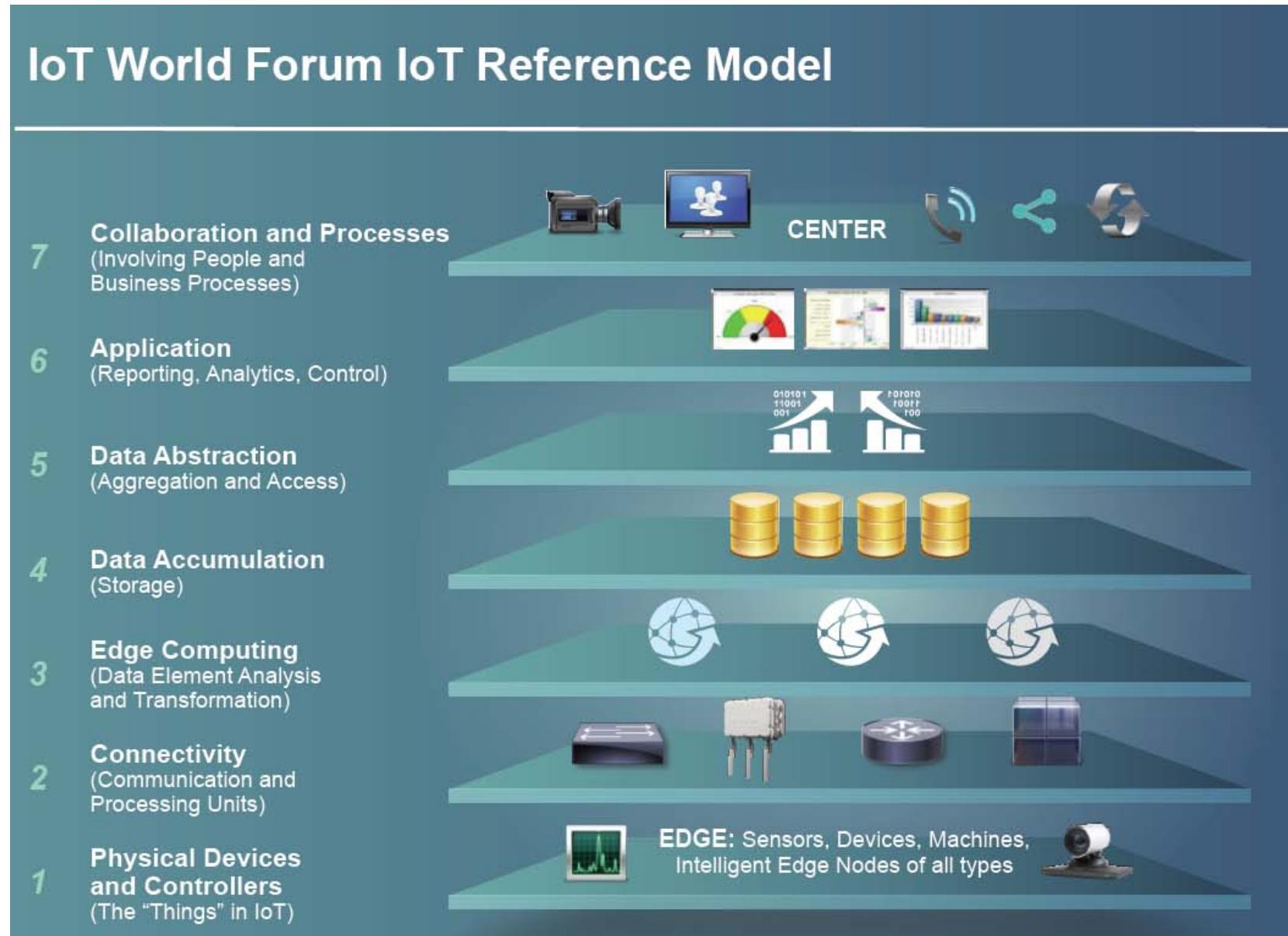


IoT Protocols & Applications  
18-738 Sports Technology

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# Overview



# How many things?

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1.1 Billion smart phones

244 Million smart meters

487 Million e-readers and tablets

2.37 Billion networked office devices

86 Million medical devices

45 Million connected automobiles

547 Million connected appliances

105 Million connected military devices

431 Million information technology devices

45 Million supervisory control and data acquisition (SCADA)

5+ Billion other (non-phone/tablet/e-reader) electronic devices

.

# The Industry Viewpoint

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- Cisco:
  - “Connecting physical objects to provide better safety, comfort, efficiency”
- IBM:
  - “A new World-Wide Web, comprised of messages that digitally empowered devices would send to each other”
- General Electric:
  - “Convergence of machine and intelligent data to create brilliant machines”

# Standardization bodies

---

- IoT will connect way more devices than mobile networks do (or will)
- These smart devices are everywhere
  - Home, car, work, healthcare
- IoT protocols standardized by
  - World Wide Web Consortium (W3C)
  - Internet Engineering Task Force (IETF)
  - EPCGlobal
  - Institute of Electrical and Electronics Engineers (IEEE)
  - European Telecommunications Standards Institute (ETSI)

# What protocols, and why?

---

- **Infrastructure**, e.g., 6LowPAN, IPv4/IPv6, RPL (**TODAY**)
- Identification, e.g., EPC, uCode, IPv6, URIs
- **Communications/Transport**, e.g., Wi-Fi, Bluetooth, LPWAN
- **Discovery**, e.g., Physical Web, mDNS, DNS-SD
- **Data Protocols**, e.g., MQTT, CoAP, AMQP (**TODAY**)
- Device Management, e.g., TR-069, OMA-DM
- **Semantic**, e.g., JSON-LD, Web Thing Model
- **Multi-layer Frameworks**, e.g., Alljoyn, IoTivity, Weave, Homekit)

# Recap: Communications/Transport Layer

---

| Technology    | Frequency            | Data Rate    | Range              | Power Usage | Cost   |
|---------------|----------------------|--------------|--------------------|-------------|--------|
| 2G/3G         | Cellular Bands       | 10 Mbps      | Several Miles      | High        | High   |
| Bluetooth/BLE | 2.4Ghz               | 1, 2, 3 Mbps | ~300 feet          | Low         | Low    |
| 802.15.4      | subGhz, 2.4GHz       | 40, 250 kbps | > 100 square miles | Low         | Low    |
| LoRa          | subGhz               | < 50 kbps    | 1-3 miles          | Low         | Medium |
| LTE Cat 0/1   | Cellular Bands       | 1-10 Mbps    | Several Miles      | Medium      | High   |
| NB-IoT        | Cellular Bands       | 0.1-1 Mbps   | Several Miles      | Medium      | High   |
| SigFox        | subGhz               | < 1 kbps     | Several Miles      | Low         | Medium |
| Weightless    | subGhz               | 0.1-24 Mbps  | Several Miles      | Low         | Low    |
| Wi-Fi         | subGhz, 2.4Ghz, 5Ghz | 0.1-54 Mbps  | < 300 feet         | Medium      | Low    |
| WirelessHART  | 2.4Ghz               | 250 kbps     | ~300 feet          | Medium      | Medium |
| ZigBee        | 2.4Ghz               | 250 kbps     | ~300 feet          | Low         | Medium |
| Z-Wave        | subGhz               | 40 kbps      | ~100 feet          | Low         | Medium |

# Choices, choices (for wireless IoT protocols alone)

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IEEE802.11

Bluetooth/BluetoothSmart

ZigBee/ZigBeeSmartEnergy2.0

IEEE802.15.6-2012:BodyAreaNetworking

WirelessHART (HighwayAddressableRemoteTransducer  
Protocol) Used between devices.

International Society of Automation (ISA)100.11a

Z-Wave

MiWi(Microchip Technology Wireless)

ANT+

Garmin Watch

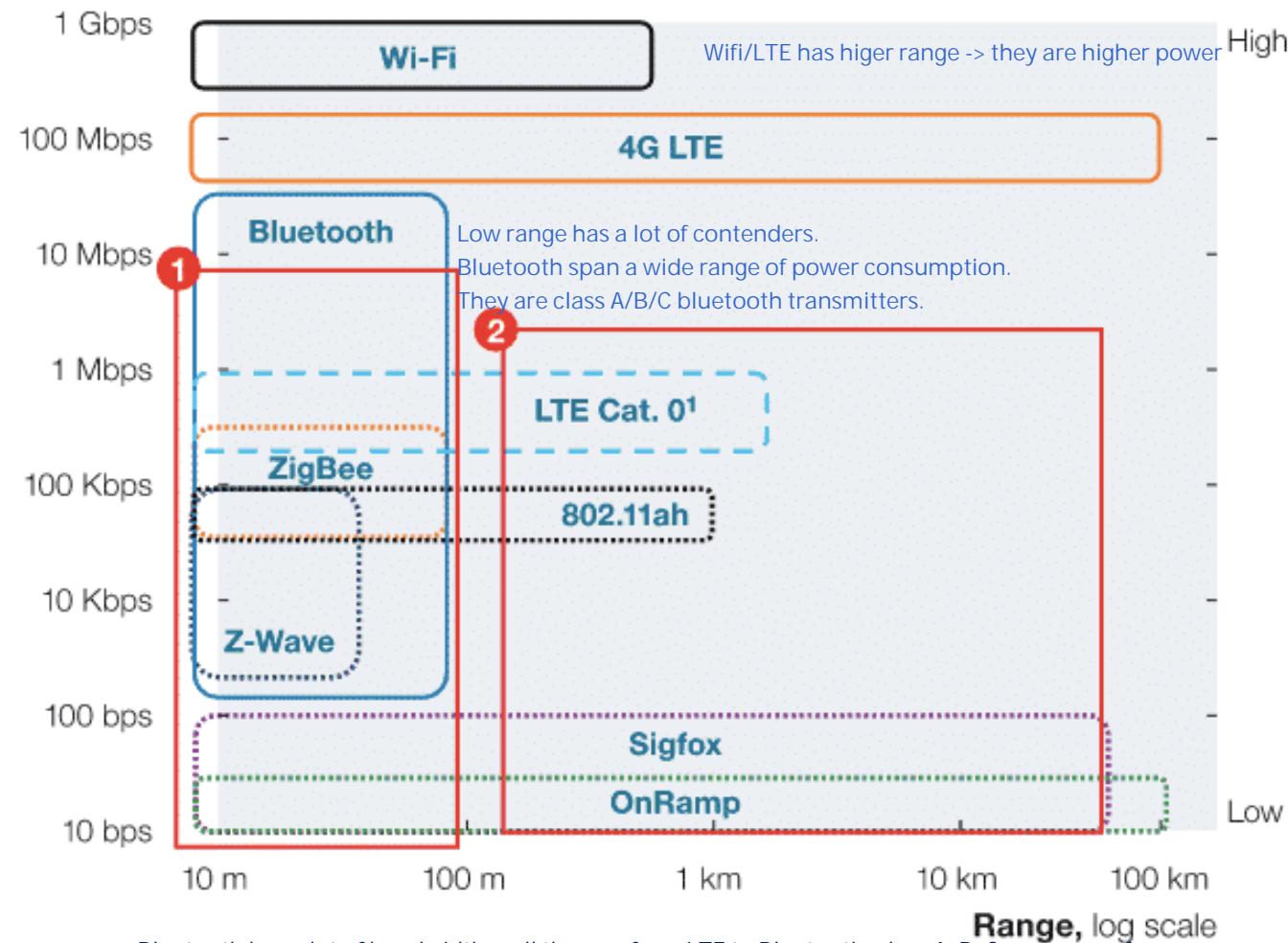
WirelessMBUS

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# Recap: Wireless Communications/Transport Layer

— Widely adopted    ----- New standard    - - - Established, adoption ongoing

**Data rate, log scale**



Several Computing Standard.

Bluetooth packet cannot be interpreted/ operated by Zigbee. They don't interoperate.

- ① Many competing standards for low-range, medium-low data rate hinder growth for many IoT applications
  - Interoperability missing
  - Consortia wars might be emerging
  - Additional incompatibilities in higher communication layers, eg, 6LoWPAN vs ZigBee Different standard group fighting each other.

- ② Standard whitespace for low-data-rate, low-power, high-range applications such as smart grid
  - Wi-Fi and LTE have high power consumption
  - Alternatives with low power and wide range (eg, LTE Cat. 0, 802.11ah, Sigfox, and OnRamp) are in very early stages and compete against each other

Zigbee -- more topologies than Bluetooth.

Bluetooth is 7 slaves + 1 master.

Zigbee can be more interesting low-power.

Zigbee -- sensor network.

Zigbee -- multi-hop routing. It hops from Node to Node. It has the ability to scale. BT cannot do that.

# How the Protocols Relate to Each Other

DNS - Service Discovery.

| Application Protocol     | DDS                   | CoAP               | AMQP      | MQTT          | MQTT-SN     | XMPP | HTTP REST |
|--------------------------|-----------------------|--------------------|-----------|---------------|-------------|------|-----------|
| Service Discovery        |                       | mDNS               |           |               | DNS-SD      |      |           |
| Infrastructure Protocols | Routing Protocol      |                    |           | RPL           |             |      |           |
|                          | Network Layer         |                    | 6LoWPAN   |               | IPv4/IPv6   |      |           |
|                          | Link Layer            |                    |           | IEEE 802.15.4 |             |      |           |
|                          | Physical/Device Layer | LTE-A              | EPCglobal | IEEE 802.15.4 | Z-Wave      |      |           |
| Influential Protocols    |                       | IEEE 1888.3, IPSec |           |               | IEEE 1905.1 |      |           |

# Example: 6LowPAN

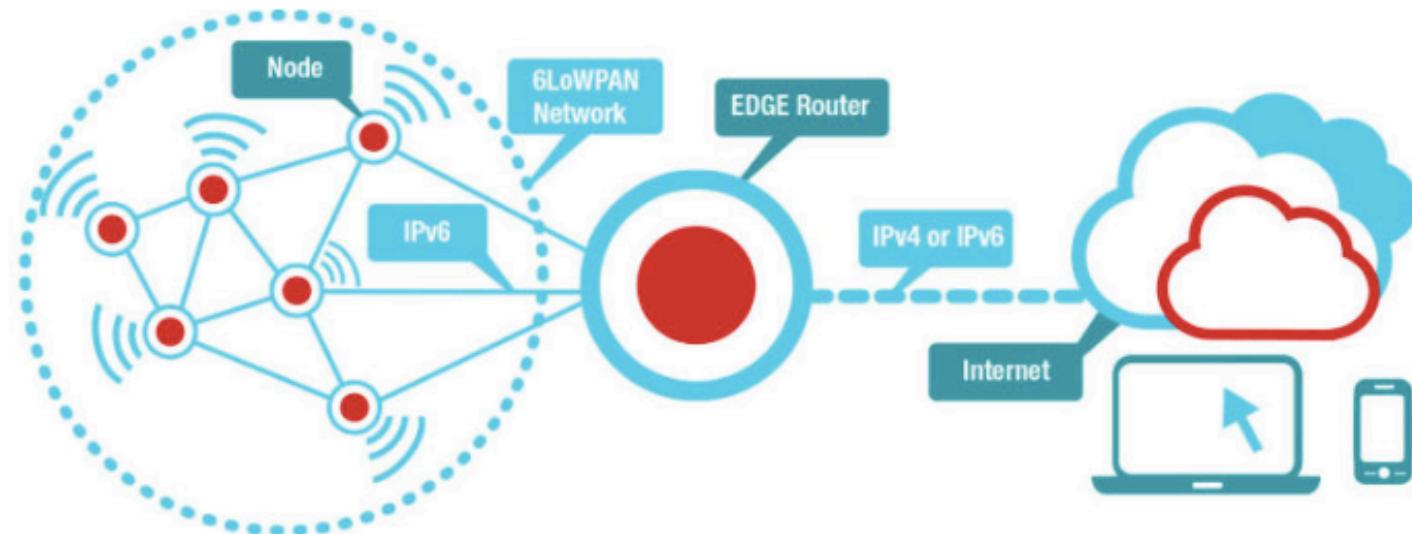
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- IPv6 over Low-Power Wireless Personal Area Networks
- Every device has its own IPv6 address
- Built on the principle that the Internet Protocol (IP) should apply to any “thing”
- End-to-end IP-addressable nodes
- Ability to create a mesh network of nodes, connected by an edge router

Create a mesh network of nodes.

The edge router can speak 6LowPAN, basically IPV6 over low power network.

6LowPAN is another protocol that helps with edge computing.



# How the Protocols Relate to Each Other

| Application Protocol     |                       | DDS                | CoAP      | AMQP          | MQTT   | MQTT-SN     | XMPP   | HTTP REST |
|--------------------------|-----------------------|--------------------|-----------|---------------|--------|-------------|--------|-----------|
| Service Discovery        |                       | mDNS               |           |               | DNS-SD |             |        |           |
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|                          | Network Layer         | 6LoWPAN            |           |               |        | IPv4/IPv6   |        |           |
|                          | Link Layer            | IEEE 802.15.4      |           |               |        |             |        |           |
|                          | Physical/Device Layer | LTE-A              | EPCglobal | IEEE 802.15.4 |        |             | Z-Wave |           |
|                          | Influential Protocols | IEEE 1888.3, IPSec |           |               |        | IEEE 1905.1 |        |           |

# Example: RPL

Routing Protocol for Lower Power and Lossy Network.

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Routing Protocol in Low Power: routing protocol tries to get one packet to another node. The routing has some topology of the network.

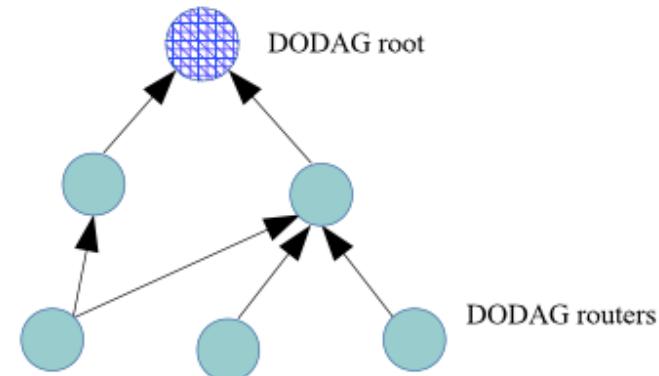
- Routing Protocol for Low Power and Lossy Networks (RPL)
  - An IETF working group standardized this for resource-constrained devices
    - Routing makes sure you can transfer packet to other parts of network.
  - Focus was on: Minimal routing, lossy links, topology
    - The routing protocol has topology related to it.
  - Different traffic models: multipoint-to-point, point-to-multipoint, point-to-point
  - Routing via a DODAG (Destination Oriented Directed Acyclic Graph)
    - A routing diagram.
  - DODAG shows a routing diagram of nodes
  - Each node is aware of parents, but not children
  - HTTP get, post, put, and delete methods as verbs
  - At least one path maintained for each node to the root
  - And a path maintained for each node via preferred parent for performance

## RPL (2)

---

- Four types of control messages
  - DIO (DODAG Information Object) message—most important type
    - Keeps current rank (level) of the node
    - Determines the distance of each node to the root based on metrics
    - Determines the choice of the preferred path
- DODAG built in waves and iteratively
  - Root sends DIO messages to all levels
  - Each level registers parent path and propagates DIO messages
  - Preferred parent path is designated based on metrics
  - Downward routes and upward routes can be flagged

'Ranked Levels of Nodes.'



# How the Protocols Relate to Each Other

| Application Protocol     |                       | DDS                | CoAP      | AMQP          | MQTT      | MQTT-SN     | XMPP | HTTP REST |
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# The Players in the Ecosystem

---

- Device (D)
  - Server (S)
  - Device-to-device (D2D)
  - Device-to-server (D2S) Device to server may not only be single straight up link, it can be device- edge server- fog server - cloud server.
  - Server-to-server (S2S)
- 
- Devices must be able to communicate with each other (D2D)
  - Device data is likely dispatched to a server (D2S)
  - Servers may communicate with each other to provide functionality (S2S)
  - Result may be provided to people, to devices, to other servers, etc.

All of these are application layer protocol, they have emphasis in different level.

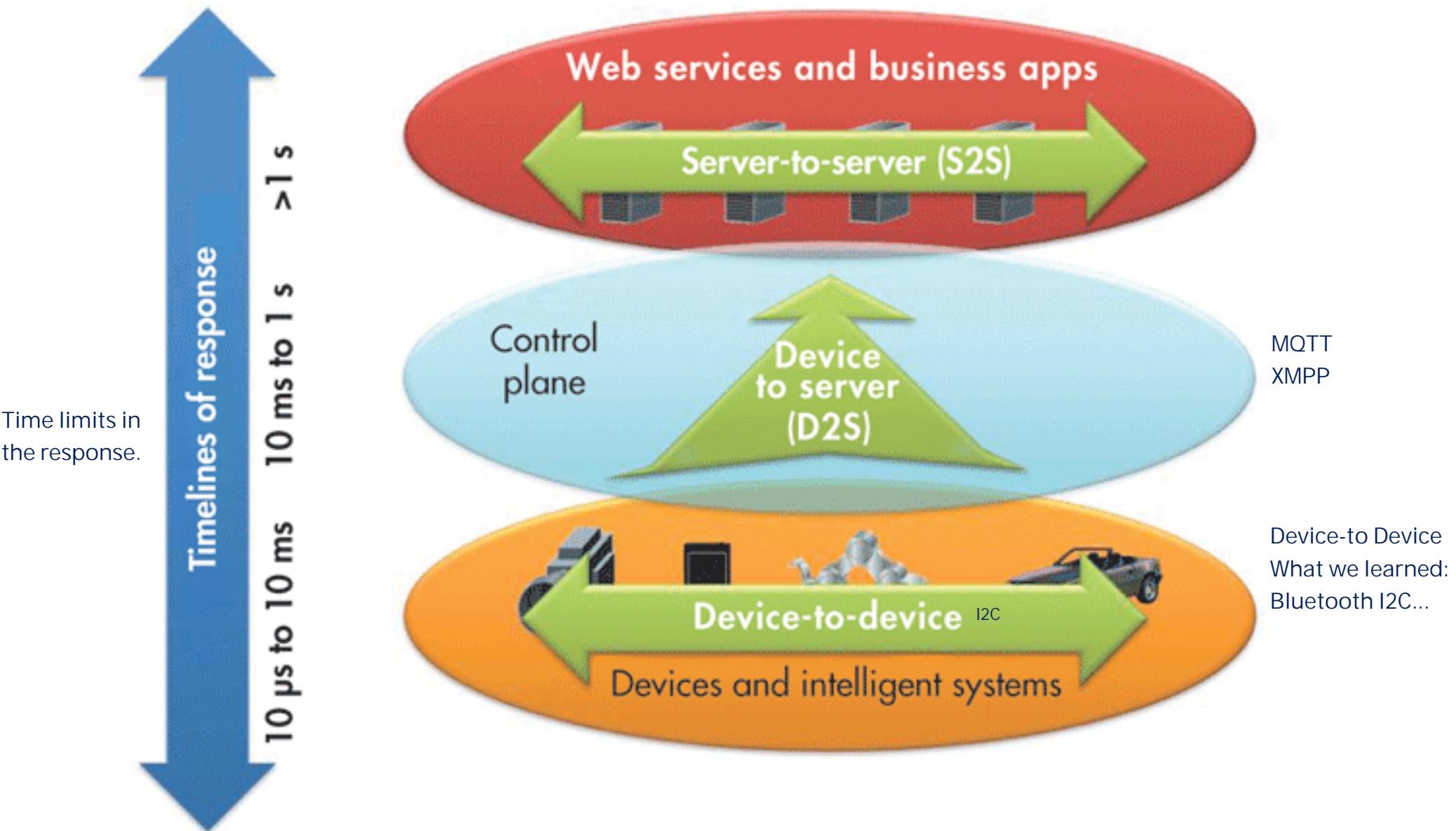
They are all quite mature.

# Example Protocols

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- **MQTT:** Protocol for collective device data and sending it to servers (D2S)
- **XMPP:** Protocol for collective device data and sending it to people (D2S)  
Xmpp not necessarily server, can be device to people.
  - Special case of D2S because people act as (or are connected to) servers
- **DDS:** Fast machine-to-machine bus for disseminating information (D2D)
- **AMQP:** Queueing system designed to connect servers to each other (S2S)
  - Each protocol widely adopted; at least 10 implementations of each
  - All claim to be
    - Real-time publish-subscribe IoT protocols
    - Able to connect 1000s of devices
    - Depends on your definition of “real-time”

# A Real-Time (Responsiveness) Perspective



# MQTT

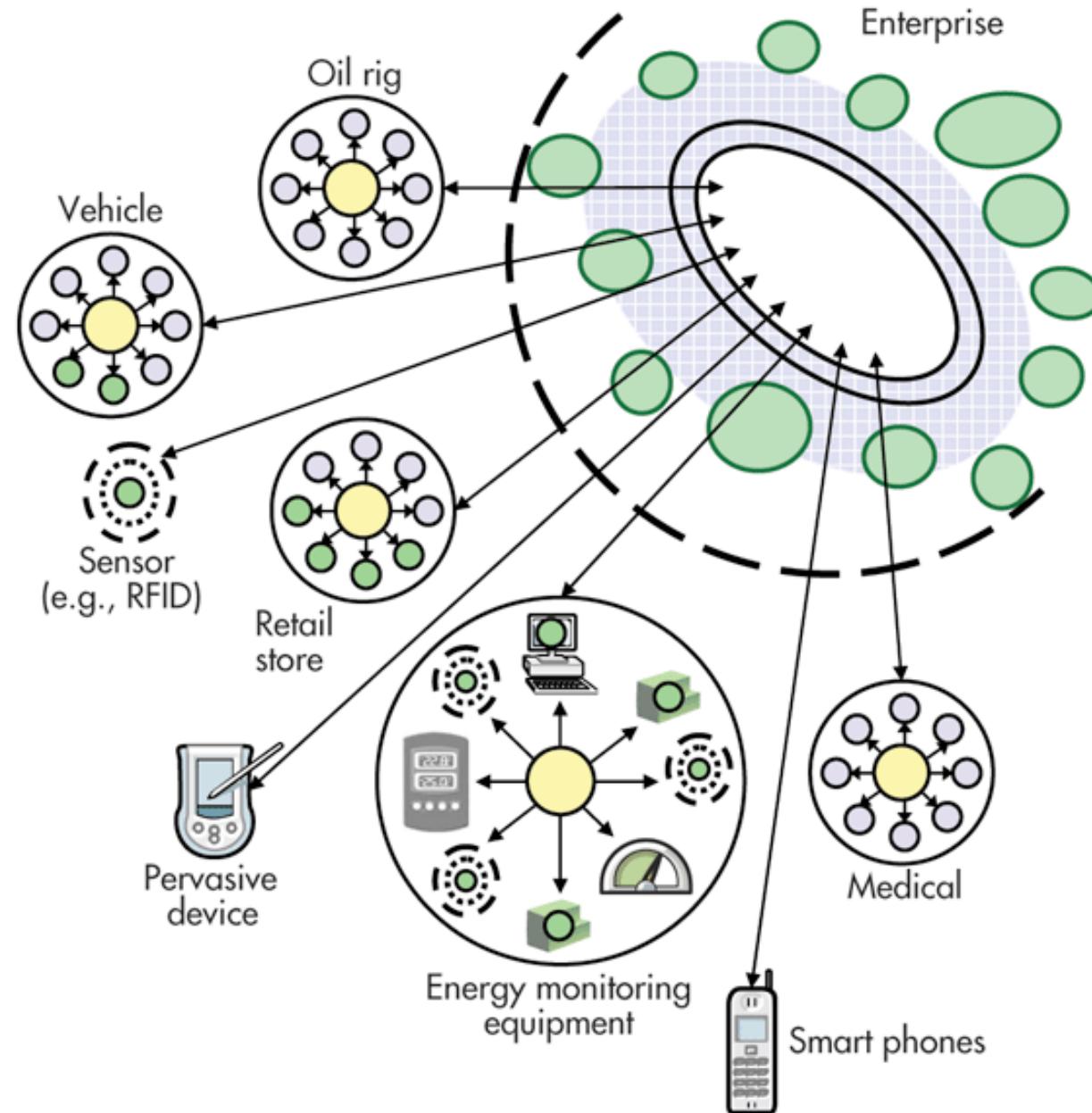
Lot of devices need to send a lot of data.

---

- **Message Queue Telemetry Transport**
  - "Telemetry": natural gas, oil field.  
Off-shore link platforms. They use a lot of them in the off-shore oil drill platforms.
- Main purpose started off with **telemetry (remote monitoring of objects)**
  - Focus is to collect a lot of data from a lot of devices and send it to servers
  - Targets large collections of devices that need to be connected to the cloud
  - Simple, not particularly fast (responsiveness in seconds)
- Makes little attempt at
  - Device-to-device (D2D) data transfer, publishing data to many recipients
- Hub-and-spoke architecture
  - Devices connect to a **“data-concentrator” server**, TCP/IP for reliable delivery
- Examples
  - data-concentrator basically the notion of edge computing , instead of millions of device directly connected to cloud server.  
No device-to-device. Message Queue means queue from device to server.
  - Vast oil-pipeline monitoring for leaks/vandalism, smart lighting/power

# MQTT

Large amount of data need to upload large amount of data.



# CoAP

Limited Resource MQTT. Tiny device need to fire and forget tiny data.

---

- **Constrained Application Protocol** CoAP is used with devices that don't have a lot of memory and processing power.
- Targets **low-footprint resource-constrained devices**
- From an architectural standpoint
  - **Smaller packets than TCP/IP flows** TCP/IP packet needs more power.
  - **Bitfields and mappings from strings to integers to save space** some tricks
  - Runs over UDP, broadcast and multicast discovery for addressing  
UDP is basically an unsafe TCP. Fire-and-forget best effort protocol.
  - **Confirmable messages require acknowledgment**
  - **Non-confirmable messages are the fire-and-forget type**
  - Primarily a one-to-one protocol (unlike MQTT's many-to-many)

## TCP vs UDP

UDP: diagram oriented- fire and forget, where you send broadcast, connection less, send and forget -- best effort.

UDP = broadcast mode protocol.

TCP: reliable ordered transmission. If packet lost, then retransmit will happen.

TCP = point to point protocol.

CoAP is UDP, is best effort. BUT confirmable message also would require acknowledgement.

# XMPP

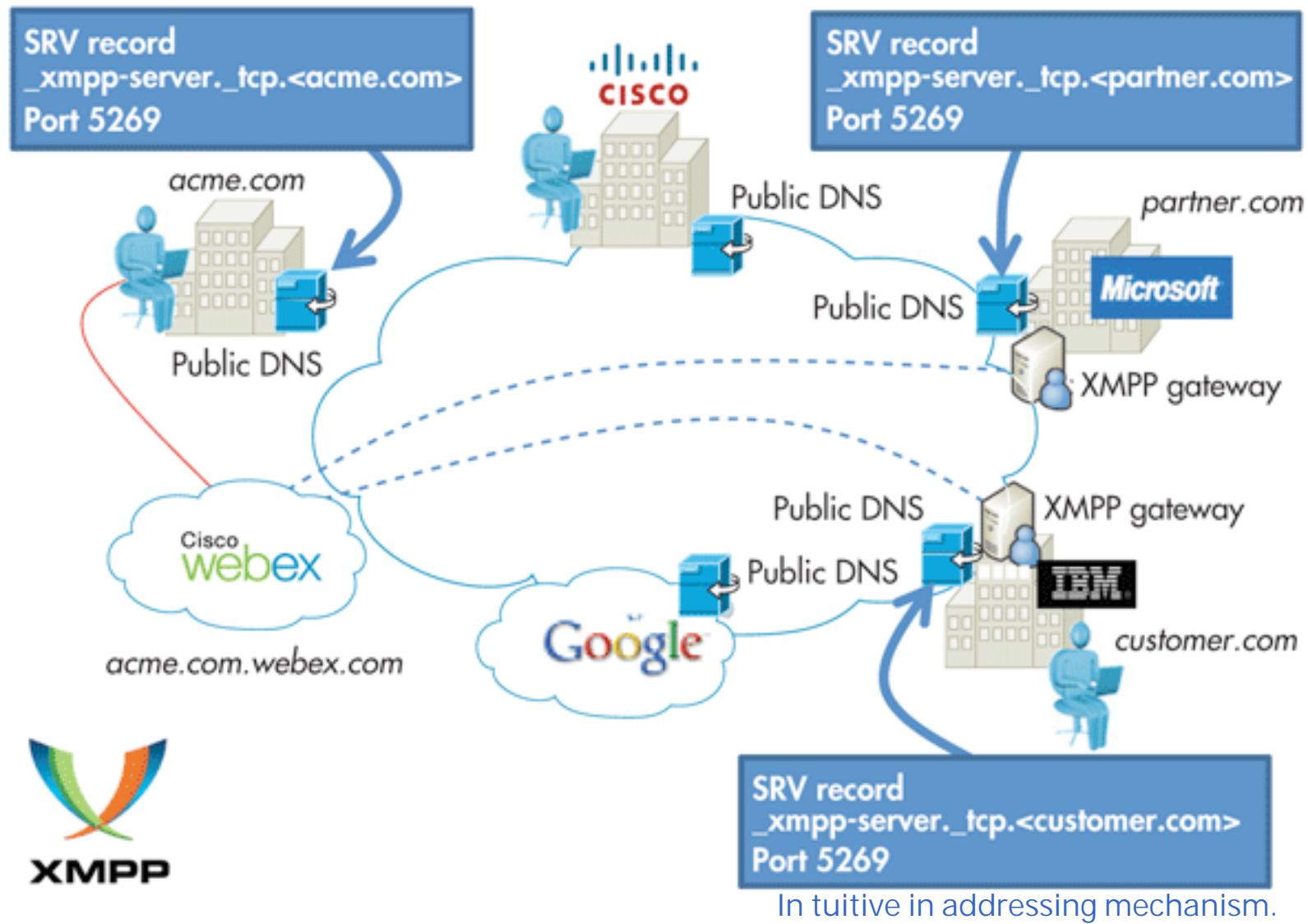
This updates sensor on some sort of data, update on single value and come back. To poll devices, get temperature and not constantly running services. You need to support polling based mechanism with XMPP.

---

- Extensible Messaging and Presence Protocol (originally called “Jabber”)
- Originated with instant messaging (IM) to connect people via text messages
- From an architectural standpoint
  - Uses XML text format as the native type for messages
    - Uses TCP, and often HTTP over TCP
- Key strength: Easy way to address a device as name@domain.com
- Primarily polling-based, for servers to check devices for updates
- Servers can push via BOSH (Bidirectional streams over Synchronous HTTP)
- Real-time on human time-scales, in several seconds.
  - Parsing may be power extensive.
- Examples
  - Advantage WITH XMPP on HTTP, ,the addressing mechanism is beautiful, you can intuitively access on a web page, enter IP address and you get information.
- Connecting your home thermostat to a Web Server to access from phone
  - XMPP is typically point to point protocol.

# XMPP

Examples, you can access devices remotely at very long distances.



DDS used in high performance military applications such as Navy / Military / Aircraft carrier.

# DDS

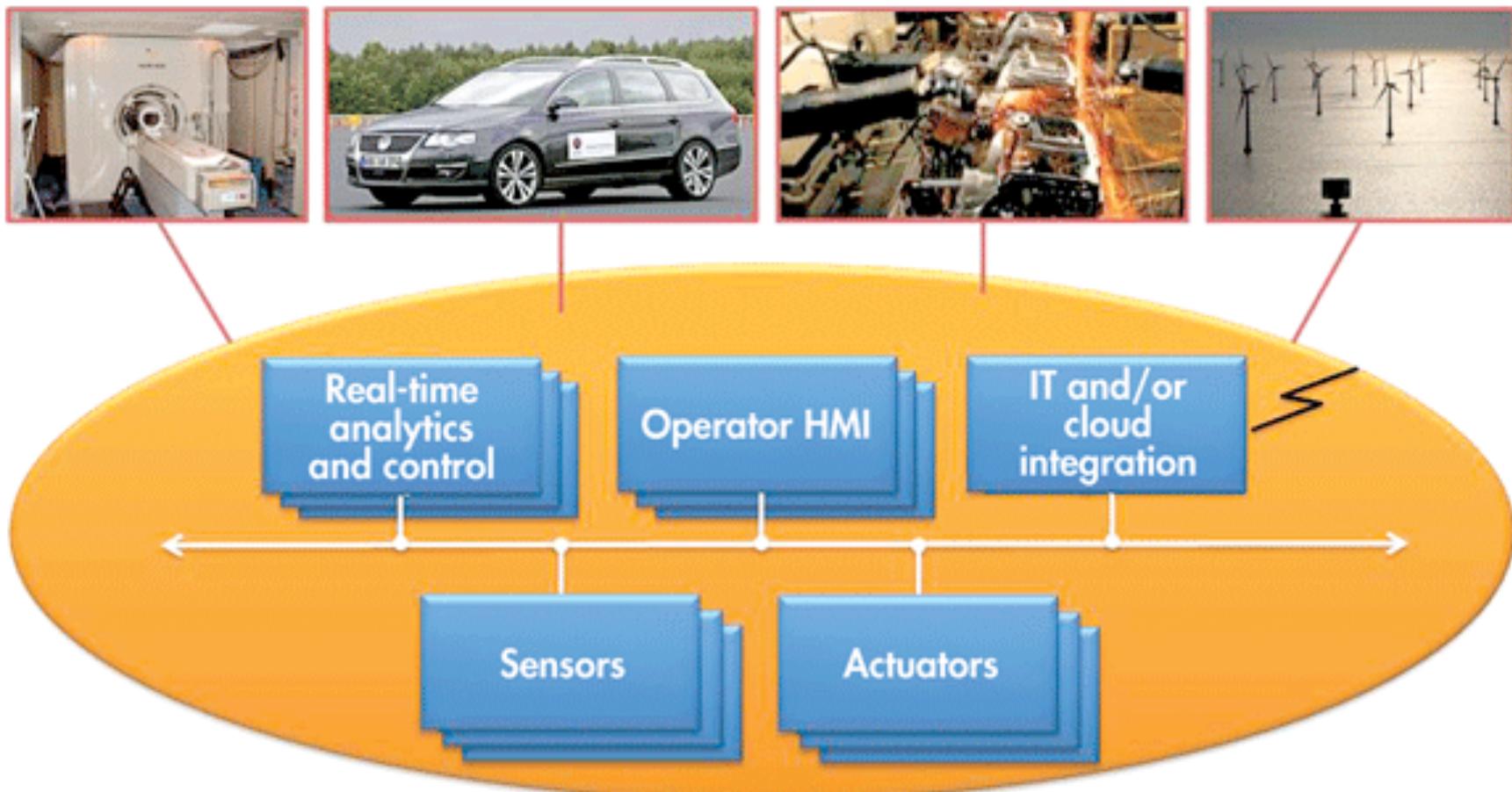
Almost a device to device bus where all devices can listen to.  
Like in an airplane, all the sensors listen to...

- 
- Data Distribution Service
    - You have really deliver millions of messages from sensors.
    - Device to device all together, a flood of thousands of device bus, in real-time of microseconds.
  - Targets devices that directly use device data (without going to a server)
  - Has its roots in high-performance industrial and military embedded applications
  - From an architectural standpoint
    - Can deliver millions of messages simultaneously to 1000s of receivers
    - TCP's point-to-point protocol too restrictive
    - Instead, uses fan-out multicast protocol with configurable QoS control
    - Publishing to a device-to-device “bus” that 1000s of devices listen on
    - Real-time on device time-scales, which means microseconds
    - Respects device constraints, so lightweight DDS implementations exist
      - Thousands of device needs to exchange data for critical decision making. This is DDS.
  - Examples: Military, wind farms, hospitals, asset-tracking systems,

DHL tracking where their packages are. There's no luxury of using edge server using TCP. This is the case where you need massive bus devices can talk directly. There's no luxury of going to cloud and going back.

# DDS

Device-device server



# AMQP

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Started in Banking Industry -- Used for Server to Server communication.

It can handle scale., Scale is different from real-time

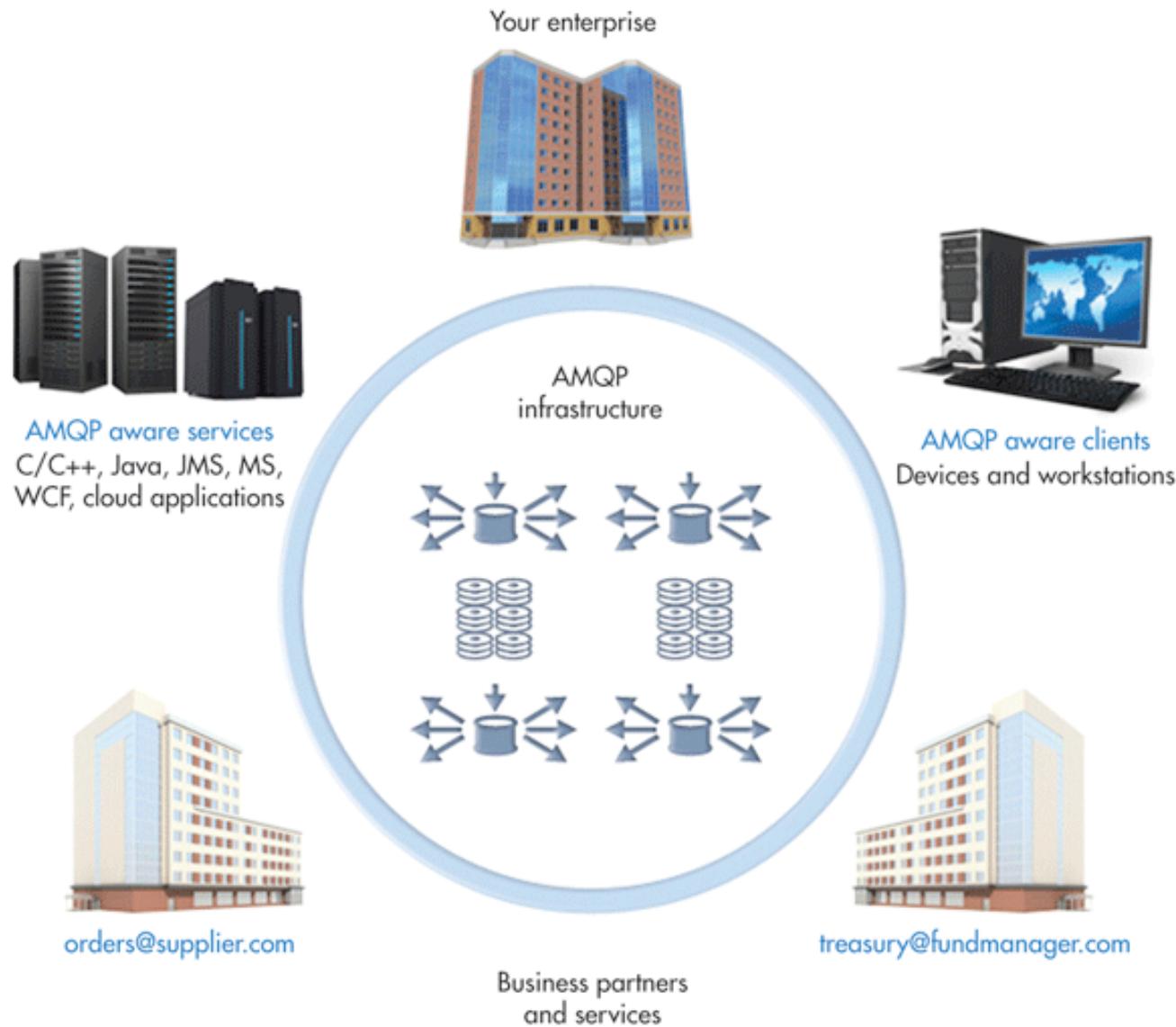
- Advanced Message Queuing Protocol
- Originated in the banking industry; sometimes considered an IoT protocol
- Sends transactional messages between end-points (servers)
- From an architectural standpoint
  - Focus on processing 1000s of reliable, queued transactions
  - Focus on reliability; uses **TCP** and requires **message acknowledgments**
  - More reliability; tracking messages, ensuring fault-tolerant delivery
  - Formal, multi-phase commit sequence
  - Device here means mobile phones connecting to back-office data centers
- Examples: Business messaging, **high-volume transactions**

Not necessarily real-time.

# AMQP

These are all server to server.

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Reliability = TCP  
Timing = Multi-line UDP.

# Which Protocol Where?

---

- **Quality-of-Service (QoS) perspective**
  - TCP provides simple, reliable, **point-to-point, ordered delivery**  
If you want to broadcast, timing - use UDP. Multi-cast is good for good throughput.
  - Lacks timing control, TCP's (single-lane) traffic backs up with slow consumer
  - Multicast may work better to decouple senders and receivers loosely
- **Addressing perspective** (“finding the data needle in the IoT haystack”)
  - XMPP provides simple, intuitive addressing of devices Turning on light switch from phone.  
XMPP make addressing intuitive, but it's not good in power or timing standard.
  - Does not work as well with large collections of devices to a single server
- **Use-case perspective**
  - Turning on your light switch (**XMPP**), generating that power (**DDS**) Power Plant in DDS.
  - Monitoring the transmission lines (**MQTT**) Make sure no surge.
  - Analyzing power usage at the data center (**AMQP**)

# How the Protocols Relate to Each Other

| Application Protocol     |                       | DDS                | CoAP      | AMQP          | MQTT        | MQTT-SN | XMPP | HTTP REST |
|--------------------------|-----------------------|--------------------|-----------|---------------|-------------|---------|------|-----------|
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| Infrastructure Protocols | Routing Protocol      | RPL                |           |               |             |         |      |           |
|                          | Network Layer         | 6LoWPAN            |           |               | IPv4/IPv6   |         |      |           |
|                          | Link Layer            | IEEE 802.15.4      |           |               |             |         |      |           |
|                          | Physical/Device Layer | LTE-A              | EPCglobal | IEEE 802.15.4 | Z-Wave      |         |      |           |
|                          | Influential Protocols | IEEE 1888.3, IPSec |           |               | IEEE 1905.1 |         |      |           |

| Application Protocol | RESTful | Transport  | Publish/Subscribe | Request/Response | Security    | QoS | Header Size (Byte) |
|----------------------|---------|------------|-------------------|------------------|-------------|-----|--------------------|
| <b>COAP</b>          | ✓       | UDP        | ✓                 | ✓                | DTLS        | ✓   | 4                  |
| <b>MQTT</b>          | ✗       | TCP        | ✓                 | ✗                | SSL         | ✓   | 2                  |
| <b>MQTT-SN</b>       | ✗       | TCP        | ✓                 | ✗                | SSL         | ✓   | 2                  |
| <b>XMPP</b>          | ✗       | TCP        | ✓                 | ✓                | SSL         | ✗   | -                  |
| <b>AMQP</b>          | ✗       | TCP        | ✓                 | ✗                | SSL         | ✓   | 8                  |
| <b>DDS</b>           | ✗       | TCP<br>UDP | ✓                 | ✗                | SSL<br>DTLS | ✓   | -                  |
| <b>HTTP</b>          | ✓       | TCP        | ✗                 | ✓                | SSL         | ✗   | -                  |

# The Smart Grid

---

Goal is to identify surges, outages, and failure points

In addition, contain damage and re-route power around failures

Balance load dynamically

Be resilient in the face of accidental or malicious faults

Accommodate new energy sources that are off the grid

## How?

Through meters at “the edge”

Light Switch, Therometer, Water Measure - sensors.

Smart Meter Outside home = edge device

Fog Nodes - aggregate data from edge for several neighborhoods.

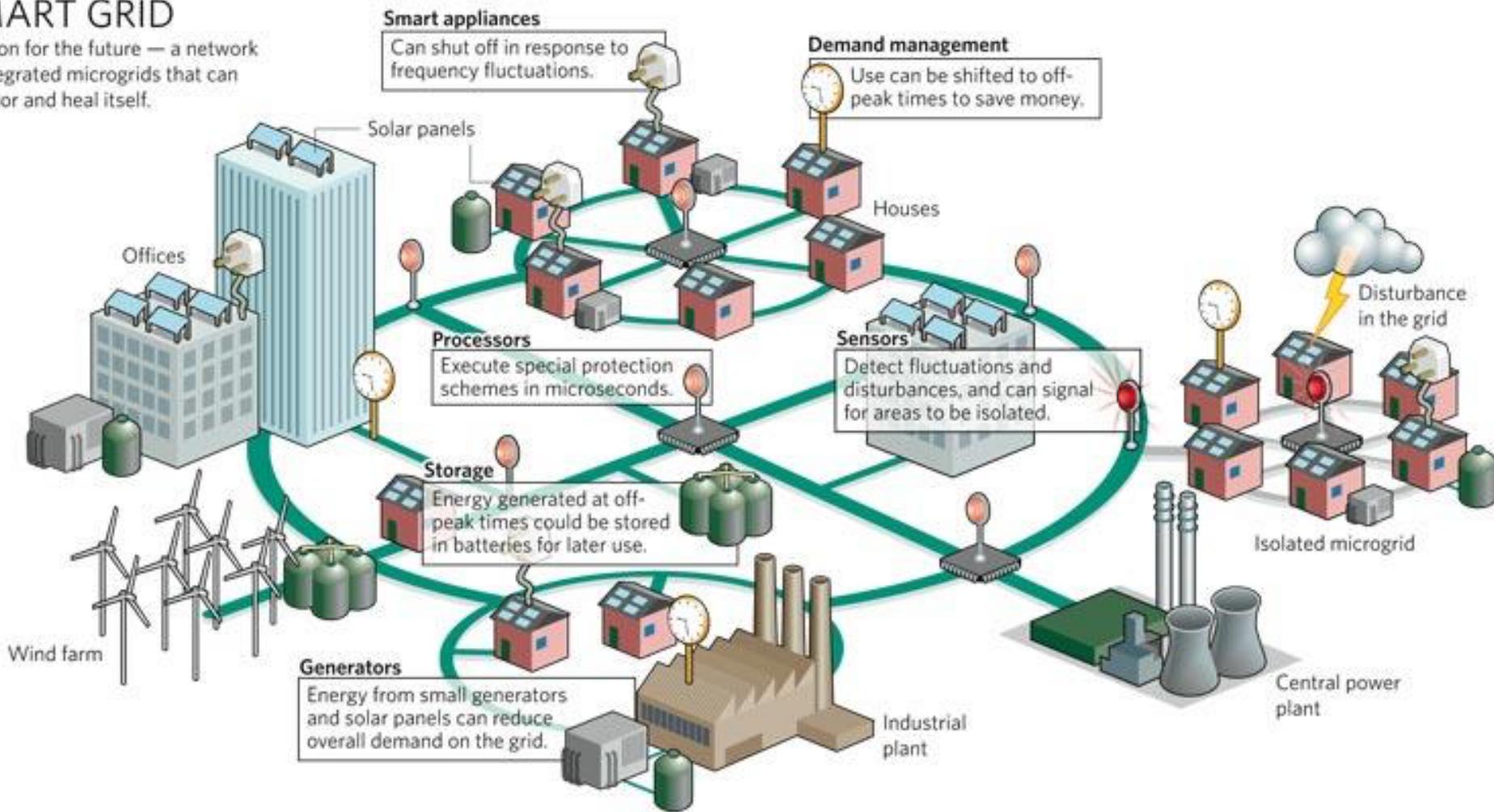
Demand Management / Power Surge Management.

- + Publish/subscribe protocols for gathering data from the edges
- + Cryptographic protocols between substations and control centers

# What is the Smart Grid?

## SMART GRID

A vision for the future — a network of integrated microgrids that can monitor and heal itself.



# How can the Smart Grid impact us everyday?

Microgrid: the ability to harness and store electricity in a grid outside of the main grid.

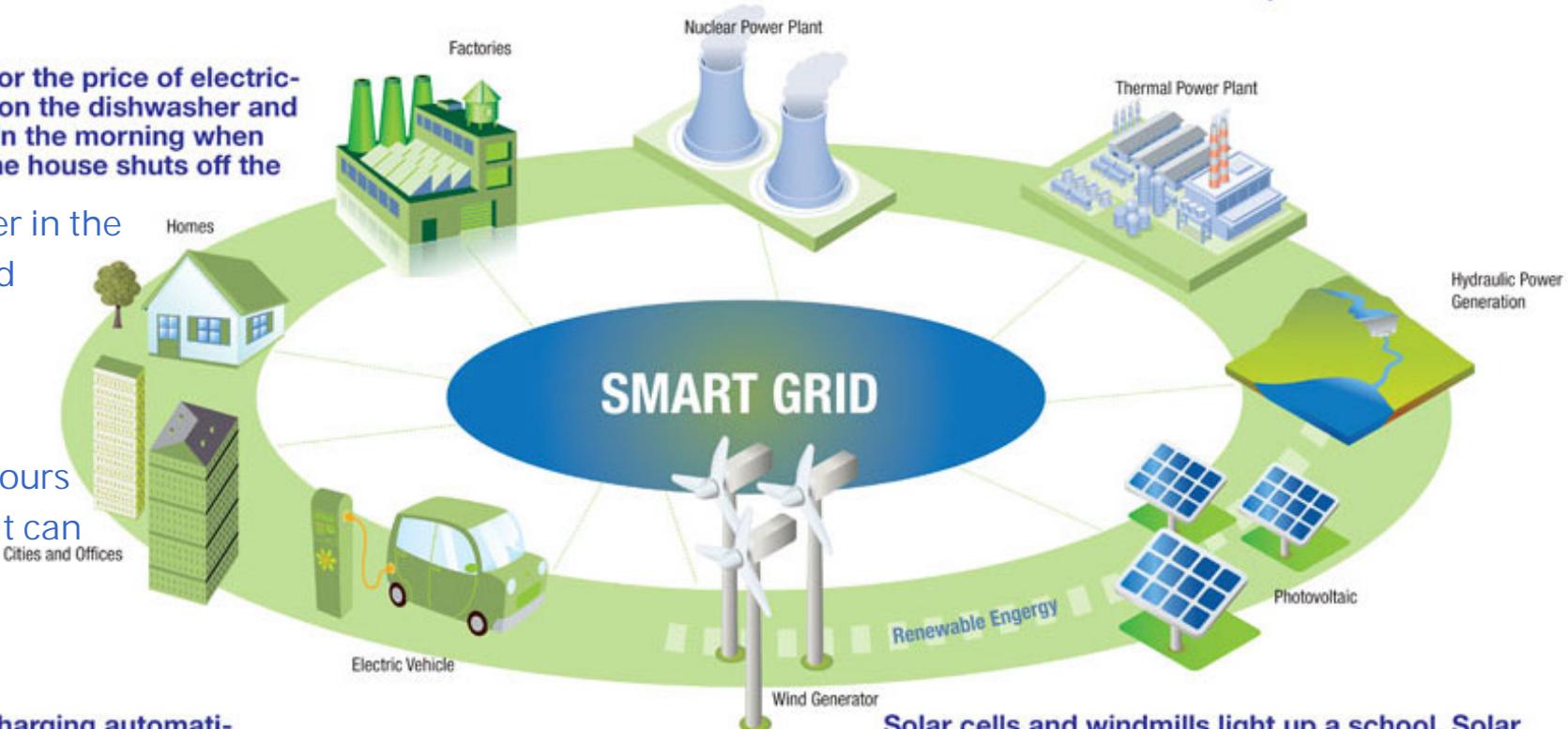
The smart house waits for the price of electricity to drop, then it turns on the dishwasher and starts charging the car. In the morning when electricity costs peak, the house shuts off the refrigerator.

Even if there's power in the main grid, you could generate power and use it.

Microgrid can be turned on at busy hours of the main grid so it can save you money.

The electric car starts charging automatically at night when electricity is least expensive. At 7 a.m. the house tells the car to stop charging and use its battery to power the coffee maker in the kitchen.

Lightning shuts down a substation. The smart grid takes it out of the loop. A dozen smart microgrids immediately access stored electricity in homes and cars, and all power from solar panels and windmills, distributing it where it's needed most. No services are interrupted.

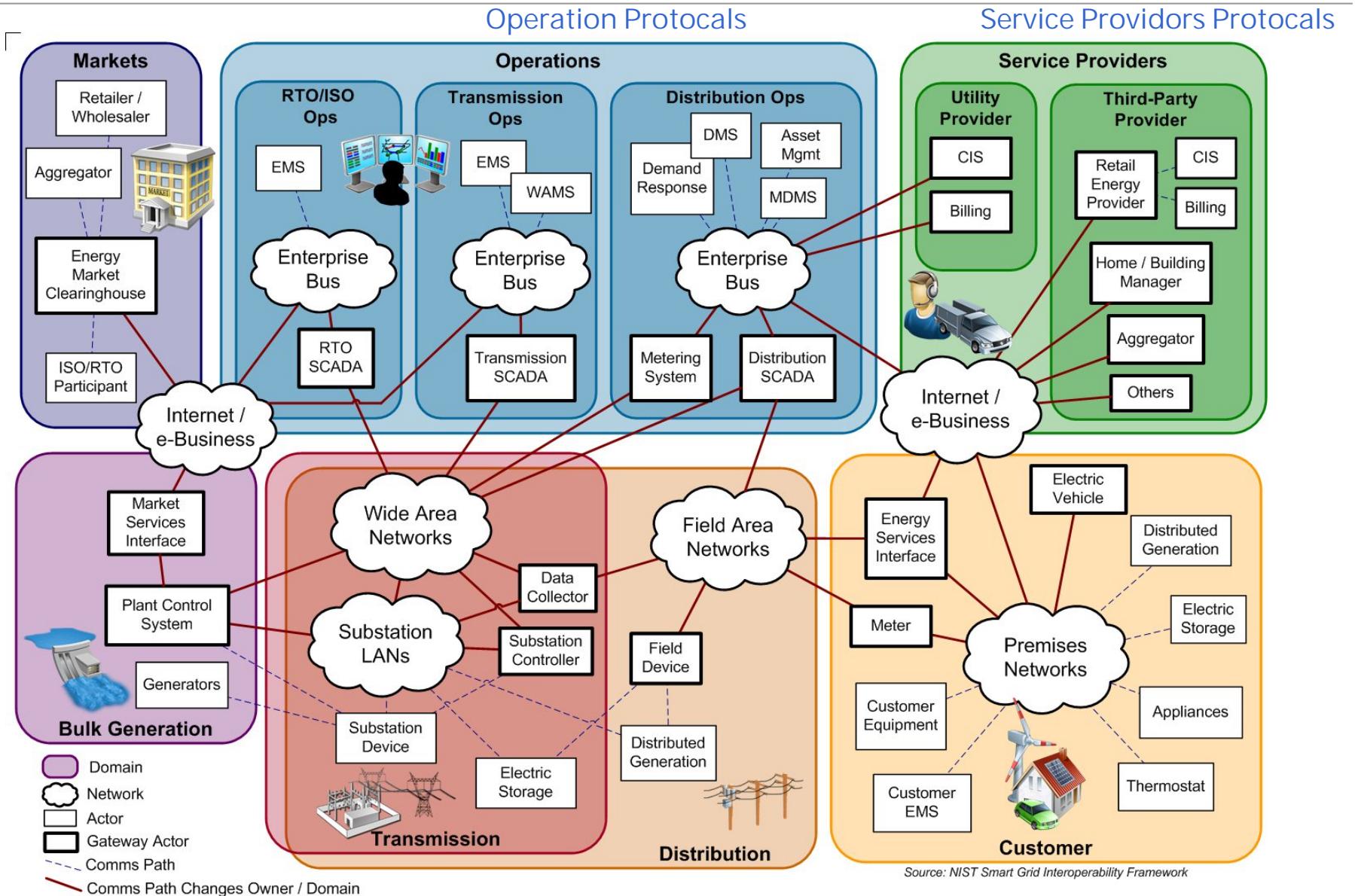


Solar cells and windmills light up a school. Solar heating keeps kids warm. At noon the school has more power stored than it needs, so the smart grid distributes it to homes and offices. The school gets a power credit.

NIST: national institute of smart technology

This is a very standardized architecture, where each part use different protocols.

# Connecting the Grid elements



# Legacy Protocols

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BACnet

LonWorks

ModBus

KNX

ZigBee

Z-Wave

M-Bus

ANSI CI-12

Device Language Message Specification (DLMS) / Company Specification  
for Energy Metering (COSEM)

# New Protocols for the Smart Grid

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MQ Telemetry Transport (MQTT)

Powerline Communications (PLC)

IPv6 over Low Power Wireless Personal Area Network (6LowPAN)

Routing Protocol for Low Power and Lossy Networks (RPL)

ZigBee Smart Energy 2.0

ETSI M2M Architecture

The powerline you take from the wall can be modulated, you are usinng the wall plug as line moden.

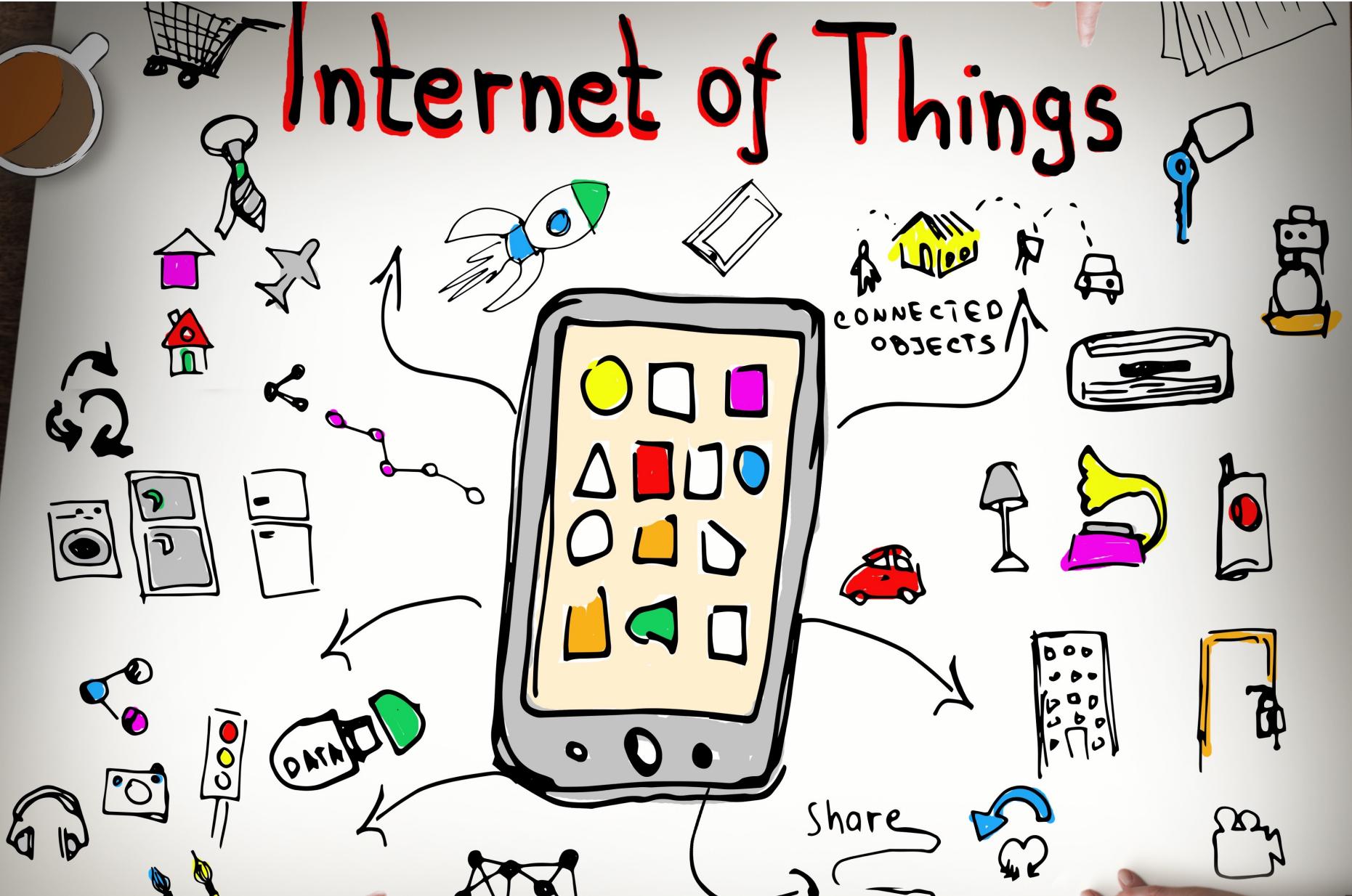
# Example: PLC (Power Line Communications)

Wall socket you plug into, you can use it to carry data, not only the power.

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The powerline can be used as a source of data.

- IoT protocol that uses electrical wiring to transmit data and AC power
- Power-line carrier/networking, power-line digital subscriber line (PDSL)
- Can be used for automation
- Can be used for Internet access (called broadband over power line—BPL)
- Interference between radio/wireless and PLC is common



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