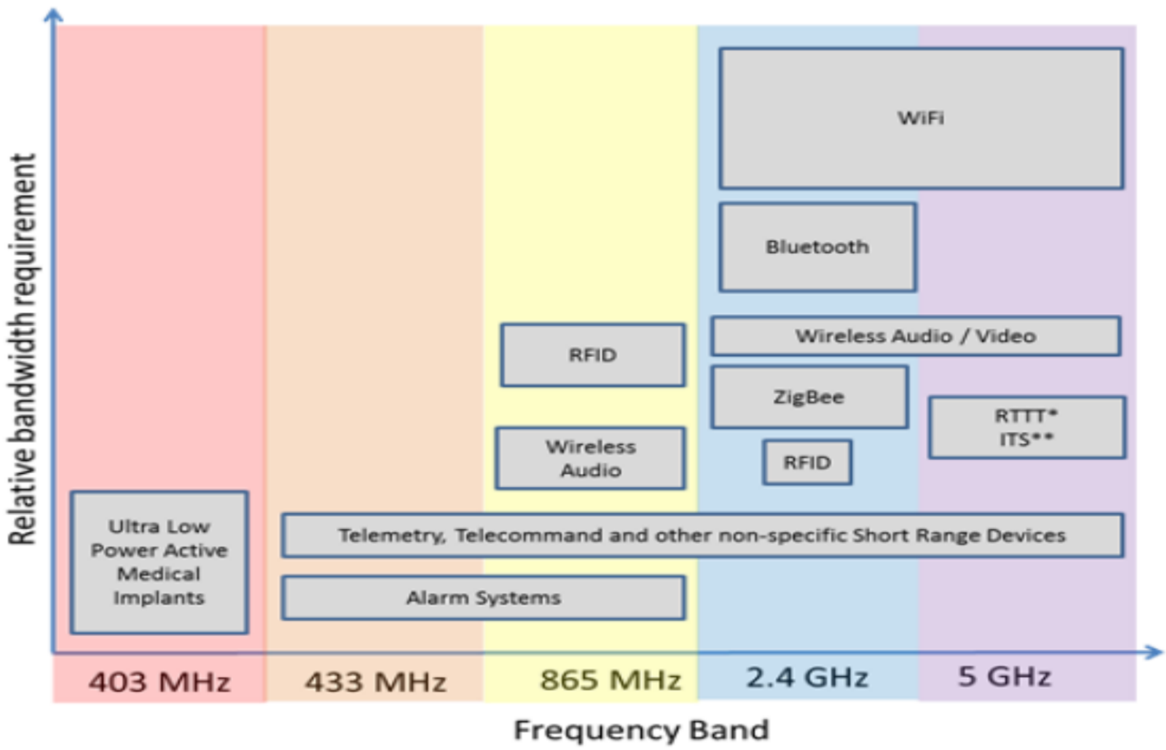
2.03 Spectrum sharing

Terms

- PMR = Personal Mobile Radio
- SRD = Short Range Device
- DECT = Digital Enhanced Cordless Telecommunications
- CSMA/CA = Carrier Sense Multiple Access / Collision Avoidance
- FSS = Fixed Satellite Service
- PAL = Priority Access License
- GAA = General Authorized Access

Relative bandwidth requirement



Benefits of unlicensed

1. Facilitating market entry
2. Quickly and cheaply using existing technology and spectrum
3. Certainty about spectrum access
4. Reduced congestion in licensed bands
5. Extend the reach of fixed communication networks

Benefits for users

1. avoiding the need for lengthy runs of cable
2. Enhanced convenience
3. reducing dependence on the mobile network

WiFi

- based on the IEEE 802.11 series of standards
- CSMA/CA interference mitigation is a key feature of the 802.11 standards, intended to facilitate equitable spectrum access between multiple Wi-Fi systems even in highly contended environments

WiFi: 1Gbps, MIMO

- 802.11n: single (2.4 GHz) or dual (2.4 / 5 GHz), incorporates MIMO antennas and wider (40 MHz) channels, over-the-air bit rate to 600 Mbps
- 802.11ac: wider channels (80 or 160 MHz), higher level modulation (256QAM), up to eight MIMO streams, over-the-air bit rate over 1 Gbps

WiFi: M2M, < 1GHz

- lower and higher frequency bands
- 802.11ah: aimed at M2M and other low bit rate applications, but may also be used to extend the coverage, provides bandwidth options of 1, 2, 4, 8, and 16 MHz

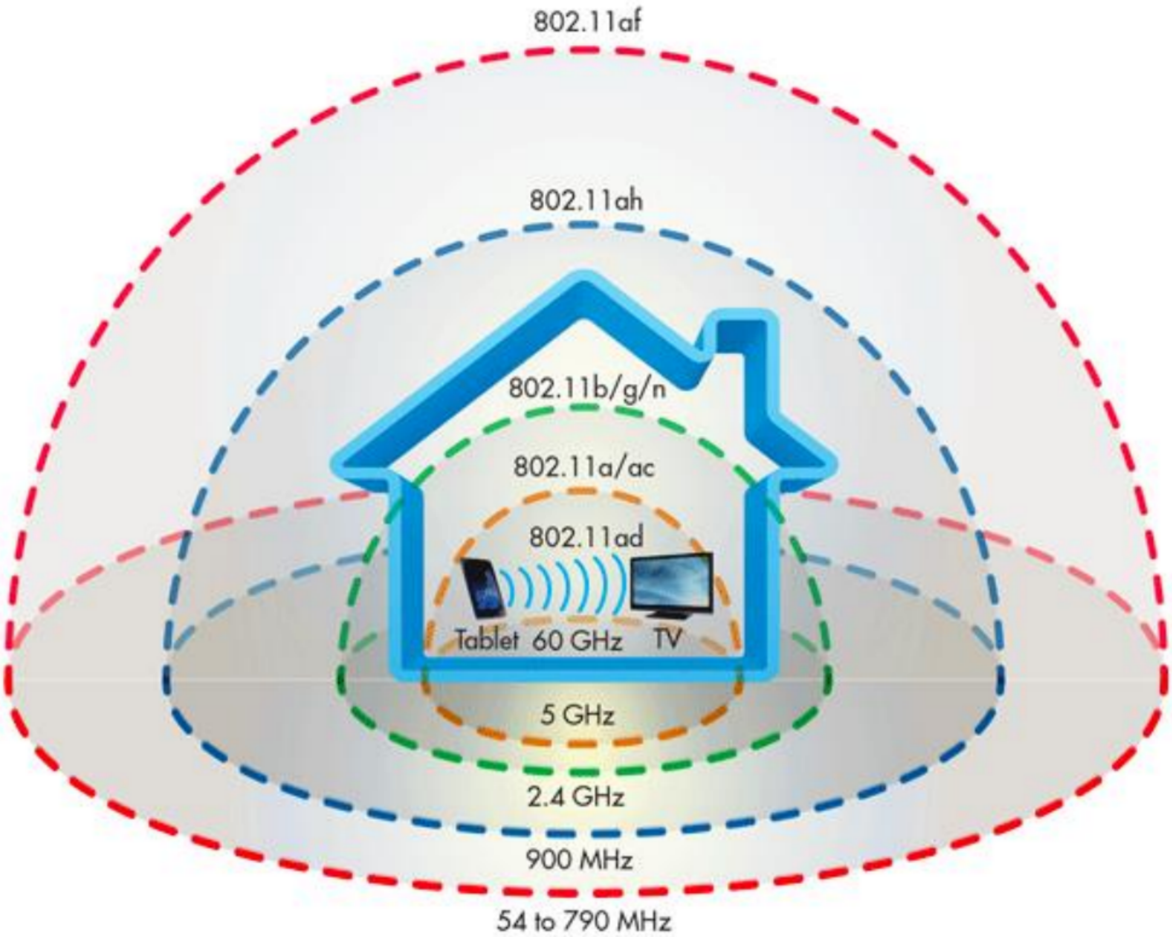
WiFi: 60GHz, ~ 7Gbps

- 802.11ad, also referred to as Wi-Gig, operates in 60 GHz millimetre wave band, for very high-speed, short-range applications
- having a total of 8 GHz of contiguous spectrum available
- Routers on the market
- up to 7 Gbps over ranges of up to 10 metres

WiFi: 60GHz, > 30Gbps

- 802.11ay: data rates in excess of 30 Gbps
- line of sight wireless backhaul and high-speed content download over very short ranges

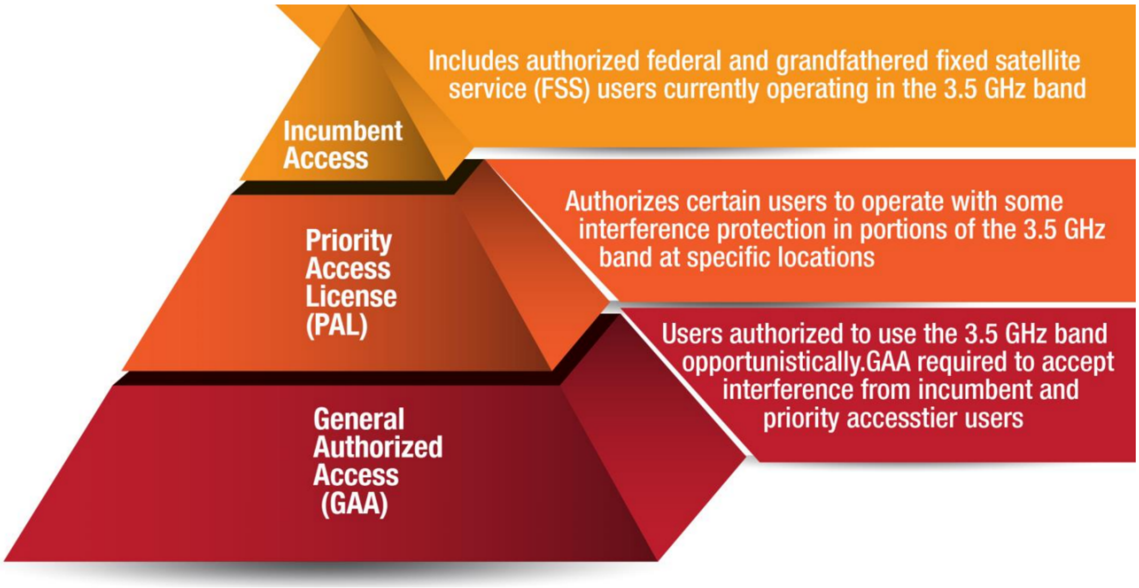
WiFi by range



5GHz

- Trade-off between capacity and coverage
- a small cell can serve a full room or a few rooms
- is relatively underutilized for now
- 60 GHz doesn’t offer useful coverage yet

Sharing the 3.5GHz band

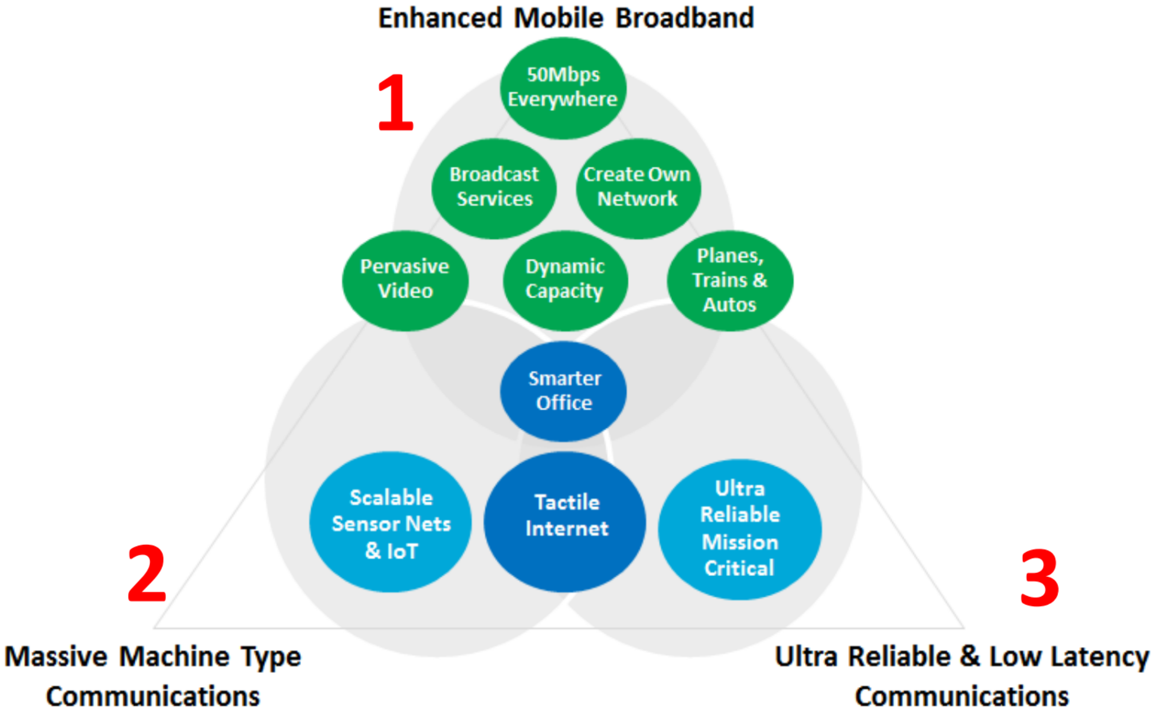


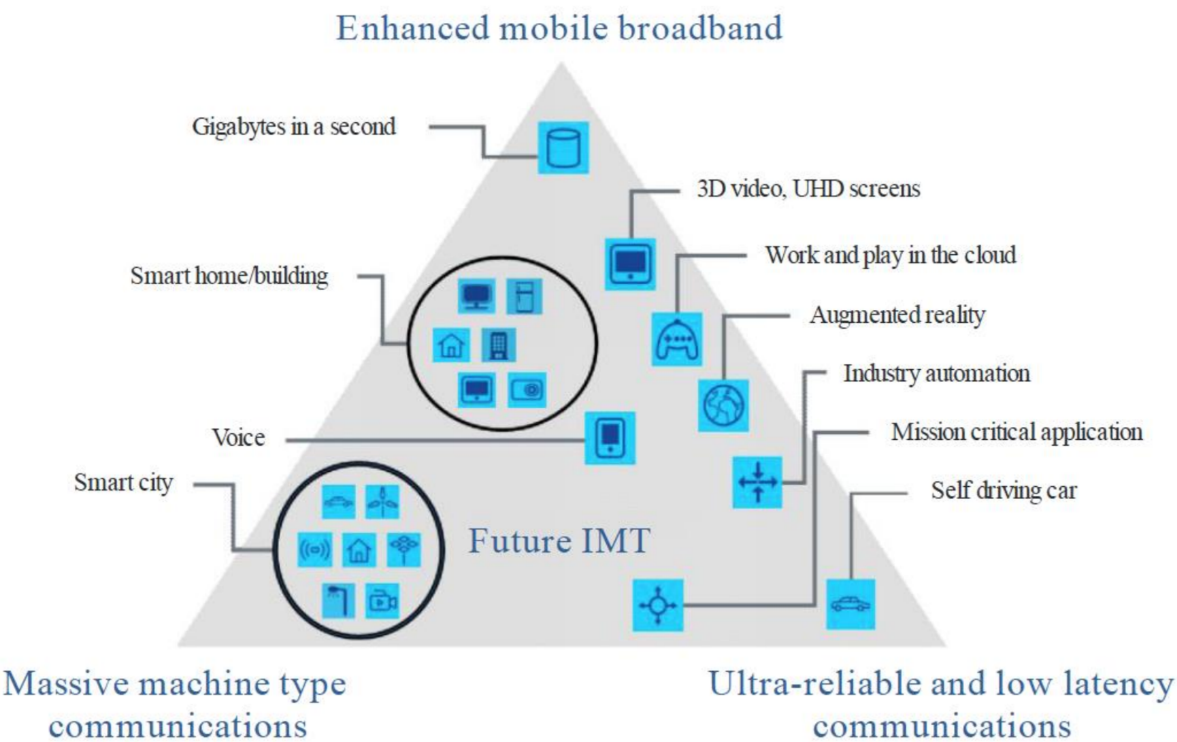
2.04 5G

Terms

- OTT = Over The Top
- SDN = Software Defined Networking
- NFV = Network Functions Virtualization
- aaS = as a Service
- DC = Data Centre
- BS = Base Station

Trade-off





Capabilities

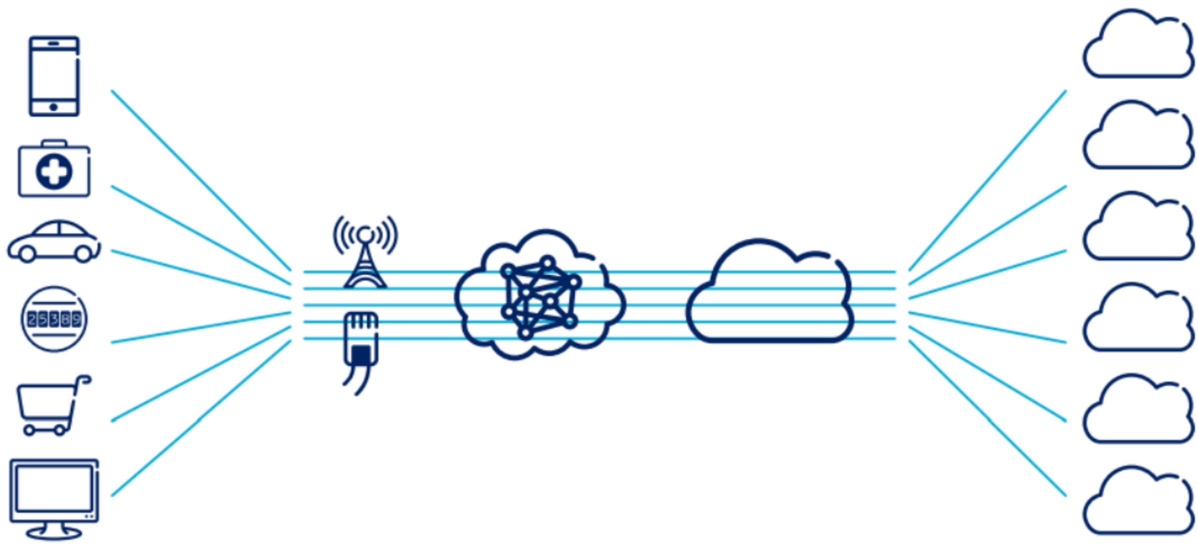
- Truly pervasive video experience
- Revolution in the smart office
- 50Mbps everywhere • Create your own network
- Support dynamic increase of capacity on the fly

- Working solution on planes, trains and cars
- Deliver a single scalable solution for sensor networks and the IoT
- Enable an ultra-reliable network for mission critical applications
- Make the realization of the tactile internet possible
- Deliver a meaningful and efficient broadcast service

Technical objectives

- 1/5 X in end-to-end latency reaching delays ≤ 5 ms.
- 1/1,000 X in service deployment time reaching a complete deployment in ≤ 90 minutes.
- Service reliability ≥ 99.999% for specific mission critical services. • Mobility support at speed ≥ 500 km/h for ground transportation.

VG



one-size-fits-all dumb bit pipe -> tailored network services

One-size-doesn't fit all

- worked well for single-service subscriber networks with predictable traffic and market growth
- Cloud, SDN and NFV technologies allow vertical systems to be broken apart into building blocks, resulting in a horizontal network architecture that can be chained together – both programmatically and virtually – to suit the services being offered and scaled

Network slicing

- Shared by multiple different user-types
- Architecture is tailored to use-type needs
- Resources allocated in a granular fashion

- Billed in a granular fashion
- Service Level Agreements (SLA) → big feature of 5G

SMART METER SERVICE

- connects a number of machine to-machine (M2M) devices with a latency and data rate
- The security level of the service is medium, and it is a data-only service that requires high availability and high reliability

SENSOR UTILITY SERVICE

- require connectivity for its fault sensors
- requires data-only coverage with high availability and robustness, and medium security and latency
- can be configured with different network functions to enable higher levels of security, or near-zero latency

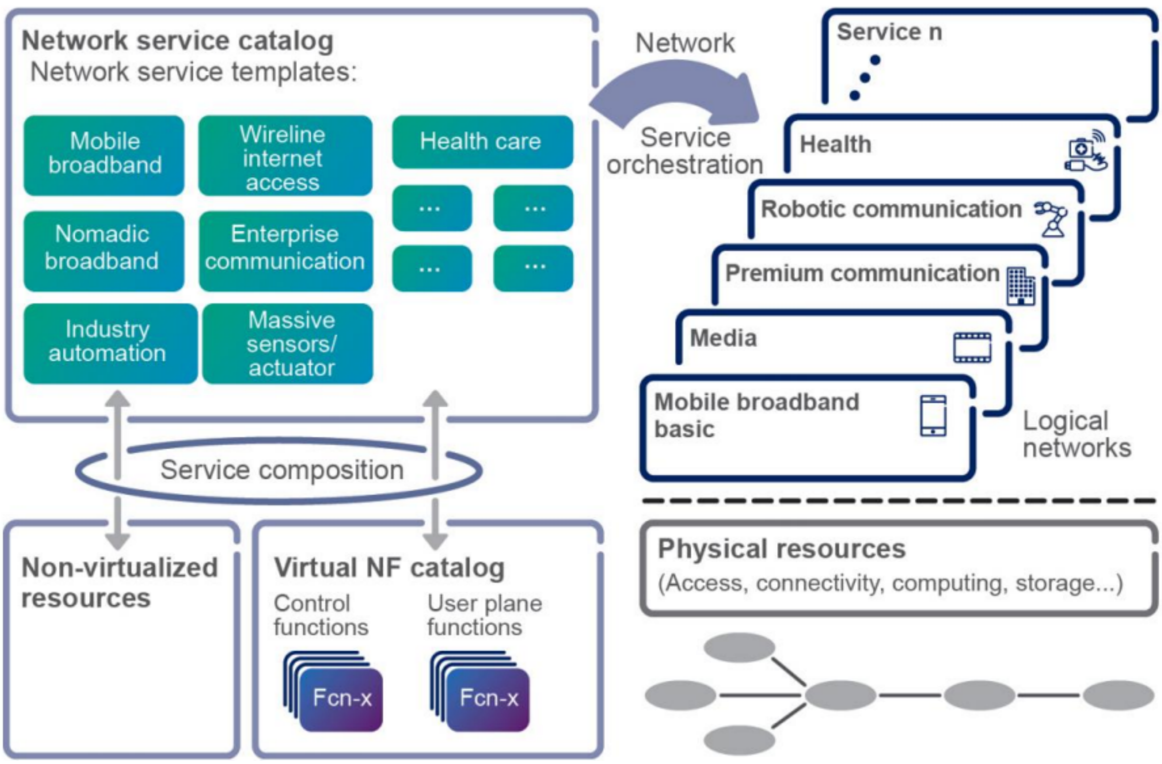
Software Defined Networks

- provide an abstraction of the physical network infrastructure
- SDN allows several network slices - customized and optimized for different service deployments - to be configured using the same physical and logical network infrastructure

Network Function Virtualisation

- NFV allows a network function to be implemented programmatically instead of by a physical piece of hardware
- flexibility to execute network functions independently of location

5G: programmable, dynamic



2.05 Internet of Things

Terms

- IoT = Internet of Things
- IIot = Industrial Internet of Things
- MTC = Machine-Type Communications
- SCADA = Supervisory Control And Data Acquisition
- LPWAN = Low Power Wide Area Networks
- BOM = Bill of Materials
- MAC = Media Access Control
- LoRa = Long Range
- RPMA = Random Phase Multiple Access
- ETSI = European Telecommunications Standards Institute
- RAN = Radio Access Network

MTC requirements

Massive MTC

- Architecturally simple devices: low-complexity transmission mode
- Long battery life devices
- Long transmission ranges for devices

- Scalable networks

Massive IoT/MTC

- very large numbers of devices, usually sensors and actuators
- low cost, long battery life
- mobile network may be used to bridge connectivity

Critical IoT (and the challenges for 5G)

- traffic safety/control, control of critical infrastructure and wireless connectivity for industrial processes
- Automotive, energy utilities, Industrie 4.0
- Real-time, latency at millisecond levels
- very high reliability and availability
- wide instantaneous bandwidths
- wireless control
- increased resilience and robustness
- support for critical device-to-device communications
- network slice can be configured so that network and application functions are physically placed
- have points of presence for data storage/computation much closer to where the control is required

Both Massive and Critical IoT (the bigger challenge for 5G)

- From network being able to handle as many different applications as possible, by means of the same basic wireless-access technology and within the same spectrum
- without having to deploy a separate network
- reduced signalling

Low Power Wide Area Networks

- supports small messages
- long battery life (10 years)
- accessing sensors in awkward spots
- Supports the creation of public networks that serve multiple uses and users

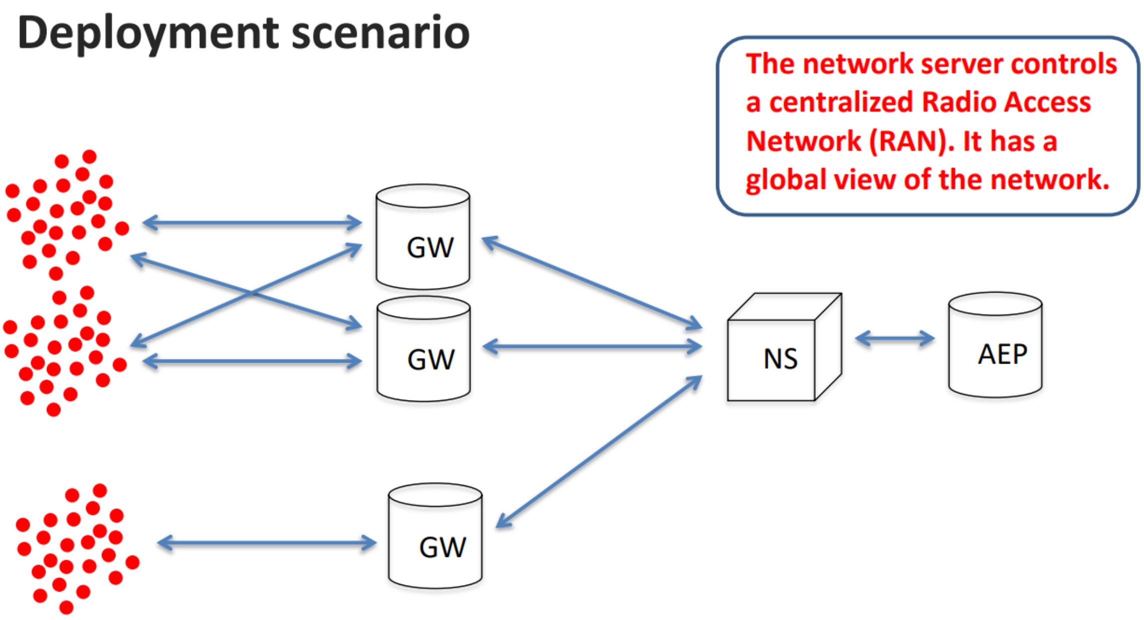
LPWAN aims

- A vast number of cheap devices that transmit bursty, small, infrequent messages
- better range and penetration
- exceed the radio link budget of 2G's GPRS by 20 dB
- 50,000 to 100,000 devices per square kilometre/cell in Non-Line Of Sight (NLOS) urban areas
- In LOS situations the aim is > ~15km range, operate in sub-1GHz
- bill of materials (BOM) for the devices must be very low
- minimum from a cost and power usage

- impacts the amount of handshaking, which directly impacts QoS levels
- allow thousands of devices to connect with small messages, rather than the current situation of fewer devices and larger capacity demands
- Challenges also centre around the immaturity of the application space

LoRa (Long Range)

- operates in the 868 MHz band
- anyone can deploy a base station, similar innovation potential to Wi-Fi
- uncertain QoS
- only controlled by lightweight duty-cycle and power rules originally designed for Short Range Devices, unlike an LPWAN deployed in licensed spectrum → ETSI rules
- large link budget Up to 154 dB (range/penetration) by using spread spectrum-based PHY
- allows for different spreading factors
- allows the LPWAN cells to breathe
- 250 bps to 50 kbps
- Battery based end-devices



Queuing systems

a/b/m/K notation (Kendall's notation)

- a = type of arrival process
  - M (Markov) denotes Poisson arrivals, so interarrival times are iid, exponential random variables
- b = service time distribution
  - M (Markov) denotes exponentially distributed
  - D (Deterministic) denotes constant service times
  - G (General) denotes iid service times following some general distribution

- m = number of servers
- K = maximum # of customers allowed in the system

M/M/1 queue

Little's law

The expected number in the system (queue) is the product of the arrival rate and the average time spent in the system (queue)

$$E[n] = \lambda E[\tau]$$

M/M/1 model

- Single-server system
- Arrivals according to Poisson process of rate λ
- Inter-arrival times exponential r.v.'s
- Service times exponential r.v.'s with mean 1/μ
- Infinite buffers

Probability mass function

- $\rho = \lambda / \mu < 1$ (called utilization)
- p_n denotes the probability that n customers are currently in the system

$$p_0 = (1 - \rho)$$

$$p_n = \rho^n p_0 = \rho^n (1 - \rho)$$

Average number in the system

$$E[n] = \sum_{j=0}^{\infty} j p_j = \frac{\rho}{1 - \rho}$$

Average delay

$$E[\tau] = \frac{1}{\lambda} \frac{\rho}{1 - \rho} = \frac{1}{\mu - \lambda}$$

average waiting time

$$E[\tau_Q] = E[\tau] - E[s] = E[\tau] - \frac{1}{\mu} = \frac{1}{\mu}\frac{\rho}{1-\rho}$$

Average number in the queue

$$E[n_q] = \lambda E[\tau_Q] = \frac{\rho^2}{1-\rho}$$

Other M/M/… queues

Other Markov queuing systems

- M/M/1/N: finite buffer (system capacity = N)
- M/M/m: m servers (rather than 1)
- M/M/: infinite number of servers (no queuing)
- M/M/m/m: m servers without queuing

M/M/1/N queue

$$P_n = \left(\frac{\lambda}{\mu}\right)^n P_0, \quad 0 \le n \le N$$

$$P_n = \frac{(1-\rho)\rho^n}{1-\rho^{N+1}}, 0 \le n \le N$$

$$\bar{n} = E[n] = \sum_{n=0}^{N} nP_n = \frac{\rho}{1-\rho} - \frac{(N+1)\rho^{N+1}}{1-\rho^{N+1}}$$

Blocking probability

the probability that an arriving customer will find the system full

```
Blocking probability:  $P_N$
Rate of rejected customers:  $\lambda P_N$
```

M/M/∞

- with an infinite number of servers
- self-service activity
- No queuing delay, only service time
- expected number in the system is N = λ / μ
- average delay per customer: T = N/λ = 1 / μ

$$P_n = \left(\frac{\lambda}{\mu}\right)^n \frac{P_0}{n!} = \left(\frac{\lambda}{\mu}\right)^n \frac{e^{-\lambda/\mu}}{n!}$$

M/M/m queue

- m servers
- **define ρ as λ / (mμ)**

$$\lambda(n) = \lambda$$

$$\mu(n) = \begin{cases} n\mu & 0 \le n \le m \\ m\mu & n \ge m \end{cases}$$

$$P_Q = \frac{(m\rho)^m}{m!(1-\rho)} P_0 = \left(\frac{1}{m!}\right)\left(\frac{\lambda}{\mu}\right)^m \frac{1}{(1-\rho)} P_0$$

expected number in the queue

$$N_Q = P_Q \frac{\rho}{(1-\rho)}$$

expected time in queue

$$W = \frac{N_Q}{\lambda} = \frac{\rho P_Q}{\lambda(1-\rho)} = \frac{P_Q}{m\mu - \lambda}$$

Expected delay per customer

$$T = \underbrace{\frac{1}{\mu}}_{\text{service delay (= 1/service rate)}} + \underbrace{W}_{\text{queuing delay}} = \frac{1}{\mu} + \frac{P_Q}{m\mu - \lambda}$$

Expected number in the system

$$N = \lambda T = \frac{\lambda}{\mu} + \frac{\lambda P_Q}{m\mu - \lambda} = m\rho + \frac{\rho P_Q}{1-\rho}$$

M/M/m/m queue

- Queuing is not allowed

$$\lambda(n) = \lambda \quad n = 0, 1, \ldots, m-1$$

$$\mu(n) = n\mu \quad n = 1, 2, \ldots, m$$

blocking probability

$$P_m = \left(\frac{\lambda}{\mu}\right)^m \frac{P_0}{m!} = \frac{\left(\frac{\lambda}{\mu}\right)^m \frac{1}{m!}}{\sum_{n=0}^{m} \left(\frac{\lambda}{\mu}\right)^n \frac{1}{n!}} = B$$

"B" = Blocking

M/G/1 queue

Average service time

$$\overline{X} = E\{X\} = 1/\mu$$

Second moment of service time

$$\overline{X^2} = E\{X^2\}$$

P-K formula

expected waiting time in queue

$$W = \frac{\lambda \overline{X^2}}{2(1-\rho)}$$

ρ is the utilization

$$\rho = \lambda/\mu = \lambda \overline{X}$$

expected total time

$$T = \overline{X} + W = \overline{X} + \frac{\lambda \overline{X^2}}{2(1-\rho)}$$

expected number of customers in queue

$$N_Q = \lambda W = \lambda \left[\frac{\lambda \overline{X^2}}{2(1-\rho)} \right] = \frac{\lambda^2 \overline{X^2}}{2(1-\rho)}$$

expected total number of customers in the system

$$\begin{aligned} N &= \lambda T = \lambda \left(\overline{X} + W \right) \\ &= \lambda \overline{X} + \frac{\lambda^2 \overline{X^2}}{2(1-\rho)} = \rho + \frac{\lambda^2 \overline{X^2}}{2(1-\rho)} \\ &= \underbrace{\rho}_{\text{utilization}} + \underbrace{N_Q}_{\text{customers in queue}} \end{aligned}$$

Traffic models

Poisson Process

$$P[(N(t+\tau) - N(t)) = k] = \frac{e^{-\lambda \tau} (\lambda \tau)^k}{k!}, \mathrm{k} = 0, 1, \ldots$$

Burstiness

- Deterministic traffic is not bursty
- Poisson process (in continuous time) and Bernoulli process (in discrete time) are bursty as single processes
- Self-similar traffic is not smoothed through aggregation ➢ Maintains its burstiness at any time scale

Self-similar phenomena

- We are concerned with time series and stochastic processes that exhibit selfsimilarity with respect to time
- Self-similar phenomena have structure at arbitrarily small scales

- A self-similar structure contains smaller replicas of itself at all scales
- Contrast with Poisson traffic, where clustering occurs in the short term but traffic smoothes out over the long term