Haute école d'ingénierie et d'architecture Fribourg
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INTERNET DES OBJETS

WIRELESS CONNECTIVITY FOR THE INTERNET OF THINGS

SERGE AYER - HEIA-FR – TÉLÉCOMMUNICATIONS
CLASSES ISC-2D // 2023-2024

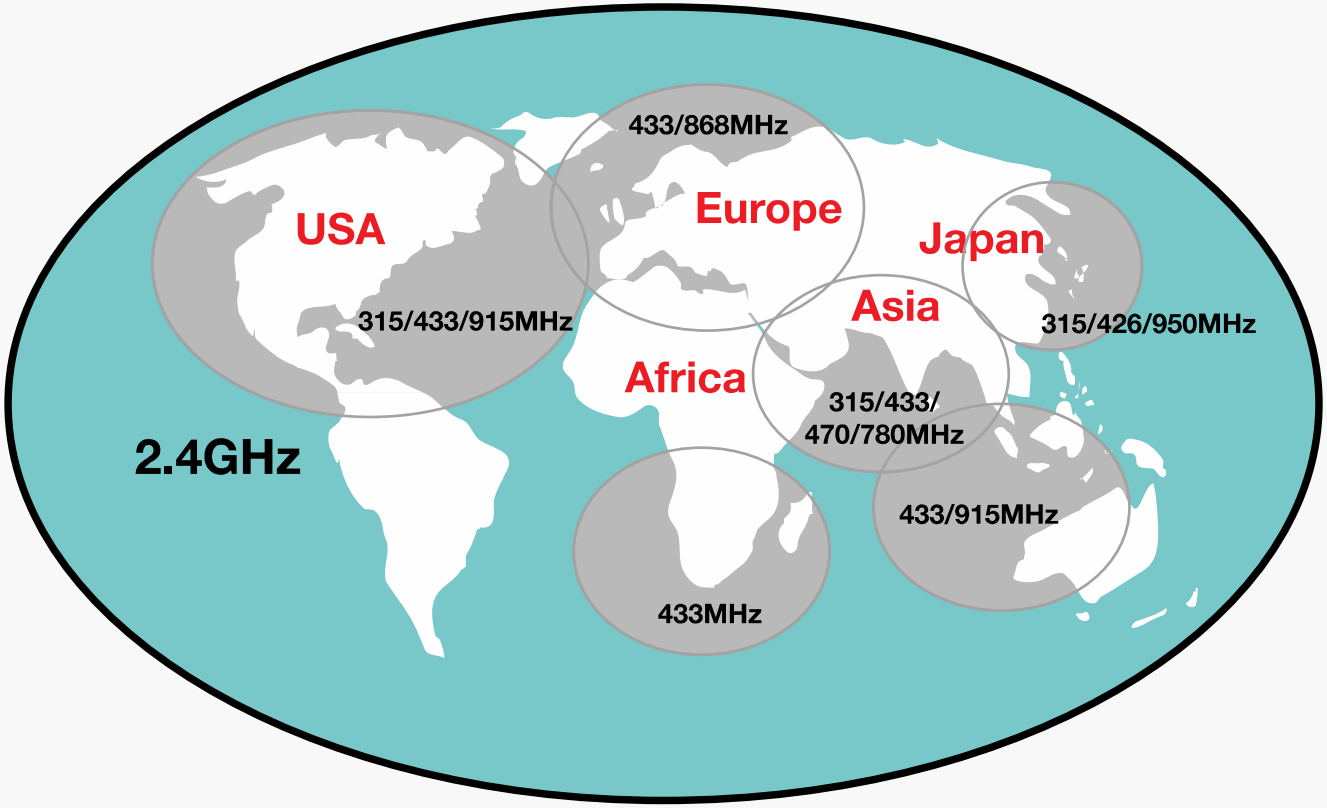
FREQUENCY BANDS AND WORLDWIDE REGULATIONS

- Radio transmissions are regulated by agencies such as
  - the Federal Communications Commission (FCC –USA)
  - the Conference of Postal and Telecommunications Administrations (CEPT – Europe)
  - the Federal Office of Communications (OFCOM - Switzerland).
- Allocation of frequency bands
  - Licensed, as for cellular communication
  - Unlicensed, as Industrial, Scientific and Medical (ISM) bands
    - 433 MHz, 868 MHz, 915 MHz, and 2.4 GHz
    - 2.4 GHz has become very popular since it is unlicensed worldwide

FREQUENCY BANDS AND WORLDWIDE REGULATIONS

- As a general rule:
  - Higher frequency bands mean
    - More channels, more bandwidth
  - Lower frequency bands mean
    - Better propagation, better range including inside buildings
  - For instance, Wi-Fi works on both 2.4 and 5 GHz ISM bands
    - 5 GHz is mainly used at the enterprise level for more bandwidth and with more access points

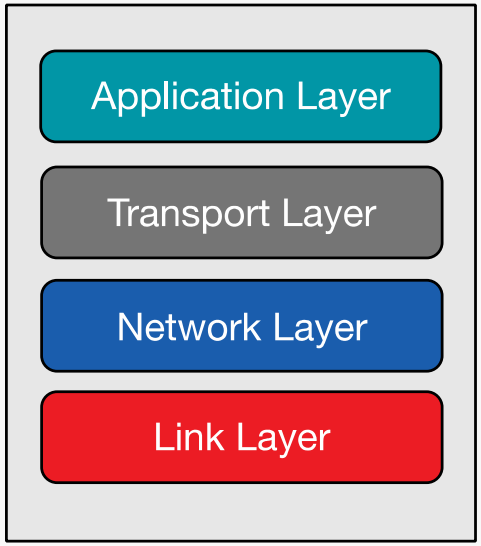
UNLICENSED FREQUENCY BANDS



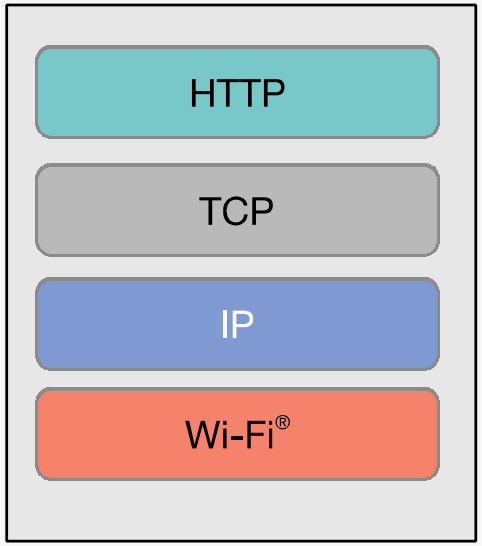
Source: Gil Reiter, TI, White paper: "Wireless connectivity for the Internet of Things"

COMMUNICATION PROTOCOLS

- Application layer:
  - Data formatting and flow
- Transport layer:
  - Communication sessions
- Network layer:
  - Addresses and data routing
- Link layer:
  - Conversion of bits to radio (and vice-versa)



The OSI network model



The TCP/IP protocol stack

LAYERED NETWORK IMPLEMENTATION

- Advantages:
  - More flexibility
  - Easier implementation of scalable and interoperable networks
- Disadvantages: the more layers, the
  - More complex
  - More code and memory
  - More data overhead

IP OR NOT IP FOR CONNECTING THINGS TO THE INTERNET ?

- Devices that are directly connected to the Internet must comply to the Internet protocols
- Can use non-IP protocols to communicate within the local network
  - Connectivity to the Internet is then achieved through an Internet gateway
  - The gateway communicates with the non-IP devices on one side and with other IP devices on the Internet on the other side

IP OR NOT IP FOR CONNECTING THINGS TO THE INTERNET ?

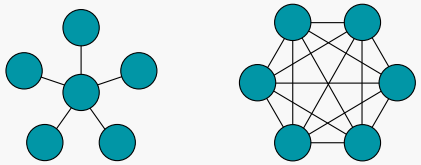
- Advantages of using IP devices on the local network:
  - The gateway can be application agnostic
    - Applications can be modified or added on the device without changing the gateway
- Disadvantages of using IP devices on the local network:
  - The IP stack is fairly complex and large
    - Requirements in processing power and memory
    - Larger data packets, requiring more power for radio transmission - This is mitigated by the use of compression technologies such as 6LoWPAN

NETWORK RANGE

- PAN:
  - About 10 meters
  - Low radio transmission power
  - Example: Wireless sensors connected to IP gateways
- LAN/WLAN
  - About 100 meters
  - WiFi
- NAN
  - About 25 kms
  - High power levels, low data traffic
  - Example: smart grid network
- WAN
  - Entire globe
  - The Internet, as a mix of wired and wireless connections

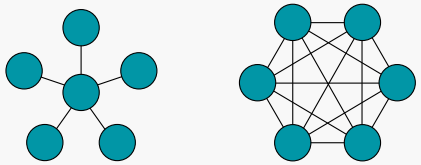
NETWORK TOPOLOGY AND SIZE

- Topology: the way nodes in the network are connected to each other
- Important for the IoT:
  - Star topology
    - The center node is acting as the Internet gateway
    - Example: WiFi with access point as center node
  - Mesh topology
    - Every node can connect to multiple other nodes
    - One or more nodes in the network serve as the Internet gateway



NETWORK TOPOLOGY AND SIZE

- Mesh topology
  - Example: ZigBee or Bluetooth Mesh
  - Extended reach though multiple hops, while maintaining low radio transmission power
  - More reliable because of multiple paths
  - More complex, requires more power



- Another important aspect to consider is the maximum number of devices that can simultaneously be connected to the network

STANDARDS AND INTEROPERABILITY

- Ability of devices from different vendors to exchange data
- Different standards
  - Defining one or several network layers
  - Defining the entire end-to-end network specifications
- IEEE (Institute of Electrical and Electronics Engineers) standards
  - IEEE 802.x family (defining the link layer of the network)
    - 802.3: Ethernet
    - 802.11: WLAN
    - 802.15.4: wireless PAN (ZigBee, 6LoWPAN, WirelessHART)

STANDARDS AND INTEROPERABILITY

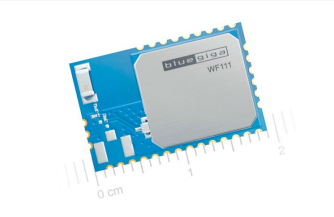
- IETF (Internet Engineering Task Force)
  - Established through RFCs (Request for comments)
  - RFC 791 (IPv4 protocol)
  - RFC 793 (TCP protocol)
  - RFC 2616 (HTTP/1.1 protocol)
- No certification program in both IEEE and IETF
- Other organizations, running certification programs
  - Wi-Fi alliance
  - Bluetooth Special Interest Group (SIG)
  - ZigBee alliance

WI-FI TECHNOLOGY

- IEEE 802.11 standard
- Defines the link layer of a local network, but is tightly integrated with the TCP/IP stack
- Integrated in almost all consumer connected products (laptops, smartphones, TVs)
- Star topology, AP as center node and Internet gateway
  - When more coverage is required, several APs are deployed
- ISM 2.4 GHz, also in the 5 GHz band

WI-FI TECHNOLOGY

- Fairly large and complex to implement
  - Not an issue with powerful microprocessors and large memory
  - Today it is possible to have silicon devices that embed the Wi-fi and TCP/IP technologies and can be integrated on systems with smaller microcontrollers (e.g. Bluegiga WF111/121)



- Wi-Fi is too power hungry to run on batteries
  - Silicon devices implement advanced sleep protocols and fast on/off times for improved power consumption
  - Enabling integration of Wi-Fi technology into IoT systems

BLUETOOTH

- Wireless technology standard for exchanging data over short distances from fixed and mobiles devices by creating personal area networks (PANs)
- Named after an ancient Scandinavian king
- Invented by Ericsson in 1994 as a standard for wireless communication between phones and computers
- Operates in the 2.4 GHz ISM band
- The Bluetooth link layer was previously standardized as IEEE 802.15.1, now controlled by the Bluetooth SIG
- Very popular in the mobile phone environment

BLUETOOTH

- Early use cases:
  - Hands-free phone calls with headsets and car kits
  - High-fidelity musing streaming
  - Health and fitness accessories
- PAN technology used as a replacement for the cable for short-range communication
- Supports data throughput up to 2 MBps
- Point-to-point or star network topology (although more complex topologies are part of the specifications)
- Supports up to eight devices connected in a star network

BLUETOOTH LOW ENERGY

- Bluetooth Low Energy (or Bluetooth Smart) was added to the specification in 2010 (part of Bluetooth 4.0)
- Enables years of operation using coin cell batteries
- Supported by the new generation of smartphones and tablets

BLUETOOTH LOW ENERGY

- Enabled a wide range of new applications spanning health and fitness, toys, automotive and industrial spaces
- Opens the door to new location-based services like beaconing and geo-fencing applications
- No limitation in the number of devices connected, although there are practical limitation (between 10 and 20)

ADVANTAGES OF BLUETOOTH LOW ENERGY

- It includes application profiles, that define in all details how application exchange information to achieve specific tasks
  - Example: Audio/Video Remote Control Profile (AVRCP) defines how a Bluetooth remote control interfaces with audio and video equipment
- Comprehensive certification program for excellent interoperability
- It is the best candidate for connecting a wireless sensor/device to a smartphone or tablet, which may act as an Internet gateway

ZIGBEE

- Transmits data over long distances by passing data though intermediate devices to reach more distant ones
- Named after the Waggle Dance that bees do when coming back from a field flight (https://www.youtube.com/watch?v=-7ijI-g4jHg)
- Analogy hints to the mesh nature of ZigBee, where data hops from node to node in multiple directions and paths throughout large scale networks
- Based on IEEE 802.15.4 link layer protocol
  - Low throughput, low power, low cost
  - Operates in the 2.4 GHz, but also in the 868 and 915 MHz ISM bands

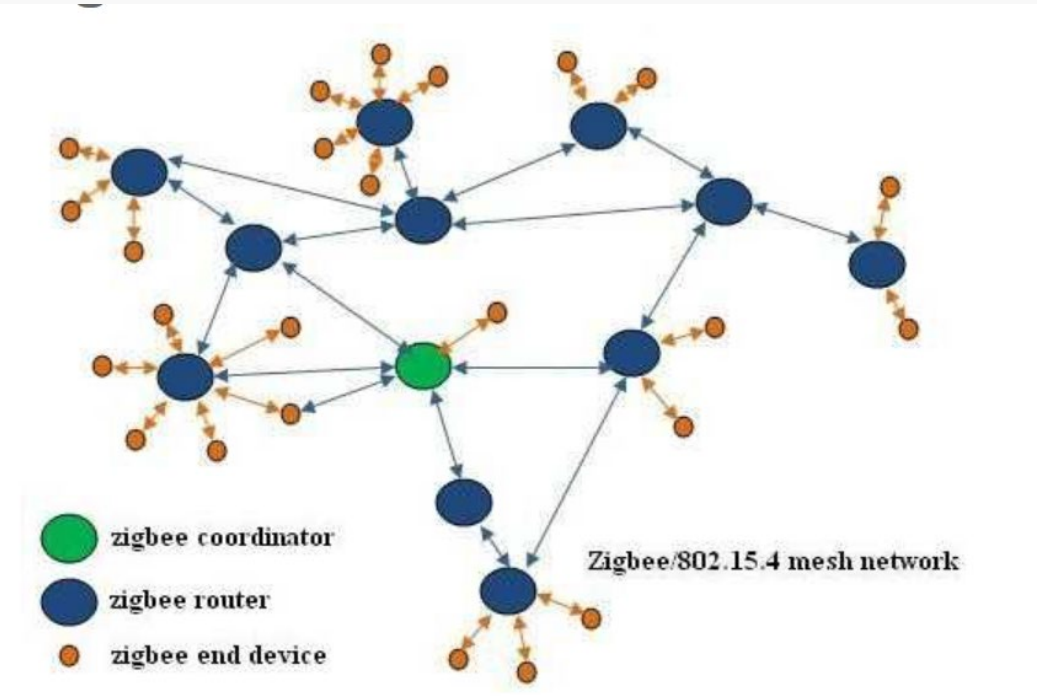
ZIGBEE

- Based on IEEE 802.15.4 link layer protocol
  - Uses two bands of operation: 868/915 MHz and 2.4 GHz
  - Can deliver up to 250 KBps (2.4 GHz) or 20-40 KBps (868/915 MHz)
  - Has the capability of maintaining very long sleep intervals and low operation duty cycles
  - Can be powered using coin cell batteries for years, or even energy harvesting techniques for battery-less operation
- Maintained by the ZigBee alliance
  - Comprehensive certification program for excellent interoperability
  - The standard also includes application profiles enabling interoperability at the system level

ZIGBEE

- Is used mainly in smart energy, home automation, medical and lighting control applications
  - Each application domain has a specific profile and certification
  - Ex. Smart energy: used to monitor and control the use of energy and water
- Using the mesh network topology, allows thousands of nodes to be connected together
- Requires an application-level gateway for Internet connectivity
  - The gateway is one of the nodes in the network
  - The gateway also runs the TCP/IP stack

ZIGBEE NETWORK TOPOLOGY



Source: http://www.rfwireless-world.com/Tutorials/Zigbee_tutorial.html

- Different roles
  - Coordinator
  - Router
  - End device
- Only the end device is intended to be battery powered
- Routing protocol
  - Ad-hoc on-demand Distance Vector Routing protocol (AODV)

ZIGBEE NETWORK PHASES

- Forming the Zigbee Network
  - Coordinator chooses the suitable RF channel, accounting for interferences
  - Coordinator starts the network (assigning PAN ID to the network)
  - Coordinator accepts join request from routers and end devices – sending broadcast beacon request frames
- Joining the Zigbee network
  - Through MAC association or network re-join
  - R/E check whether they can join the network and send an association request frame

ZIGBEE EXAMPLES

- Nest thermostat

- Hue light bulb

IP / 6LOWPAN

- IPv6 over Low power Wireless Personal Area Networks
- Defines encapsulation and header compression mechanism that allow IPv6 packets to be sent to and received from over IEEE 802.15.4 based networks (low-rate wireless PANs)
- Promise:
  - Apply IP to the smallest, lowest-power and most limited processing power device
  - One of the first wireless connectivity standard created for the IoT
  - Typically used to form LANs rather than PANs

IP / 6LOWPAN

- Formalized under IETF RFC 6282
  - Defines an efficient adaptation layer between the 802.15.4 link layer and a TCP/IP stack
  - No existing industry standard for the entire protocol stack, no certification program
  - Interoperability is not as good as for other standards
- 6LoWPAN also require a gateway to access the Internet

THREAD

- Open standard
- Reliable, cost-effective, low-power
- Wireless device-to-device
- Designed for connected home applications
  - IP-based networking
  - Variety of application layers can be used on the stack
- Simple network operation (including installation and startup)
  - Self-configuration and self-fixing of routing problems
- Secure, no single point of failure

THREAD

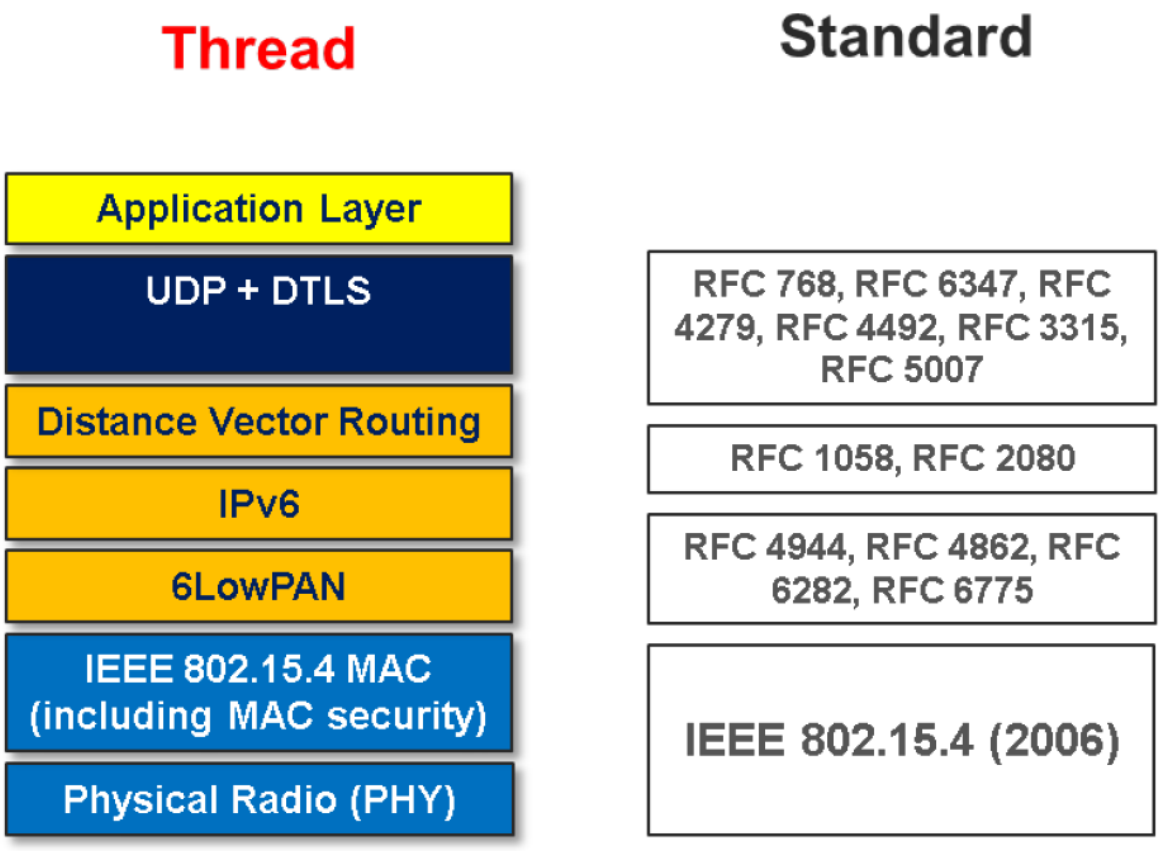


Figure 1. Overview of Thread Stack

THREAD: DEVICE TYPES

- Border routers
  - Connectivity from the 802.15.4 network to adjacent networks
  - One or more Border routers in a Thread network
- Routers
  - Provide routing services to network devices
  - Provide joining and security services for other devices
  - Can downgrade their functionality and become REEDs
- Router-eligible End Devices (REEDs)
  - Capability to become routers but not acting as such
  - Are elected to Routers by the Thread network without user interaction
- Sleeping End devices
  - Host devices communicating only through their Parent router
  - Cannot forward messages for other devices

THREAD: IP STACK

- Is IPv6 based
  - IPv6 addressing: one or more ULA or GUA.
  - Multicasting supported, including link-local all-node multicast, link-local all-router and realm-local.
  - 6LoWPAN is used for all devices
  - ICMPv6 supported
  - UDP for messaging between devices
- With a single Router or Border Router, a basic star topology is formed, otherwise a mesh topology is formed

THREAD: NETWORK TOPOLOGY

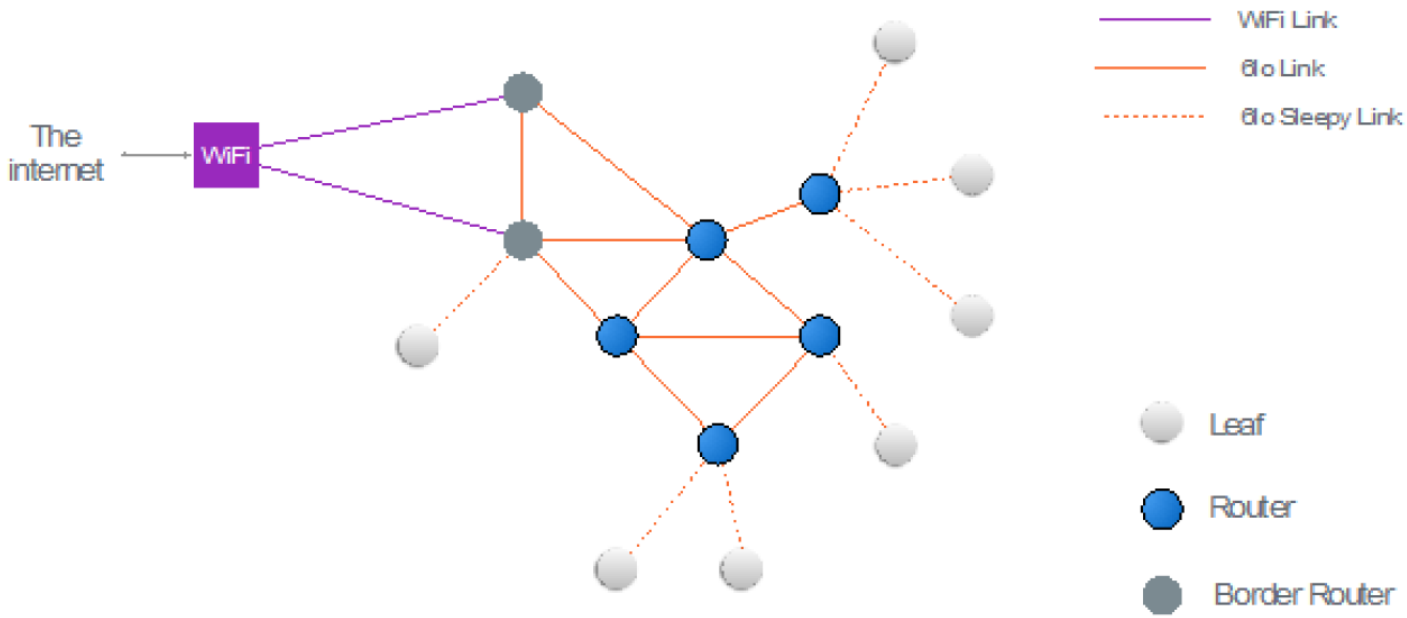


Figure 3. Basic Thread Network Topology and Devices

OTHER PROTOCOLS FOR SENSOR NETWORKS, BUILDING AUTOMATION AND HOME AUTOMATION

- BACnet
  - Stands for Building Automation and Control Networks
  - Scope of BACnet applications is very large, including HVAC (heating, ventilating, and air conditioning) applications, lighting control, fire control and alarm, security, and interfacing to utility companies
- KNX
  - Konnex (or KNX) Association was set up in 1999 for promoting intelligent homes and buildings
  - Works over twisted pairs, PLC, RF and IP
- Z-Wave
  - Popular proprietary protocol offering a wide range of devices
  - Operating in the 868 MHz Band
- Power line communication (PLC)

LONG RANGE TRANSMISSION

- Mostly proprietary radio and protocols
- Use the lower ISM frequency bands: 433, 868, 915 MHz - called Sub-1GHz solutions
- Can reach over 25 km with a simple point-to-point or star topology
- Applications:
  - Metering applications: relay meter readings in a NAN
  - Security
  - Industrial control and monitoring
- Requires the use of a application-layer Internet gateway
- Examples: LoRa, Sigfox, LTE-M

WHAT IS NEW OUT THERE ?

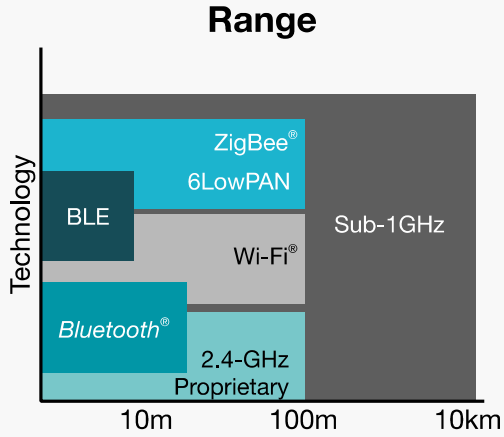
- Things connected to the Internet such as sensors, controls, home appliances, or meters hardly contain the capability to run complex networking capabilities (e.g. a full protocol stack).
- Incredible breadth and scope
  - Number of devices
  - Incredible variety of devices
    - Will be all connected in one way or another
- The way these devices communicate together and with the Internet needs to be reconsidered

HOW TO CHOOSE THE RIGHT WIRELESS TECHNOLOGY

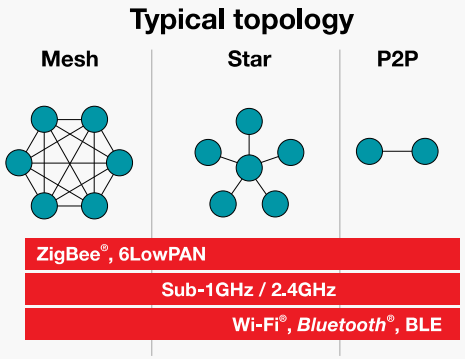
- Frequency band
  - Choose an ISM band for worldwide distribution
- IP or not IP ?
  - IP in the local network, or
  - Access to the Internet via an Internet gateway
- Interoperability
  - Interoperability with smartphones, tablets and PCs: BLE
  - Interoperability for specific applications: BLE or ZigBee
- Access to the Internet
  - Using a local gateway: BLE, ZigBee, Z-Wave
  - Using a gateway operated by a network operator: LoRa, Sigfox

HOW TO CHOOSE THE RIGHT WIRELESS TECHNOLOGY

- Network range

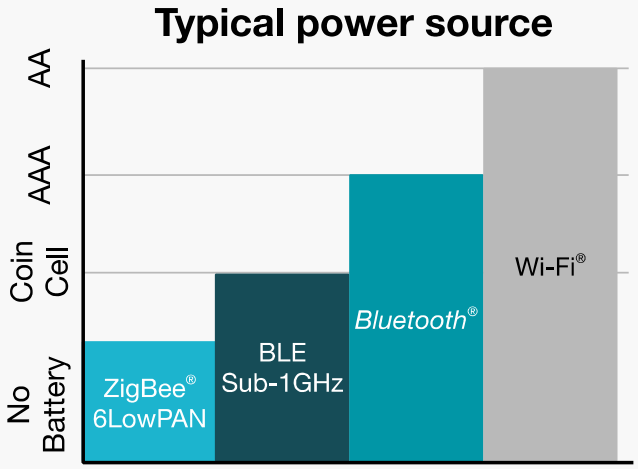


- Network topology and size

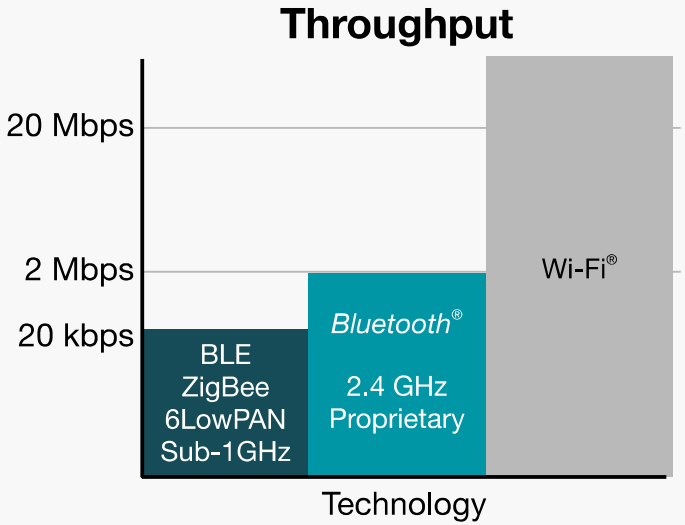


HOW TO CHOOSE THE RIGHT WIRELESS TECHNOLOGY

- Power source



- Network throughput



BLUETOOTH VS ZIGBEE

Technology	Classic *Bluetooth* technology (BR/EDR)[1]	*Bluetooth* low energy technology[2]	ZigBee
Radio Frequency	2.4 GHz	2.4 GHz	2.4 GHz
Distance / Range	10 to 100 meters[3]	10 to 100 meters[3]	10 to 200 meters[4]
Over the air Data Rate	1-3Mbps	1Mbps	250kbps at 2.4 GHz.
Application Throughput	0.7-2.1 Mbps	0.2 Mbps	<0.1 Mbps
Nodes/Active Slaves	7 / 16777184[5]	Unlimited[6]	65535[7]
Security	64b/128b and applications layer user defined	128b AES and application layer user defined	128b AES and application layer user defined
Robustness	Adaptive fast frequency hopping, FEC, fast ACK	Adaptive fast frequency hopping	DSSS, Uses only 16 ch. in ISM band, optional mesh topology has long recovery time
Latency (from a non connected state)			
Total time to send data (det.battery life)[8]	100ms	<3ms	<10ms
Government Regulation	Worldwide	Worldwide	Worldwide
Certification Body	Bluetooth SIG	Bluetooth SIG	ZigBee Alliance
Voice capable	Yes	No	No
Network topology	Scatternet	Star-bus	Star or Mesh
Power Consumption	1 as the reference	0.01 to 0.5(depending on use-case)	2 (router) / 0.1 (end point)
Peak current consumption (max 15 mA to run on coin cell battery)	<30 mA	<15 mA	<15 mA
Service discovery	Yes	Yes	No
Profile concept	Yes	Yes	Yes
Primary Use Cases	Mobile phones, gaming, headsets, stereo audio streaming, automotive, PCs, consumer electronics, etc.	Mobile phones, gaming, PCs, watches, sports & fitness, healthcare, automotive, consumer electronics, automation, industrial, etc.	Fixed location industrial, building & home automation, AMI/SmartEnergy

[Ayr/c