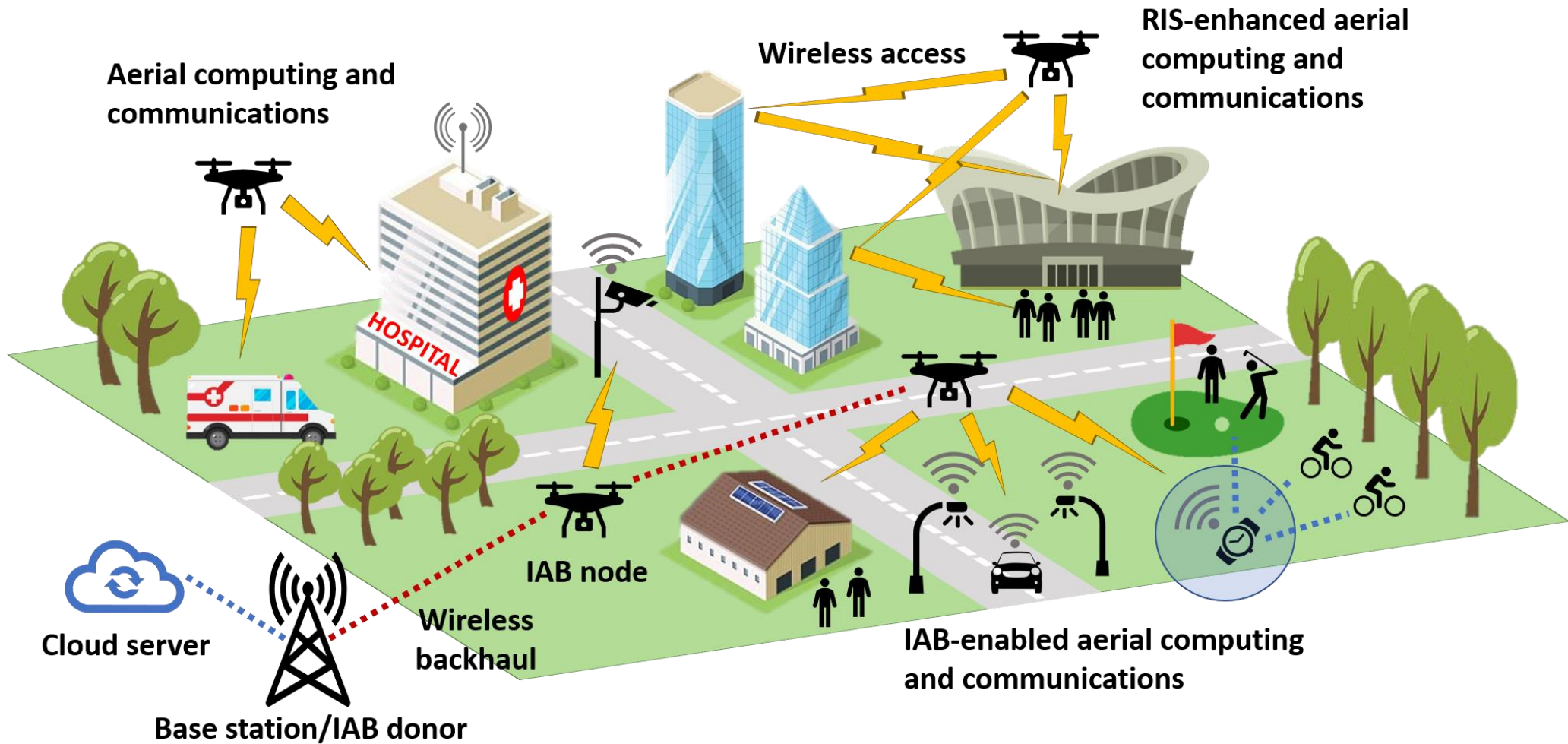


Wireless Communication & Computing Reality in 5G/B5G





Communications and Computing Mobilization





Drone-enabled Aerial Computing Paradigm

- Owing to: drones' inherent features and characteristics, such as mobility, flexibility, maneuverability and easy deployment.
- Unmanned Aerial Vehicles (UAVs) have been employed to act as flying base stations to support IoT in smart cities environments, or provide computing support to the end-users by acting as UAV-mounted edge computing servers
- Task execution may be realized either at: a) the local user itself, or b) at the UAV, acting as edge computing server providing computation on the fly (being of importance for delay-sensitive computing tasks, or c) at the cloud, with the UAV acting simply as a relay/forwarding station (being of particular interest in the case of highly computing-intensive tasks).



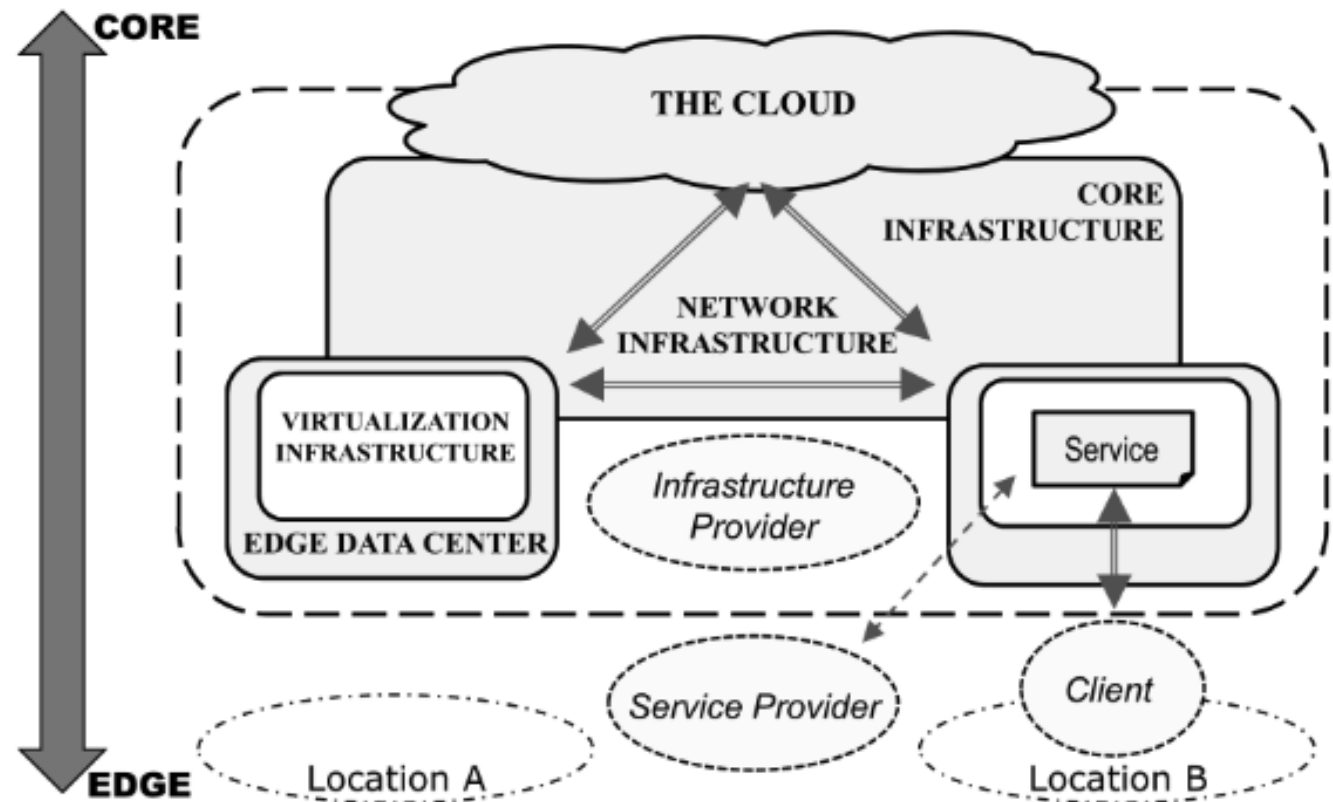
Computing Continuum – In Network Computing

Massive amount of data generated by IoT and connected devices.

Cloud Computing not able to satisfy:

- i. low-latency
- ii. location awareness
- iii. mobility awareness
- iv. data scalability

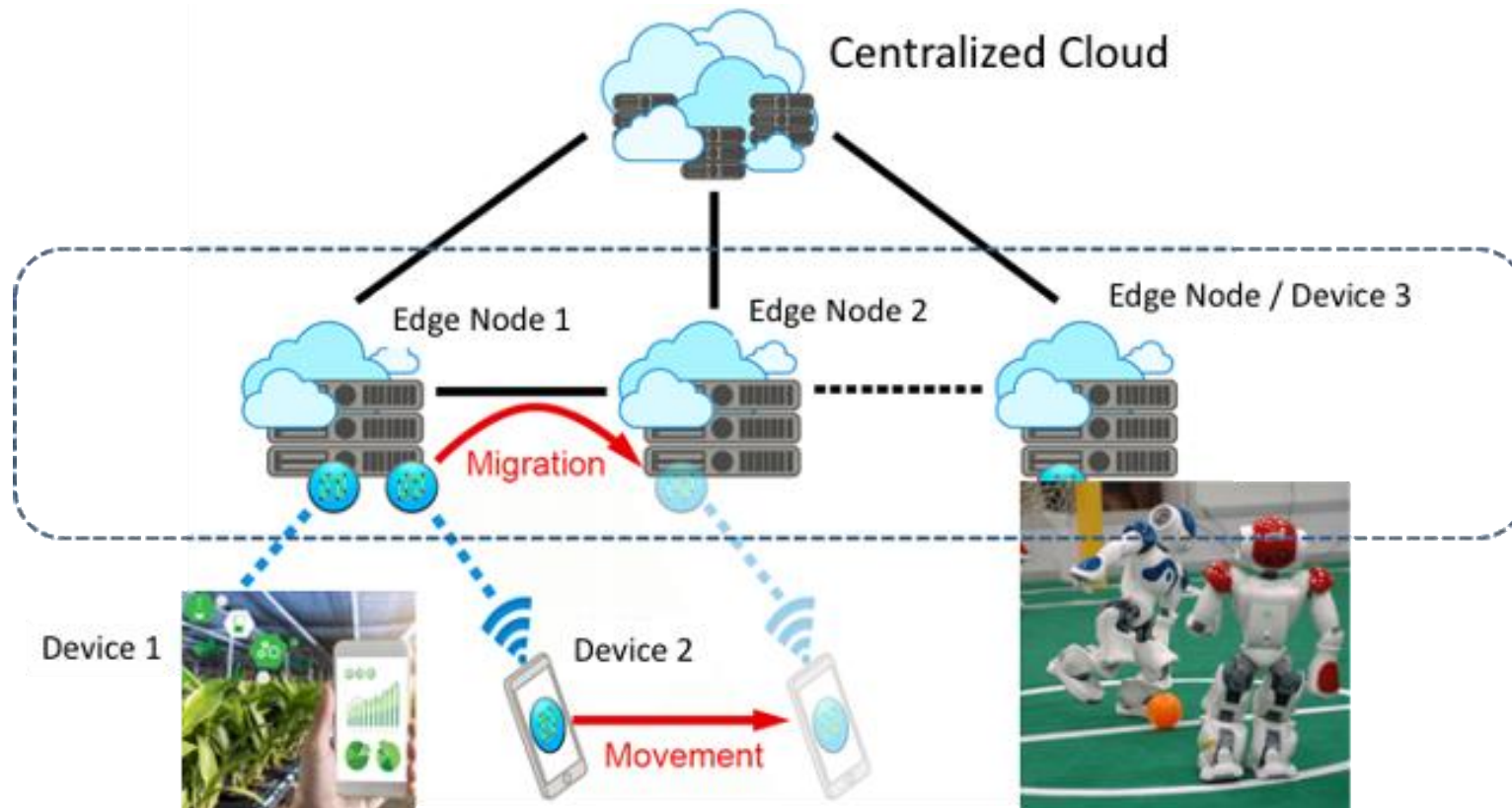
Moving towards the network Edge.





Smart Computation: Leveraging the Power of Edge Computing

- Pushing the frontier of processing and decision making away from the cloud to the network edge, closer to the sources of data.



Advantages:

- reduce network traffic
- decrease network latency
- improve system response time



Edge computing paradigms

Mobile Cloud Computing (MCC)

- ✓ On-demand, low-latency and secure access to a resourceful group of servers in the spatial vicinity of mobile users.

Fog Computing

- ✓ Computation, storage, networking, decision making, and data management occur along the path between IoT devices and the cloud.

Mobile/Multi-access Edge Computing (MEC)

- ✓ Similar to Fog, closeness to end-users, mobility support, and dense geographical deployment of the MEC servers.

Computational Offloading

- allows applications to migrate part of their code from the mobile devices to cloud-based computing resources located at the edge.

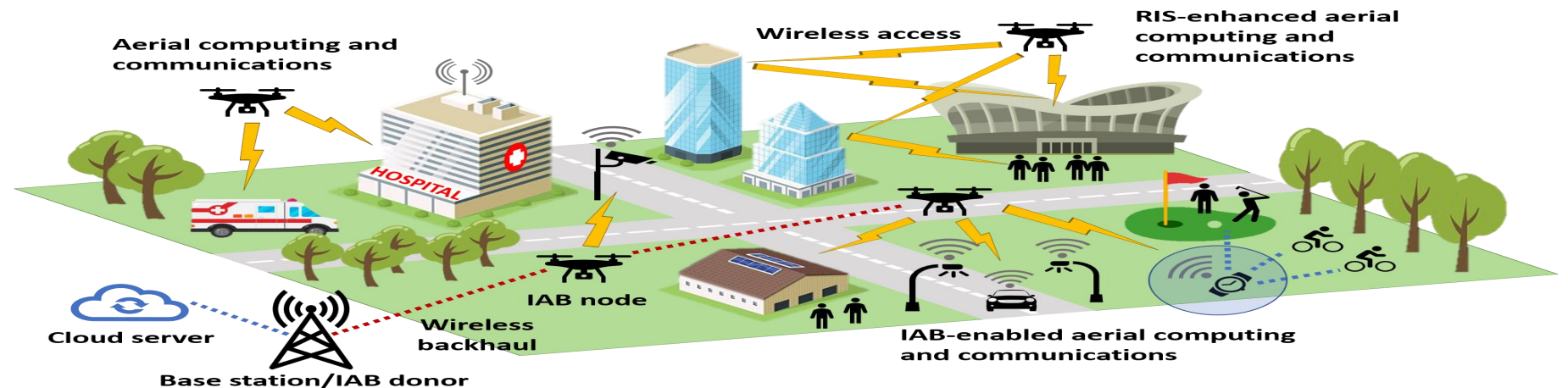
Application Examples

1. Natural Disasters (e.g. *UAV-enabled firefighting*)
2. Industry 4.0 (e.g. *Fog Robotics*)



Enabling Technologies: Reconfigurable Intelligent Surfaces (RIS) and Integrated Access and Backhaul (IAB)

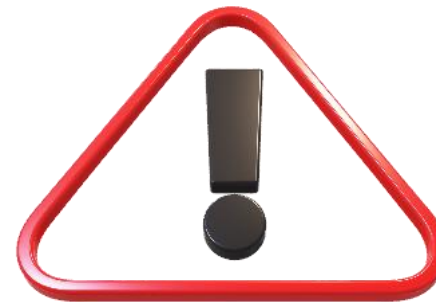
- A new flexible and reconfigurable wireless architecture paradigm is introduced
- Reconfigurable Intelligent Surfaces (RISs) facilitate the software-based control over the electromagnetic properties of the wire-less environment.
- Overcome the negative effects of Non-Line-of-Sight (NLOS) propagation and reduce the nodes' transmission power, extending the nodes' battery life, contributing to the mitigation of the overall interference, reducing communication holes and service disruption.
- Integrated Access and Backhaul (IAB) technology, provides a new definition and view of the backhauling problem
- IAB proposes the Next Generation Node Bases (gNBs) wirelessly relay the mobile traffic among each other in a multi-hop manner, referred to as IAB nodes, to finally reach the IAB donor, which is connected to the core Internet with fiber infrastructure





Competitive Communications & Computing Environments

- 5G /B5G communication systems
- Internet of Things
- Mobile Edge Computing
- Cyber-physical social systems



Inter-dependencies among behaviors and decisions within the era of resource orchestration



Human-Centric Resource Orchestration



Why Human-centric Solutions?

5G is based on user-centric concept instead of operator-centric as in 3G, or simply service-centric as in 4G

- **Capture humans' risk-aware behavior**
- **Satisfaction of humans' QoS prerequisites**
- **Transform qualitative models to mathematically tractable tools**

So far...

Principles of Expected Utility Maximization: users aim at selfishly maximizing their utility

The stability of these solutions depends on whether or not each user achieves the highest performance possible

Users in real life do not behave as neutral expected utility maximizers

Users exhibit risk-seeking or loss-aversion behavior under uncertain environments

Applicability and accuracy suffers from the dynamicity, incompleteness (partiality) of the available information

Lack of detailed knowledge about the potential actions of the rest of the competing users/devices

Research Gaps and Challenges

Real-life Modeling in Risks – Theoretical yet Pragmatic Approach



QoS Satisfaction Equilibrium vs Expected Utility Maximization –
energy/resource efficiency



Prospect Theory vs Risk-Neutral Behavior - risk seeking behavior
under losses, risk averse behavior under gains



Game Theory & Distributed Solutions vs Centralized Approaches
- user intelligence, distributed, complexity/convergence, competitive
environment, games in satisfaction form



**Reinforcement Learning (incomplete information) vs Complete
Information** -past experience, decentralized solutions, sense the
environment's reaction



**Novel holistic real-life modeling, optimization framework and
pragmatic resource orchestration paradigm**



Satisfy instead of Maximize

- Non-cooperative games among users in Satisfaction Form

$$G = \left[N, \{A_i\}_{i \in N}, \{U_i\}_{i \in N}, \{f_i\}_{i \in N} \right]$$

- N : the set of users
- A_i : the set of all possible strategies of user i
- U_i : user's i utility function
- f_i : the set of all satisfied strategies under a constraint of the user i

- Novel mathematical concept within Game Theory: **Satisfaction Equilibrium**

$$\mathbf{a}^* = (a_1^*, a_2^*, \dots, a_{|N|}^*) \in A, A = A_1 \times \dots \times A_{|N|}$$

- **SE**: all the users satisfy their minimum QoS requirements irrespective of the utility value they achieve

$$a_i^* \in f_i(\mathbf{a}_{-i}^*)$$

- Enlarge the set of feasible strategies

- **Efficient satisfaction equilibrium (ESE)**: Users satisfy their individual QoS by investing the minimum effort

$$a_i^* \in f_i(\mathbf{a}_{-i}^*) \text{ and } c_i(\mathbf{a}^*) \leq c_i(\mathbf{a})$$

- **Valued Satisfaction Equilibrium (VSE)**: quantify the tradeoff among the user's utility to the corresponding cost of investing the personal resources

$$a_i^* \in f_i(\mathbf{a}_{-i}^*) \text{ and } \frac{c_i(\mathbf{a}^*)}{U_i(\mathbf{a}^*)} \leq \frac{c_i(\mathbf{a})}{U_i(\mathbf{a})}$$

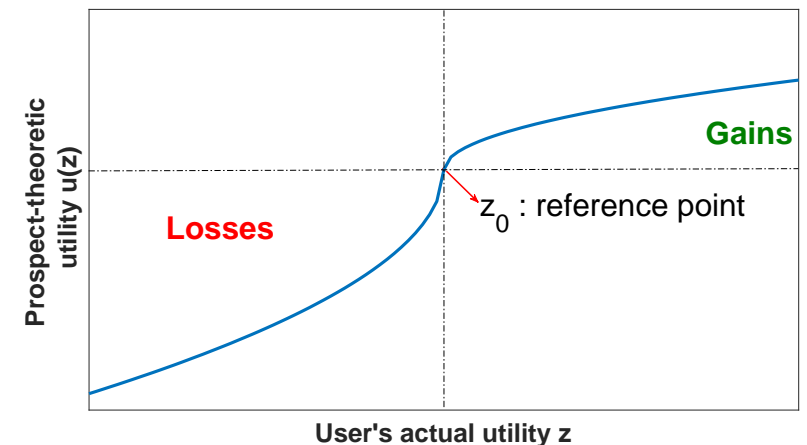
Risk-aware Utility Functions

- **Reference Dependence:** Users' derived psychological gains or losses are determined with respect to a reference point (i.e., ground truth)
- **Probability Weighting:** Individuals make autonomous decisions under risk and uncertainty of the associated payoff of their choices, which is estimated with some probability - overestimate low probability events, underestimate events of high probability.
- **Loss Aversion:** Individuals perceive greater dissatisfaction from a potential outcome of losses compared to their satisfaction from gains of the same amount
- **Diminishing Sensitivity:** humans demonstrate risk averse behaviour in gains (concave) and risk seeking attitude in losses (convex steeper)

Prospect Theory: A behavioral model, in which the users make actions under risk and uncertainty regarding the corresponding payoff of their actions.

Each user's satisfaction is evaluated with respect to a reference point (i.e., ground truth).

$$u(z) = \begin{cases} (z - z_0)^\alpha & \text{when } z \geq z_0 \\ -k(z_0 - z)^\beta & \text{otherwise,} \end{cases}$$





Tragedy of the Commons

- Utilization of Common Pool of Resources
- If the common pool of resources are overutilized...it fails...no one is satisfied
- Safe resources: guaranteed satisfaction (less attractive than the common pool of resources)
- Where to invest my personal resources? ...safe resources? Common pool of resources?
- Make decisions based on their personal characteristics, as they have been captured in the prospect-theoretic utility functions



Internet of Things Devices Constraints and Goals

❑ Constraints

- Limited memory
- Limited Computational Capability
- Limited Battery Life
- No knowledge of the environment

❑ Goals

- Energy Efficiency
- Store and Process Data
- Satisfy IoT Devices' Quality of Service Prerequisites

Challenges

I want to process data

I want to store Data

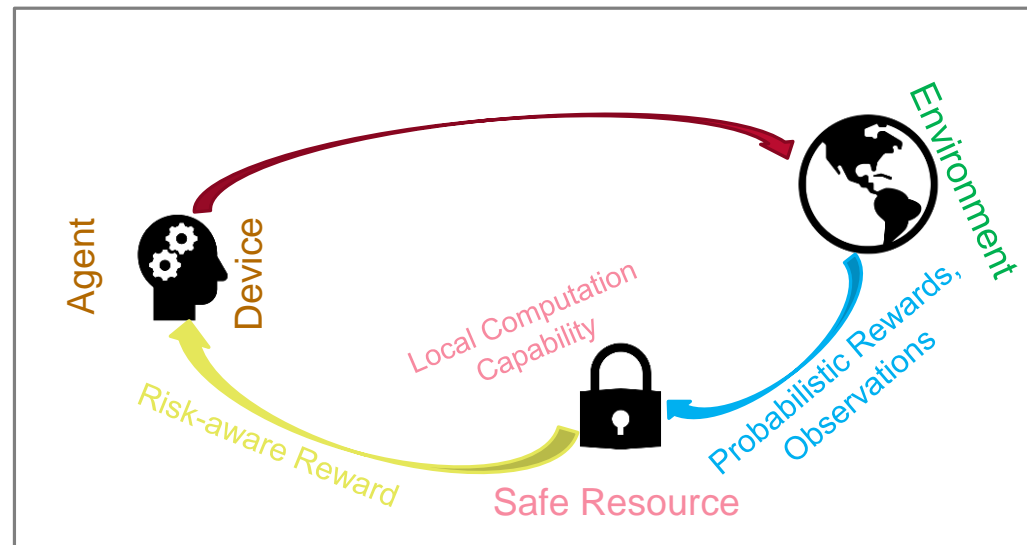
I have an application to execute





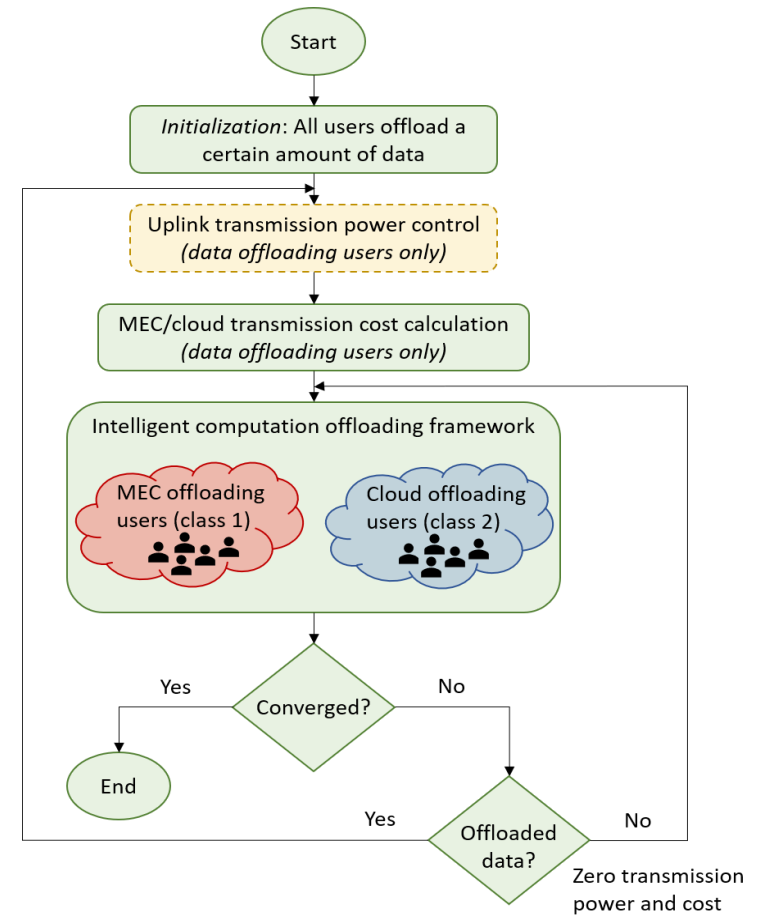
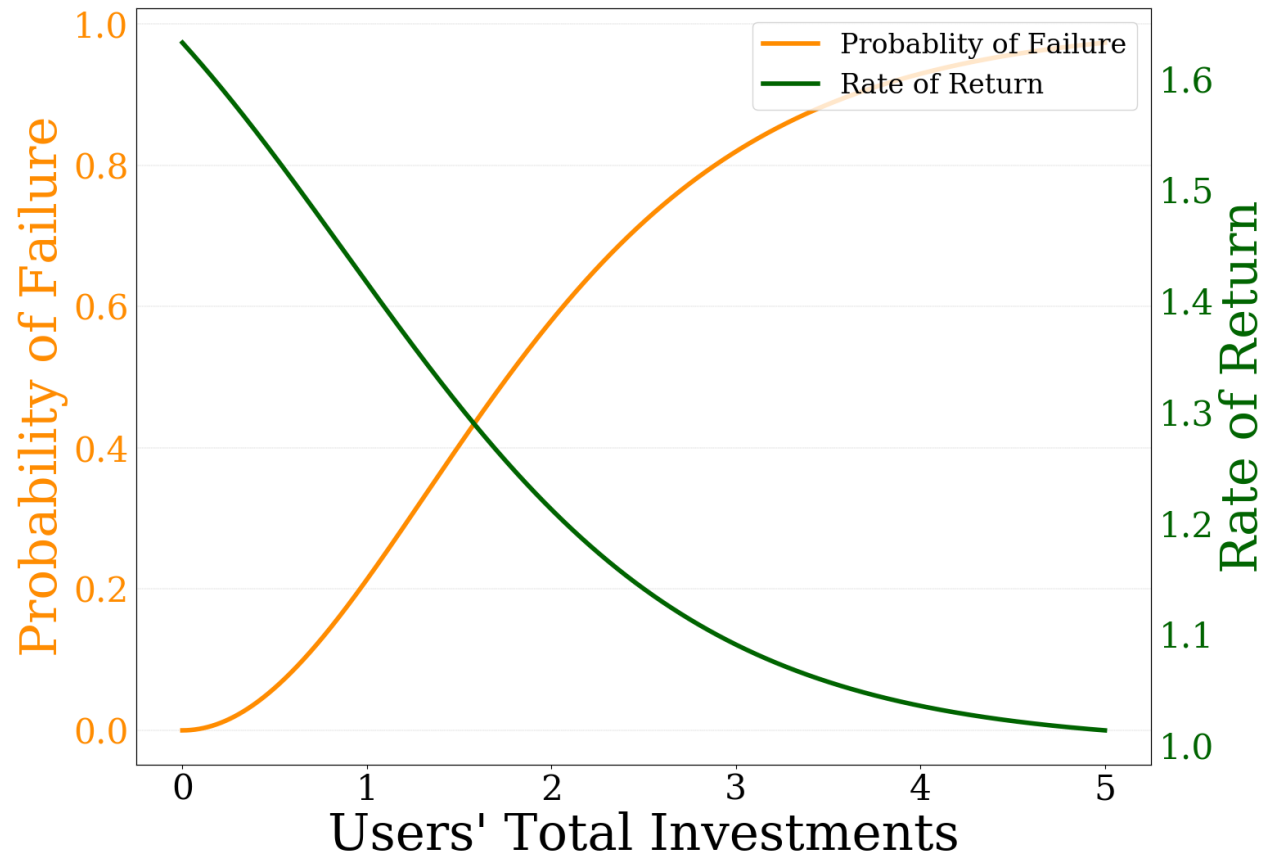
Cognitive Data Offloading in Mobile Edge Computing for Internet of Things (1/3)

- ❑ Each device act as an autonomous agent, and determines the optimal amount of data that should be offloaded to the MEC server, while the rest are being process locally at the device.
- ❑ Due to sharing nature of the access environment and the MEC server's computational characteristics, the MEC server is treated as a shared resource with uncertain reward, while the local computation capability of each device is treated as a safe option.



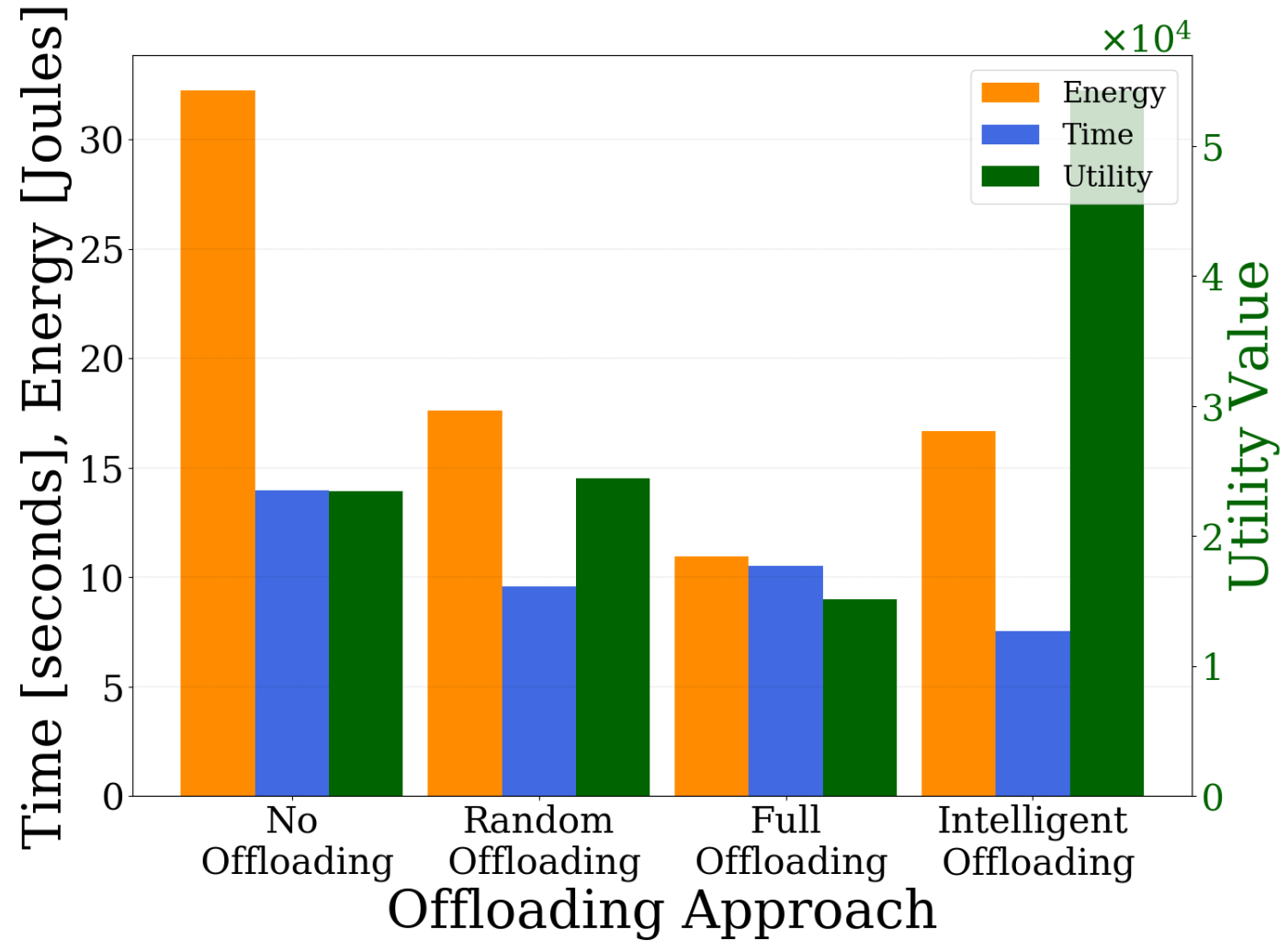


Cognitive Data Offloading in Mobile Edge Computing for Internet of Things (2/3)





Cognitive Data Offloading in Mobile Edge Computing for Internet of Things (3/3)





Reinforcement Learning



- *"In theory, there is no difference between theory and practice. But in practice, there is." (Y. Berra)*

- technical and implementation challenges

- lack of detailed knowledge or complete information about the actions of the rest of the competing humans
- influence decision-making and equilibrium identification and convergence

Reinforcement Learning

- ✓ Learn from the past personal actions
- ✓ Limited necessary information
- ✓ Sense the environment's reactions

Learning Algorithms

- Q-Learning
- Stochastic Learning Automata
- Exponential Learning
- Cellular Automata
- Bayesian Reinforcement Learning

Data Offloading/Processing and In-Network Computing



Mobile Edge Computing Servers: Common Pool of Resources (Multi-CPR with Ground and UAVs Servers)



Local Computing and Cloud: Safe Resources



User's investment: load of data



Prospect-theoretic probabilistic utilities



Problem Formulation

$$\max_{b_i \in \mathcal{S}_i} E(U_i)$$



Problem Solution: Satisfaction Equilibrium operation points and learning for distributed operation

Remaining Challenges

- ❑ Data value
- ❑ Achieving large-scale connectivity
- ❑ Distributed intelligence
- ❑ Advanced big data analytics
- ❑ Multi-domain multi-source data fusing and correlations
- ❑ Learning and adapting to changes leveraging rich contexts (including human knowledge)
- ❑ Learning approaches are required to account for partial information availability
- ❑ High-impact real-world applications – realizing the true value
- ❑ Large scale realistic testing/testbeds



Thank you!

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Acknowledgement: This work is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “1st Call for H.F.R.I. Research Projects to support Faculty Members & Researchers and the Procurement of High-and the procurement of high-cost research equipment grant” (Project Number: HFRI-FM17-2436).