Unit II
IOT Architecture

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Unit II
IOT Architecture (05)

- Introduction,
- Functional View,
- Information View,
- Deployment and Operational View,
- Other Relevant architectural views.
- Real-World Design Constraints- Introduction, Technical Design constraints ,
- IoT reference model.

RTMNU S-23 Questions

3.		Write short note on any two.		14
		i) IOT functional view	ii) IOT Information view	
		iii) IOT deployment levels		
		OR		
4.	a)	Draw and explain IOT reference model.		8
	b)	Discuss the real world design challenges of IOT.		6

RTMNU W-23 Questions

3.	a)	Explain the IoT functional view with diagram.	8
	b)	Describe in detail about function models.	6
		OR	
4.	a)	Describe in detail about the IoT reference model.	8
	b)	Explain the deployment view with diagram.	6

IoT Reference Architecture

- The Reference Architecture is a starting point for generating concrete architectures and actual systems.
- A concrete architecture addresses the concerns of multiple stakeholders of the actual system, and it is typically presented as a series of views that address different stakeholder concerns (Kruchten 1995; SEI CMU 2013; Rozanski & Woods 2005, 2011).

- A Reference Architecture, on the other hand, serves as a guide for one or more concrete system architects.
- However, the concept of views for the presentation of an architecture is also useful for the IoT Reference Architecture.
- Views are useful for reducing the complexity of the Reference Architecture blueprints by addressing groups of concerns one group at a time.
- However, since the IoT Reference Architecture does not contain details about the environment where the actual system is deployed, some views cannot be presented in detail or at all;
- for example, the view that shows the concrete Physical Entities and Devices for a specific scenario.

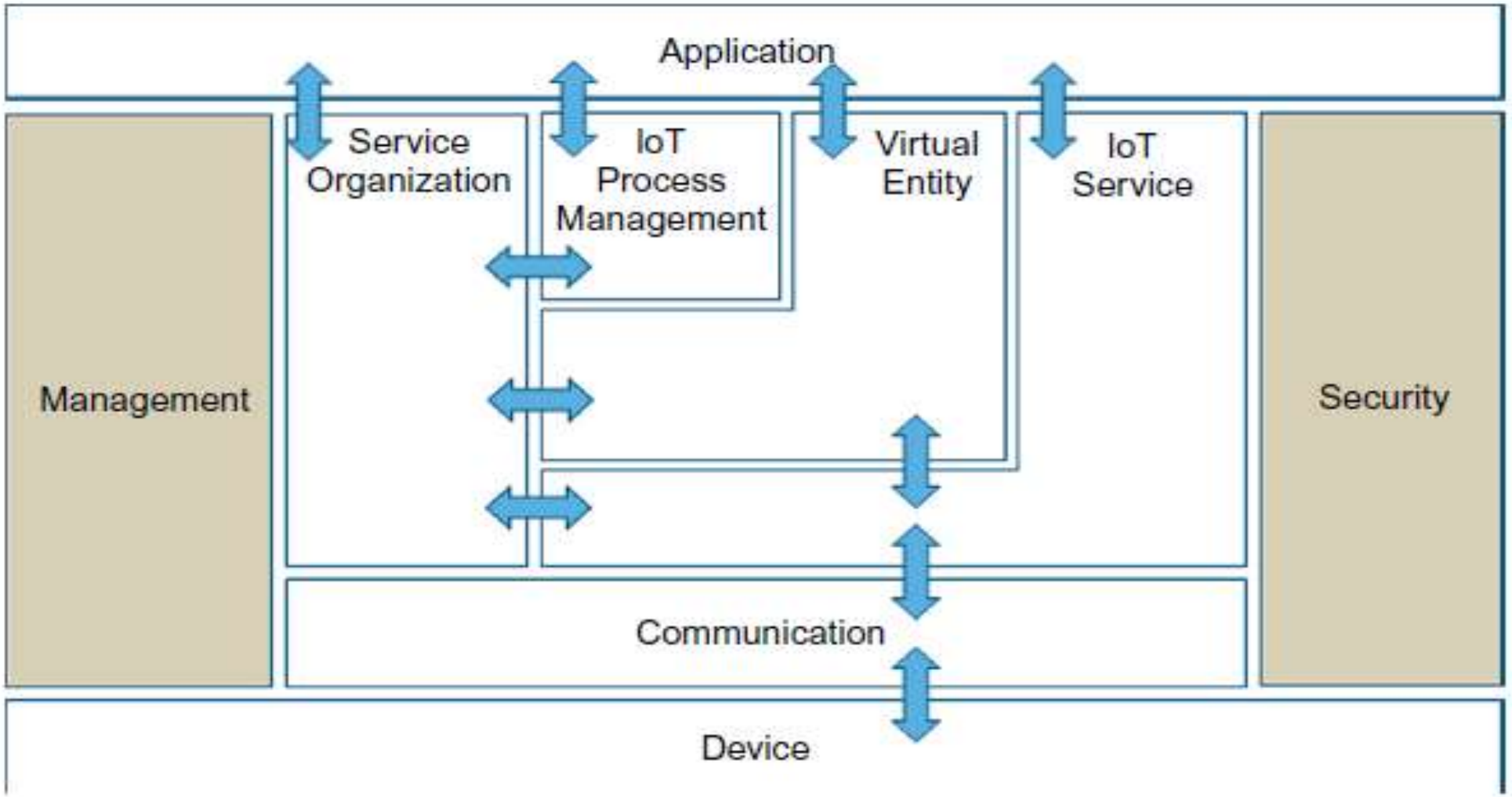
- The stakeholders for a concrete IoT system are the people who use the system (Human Users); the people who design, build, and test the Resources, Services, Active Digital Artifacts, and Applications; the people who deploy Devices and attach them to Physical Entities; the people who integrate IoT capabilities of functions with an existing ICT system (e.g. of an enterprise);the people who operate, maintain, and troubleshoot the Physical and Virtual Infrastructure; and the people who buy and own an IoT system or parts thereof (e.g. city authorities).

- In order to address the concerns of mainly the concrete IoT architect,
- and secondly the concerns of most of the above stakeholders, we have chosen to present the Reference Architecture as a set of architectural views (Kruchten 1995; SEI CMU 2013; Rozanski & Woods 2005, 2011):

- Functional View: Description of what the system does, and its main functions.
- Information View: Description of the data and information that the system handles.
- Deployment and Operational View: Description of the main real world components of the system such as devices, network routers,servers, etc.

Functional model

- The IoT Functional Model aims at describing mainly the Functional Groups (FG) and their interaction with the ARM (Architectural Reference Model), while the Functional View of a Reference Architecture describes the functional components of an FG, interfaces, and interactions between the components.
- The Functional View is typically derived from the Functional Model in conjunction with high level requirements.



FIGURE

IoT-A Functional Model.

(Carrez et al. 2013)

The IoT functional view

- The IoT functional view describes the structure, behavior, and key functionalities of an IoT system.
- It provides a layered approach to understanding how IoT devices, systems, and applications work together to enable seamless communication, data collection, analysis, and decision-making.
- Below is a detailed explanation of the IoT functional view with its layers:

The IoT functional view……

1. Perception Layer

- **Function:**
  - This layer is responsible for sensing and collecting data from the physical world.
  - It consists of sensors, actuators, and other devices that interact with the environment.
- **Examples:**
  - Temperature sensors, humidity sensors, motion detectors, cameras, RFID tags.
- **Key Role:**
  - Translates physical parameters into digital signals.
  - Sends raw data to the network layer.

The IoT functional view……

2. Network Layer

- **Function:**
  - Responsible for transmitting the collected data from the perception layer to the processing units.
  - Utilizes various communication protocols and network infrastructures.
- **Examples:**
  - Wi-Fi, Bluetooth, ZigBee, LoRaWAN, 4G/5G, Ethernet.
- **Key Role:**
  - Ensures reliable, secure, and efficient data transmission.

The IoT functional view……

3. Edge/Processing Layer

- **Function:**
  - Performs preliminary data filtering, aggregation, and computation close to the source.
  - Reduces latency and bandwidth usage by handling some tasks locally.
- **Examples:**
  - Edge devices like gateways, Raspberry Pi, NVIDIA Jetson Nano.
- **Key Role:**
  - Offloads tasks from the cloud and provides faster responses for time-sensitive applications.

The IoT functional view……

4. Application Layer

- **Function:**
  - Provides the user interface and application-specific functionalities.
  - Converts processed data into meaningful insights or actionable outputs.
- **Examples:**
  - IoT applications like smart homes, industrial automation, health monitoring.
- **Key Role:**
  - Enables interaction between users and the IoT system via dashboards, mobile apps, or APIs.

The IoT functional view……

5. Business Layer

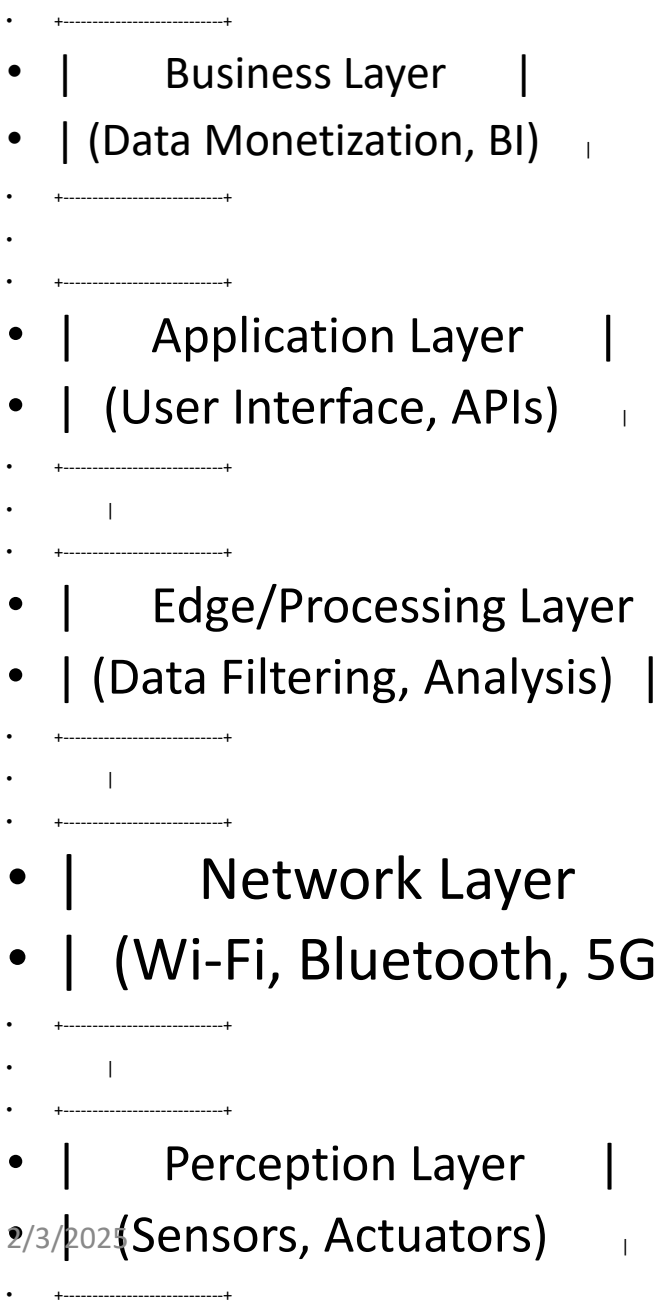
- **Function:**
  - Focuses on business-related aspects of IoT, such as decision-making, data monetization, and operational improvements.
  - Involves analytics, visualization, and integration with enterprise systems.
- **Examples:**
  - Business intelligence tools, cloud platforms for analytics.
- **Key Role:**
  - Turns insights into actionable strategies for improving services or products.

The IoT functional view……

Key Features of the IoT Functional View:

- **Layered Approach:**
  - Ensures modularity and ease of understanding.
  - Different functionalities are isolated, promoting scalability and manageability.
- **Real-Time Operation:**
  - Collects, transmits, and processes data in real time for timely insights.
- **Interconnectivity:**
  - Integrates diverse devices and protocols for seamless communication.
- **Scalability and Flexibility:**
  - Supports various devices and can scale with business needs.

IoT Functional View block diagram



Functional view…..

- The functional view for the IoT Reference Architecture is presented in
- Figure 2.1, and is adapted from IoT-A (Carrez et al. 2013).
- It consists of the Functional Groups (FGs), each of which includes a set of Functional Components (FCs).
- It is important to note that not all the FCs are used in a concrete IoT architecture.

Functional view….

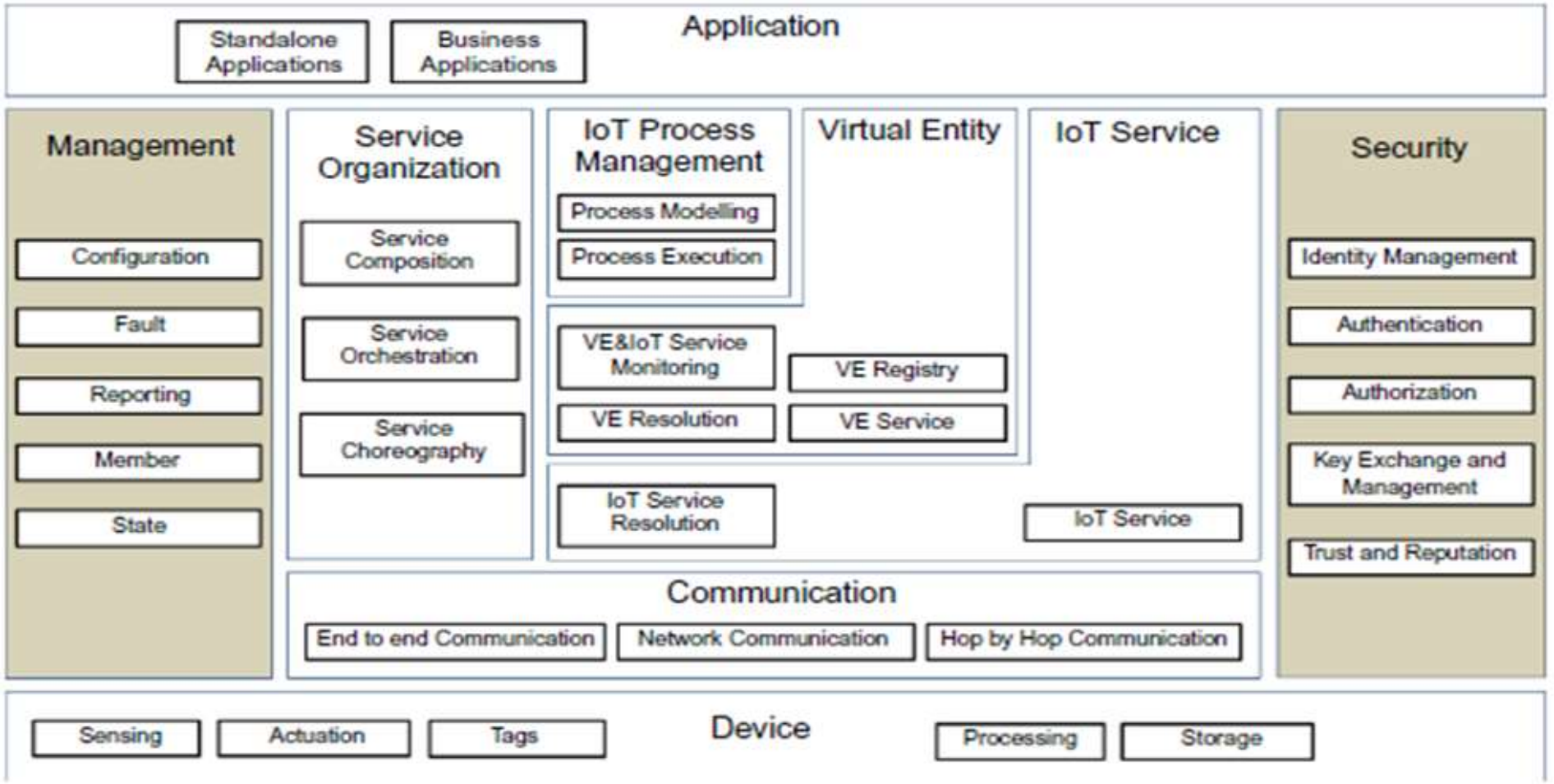


Fig 2.1 :IoT Functional View

Device and Application functional group

- The Device FG contains the Sensing, Actuation, Tag, Processing, Storage FCs, or simply components.
- These components represent the resources of the device attached to the Physical Entities of interest.
- The Application FG contains either standalone applications (e.g. for iOS, Android, Windows phone), or Business Applications that connect the IoT system to an Enterprise system.

Communication functional group

- The Communication FG contains the End-to-End Communication, Network Communication, and Hop-by-Hop communication components:
- The Hop-by-Hop Communication is applicable in the case that devices are equipped with mesh radio networking technologies such as IEEE 802.15.4 for which messages have to traverse the mesh from node-to-node (hop-by-hop) until they reach a gateway node which forwards the message (if needed) further to the Internet.

Communication functional group…

- The hop-by-hop FC is responsible for transmission and reception of physical and MAC layer frames to/from other devices.
- This FC has two main interfaces:

(a) one “southbound” to/from the actual radio on the device, and

(b) one “northbound” to/from the Network FC in the Communication FG.

- The Network FC is responsible for message routing & forwarding and the necessary translations of various identifiers and addresses.

  The translations can be

(a) between network layer identifiers to MAC and/or physical network identifiers,

(b) between high-level human readable host/node identifiers to network layer addresses (e.g. Fully Qualified Domain Names (FQDN) to IP addresses, a function implemented by a Domain Name System (DNS) server), and

(c) translation between node/service identifiers and network locators in case the higher layers above the networking layer use node or service identifiers that are decoupled from the node addresses in the network (e.g. Host Identity Protocol (HIP; Moskovitz & Nikander 2006) identifiers and IP addresses).

- The End-to-End Communication FC is responsible for end-to-end transport of application layer messages through diverse network and MAC/PHY layers.

IoT Service functional group

- The IoT Service FG consists of two FCs: The IoT Service FC and the IoT Service Resolution FC:
- The IoT Service FC is a collection of service implementations, which interface the related and associated Resources.
- The IoT Service Resolution FC contains the necessary functions to realize a directory of IoT Services that allows dynamic management of IoT Service descriptions and discovery/lookup/resolution of IoT Services by other Active Digital Artifacts.

Virtual Entity functional group

- The Virtual Entity FG contains functions that support the interactions between Users and Physical Things through Virtual Entity services.
- An example of such an interaction is the query to an IoT system of the form, “What is the temperature in the conference room Titan?”
- The Virtual Entity is the conference room “Titan,” and the conference room attribute of interest is “temperature.”

- Assuming that the room is actually instrumented with a temperature sensor, if the User had the knowledge of which temperature sensor is installed in the room (e.g. TempSensor #23),
- Then the User could re-formulate and re-target this query to, “What is the value of TempSensor #23?”

- The Virtual Entity Service FC enables the interaction between Users and Virtual Entities by means of reading and writing the Virtual Entity attributes (simple or complex), which can be read or written, of course.
- Some attributes (e.g. the GPS coordinates of a room) are static and non-writable by nature, and some other attributes are non-writable by access control rules.

- In general attributes that are associated with IoT Services, which in turn represent Sensor Resources, can only be read.
- There can be, of course, special Virtual Entities associated with the same Sensor Resource through another IoT Service that allow write operations.
- The Virtual Entity Registry FC maintains the Virtual Entities of interest for the specific IoT system and their associations.

Information model

- According to the Data Information Knowledge Wisdom Pyramid (Rowley 2007),
- Information is defined as the enrichment of data (raw values without relevant or usable context) with the right context, so that queries about who, what, where, and when can be answered.
- Because the Virtual Entity in the IoT Domain Model is the “Thing” in the Internet of Things, the IoT information model captures the details of a Virtual Entity centric model.

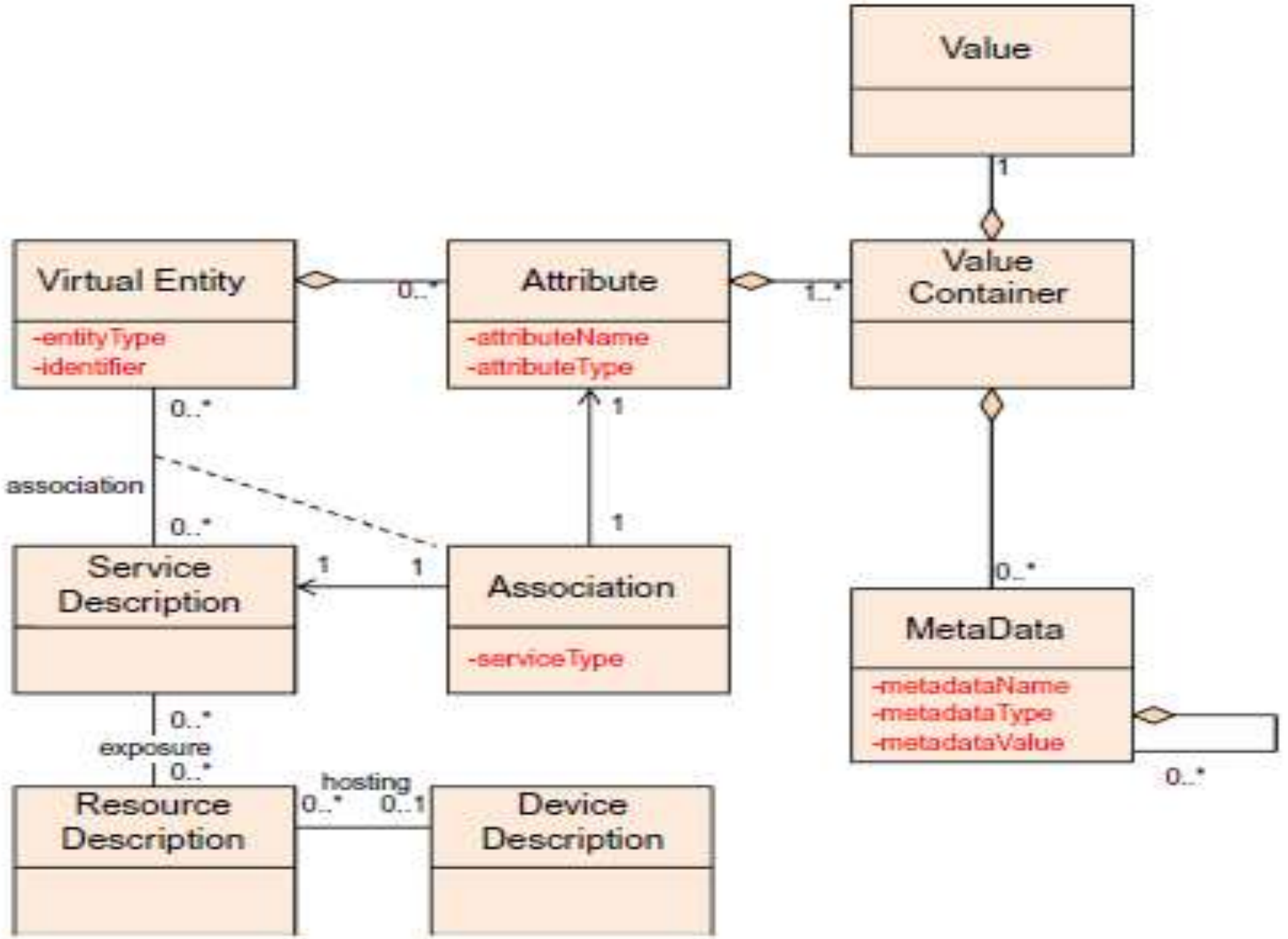
Data Information Knowledge Wisdom Pyramid (Rowley 2007),

- Similar to the IoT Domain Model, the IoT Information Model is presented using Unified Modeling Language (UML) diagrams
  - In UML models, attributes **represent the information, data, or properties that belong to instances of a classifier**.
  - A classifier can have any number of attributes or none at all.
  - Attributes describe a value or a range of values that instances of the classifier can hold.

- Each class in a UML diagram contains zero or more attributes.

These attributes are typically of simple types such as integers or text strings, and are represented with red text under the name of the class (e.g. entityType in the Virtual Entity class in Figure next slide).

A more complex attribute for a specific class A is represented as a class B, which is contained in class A with an aggregation relationship between class A and class B.



FIGURE

High-level IoT Information Model.

(Adapted from Carrez et al. 2013)

- Metadata means "data about data". Metadata is defined as the data providing information about one or more aspects of the data; it is used to summarize basic information about data that can make tracking and working with specific data easier.
- For example, a digital image may include metadata that describes the size of the image, its color depth, resolution, when it was created, the shutter speed, and other data.
- A text document's metadata may contain information about how long the document is, who the author is, when the document was written, and a short summary of the document.
- Metadata within web pages can also contain descriptions of page content, as well as key words linked to the content.

Information View

- The **Internet of Things (IoT) Information View** provides a perspective on how information is managed, processed, and exchanged in IoT systems.
- It focuses on the data lifecycle within IoT, including its collection, transmission, storage, processing, and usage.
- This view is critical for designing IoT systems that ensure data is effectively utilized while maintaining security, privacy, and integrity.

Information View…..

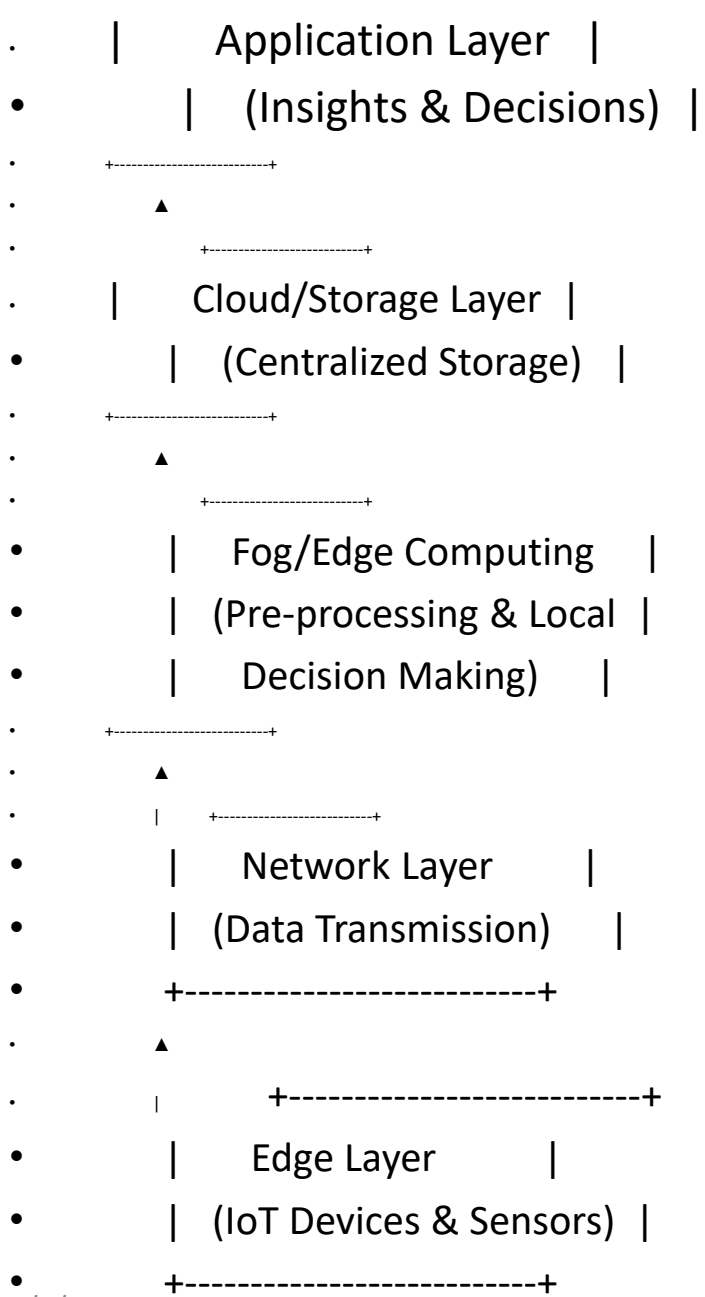
- **Key Elements of IoT Information View**
- **Data Sources (Edge Layer)**
  - These are IoT devices or sensors that collect data from the environment. Examples include temperature sensors, cameras, or smart appliances.
  - Characteristics:
    - Variety: Data types include structured, semi-structured, and unstructured.
    - Volume: Large amounts of data due to numerous devices.
    - Velocity: Real-time or near-real-time data generation.
- **Data Transmission (Network Layer)**
  - The collected data is transmitted from devices to higher layers for processing.
  - Communication protocols such as MQTT, CoAP, HTTP, and WebSocket ensure reliable and efficient data transfer.
  - Networks can include Wi-Fi, LoRaWAN, Zigbee, Bluetooth, or cellular technologies.

Information View.....

- **Data Processing and Analysis (Fog/Edge Computing)**
- Pre-processing of data close to the data source to reduce latency and bandwidth requirements.
- Tasks include filtering, aggregation, and local decision-making.
- **Data Storage and Management (Cloud Layer)**
- Data is stored in centralized systems for long-term analysis and integration.
- Technologies include relational databases (SQL), NoSQL databases, and distributed storage systems.
- Scalable storage solutions are vital to handle the massive influx of IoT data.
- **Data Analysis and Insights**
- Advanced analytics, such as machine learning and AI, are applied to derive actionable insights.
- Real-time dashboards and predictive analytics tools are common.

Information View.....

- **Data Security and Privacy**
- Encryption, authentication, and access control mechanisms protect data integrity and confidentiality.
- Compliance with regulations (e.g., GDPR, HIPAA) is essential.
- **Application Layer**
- Insights from data are utilized in IoT applications for decision-making, automation, and user interaction.
- Examples: Smart home systems, predictive maintenance, and healthcare monitoring.


Application Layer
(Insights & Decisions)
Cloud/Storage Layer
(Centralized Storage)
Fog/Edge Computing
(Pre-processing & Local
Decision Making)
Network Layer
(Data Transmission)
Edge Layer
(IoT Devices & Sensors)

Information View

- The information view consists of

(a) the description of the information handled in the IoT System, and (b) the way this information is handled in the system;

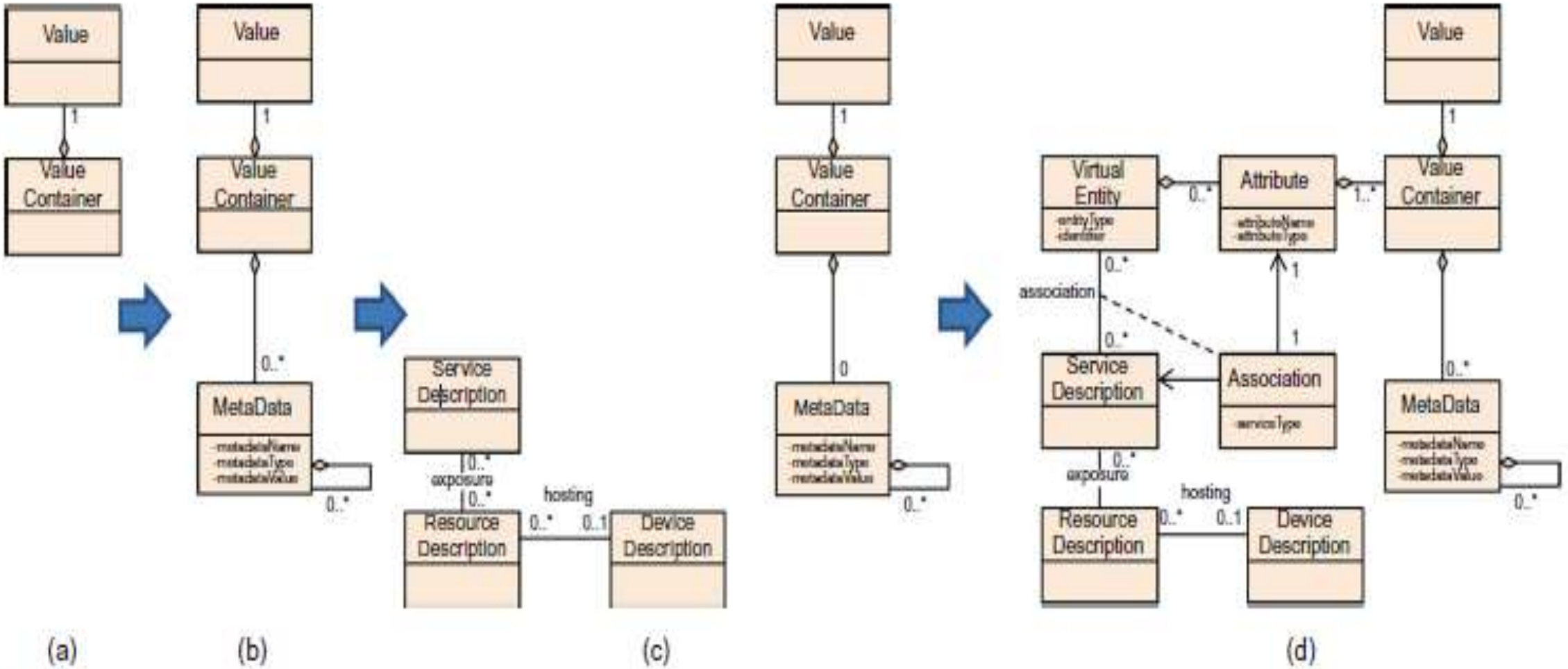
- In other words, the information lifecycle and flow (how information is created, processed, and deleted), and the information handling components.

Information description

- The pieces of information handled by an IoT system
- Virtual Entity context information, i.e. the attributes (simple or complex) as represented by parts of the IoT Information model.
- IoT Service output itself is another important part of information generated by an IoT system. For example, Sensor or a Tag Service.
- Virtual Entity descriptions in general, contain not only the attributes coming from IoT Devices (e.g. ownership information) but also the Virtual Entity Associations with other Virtual Entities (e.g. Room #12 is on floor#7)
-

Information description…..

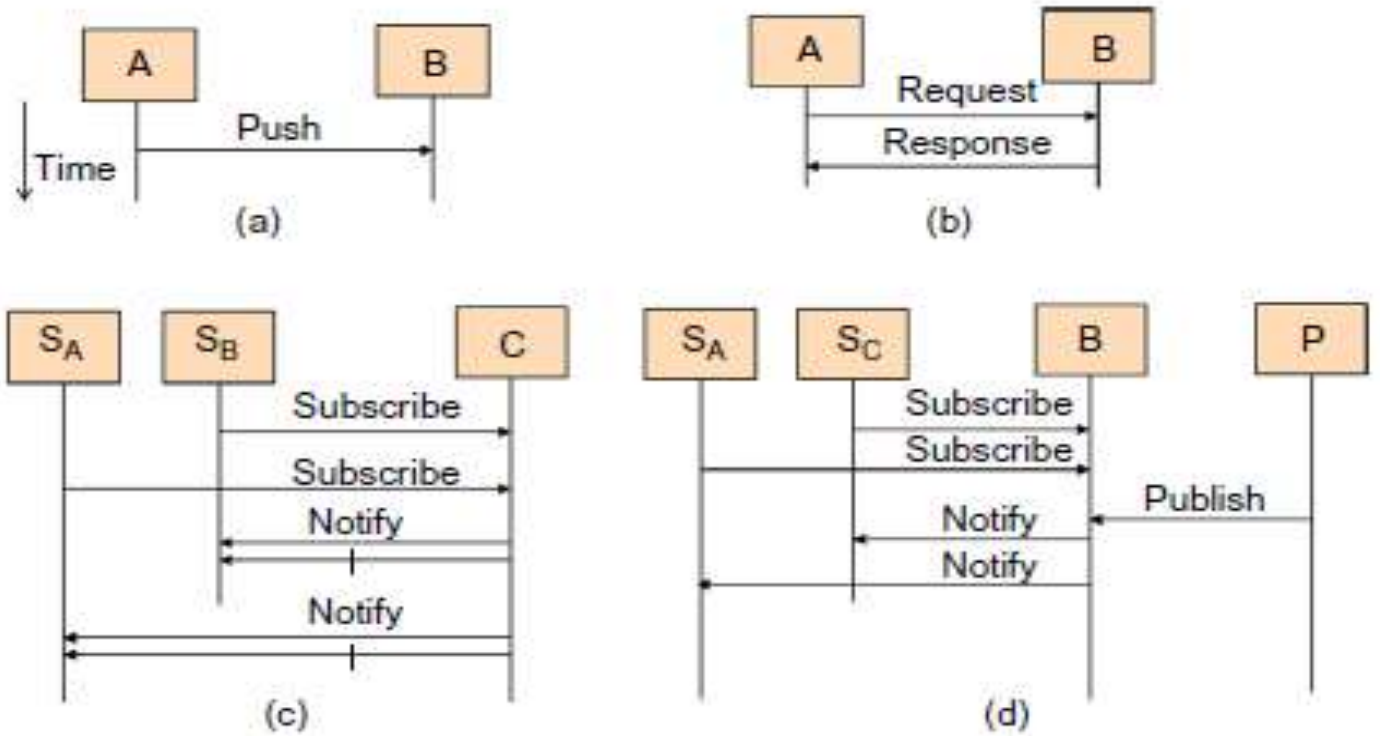
- **Resource Descriptions –>** type of resource (e.g. sensor), identity, associated Services, and Devices.
- **Device Descriptions –>** device capabilities (e.g. sensors, radios).
- **Descriptions of Composed Services –>** the model of how a complex service is composed of simpler services.
- **IoT Business Process Model describes –>** the steps of a business process utilizing other IoT-related services.
- Management information such as state information from operational FCs used for fault/performance purposes, configuration snapshots, reports, membership information, etc.



FIGURE

Information-enrichment process.

IOT Information handling



FIGURE

Information exchange patterns.

(Adapted from IoT-A; Carrez et al. 2013)

Deployment and operational view

- The **Internet of Things (IoT) Deployment and Operational View** provides a comprehensive perspective on how IoT devices, infrastructure, and systems are deployed, managed, and operated to achieve a seamless flow of data and services.
- It integrates **both the technical and functional aspects of IoT systems to meet the needs of various stakeholders.**

1. Deployment View

- This focuses on the physical and logical layout of IoT components, including hardware, software, and network resources.
- **Key Aspects of Deployment View:**
- **Device Layer:**
  - IoT devices (sensors, actuators, edge devices) deployed in specific locations.
  - Devices communicate with each other or a centralized system.

Deployment View….

- **Network Layer:**
- Connectivity options such as Wi-Fi, Bluetooth, ZigBee, LoRa, 5G, or Ethernet.
- Gateways acting as intermediaries between IoT devices and the cloud.
- **Cloud Layer:**
- Cloud platforms hosting applications, analytics, and storage.
- Provides scalability, data processing, and remote accessibility.
- **Edge Layer:**
- Edge computing resources process data locally to reduce latency.
- Involves microcontrollers, Raspberry Pis, or edge servers.

Deployment View….

- **Deployment Tools:**Provisioning tools for setting up IoT devices.
- Configuration management for device settings.

2. Operational View

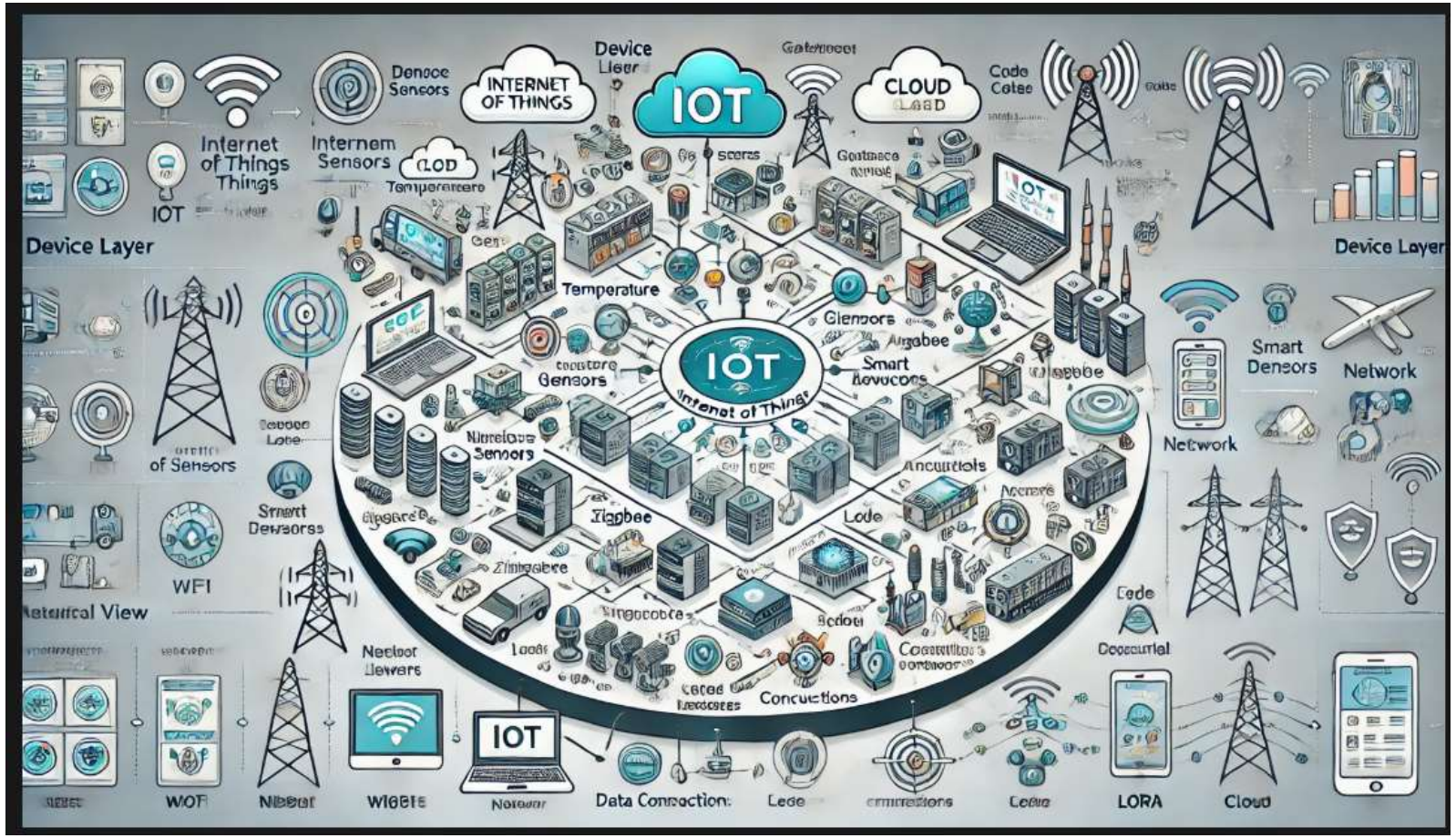
- This focuses on the ongoing management, monitoring, and operation of the IoT system to ensure its functionality and reliability.
- **Key Aspects of Operational View:**
- **Monitoring and Control:**
  - Real-time data monitoring for device health and environmental conditions.
  - Actuation based on predefined rules or real-time inputs.
- **Data Management:**
  - Collecting, storing, and analyzing sensor data.
  - Ensuring data security and privacy.

Operational View....

- **Maintenance:**
  - Remote diagnostics and troubleshooting.
  - Over-the-air (OTA) updates for firmware and software.
- **Security:**
  - Encryption of data in transit and at rest.
  - Secure authentication and access control for IoT devices.
- **Scalability:**
  - Adding new devices and resources dynamically.
  - Supporting a growing number of users and applications.

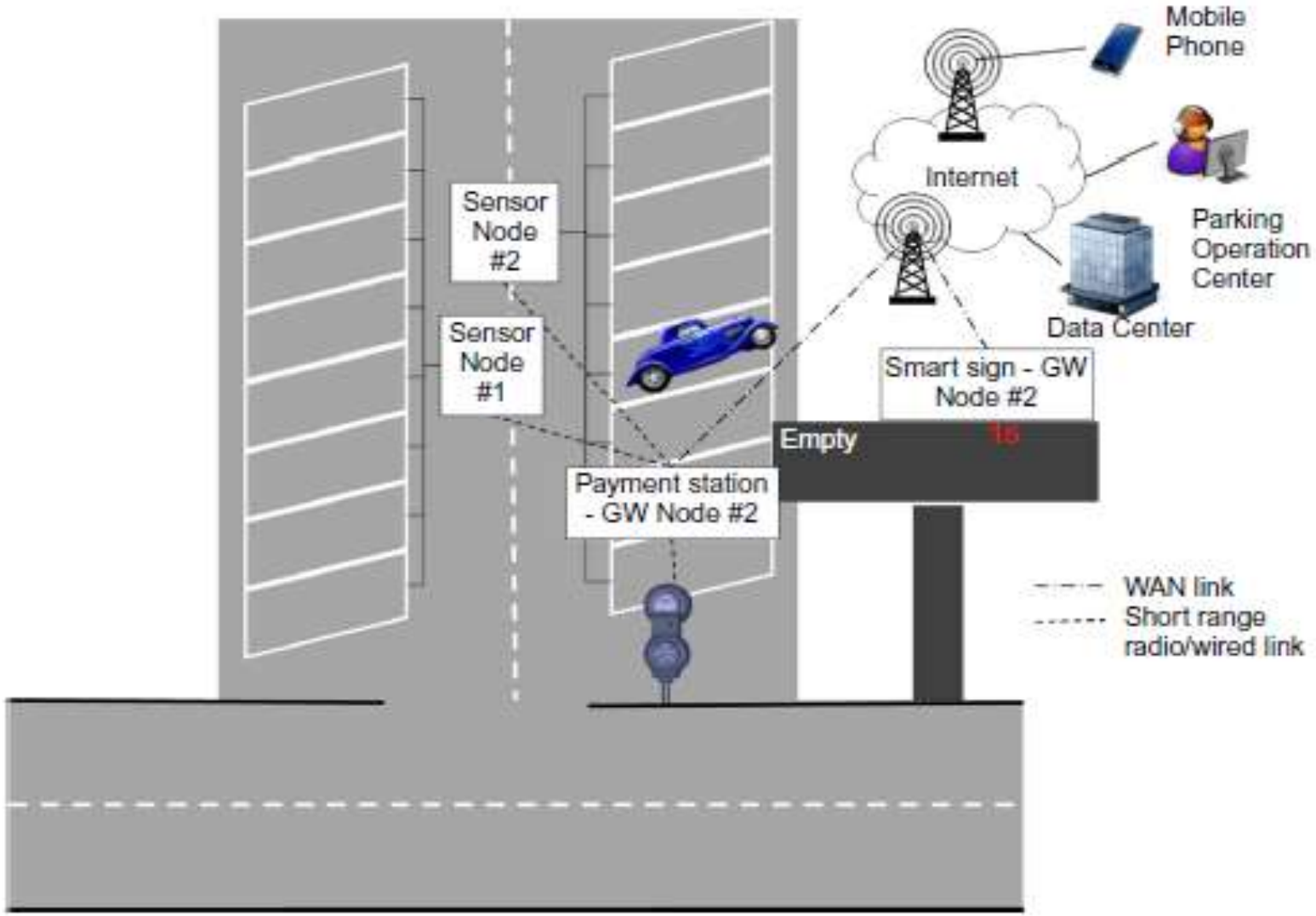
- **Diagram: IoT Deployment and Operational View**
- Here's a description for the diagram:
- **Device Layer**: Icons of IoT sensors (e.g., temperature, motion), actuators, and smart devices connected wirelessly or via cables.
- **Gateway Layer**: Central hubs that connect devices to the network.
- **Network Layer**: Connectivity options like Wi-Fi, ZigBee, LoRa, and cellular towers.
- **Cloud and Edge Layers**: Representing cloud servers for large-scale processing and edge devices for local processing.
- **User Interaction Layer**: A smartphone, tablet, or dashboard to manage and control the IoT system.
- **Operational Tools**: Software modules for monitoring, analytics, and updates.

Here is the visual representation of the Internet of Things (IoT) Deployment and Operational View.



Deployment and operational view

- The Deployment and Operational View depends on the specific actual use case and requirements, and therefore we present here one way of realizing the Parking Lot example mentioned earlier.
- It is by no means an exhaustive or complete example.
- Figure on next slide depicts the Devices view as Physical Entities deployed in the parking lot, as well as the occupancy sign.



FIGURE

Parking Lot Deployment and Operational View, Devices.

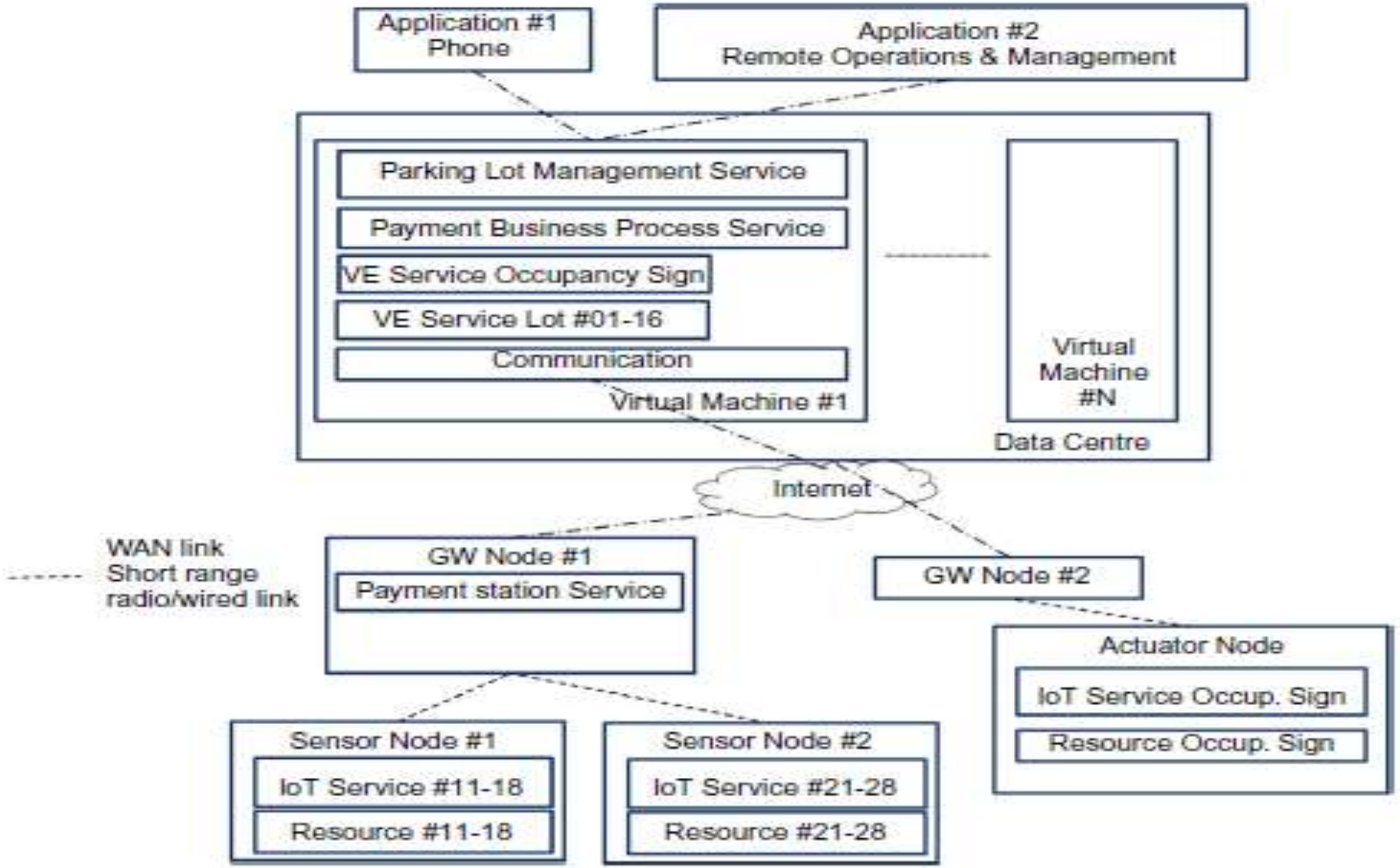
Parking lot Example….

- There are two sensor nodes (#1 and #2), each of which are connected to eight metal/car presence sensors.
- The two sensor nodes are connected to the payment station through wireless or wired communication.
- The payment station acts both as a user interface for the driver to pay and get a payment receipt as well as a communication gateway that connects the two sensor nodes and the payment interface physical devices (displays, credit card slots, coin/note input/output, etc.) with the Internet through Wide Area Network (WAN) technology.
- The occupancy sign also acts as a communication gateway for the actuator node (display of free parking spots)

Parking lot Example….

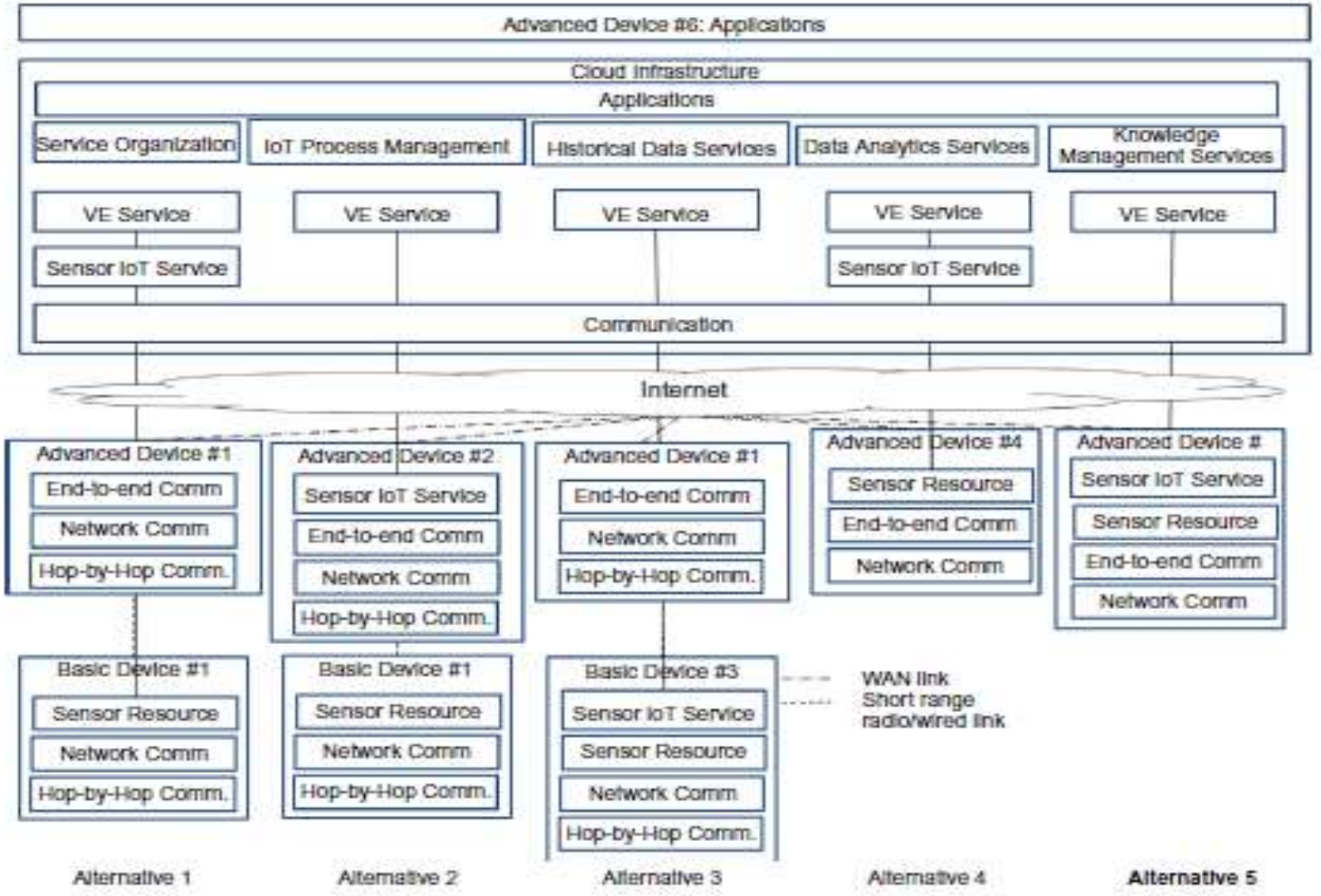
- and we assume that because of the deployment, a direct connection to the payment station is not feasible (e.g. wired connectivity is too prohibitive to be deployed or sensitive to vandalism).
- The physical gateway devices connect through a WAN technology to the Internet and towards a data center where the parking lot management system software is hosted as one of the virtual machines on a Platform as a Service (PaaS) configuration.
- The two main applications connected to this management system are human user mobile phone applications and parking operation center applications.
- We assume that the parking operation center manages several other parking lots using similar physical and virtual infrastructure.

- Figure on next slide shows two views superimposed, the deployment and functional views, for the parking lot example.
- Note that several FGs and FCs are omitted here for simplicity purposes, and certain non-IoT-specific Services appear in the figure because an IoT system is typically part of a larger system.



FIGURE

Parking Lot Deployment & Operational View, Resources, Services, Virtual Entities, Users.



FIGURE

Mapping IoT Domain Model concepts to Deployment View

Other relevant architectural views

- Apart from these functional views, there are a few more that are very important for a system that interfaces the physical world.
- The two most important are the Physical Entity View and the Context View.

- The Physical Entity View describes the Physical Entities from the IoT Domain Model in terms of physical properties (e.g. dimensions for spaces/objects).
- The description of the Physical Entities may also include the relationship between Physical Entities (e.g. an entity is included in the other and may be stationary in a specific location or mobile).
- The large number of possibilities for Physical Entities cannot be captured in a Reference Architecture, nevertheless, an architect needs to outline all the details of the Physical Entities from the beginning in order to assess if any Physical Property affects the rest of the architectural views and models.

- According to Rozanski & Woods (2011), the Context of a system, "describes the relationships, dependencies, and interactions between the system and its environment (people, systems, external entities with which it interacts)."
- Therefore, the Context View should capture external entities interacting with the system, impact of the system on its environment, external entity properties/identities, system scope and responsibilities ,etc.
- Since the possibilities for external entities and their interactions with an IoT system depend on the assumptions on the actual system, this view is also constructed in the beginning of the design process because it sets the boundary conditions for the problem at hand.

- In the parking lot example above, we described briefly parts of the Physical Entity and Context View without explicit individual presentations of these views.

- For example, the dimensions of the parking spots are a Physical Entity property, and the fact that there are sixteen parking spots physically placed in a possibly gated parking lot, the fact that there is an occupancy display near the parking lot on the roadside, and other details outline both Physical Entity properties as well as relationships between the system and its environment.

Real-World Design Constraints- Introduction

- Real-world design constraints in the context of IoT (Internet of Things) can significantly impact the functionality, scalability, and reliability of IoT systems.
- Here are the key constraints to consider: Power Consumption, Connectivity and Network Bandwidth, Scalability, Latency, Security and Privacy, Cost Constraints, Processing Power and Memory, Environmental Constraints, Interoperability, Regulatory and Legal Constraints & Reliability and Maintenance

Real-World Design Constraints…..

1. Power Consumption:

- **Constraint**: Many IoT devices, such as sensors or wearables, operate on batteries or low-power sources.
- **Impact**: Devices need energy-efficient components and protocols to extend battery life.
- **Solutions**: Use low-power microcontrollers, energy-efficient communication protocols (e.g., Zigbee, LoRaWAN, BLE), and implement sleep modes.

Real-World Design Constraints…..

2. Connectivity and Network Bandwidth: Connectivity is the quality, state, or capability of being connective or connected. **Bandwidth** in networking is the maximum possible data transfer rate of a network or internet connection.

- **Constraint**: Limited or unreliable network coverage, especially in remote areas.
- **Impact**: Impacts the ability of devices to transmit data in real time.
- **Solutions**: Employ long-range, low-bandwidth communication protocols (e.g., LoRa, NB-IoT) and local data processing.

3. Scalability: The ability of a technology, system, or software to handle an increasing amount of work, users, or data without a significant decrease in performance or a need for major modifications.

- **Constraint**: IoT systems often need to handle thousands or millions of devices.
- **Impact**: Strain on network resources, cloud servers, and data processing systems.
- **Solutions**: Use edge computing, distributed systems, and scalable cloud architectures.

Real-World Design Constraints…..

4. Latency: The delay before a transfer of data begins following an instruction for its transfer.

- **Constraint**: Certain IoT applications (e.g., autonomous vehicles, industrial automation) require real-time data processing.
- **Impact**: Delays can lead to operational inefficiencies or safety risks.
- **Solutions**: Deploy edge computing and use low-latency protocols like MQTT or CoAP.

5. Security and Privacy: The process of securing the devices and ensuring they do not introduce threats into a network. Anything connected to the Internet is likely to face attack at some point. Attackers can try to remotely compromise IoT devices using a variety of methods, from credential theft to vulnerability exploits.

- **Constraint**: IoT devices are often deployed in unsecured environments, making them vulnerable to cyberattacks.
- **Impact**: Data breaches, unauthorized control of devices, and compromised privacy.
- **Solutions**: Use encryption, secure boot, firewalls, secure communication protocols (e.g., TLS), and regular updates.

Real-World Design Constraints…..

6. Cost Constraints

- **Constraint**: IoT devices need to be affordable for widespread adoption.
- **Impact**: Affects the choice of components and manufacturing processes.
- **Solutions**: Use cost-effective materials, modular design, and optimize the device for specific use cases.

7. Processing Power and Memory

- **Constraint**: Many IoT devices have limited computational capabilities due to cost and power restrictions.
- **Impact**: Reduces the ability to perform complex tasks or store large amounts of data.
- **Solutions**: Offload tasks to the cloud or edge devices and use lightweight algorithms.

Real-World Design Constraints…..

8. Environmental Constraints

- **Constraint**: IoT devices may need to function in extreme conditions (e.g., high temperatures, humidity, or vibration).
- **Impact**: Device reliability and lifespan are affected.
- **Solutions**: Use robust materials, weatherproof enclosures, and temperature-tolerant components.

9. Interoperability: Interoperability refers to the ability of IoT systems and components to communicate and share information among them. This crucial feature is the key to unlock all of the IoT paradigm´s potential, including immense technological, economic and social benefits.

- **Constraint**: IoT ecosystems involve devices from different manufacturers with varying protocols.
- **Impact**: Limits seamless integration and data exchange.
- **Solutions**: Adopt open standards (e.g., MQTT, CoAP) and provide APIs for communication.

Real-World Design Constraints…..

10. Regulatory and Legal Constraints

- **Constraint**: IoT deployments must comply with regional regulations (e.g., GDPR for data privacy, FCC for spectrum use).
- **Impact**: Adds complexity to design and deployment.
- **Solutions**: Design with compliance in mind and consult legal experts.

11. Reliability and Maintenance: Reliability analysis aims to quantify the probability that a system performs its intended function correctly throughout its mission time, or its complement value, that is, the probability of the system failure during the mission time (i.e., system unreliability).

- **Constraint**: Devices often operate in remote or hard-to-reach areas, making maintenance challenging.
- **Impact**: Failure of a single device can disrupt the system.
- **Solutions**: Use self-diagnostic features, over-the-air (OTA) updates, and predictive maintenance.

Real-World Design Constraints…..

- Addressing these constraints requires careful planning and balancing trade-offs to design IoT systems that are efficient, secure, and scalable.

Technical design constraints hardware is popular again

- The technical design constraints to illustrate the questions that need to be taken into account when developing and implementing M2M and IoT solutions in the real world.
- The IoT will see additional circuitry built into a number of existing products and machines from washing machines to meters.
- Giving these things an identity, and the ability to represent themselves online and communicate with applications and other things, represents a significant, widely recognized opportunity.

- For manufacturers of products that typically contain electronic components, this process will be relatively straightforward.
- Selection of appropriate communications technologies that can be integrated with legacy designs (e.g. motherboards) will be relatively painless.
- The operational environments and the criticality of the information transmitted to and from these products, however, will present some unconventional challenges and design considerations.

- The IoT will, on the other hand, allow for the development of novel applications in all imaginable scenarios.
- Emerging applications of M2M and wireless sensor and actuator networks have seen deployment of sensing capabilities in the wild that allow stakeholders to optimize their businesses, glean new insight into relevant physical and environmental processes, and understand and control situations that would have previously been inaccessible.

- The technical design of any M2M or IoT solution requires a fundamental understanding of the specificity of the intended application and business proposition, in addition to heterogeneity of existing solutions.
- Developing an end-to-end instance of an M2M or IoT solution requires the careful selection, and in most cases, development of a number of complementary technologies.
- This can be both a difficult conceptual problem and integration challenge, and requires the involvement of the key stakeholder (s) on a number of conceptual and technological levels.

- Typically, it can be considered to be a combinatorial optimization problem where the optimal solution is the one that satisfies all functional and nonfunctional requirements, whilst simultaneously delivering a satisfactory cost-benefit ratio.

- This is particularly relevant for organizations wishing to compete with existing offerings, or for start-up ventures in novel application areas. Typically, capital costs in terms of “commissioning” and operational costs in “maintenance” must be considered. These may be balanced by resultant optimizations.

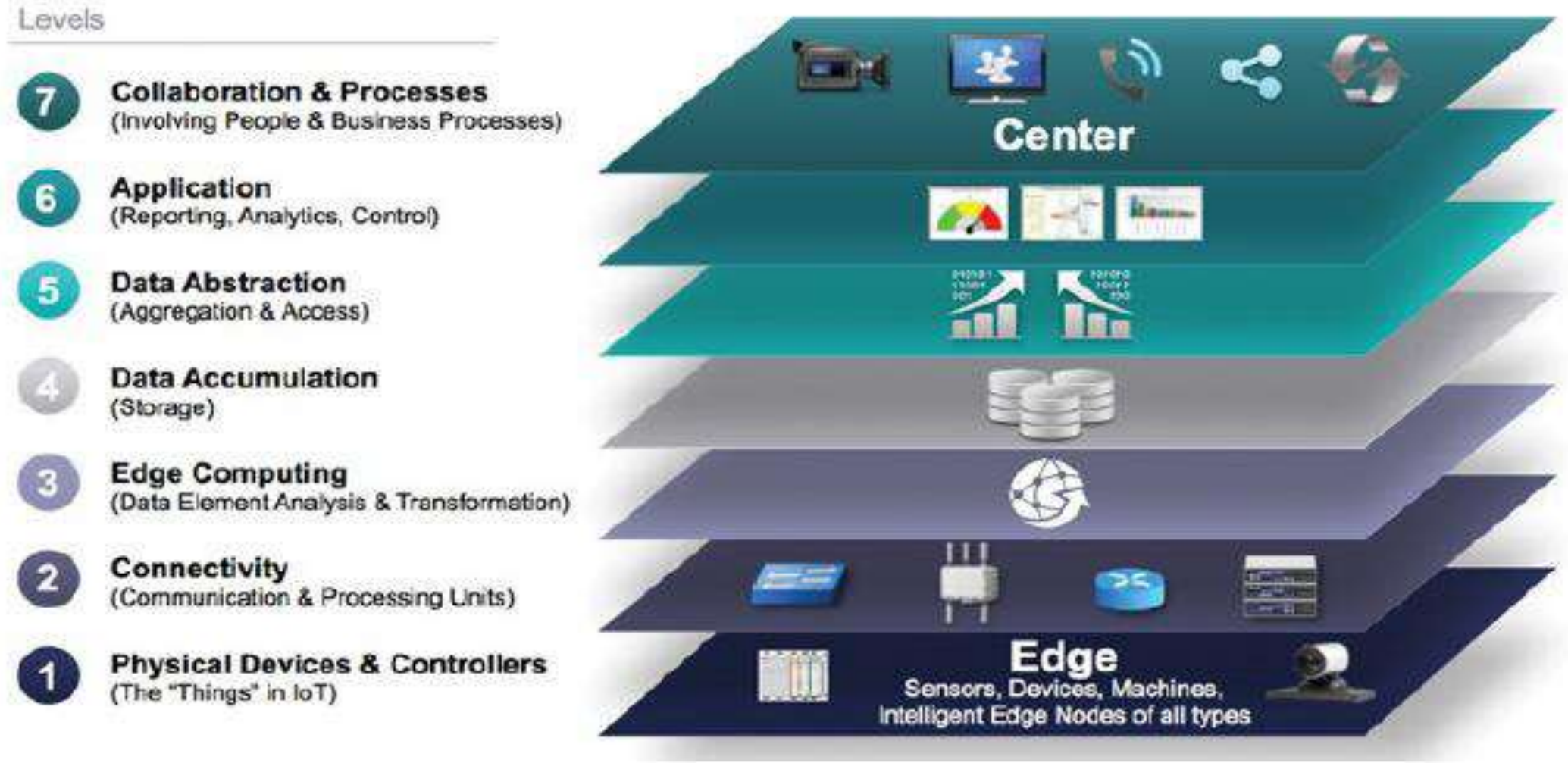
Devices and networks

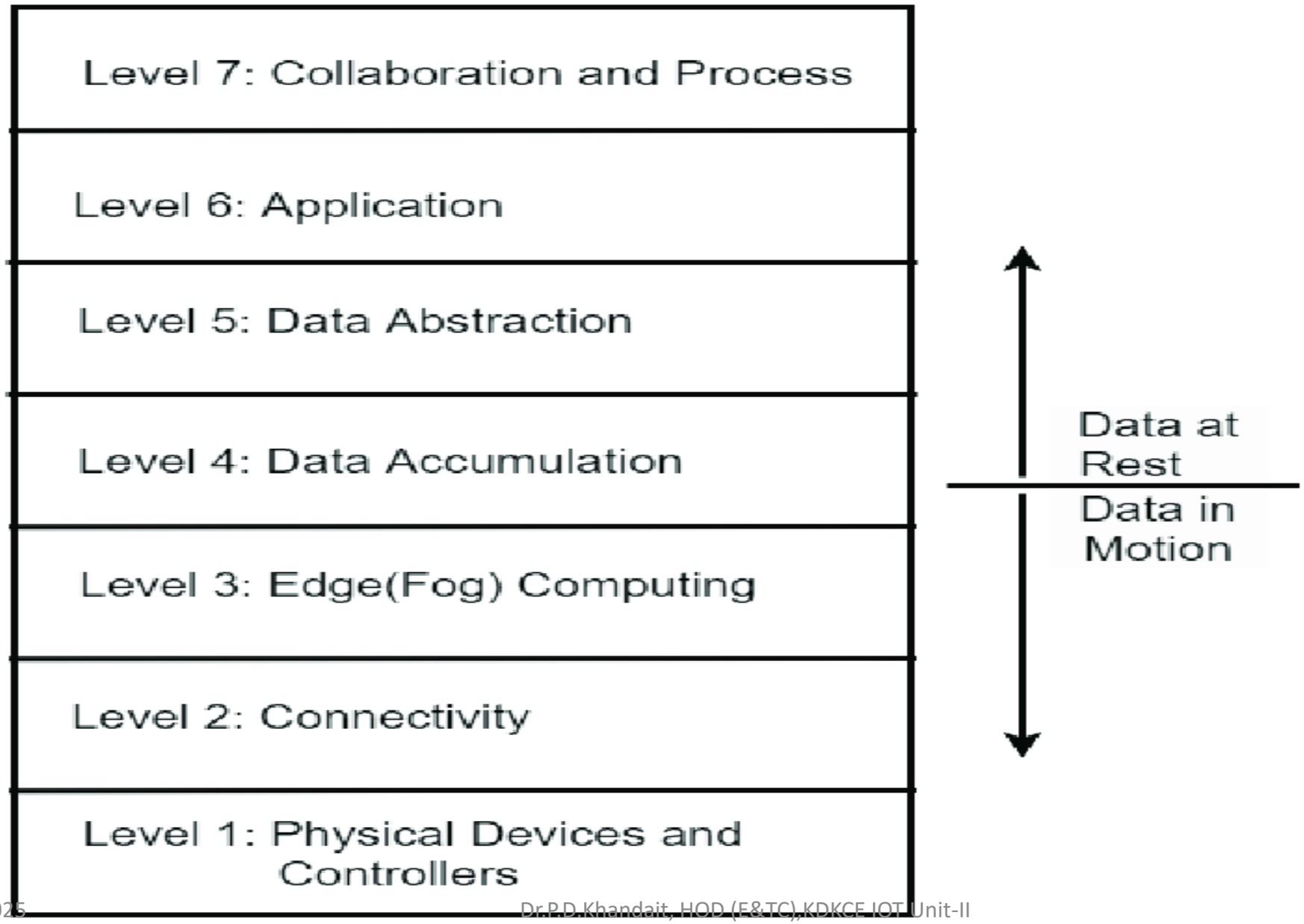
- Devices that form networks in the M2M Area Network domain must be selected, or designed, with certain functionality in mind.
- At a minimum, they must have an energy source (e.g. batteries, increasingly EH), computational capability (e.g. an MCU), appropriate communications interface (e.g. a Radio Frequency Integrated Circuit (RFIC) and front end RF circuitry), memory (program and data), and sensing (and/or actuation) capability.

IoT reference model

- In 2014 **The IoT World Forum (IoTWF) Standardization** architectural committee (led by Cisco, IBM, Rockwell Automation, and others)published a seven-layer IoT architectural reference model.
- While various IoT reference models exist, the one put forth by the IoT World Forum offers a clean, simplified perspective on IoT and includes edge computing, data storage, and access. It provides a succinct way of visualizing IoT from a technical perspective.
- Each of the seven layers is broken down into specific functions, and security encompasses the entire model. Figure below details the IoT Reference Model published by the IoTWF.

IoT reference model




Level 7: Collaboration and Process
Level 6: Application
Level 5: Data Abstraction
Level 4: Data Accumulation
Level 3: Edge(Fog) Computing
Level 2: Connectivity
Level 1: Physical Devices and Controllers
Data at Rest
Data in Motion

- the IoT Reference Model defines a set of levels with control flowing from the center (this could be either a cloud service or a dedicated data center), to the edge, which includes sensors, devices, machines, and other types of intelligent end nodes.
- In general, data travels up the stack, originating from the edge, and goes northbound to the center.
- Using this reference model, we are able to achieve the following:
- Decompose the IoT problem into smaller parts
- Identify different technologies at each layer and how they relate to one another
- Define a system in which different parts can be provided by different vendors
- Have a process of defining interfaces that leads to interoperability
- Define a tiered security model that is enforced at the transition points between levels

The Seven Layers

- **Layer 1: Physical Devices and Controllers Layer**

- The first layer of the IoT Reference Model is the physical devices and controllers layer.
- This layer is home to the “things” in the Internet of Things, including the various endpoint devices and sensors that send and receive information.
- The size of these “things” can range from almost microscopic sensors to giant machines in a factory.
- Their primary function is generating data and being capable of being queried and/or controlled over a network.

- **Layer 2: Connectivity Layer**
- In the second layer of the IoT Reference Model, the focus is on connectivity.
- The most important function of this IoT layer is the reliable and timely transmission of data.
- More specifically, this includes transmissions between Layer 1 devices and the network and between the network and information processing that occurs at Layer 3 (the edge computing layer).
- Note that, the connectivity layer encompasses all networking elements of IoT and doesn't really distinguish between the last-mile network (the network between the sensor/endpoint and the IoT gateway), gateway, and backhaul networks. Functions of the connectivity layer are detailed in Figure next slide.

② **Connectivity**
(Communication and Processing Units)

Layer 2 Functions:

- Communications Between Layer 1 Devices
- Reliable Delivery of Information Across the Network
- Switching and Routing
- Translation Between Protocols
- Network Level Security

Figure *IoT Reference Model Connectivity Layer Functions*

- **Layer 3: Edge Computing Layer**

- Edge computing is the role of Layer 3. Edge computing is often referred to as the “fog” layer and is discussed in “Fog Computing,” .
- At this layer, the emphasis is on data reduction and converting network data flows into information that is ready for storage and processing by higher layers.
- One of the basic principles of this reference model is that information processing is initiated as early and as close to the edge of the network as possible. Figure next slide highlights the functions handled by Layer 3 of the IoT Reference Model.

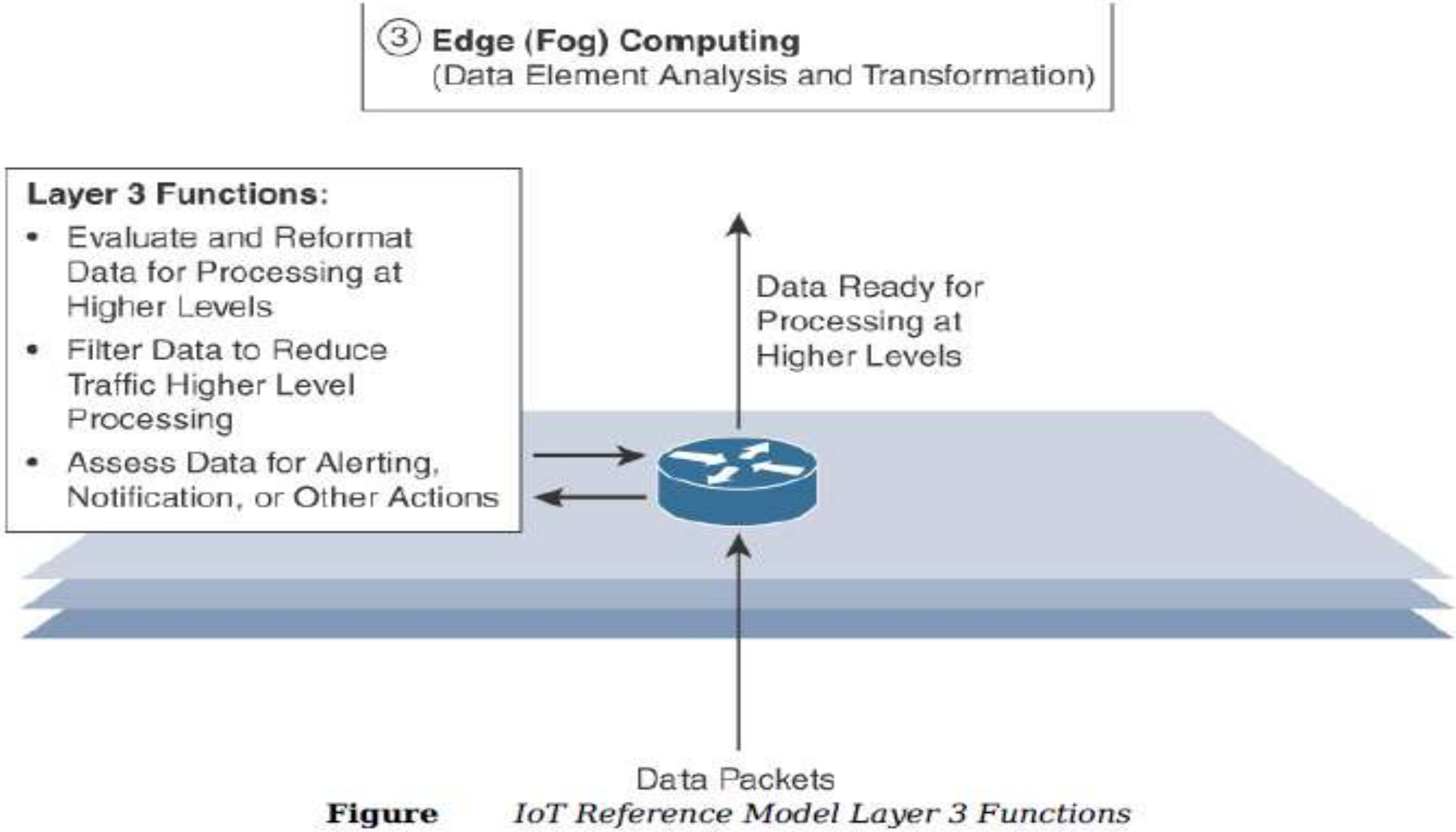


Figure *IoT Reference Model Layer 3 Functions*

Layer 3: Edge Computing Layer ….

- Another important function that occurs at Layer 3 is the evaluation of data to see if it can be filtered or aggregated before being sent to a higher layer.
- This also allows for data to be reformatted or decoded, making additional processing by other systems easier. Thus, a critical function is assessing the data to see if predefined thresholds are crossed and any action or alerts need to be sent.

Upper Layers: Layers 4–7

- The upper layers deal with handling and processing the IoT data generated by the bottom layer.
- For the sake of completeness, Layers 4–7 of the IoT Reference Model are summarized in Table next slide.

IoT Reference Model Layer	Functions
Layer 4: Data accumulation layer	Captures data and stores it so it is usable by applications when necessary. Converts event-based data to query-based processing.
Layer 5: Data abstraction layer	Reconciles multiple data formats and ensures consistent semantics from various sources. Confirms that the data set is complete and consolidates data into one place or multiple data stores using virtualization.
Layer 6: Applications layer	Interprets data using software applications. Applications may monitor, control, and provide reports based on the analysis of the data.
Layer 7: Collaboration and processes layer	Consumes and shares the application information. Collaborating on and communicating IoT information often requires multiple steps, and it is what makes IoT useful. This layer can change business processes and delivers the benefits of IoT.

Table *Summary of Layers 4–7 of the IoTWF Reference Model*