Wireless / IoT Sensor Networks

Assoc Prof THAM Chen-Khong

E-mail: eletck@nus.edu.sg

Overview of Part II

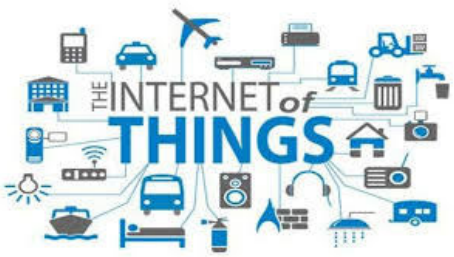
- Introduction
- Internet of Things (IoT) protocols and platforms
  - LoRa, NB-IoT, Zigbee, MQTT, edge, platforms
- Energy Models for Sensor Networks
  - Energy-efficient packet transmission and operation
- Low Energy Clustering and Routing for Sensor Networks
  - LEACH
- Data Fusion in Sensor Networks
- Collaborative Signal Processing and Tracking
  - Information-Driven Sensor Querying (IDSQ)

Module Details

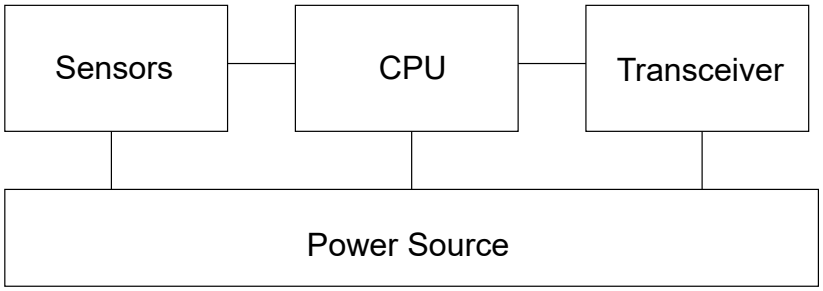
- Lectures, some based on recent papers
  - Balance between rigour and applications
- Part I (50%) + Part II (50%)
- Part II: Assignment (20%) + Exam (30%)
- Assignment on Low Energy Clustering and Routing
  - Details will be released in Week 9
  - Group-based
    - each group will consist of 6 or 7 members
  - Design of Solution + Analysis + Implementation (several parts) in Matlab + Results + Presentation & Demonstration + Report

Wireless Sensor Networks

- Wired Sensor Networks already exist
  - Primarily for factory automation and control
- What if we could put small wireless sensor nodes on various objects and query for information?
- What kind of applications will this bring about?
- Interest in this area is increasing in what is known now as the **Internet of Things (IoT)**



Basic Architecture



Example: Crossbow Mote

- Developed at UC Berkeley
- ATMEL ATMEGA103
  - 4 MHz, 8 bit CPU
  - 128 kB Instruction memory
  - 4 kB RAM
- 128 Kbit Flash
- 50 kbps, OOK or ASK
- Power source: 2 alkaline AA batteries
- Temperature, light, humidity, pressure, magnetometer, 3 axis accelerometer
- TinyOS

Sensor Platforms

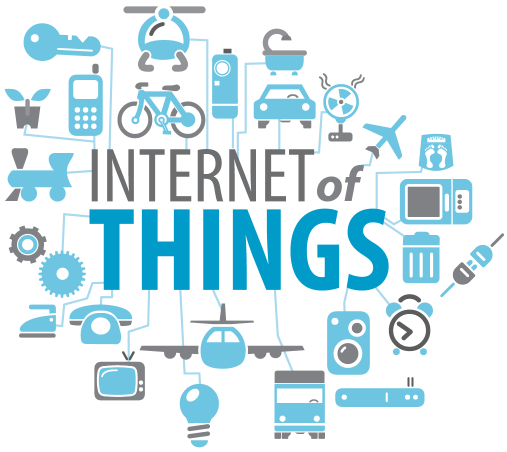
- Crossbow ‘mote’ (ref. MEMSIC)
- Sensoria
- Prospeckz
- µAMPS (MIT)
- Waspmote (Libelium)
- Many more exist …

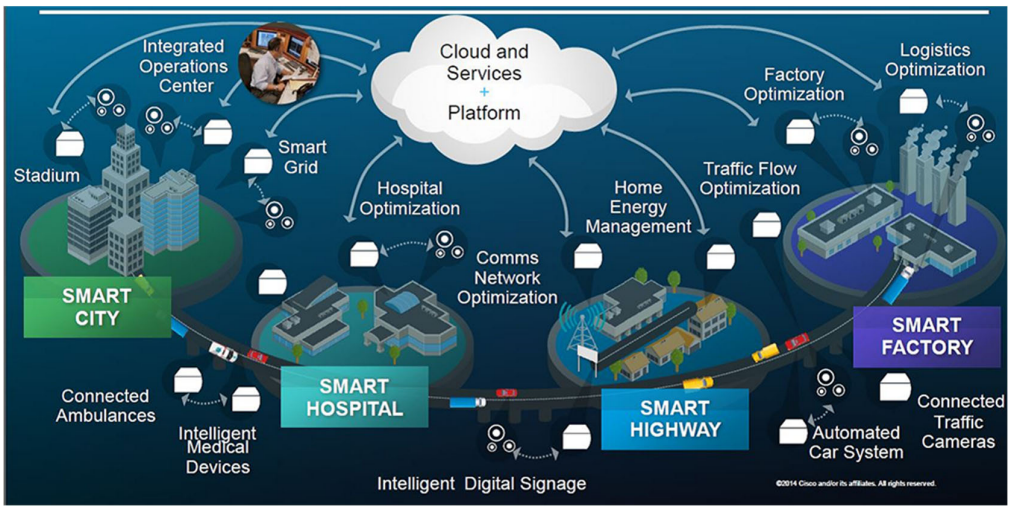
IoT Devices

- Temperature, light, humidity, motion sensors
- Smart meters: water, electricity, gas
- Surveillance cameras
- Monitor and interact with its surrounding environment
- Home, manufacturing, healthcare etc.

NB-IoT gas meter

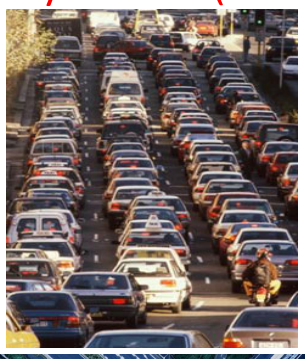
The Internet of Things is Everywhere

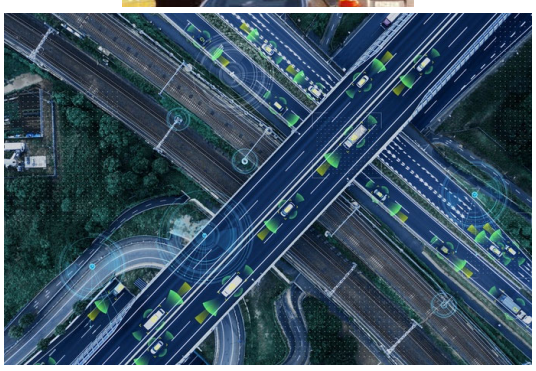




Example: Intelligent Transportation System (ITS)

- Sensors in vehicles, roads etc.
- V2V, V2I, V2X connectivity
- Allows drivers to look ahead
- Determine traffic conditions, optimal alternative routes etc.





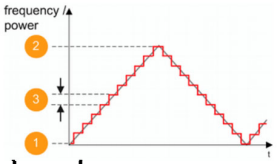
Smart Cities

source: ST Engineering

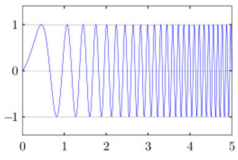
Low Power Wide Area Network (LPWAN)

Wireless Sensor Nodes

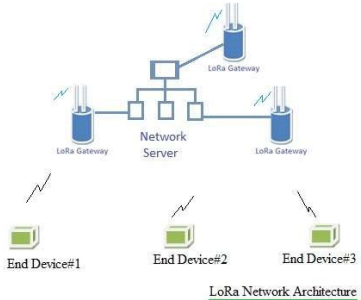
LoRa (Long Range)



- LoRa is a low power, long range and low data rate based technology developed by Semtech
  - *proprietary* physical layer or wireless modulation technique
  - based on chirp spread spectrum (CSS) modulation



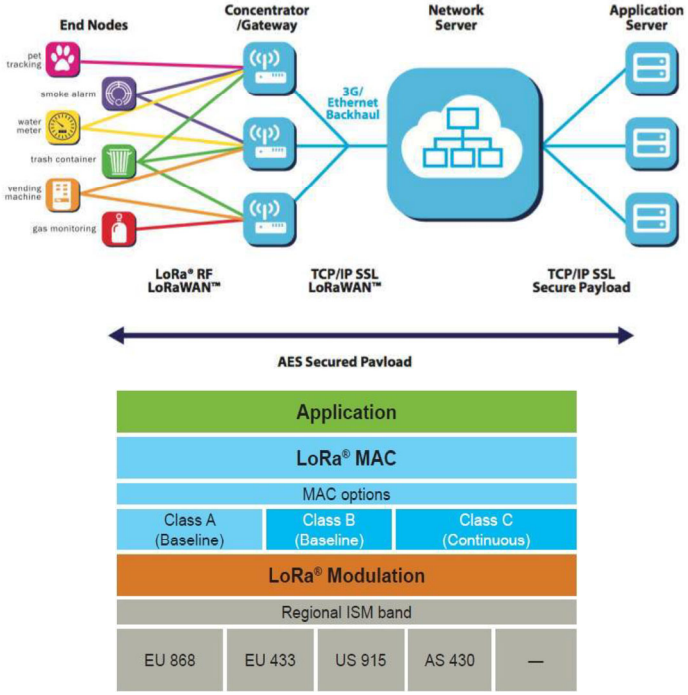
- Range: 2-5 km in dense urban and 15 km in suburban areas
- Different ISM frequency bands defined in USA (902 to 928 MHz), EU (863 to 870 MHz), China (779 to 787 MHz) and other regions.
- One LoRa gateway can take care of thousands of nodes.
- Long battery life (~10 years)
- Data rate: <5 kbps
- Low cost: ~$5 per module



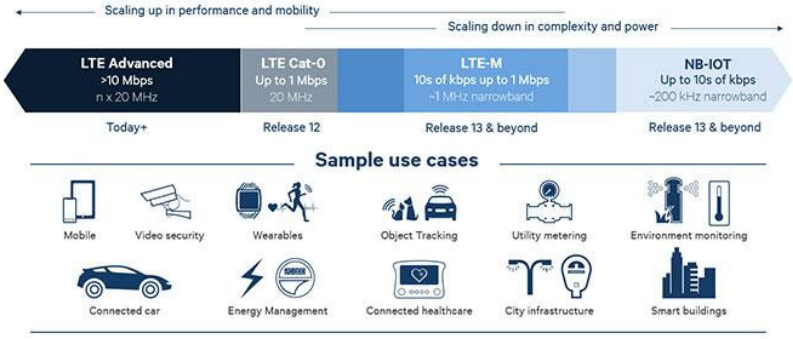
LoRa Network Architecture

LoRaWAN (Wide Area Network)

- LoRa technology is used to create a wide area wireless network.
- LoRaWAN network consists of gateways, network servers and end devices.
- The network topology is star of stars.
- End devices are also known as nodes and gateways are known as base stations or concentrators.
- End devices and Gateways are connected wirelessly using ISM bands specified with a single hop.
- Gateways and network servers are connected using IP backhaul connections.

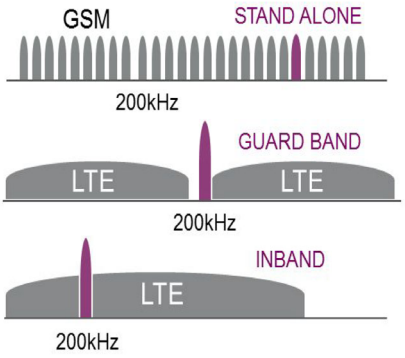


NB-IoT (NarrowBand Internet of Things)



- Technology standardized by the 3GPP standards body (hence, *open* standard)
- Narrow band technology designed for IoT which can be deployed in GSM and LTE spectrum (frequency bands)
- Also termed as cellular based IoT
- Standardization of NB-IoT completed with Release 13 of 3GPP published on 22 June 2016
- Launched in early 2017

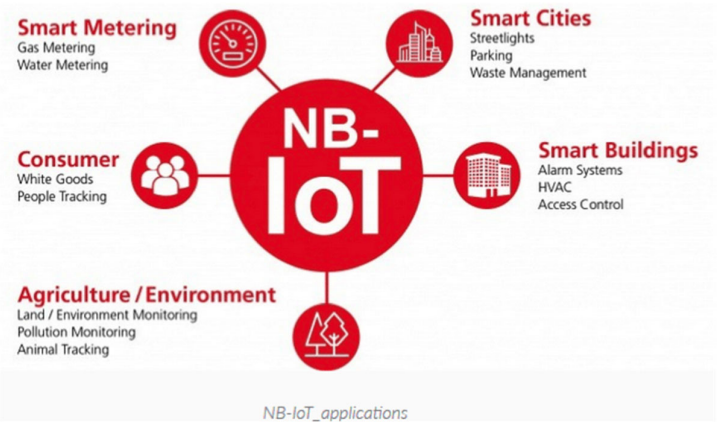
NB-IoT



- Minimum system **bandwidth** for both downlink and uplink - 180 kHz
- Transmission schemes:
  - GSM carrier of 200 kHz
  - 1 PRB (Physical Resource Block) inside an LTE carrier/guardband could be replaced by NB-IoT carrier
- 12 subcarriers of 15 kHz in downlink using OFDM and 3.75/15 kHz in uplink using SC-FDMA
- Simple and inexpensive transceiver design

NB-IoT

- NB-IoT stands for Narrowband-IoT.
- Uses existing cellular infrastructure.
- It is specified in LTE Rel.13. It is the successor to LTE Cat-M version specified in Rel.12.
- Developed to meet the requirements of LPWA (Low Power Wide Area) type of networks.
- NB-IoT has better geographical coverage compared to LTE-M, but with lower data rates.
- This allows long battery life (about 10 years).
- NB-IoT devices support narrower frequency spectrum of bandwidth 180 kHz to 200 kHz, and hence, its name.

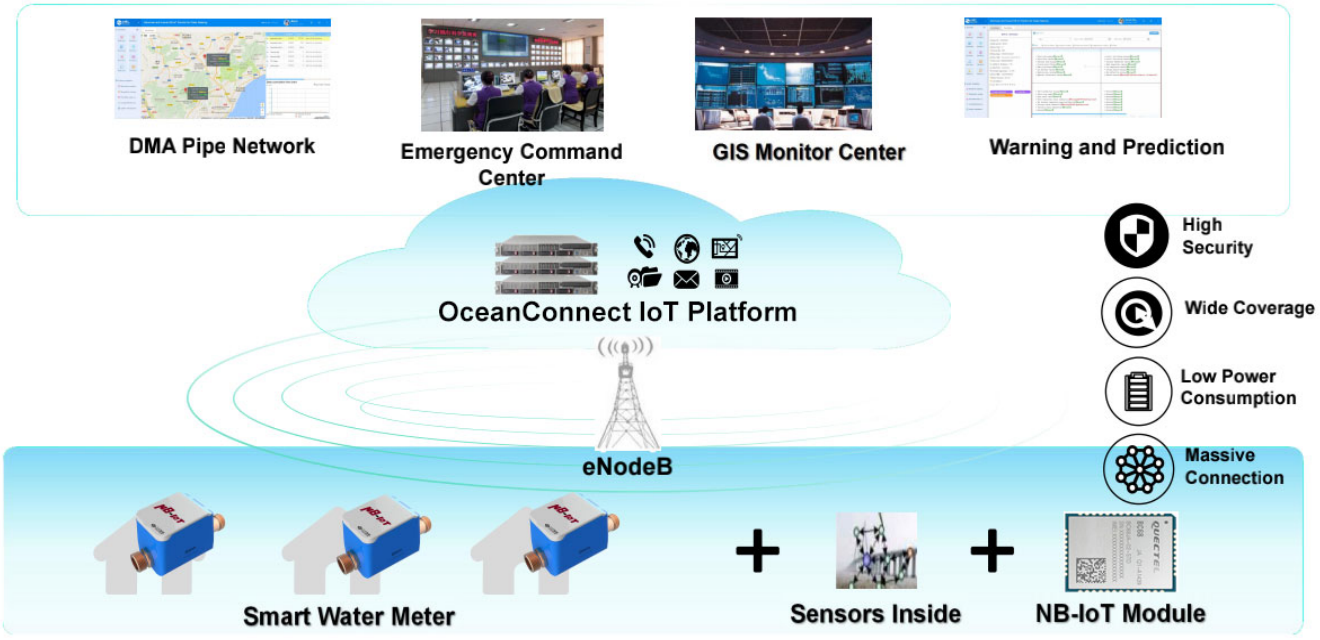


NB-IoT_applications

NB-IoT

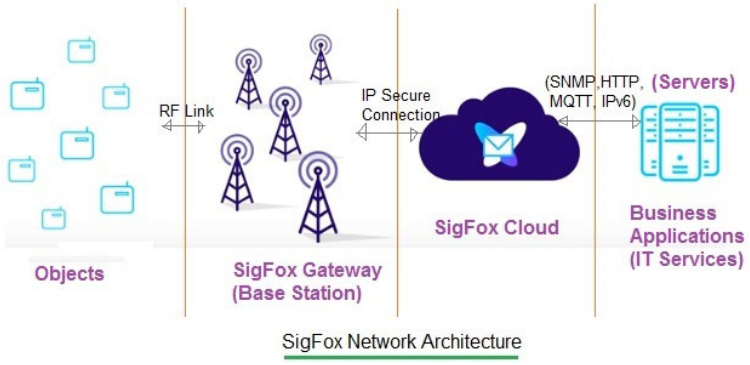
Specifications	**NB-IoT** supports:
Extended Coverage and Distance	20 dB better compared to GSM/GPRS, covers about less than 22 km from cell
Frequency Spectrum	700 MHz, 800 MHz, 900 MHz
Bandwidth	180 kHz to 200 kHz
Capacity-Number of Connections	50K connections per cell, supports about 40 devices per household
Power Consumption	very low power consumption, and hence extends battery life to 10 years
Latency	less than 10 seconds (uplink)
Data Rate	~100 Kbps
Transmit Power	+20 dBm or +23 dBm
Device Cost	low, about $10 per module

NB-IoT Smart Water Metering



SigFox

Specification/feature	SIGFOX supports
Frequency	Unlicensed ISM Band 868 MHz (Europe) 915 MHz (USA)
Range	30 to 50 km (rural areas) 3 to 10 km (urban areas)
Throughput	100 bps
Payload size to be transmitted	Very small (about 12 bytes)
Power consumption	Very little, for example, energy meter in SIGFOX will consume 50 microwatts while in GSM cellular system it consumes 5000 microwatts
Stand by time for 2.5Ah battery	It lasts 20 years in SIGFOX, while GSM cellular lasts much less about 0 to 2 years
uplink/downlink	supports mono as well as bi-directional communication
Frequency Hopping	Supported
Security/Privacy	SIGFOX employs various techniques to support this

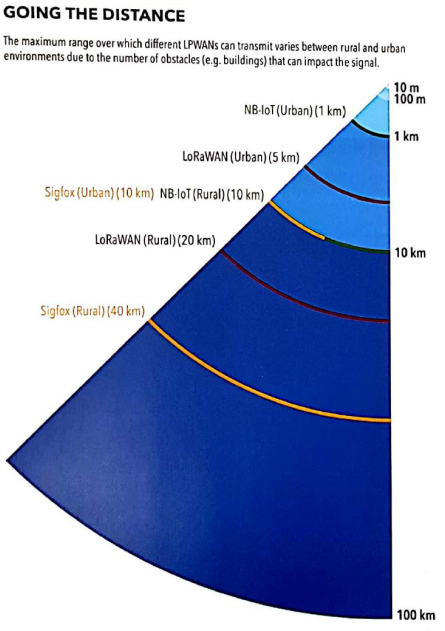


SigFox Network Architecture

Cost: $5 per module

Summary of LPWAN

	LoRa / LoRaWAN	Sigfox	NB-IoT	LTE-M	RPMA	Weightless-P	Symphony Link
Origin	France	France	USA (Global)	USA (Global)	USA	UK	USA
Proprietary or open	LoRa – proprietary LoRaWAN - open	Net – proprietary Devices – open	Open	Open	Proprietary	Open	Proprietary
Cellular	No	No	Yes	Yes	No	No	No
Spectrum	Unlicensed	Unlicensed	Licensed	Licensed	Unlicensed	Unlicensed	Unlicensed
Range, km	urban: 2-5 rural: 15	urban: 3-10 rural: 30-50	urban: 1-5 rural: 10-15	urban: 2-5	urban: 1-3 rural: 25-50	urban: 2	urban: 2-5 rural: 15
Speed, uplink / downlink	50 kbps / 50 kbps	300 bps / –	250 kbps / 250 kbps	1 Mbps / 1 Mbps	634 kbps / 156 kbps	100 kbps / 100 kbps	100 kbps / 100 kbps
Power consumption	●●●	●	●	●●●	●●	●	●●
Security	●●	●●	●●●	●●●	●●●	●●●	●●●
Availability of devices	●●	●●●	●●	●	●●	●	●●
Price*	●●	●	●●	●●●	●●●	●	●●
Areas of application	Precision farming, manufacturing automation, pipeline monitoring	Predictive maintenance, capacity planning, demand forecasting	Electric metering, manufacturing automation, retail PoS	tracking objects, wearables, energy management, utility metering, city infrastructure	Digital oilfield, connected cities, usage-based insurance, agriculture	Smart grid, healthcare, automotive, smart cities, asset tracking	Industrial control systems, lighting control, alarm systems
Supporting companies	IBM, Semtech, Cisco, HP, Orange, Kerlink, Actility	STMicroelectronic, Texas Instruments, Atmel, Silicon Labs	Huawei, Ericsson, Qualcomm, Vodafone	Verizon, AT&T, Nokia	Ingenu	Accenture, Sony Europe, uniik, ARM, Telensa	Link Labs



flespi
FLEXIBLE TELEMATICS BACKEND

Short Range Wireless (Low Power)

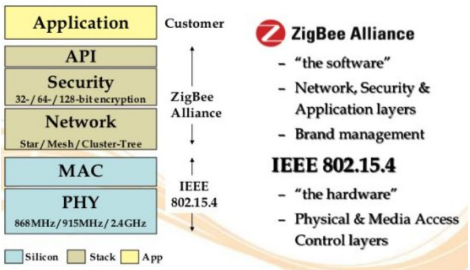
Low-Rate Wireless Personal Area Network (LR-WPAN)

ZigBee

- ZigBee is based on the IEEE 802.15.4 standard
- ZigBee is built with emphasis on low data rate control system sensors featuring slower data of up to 250 kbps
- Data rate of 250 kbps in 2.4 GHz ISM band, 20 kbps in the 868 MHz band in Europe, and 40 kbps in 915 MHz band used in North America and Australia
- ZigBee can choose up to 16 different 5 MHz channels within 2.4 GHz band, several do not overlap with 802.11 and Wi-Fi
- ZigBee has active and sleep modes
- All devices have a short 16-bit PAN address and 64-bit extended address
- Application layer maintains a binding table for matching two or more devices

ZigBee

7 Layer ISO-OSI-Model	Simplified 5 layer ISO-OSI-Model	Zigbee Model	
Application	User Application	Applications	Zigbee or OEM
Presentation	Application Profile	Application Profiles	
Session		Application Support Sub Layer	
Transport		Network and Security Layer	Zigbee Alliance Platform
Network	Network		
Data Link	Data Link		
		Media Access Control (MAC)	
Physical	Physical	Physical	IEEE 802.15.4



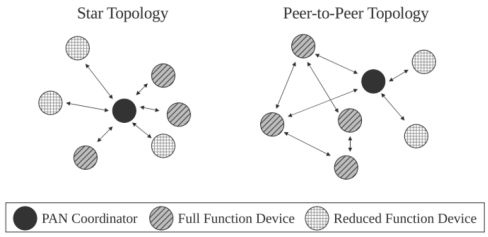
ZigBee architecture – 1

PHY & MAC : IEEE 802.15.4

- Physical Layer:
  - 3 frequency bands for transmission:
    - 868 MHz band with a single channel has a raw data rate of 20 kbps
    - 915 MHz band with 10 channels of 40 kbps each
    - 2.4 GHz ISM band with 16 channels of 250 kbps each
  - ZigBee transmitters use Energy Detection (ED) and Link Quality Indication (LQI) to reduce transmitted power
  - Performs channel assessment
- MAC Layer:
  - Carrier Sense Multiple Access-Collision Avoidance (CSMA-CA)
  - Depending on mode of transmission, i.e. Beacon or Non-Beacon mode, the MAC layer decides whether to use slotted or unslotted CSMA-CA, respectively
  - Takes care of scanning the channel, starting PANs, detecting and resolving PAN ID conflicts, sending beacons, performing device discovery, association and disassociation, synchronizing network device and realigning orphaned devices on the network
  - Provides some standard security features like access control, encryption of data, duplicate rejection and frame integrity

ZigBee architecture - 2

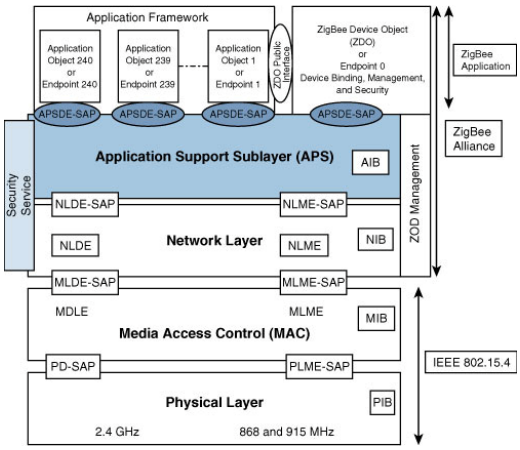
Network layer & above : ZigBee



- A Zigbee network has three types of devices:
  (leverages IEEE 802.15.4 FFD and RFD)
  (i) Zigbee Router (ZR) [FFD],
  (ii) Zigbee Coordinator (ZC) [PAN Coordinator, FFD], and
  (iii) Zigbee Device (ZD) [RFD].
- Network and Security Layer:
  - Takes care of network start-up, device configuration, topology-specific routing (peer-to-peer/mesh (multi-hop)), and providing security.
  - Nodes use unique 64-bit addresses as per the IEEE 802.15.4 standard, supporting a maximum of 65,536 16-bit network address devices which can have 256 sub addresses.
  - Network routing table is populated when the device comes alive in the network for the first time by generating Broadcast Routing Request Packets (RREQ) (AODV is used).
    Endpoint routers respond to these packets as Routing Response Packets (RREP).

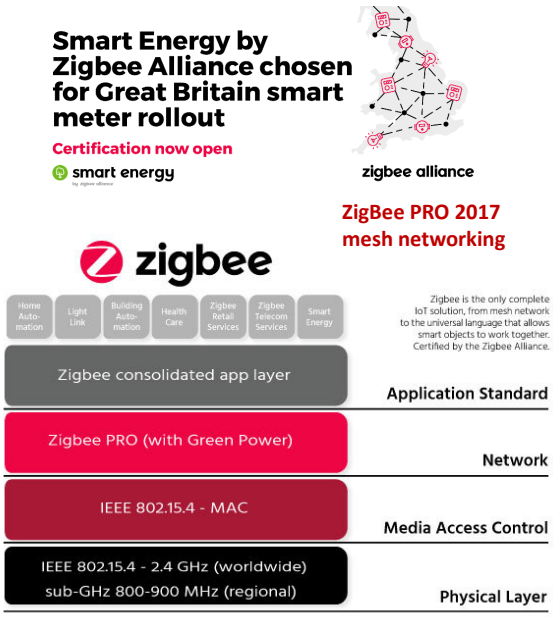
ZigBee architecture - 3

- Application Support Sub-Layer (APS):
  - Interfaces network layer and application layer providing a general set of services through two entities, the APS Data Entity (APSDE) and APS Management Entity (APSME) accessed through their respective Service Access Points (SAP).
  - Provides services like binding management, making application level PDU, group filtering, and managing Object database called APS Information Base, providing reliability of transaction, etc.



ZigBee architecture - 4

- **ZigBee Device Objects (ZDO)** provide the interface between application objects, device profiles, and APS layer in ZigBee devices.
  ZDO are responsible for initializing the APS, the network layer, and the Security Service Provider, and also forming the configuration information from applications to implement discovery, security, network and binding management.
- Application Framework:
  - Environment to host application objects on ZigBee devices.
  - Up to 240 distinct application objects can be defined by manufacturers.
  - Consists of **application profiles** as the top layer over **ZigBee Device Objects (ZDO)** which provide the base functionality.
  - **Application Profiles** define language for exchanging data and provide interoperable services. ZigBee Alliance released several Standard Profiles which contain different device descriptors which have unique identifiers, e.g. Smart Energy Profile.



MQTT: Message Queuing Telemetry Transport

What is MQTT ?

- A way to obtain real world data
  - Information is gathered by an increasing number of sensors and devices deployed all over
- A way to provide real time information
  - e.g. locate an item in a supply chain
  - Accurate current load of a any system (e.g. electricity meters)
  - Current status of a system (level of liquid in a container, temperature, pressure etc.)
- A way to connect all the devices and sensors directly to a messaging infrastructure

What is MQTT ?

- MQTT = MQ Telemetry Transport
- Lightweight messaging protocol designed for sensors and devices with
  - Flaky network connectivity, low bandwidth or high latency
  - Low computing power
  - Connections where bandwidth is at a premium
- Protocol specification is open source
- MQTT is nearly 10 years old
  - Mature and evolving

MQTT Key Facts

- Machine-to-machine (M2M)/"Internet of Things" connectivity protocol
- Invented by Dr Andy Stanford-Clark of IBM and Arlen Nipper of Arcom (now Eurotech) in 1999
- OASIS (Organization for the Advancement of Structured Information Standards) standard
- ISO standard (ISO/IEC PRF 20922)
- Public and royalty-free license
- Used by Amazon Web Services, IBM WebSphere MQ, Microsoft Azure IoT, Adafruit, Facebook Messenger etc.

MQTT Features - 1

- Publish and subscribe to topics
- 3 qualities of service
  - 0 Best effort to deliver a message
  - 1 Deliver at least once
  - 2 Deliver exactly once
- Supports Retained publications
- Minimal transport overhead to reduce network traffic
  - As little as 2 bytes
- Last Will and Testament

MQTT Features - 2

- Small code footprint
- Ideal if processor or memory resources are limited
- Ideal if bandwidth is low or network is unreliable
- Publish/subscribe message exchange pattern
- Works on top of TCP/IP; more lightweight than HTTP
- Quality of service: at most once, at least once, exactly once
- Client libraries for Android, Arduino, C, C++, C#, Java, JavaScript, .NET
- Security: authentication using user name and password, encryption using SSL/TLS
- Persistence: MQTT has support for persistent messages stored on the broker
- MQTT-SN (protocol for sensor network) works on non-TCP/IP networks (e.g. Zigbee)
- MQTT over websocket possible (browser as MQTT client)
- Request/response message exchange pattern as add-on

Fields of application

- Home automation (e.g. lighting, smart meter)
- Healthcare
- Mobile phone apps (e.g. messaging, monitoring)
- Industrial automation
- Automotive
- IoT applications in general

Publish/Subscribe

- Multiple clients connect to a broker and subscribe to topics that they are interested in.
- Clients connect to the broker and publish messages to topics.

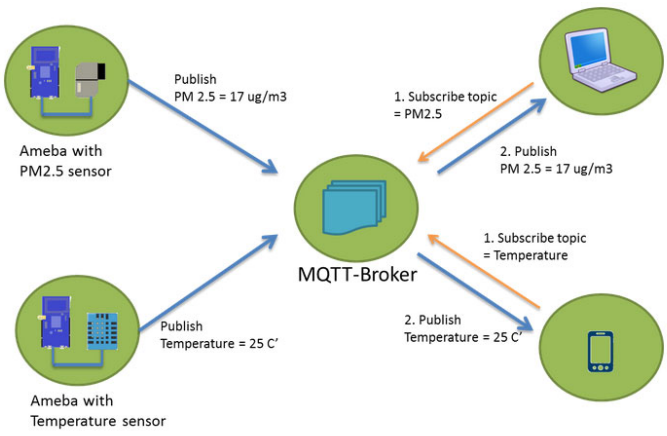
- Topics are treated as a hierarchy, using a slash (/) as a separator.

- Example: multiple computers may all publish their hard drive temperature information on the following topic, with their own computer and hard drive name being replaced as appropriate:
  `sensors/COMPUTER_NAME/temperature/HARDDRIVE_NAME`

- Clients can receive messages by creating subscriptions. A subscription may be to an explicit topic, in which case only messages to that topic will be received, or it may include wildcards.
- Two wildcards are available, + or #

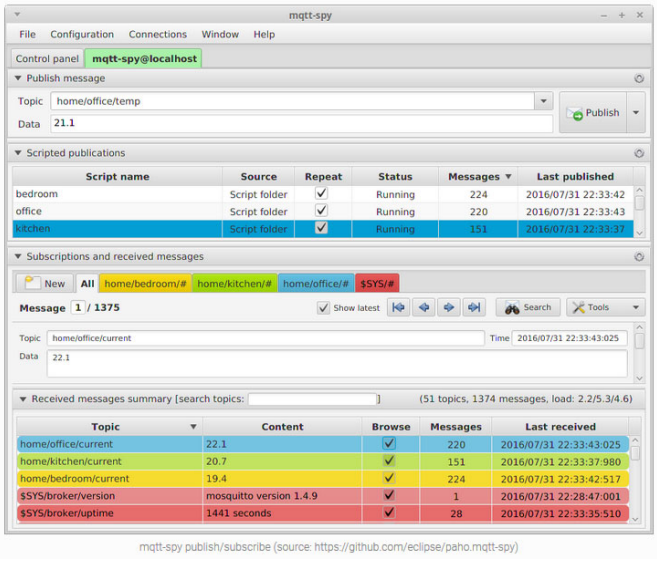
- MQTT clients can register a custom 'last will testament' message to be sent by the broker if they disconnect.
- This message can be used to signal to subscribers when a device disconnects.

Publish/Subscribe



`mqtt publish/subscribe`

Client tool



mqtt-spy publish/subscribe (source: https://github.com/eclipse/paho.mqtt-spy)

Benchmarks

- The scalability of a server with the number of clients is a critical factor to consider when a MQTT broker is selected.
- The mosquitto MQTT broker can handle up to 60,000 publishers (connections) per second with a latency varying from 10 ms to about 1 s (QoS = “at least once”, payload 64 bytes, CPU load (1 core) 100%).
- libmosquitto (client library) is about 1.3 MB.

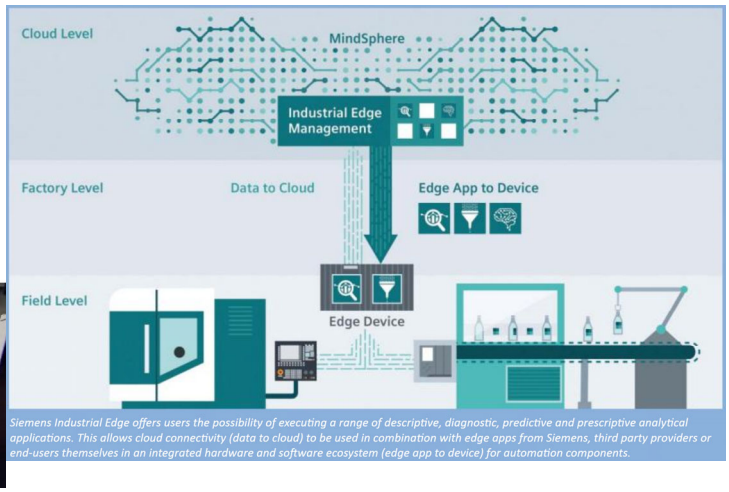
Edge Computing

Edge Computing

- ***Edge computing*** involves placing a computing device near routers and gateways between the cloud and end users and IoT devices
- **Benefits and Use Cases**
- Latency - when extremely low latency is essential for near real-time control of the industrial machines
- Bandwidth - when limited bandwidth prevents data from being pushed to the cloud
- Connectivity - when location has limited, intermittent or no connectivity
  - also reduces cloud connectivity costs
- Time-sensitive compute-intensive workloads, such as machine learning inference, predictive maintenance and asset performance assessment
- Keeps data private by doing more computations locally
- Small form factor - when smaller footprint apps/services are required to achieve flexibility
- Connectivity to cloud for 'digital twin' and system-wide monitoring and optimization

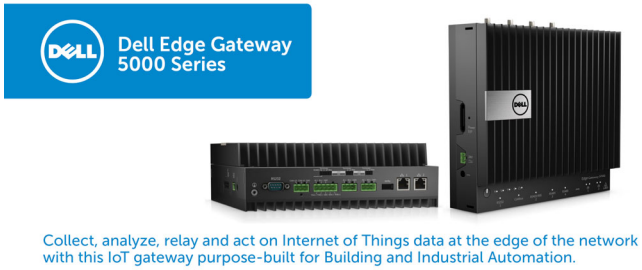
Edge Computing Devices & Frameworks

Edge Computing: Driving New Outcomes from Intelligent Industrial Machines

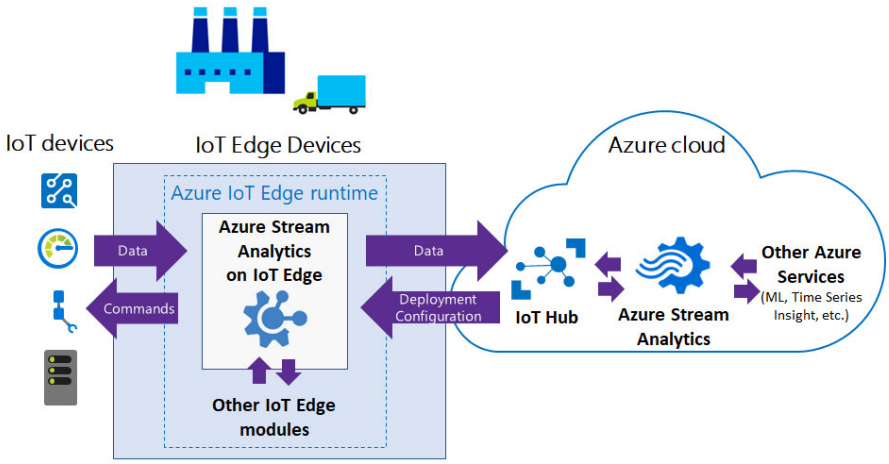


Siemens Industrial Edge offers users the possibility of executing a range of descriptive, diagnostic, predictive and prescriptive analytical applications. This allows cloud connectivity (data to cloud) to be used in combination with edge apps from Siemens, third party providers or end-users themselves in an integrated hardware and software ecosystem (edge app to device) for automation components.

Edge Computing Devices & Frameworks

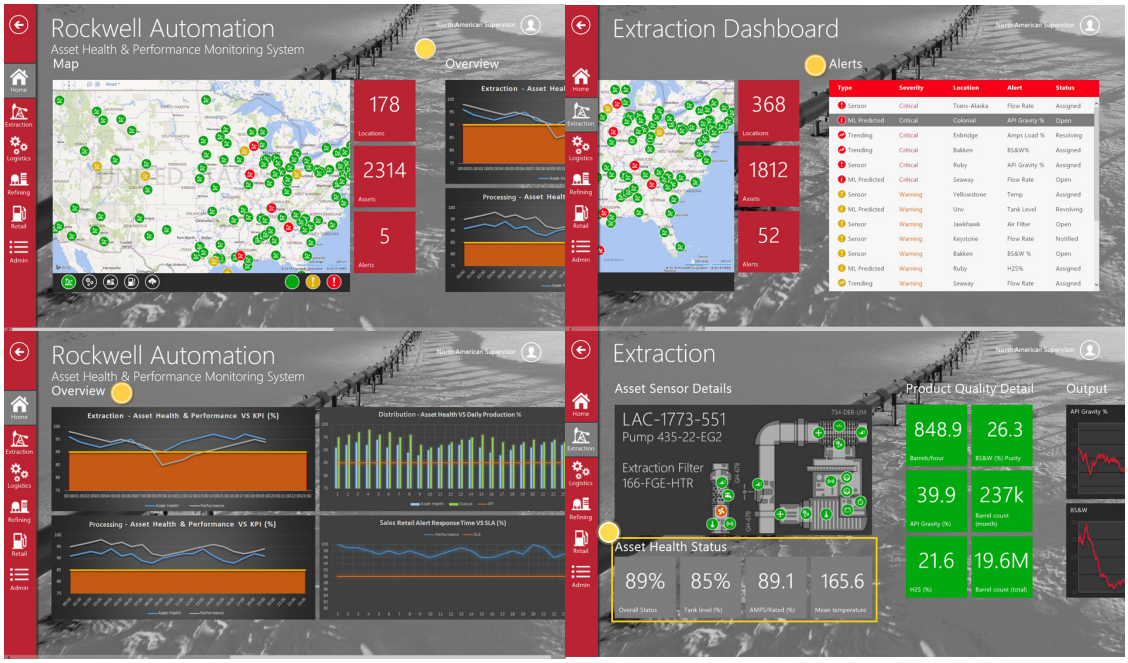


Collect, analyze, relay and act on Internet of Things data at the edge of the network with this IoT gateway purpose-built for Building and Industrial Automation.



IoT and Data Platforms

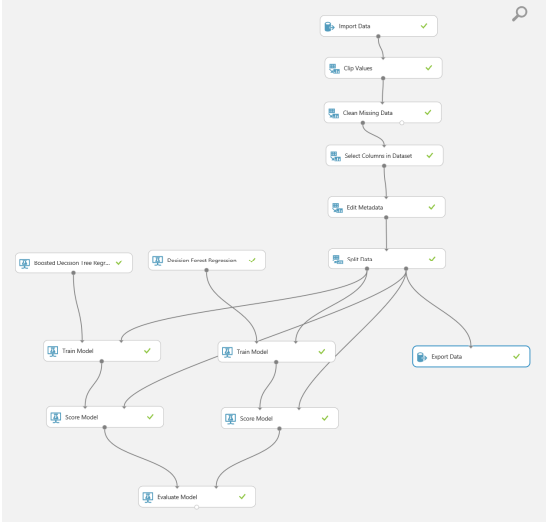
IoT connected to the Cloud

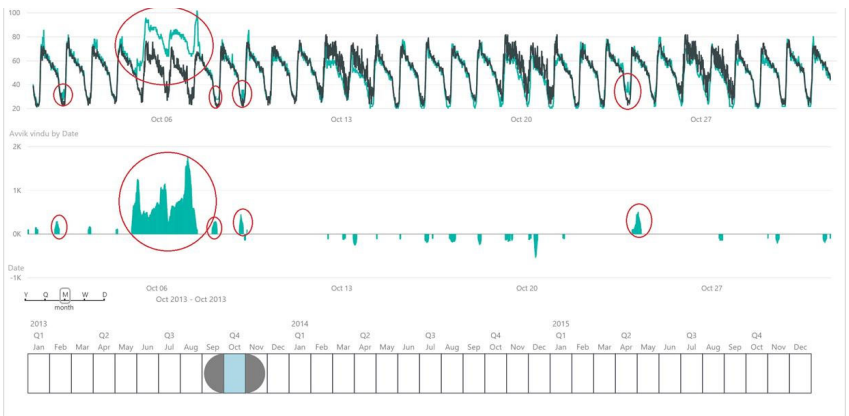


source: Microsoft Azure

Microsoft Azure IoT – Water Management

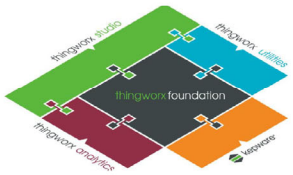
Raw Data → Pre-Process → Analyze / QA → Machine Learning Experiments → Trained Model → Test Model → Use Model



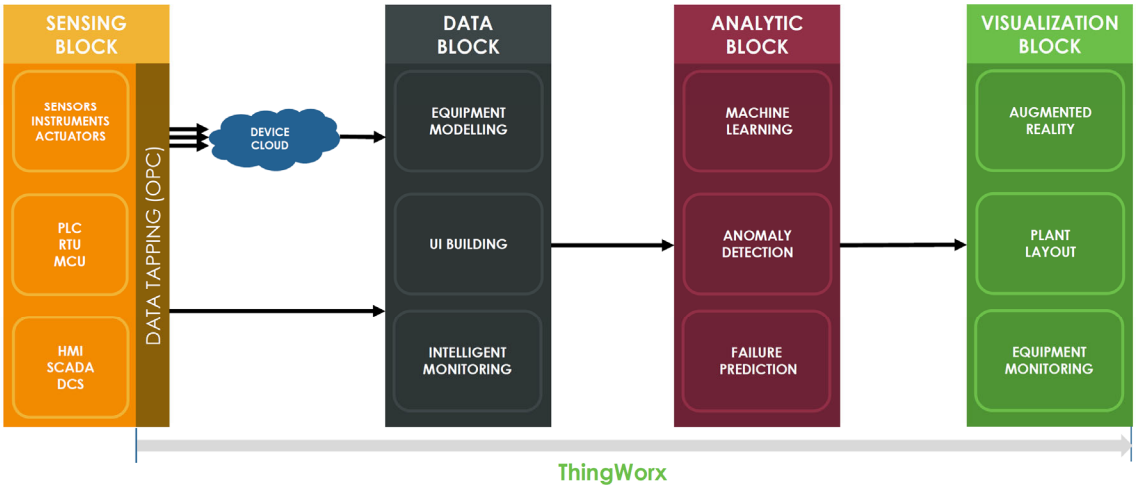


PTC ThingWorx

END-TO-END IOT PLATFORM



thingworx

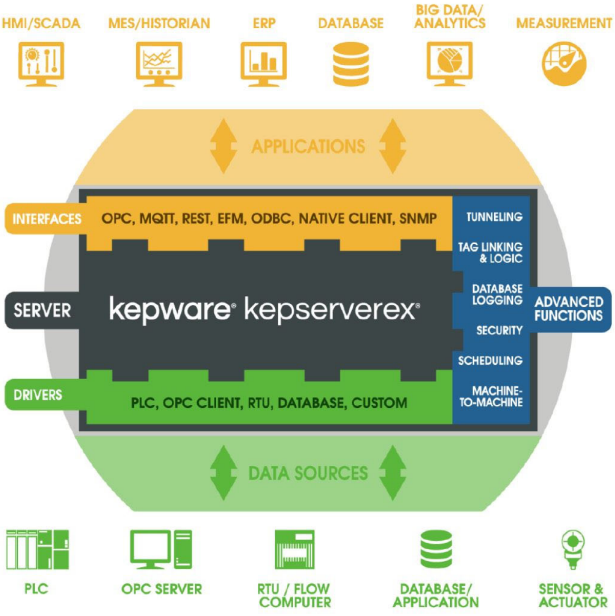


THINGWORX INDUSTRIAL CONNECTIVITY

thingworx

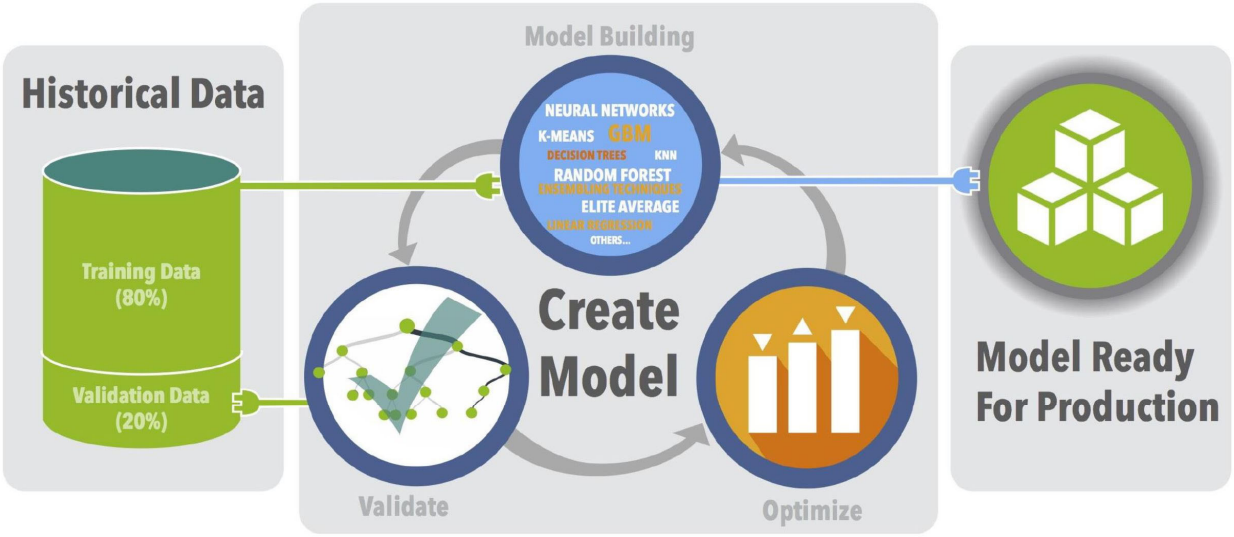
- **150+ Driver Library** - Offers a library of 150+ device drivers, client drivers, and advanced plug-ins—supporting thousands of devices and other data sources
- **OPC + Proprietary Protocols** - Provides industrial operations data to traditional Industrial Automation clients (via OPC and proprietary protocols)
- **IoT Protocols** – Connectivity to new IoT solutions (via MQTT and IT-centric protocols)

kepware



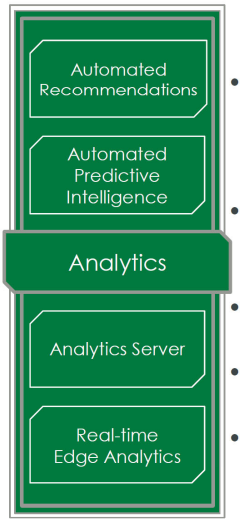
THING PREDICTOR: AUTOMATED LEARNING TECHNOLOGY

thingworx



IOT FAILURE PREDICTION

thingworx



- Enables developers to quickly and easily add analytics into the solutions they build
- Does not require expertise from a data scientist
- Detect anomalies in real time
- Predicts future outcomes
- Simulates and prescribes actions to improve future performance and results

Questions?