

# 2024 - Short Questions

Thursday 13 November 2025 17:05

Which one among the following characteristics does not refer to path loss?

- a) The signal attenuates with distance
- b) It can also happen in Line of Sight (LoS) conditions
- c) It models the attenuation from obstacles
- d) The signal power attenuation is proportional to  $\frac{1}{d^2}$ , where d is the distance between transmitter and receiver

Ans - C: path loss does NOT model the attenuation from obstacles

Which one among the following statements does not relate to a millimetre Wave (mmWave) communication system?

- a) It can provide high link data rates
- b) It can easily support mobility
- c) It can leverage insights from WiGig standard
- d) It needs to use highly directional antennas

Ans - B: mmWave design CANNOT easily support mobility

mmWave has a huge bandwidth so it has the capacity to provide high link data rates

It can leverage insights from WiGig standard (60GHz)

mmWave signals weaken very quickly so highly directional antennas can be used to mitigate this

mmWave experiences difficulty in mobility because beams must constantly track the user and signals are easily blocked

Which one among the statements about Cellular Automata (CA) is correct?

- a) The state value of cell n at time t+1 only depends on the state value of cell n at time t
- b) The state value of cell n at time t+1 only depends on the state value of the neighbouring cells at time t
- c) The state value of cell n at time t only depends on the state value of the neighbouring cells at time t
- d) The state value of cell n at time t+1 only depends on the state value of cell n at time t and on the state value of the neighbouring cells at time t

Ans - D: the state value of cell n at time t+1 only depends on the state value of the cell n at time t and on the state value of the neighbouring cells at time t.

The cell in the cellular automata must also pay attention to its own current state value before changing its state value depending on its neighbours.

The cell may not require a change based on its neighbours if it is already in the correct state

Which one among the statements about a Reconfigurable Intelligent Surface (RIS) is incorrect?

- a) It consists of a planar surface with a small amount of reconfigurable elements
- b) It can adjust the propagation of incident signal via phase changes
- c) It can adjust the propagation of incident signal via amplitude changes
- d) It consumes little energy

Ans - A: Reconfigurable Intelligence Surface does NOT consist of a planar surface with a small amount of reconfigurable elements.

RIS is a large surface which consists of a very large number of tiny reconfigurable elements

Why is wavelength dependent gain in optical amplifiers a problem for optical transmission networks?

- a) Because it reduces the number of channels that can be used in an amplified WDM system
- b) Because it causes additional polarisation mode dispersion to some of the channels
- c) Because it causes additional chromatic dispersion to some of the channels
- d) Because it leads to different channels being amplified differently and thus having different OSNR.

Ans - D: Because it leads to different channels being amplified differently and thus having different OSNR

Given several equal instances of the following quantum state  $|\psi\rangle = \frac{\sqrt{2}}{5}|0\rangle + \frac{\sqrt{3}}{5}|1\rangle$ .

What probabilities can you infer if you measure the multiple instances of that state?

- a) There is not sufficient information to determine the probability of getting a 0 or a 1.
- b) The probability of getting 0 is 40% and the probability of getting 1 is 60%
- c) The probability of getting 0 is 20% and the probability of getting 1 is 30%
- d) The probability of getting 0 is 50% and the probability of getting 1 is 50%

Ans - B: the probability of getting 0 is 40% and the probability of getting 1 is 60%.

Make sure to pay attention to where the  $\sqrt{\quad}$  symbol is. When it is on the bottom, it is indicating an entanglement.

When you measure a qubit, you take the square of the amplitude

$$\left(\frac{\sqrt{2}}{5}\right)^2 = \frac{2}{5} \text{ \& } \left(\frac{\sqrt{3}}{5}\right)^2 = \frac{3}{5}$$

Given several equal instances of the following quantum state:

$|\Psi\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$ . What happens if you measure the first qubit and the results is 1?

- a) The second qubit has 50% probability of being 0 and 50% probability of being 1
- b) The second qubit has 100% probability of being 1
- c) The second qubit has 100% probability of being 0
- d) It is not possible to estimate the probability of the outcome following a measurement of the second qubit

Ans - C: the second qubit has a 100% probability of being 0

This is due to entanglement of the qubits. Once the state of the first qubit is revealed, then the state of the second qubit must be known.

Which one among the following statements about entangled qubits is false?

- a) Since entanglement works instantly at any distance, it can be used to transmit information faster than the speed of light
- b) Entanglement can be used to teleport the information of one qubit at any distance
- c) Entanglement can be produced in a quantum circuit using a Hadamard gate followed by a CNOT gate
- d) Bell states are maximally entangled states

Ans - A: since entanglement works instantly at any distance, it does not mean that it can be used to transmit information faster than the speed of light. Quantum entangled qubits still must obey the laws of physics.

# 2024 - Shannon / System Design

Thursday 13 November 2025 17:39

In the following equation:

$$C = m \cdot B \log_2 \left( 1 + \frac{S}{N} \right) \quad (1)$$

C represents the channel capacity [bps], B the system bandwidth [Hz], S the useful signal power [W], N the noise power [W], and  $m = R_s \cdot O_m \cdot R_c$ , where  $R_s$  is the multiple antenna spatial rate,  $O_m$  is the modulation order [bits / modulated symbol], and  $R_c$  is the channel coding rate. Assume that  $\frac{S}{N} = 1$ .

(a) Assume the following system components are available:

- Multiple antenna schemes: spatial multiplexing mode with a spatial rate of 2, 3, or 4;
- Modulation schemes: QPSK, 8-PSK, 16-QAM;
- Channel coding rates: 1/4, 1/2, 3/4;
- Bandwidth: 100 MHz, 150 MHz, 200 MHz.

One wants to achieve a channel capacity equal to 1 Gbps or higher. Outline two systems obtaining that by using the above-mentioned system components.

Bandwidth is similar to that of broadcast or digital TV which operates around 100-200MHz

(b) Considering equation (1) above, suppose that an adaptive system can switch among the below configurations A, B and C, where:

- A = {spatial rate = 4, 16-QAM modulation, channel coding rate = 3/4}, if the user is positioned close to the base station, where  $\frac{S}{N} = 100$  (or 20 dB);
- B = {spatial rate = 3, 8-PSK modulation, channel coding rate = 1/2}, if the user is positioned in an intermediate region between the base station and the cell edge, where  $\frac{S}{N} = 10$  (or 10 dB);
- C = {spatial rate = 2, QPSK modulation, channel coding rate = 1/4}, if the user is positioned close to the cell edge, where  $\frac{S}{N} = 1$  (or 0 dB).

If we assume a uniform probability distribution for the three user position regions, calculate the average spectral efficiency of the adaptive system.

In case you want to provide a better service to mobile users that are positioned far away with respect to the base station, what values

**(choosing between 'high' and 'low' values) of coding rate, modulation order and multiple antenna spatial rate should you choose? What will be the impact of the above choice on the system's spectral efficiency? Motivate your answers.**

# 2024 - Kendall's Notation

Thursday 13 November 2025 17:39

**In a single server system, arrivals can be modelled as a Poisson process with rate of 2 min<sup>-1</sup> and the service times are exponentially distributed with mean 20 s.**

• Give the Kendall's notation, motivating your choice.

M/M/1

a: Arrivals which can be modelled as a Poisson process are considered Markovian arrivals (M)

b: Service time distributions which are exponential are also considered Markovian (M)

These arrivals and services are called M because the resulting queue can be modelled as a Markov chain. When an arrival is made into the queue, the Markov chain progresses into the next state. When a customer is processed by the service, the Markov chain regresses back into the former state.

m: It is explicitly stated in the question that there is 1 server

K: Irrelevant, there are no limits to who can be in the queue

• Calculate the average number of customers in the system.

2 customer is arriving into the system every minute  $\lambda$

1 customer is serviced every 20 seconds.

3 customers are serviced every minute.  $\mu$

The system utilisation is  $\lambda/\mu$

$p = 2/3 = 0.6666667$  seconds

The average number of users in the system

$L = p/(1-p) = (2/3)/(1/3) = 2$

• Calculate the average delay and the average waiting time.

The average delay is the time spent in the *entire system*, from queue to the point where servicing is finished.

The average system delay can be modelled by Little's law which is  $1/\lambda - \mu$  or  $L/\lambda$

$L/\lambda = 2 / 2 = 1$  second

The average waiting time is the time spent in the *queue*.

Taking the average number of customers in the queue and dividing this by  $\lambda$  gives the average time spent in the queue.

$1.3333333333 / 2 = 0.66666666665$  seconds

• Calculate the average number of customers in the queue.

$p^2/(1-p) = (2/3)^2/(1/3) = 1.33333333333$  customers

• What happens to the average number of customers in the system, if service times are exponentially distributed with mean 30 s? Why?

With a service time distribution of 30 seconds, 2 customers are being serviced every minute.

This makes the utilisation of the system  $2/2 = 1$

The system is then running at full utilisation

This means that the queue can grow to infinity.

**In a certain system the arrivals, which can be modelled as a Poisson process, occur at a rate of one every 50 ms, and the service times are exponentially distributed with mean 3 s. Also, there is no limit in the number of servers available.**

• Give the Kendall's notation, motivating your choice.

M/M/ $\infty$

a: Arrivals which can be modelled as a Poisson process are considered Markovian arrivals (M)

b: Service time distributions which are exponential are also considered Markovian (M)

These arrivals and services are called M because the resulting queue can be modelled as a Markov chain. When an arrival is made into the queue, the Markov chain progresses into the next state. When a customer is processed by the service, the Markov chain regresses back into the former state.

m:  $\infty$ , it is explicitly stated that the number of servers could be infinite

K: Irrelevant, there should not be any need for a queue if there is an infinite number of servers

One customer arrives into the system every 50ms

1/50 customers arrive into the system every ms

20 customers arrive into the system every second  $\lambda$

One customer is serviced every 3 seconds.

1/3 customers are serviced every second  $\mu$

The utilisation of the system is  $\lambda/\mu$   
 $20 / (1/3) = 60$

- **Calculate the average number of customers in the system.**

For a system where the number of servers is infinite, the average number of customers in the system is simply equal to the utilisation formula.

Therefore there is an average of 60 customers in the system

- **Calculate the average delay per customer.**

In a system where the number of servers is infinite, the average system delay is simply equal to the service time. The average delay per customer is 3 seconds.

- **Calculate the average queuing delay. What do you notice? Why it is so?**

There is no queuing delay in a system where there is an infinite number of servers. Each new arrival can simply access a different server if some other server is occupied.

# 2024 - Describing Optical Networks

Wednesday 19 November 2025 21:21

**a) Describe what is the use of modulation in optical communications, the different types of modulation you know, considering both direct detection and coherent detection.**

**Use:**

Modulation in Optical Communications is used to:

1. Encode information onto an optical carrier
2. Improve spectral efficiency - using more bits per unit bandwidth
3. Increase reach by choosing formats robust to noise, dispersion and nonlinearities
4. Support advanced receivers such as coherent detectors that decode amplitude, phase and polarisation.
5. Enables multiplexing (WDM)

Without modulation, a laser output is constant and carries no information

**Types:**

**Direct Detection** measures **optical power only (no phase recovery)**. Thus, the modulation must be intensity based.

An example of direct detection modulation is **on-off keying**, where when the transmit power is on, the bit encoded is equal to 1 and when the transmit power is off, the bit encoded is equal to zero. Direct detection modulation systems are **simpler** to build than coherent systems.

**Coherent systems** use a **local oscillator** to recover both the **phase and the amplitude** of the signal, unlike direct detection modulation which cannot recover the phase. This enables much **higher spectral efficiency**.

An example of coherent detection modulation is Phase Shift Keying (**PSK**), Quadrature Amplitude Modulation (**QAM**) and Orthogonal Frequency Division Multiplexing (**OFDM**).

PSK: BPSK, QPSK, 8-PSK, information is encoded in the optical phase

QAM: Encoded data in both the amplitude and the phase (16-QAM, 64-QAM) can encode a different number of bits per symbol depending on type of QAM used.

OFDM: Multi-carrier modulation. Strong against dispersion but more complex

Coherent detection enables **higher-order modulation** and **higher data rates**.

Coherent systems let the receiver fix pulse spreading using software instead of adding extra fiber

Coherent detection is **more sensitive**, allowing **operation at lower input** power.

Coherent systems are more complex due to the use of local oscillators and advanced digital signal processing.

**b) Describe the different types of fibre dispersion, which one is more severe in multi mode and single mode fibre and what is their effect on a transmission channel.**

In multimode fibre, **modal dispersion** is the most severe form of dispersion.

In single mode fibre, **chromatic dispersion** is the most severe form of dispersion.

Dispersion refers to different portions of the optical signal arriving at different times, causing pulse broadening and inter-symbol interference.

**Modal Dispersion** occurs from two different modes taking different paths. This therefore does not exist in single-mode fibre.

Modal dispersion causes **severe pulse spreading**, and severely limits the bandwidth

**Chromatic Dispersion** occurs from **different wavelengths** travelling at **different speeds**.

The **refractive index varies** with the wavelength and the **wavelength propagation** is affected.

In coherent systems, this is mitigated by **dispersion compensating fibre**.

**Polarisation Dispersion** occurs as two **polarisation axes** may have slightly different angles.

This effect is **small** compared to chromatic dispersion but important for **high bit rates**

It causes intersymbol interference through a timing **jitter** and is **harder to compensate**

**c) Describe the meaning of optical signal to noise ratio for a transmission channel, how it evolves in an amplified transmission system with multiple spans and how it is calculated for a chain of 5 amplifiers.**

OSNR is the optical signal to noise ratio.

It is the ratio of signal power to amplified spontaneous emission (ASE) noise power.

High OSNR --> clean signal

Low OSNR --> noisy signal.

Every optical amplifier adds:

G: gain to compensate the effects of path loss in fibre

ASE: noise with a noise figure NF

After each span:

Signal power remains roughly consistent (loss + gain = 0)

Noise accumulates

OSNR degrades with each amplifier

For N identical spans: signal power = constant, noise power =  $N \cdot NF$

Therefore for N identical spans:  $\frac{P_s}{N \times NF}$

OSNR decreases as  $\frac{1}{N}$

For a chain of 5 amplifiers:

$5 \times N_{ASE}$  if all 5 amplifiers are identical.

Signal power after the span =  $P_s$  (unchanged due to gain = loss)

Therefore:  $\frac{P_s}{5 \times N_{ASE}}$  is the OSNR

# 2024 - WDM Calculations

Wednesday 19 November 2025 21:22

## Q.4

A transmission system uses 30 channels to operate Wavelength Division Multiplexing (WDM) over 600 km distance. Amplifiers have 15 dBm of power and noise figure of 6 dB. Amplifiers gain can be set in Automatic Gain Control (AGC) mode and set to a gain between 8 and 22 dB. The fibre loss is 0.3 dB/km and you require margins of 4 dB. The baud rate of each channel is 60 GBaud and the spectral width 70 GHz.

Given:

- 30 WDM channels - sending over the fibre
- 600km total distance for the signal to travel
- Amplifier spacing - 60km apart from each other
- Amplifier power - 15 dBm
- Amplifier noise - 6dB
- Amplifier gain range - 8-22dB
- Amplifier spacing - 60km apart
- Fiber loss - 0.3dB/km =  $0.3 \times 600 = 180.0$  total
- Required network safety margin - 4dB
- Baud rate per channel - 60GBaud
- Spectral width/channel spacing bandwidth - 70GHz
- 16QAM & 18dB OSNR
- 32QAM & 23dB OSNR
- 64QAM & 28dB OSNR

a) If the amplifier spacing is 60 km, calculate: - what is the gain you should set your amplifiers at. - what is the maximum capacity your system can achieve, considering all WDM channels. Consider the following possible modulation formats: 16QAM, 32 QAM and 64 QAM, which require, respectively, 18, 23 and 28 dB OSNR.

**What is the gain you should set your amplifiers at?**

1. Calculate the loss in each span (each segment without amplification)  
 $60\text{km span length} \times 0.3\text{dB/km fibre loss} = 60 \times 0.3 = 18.0 \text{ dB}$
2. Account for the required network margins  
 $18 + 4 = 22 \text{ dB}$
3. Choose an amplifier gain (options: 8-22dB)  
Automatic Gain Control (AGC) must match the loss + margin.  
Therefore choose the amplifier gain of 22dB to breakeven.  
 $G = 22\text{dB}$

**What is the maximum capacity your system can achieve considering all WDM channels**

1. Calculate the OSNR  $OSNR = Power_{Total} - NoiseFigure - Gain - 10\log_{10}(NumberOfChannels) - 10\log_{10}(Number\ of\ Amplifiers) + 58 - Margins$

**NEVER DOUBLE-COUNT THE MARGIN. INCLUDE IN THE GAIN OR DO NOT. NEVER BOTH.**

Power = given = 15dBm  
Noise Figure = given = 6dB  
Number of Channels = given = 30  
Margin = given = 4dB  
Gain = 22dB

600km total distance to travel/60km spacing between amplifiers = 10 amplifiers are used

$$\text{OSNR} = 15 - 6 - 22 - 10\log_{10}(30) - 10\log_{10}(10) + 58 = 20.2\text{dB}$$

OSNR requirements for different modulations:

16QAM	18
32QAM	23
64QAM	28

This means that none of the modulations stated can be used to increase the capacity of the system. The OSNR requirements are not met.

The system must fall back to QPSK.

*QPSK - encodes two bits per symbol:*

- Bits per symbol = 2
- Baud rate per channel - 60GBaud
- Spectral width/channel spacing bandwidth - 70GHz

*Per channel data rate:*

$$60\text{GBaud} * 2 = 120\text{Gbps}$$

*Total capacity, all channels:*

$$120\text{Gbps} * 30 = 3600\text{Gbps}$$

**Total system capacity:**  $3600\text{Gb/s} = 3.6\text{Tb/s}$

**b) Assume you need to compensate dispersion by using dispersion compensating fibre (DCF). If the dispersion of the transmission fibre is 17 ps/nm/km, while the dispersion of the DCF is -200 ps/nm/km, how many meters of DCF would you need at each amplifier location to eliminate the average dispersion at each span? (use the conversion that 100GHz = 0.8 nm)**

10 amplifiers total which are 60km apart.

1. *Compute the Dispersion associated with one span - one portion of 60km*

Spans are 60km long.

Fibre dispersion is 17ps/nm/km

$$17 * 60 = 1020\text{ps/nm dispersion at each span.}$$

2. *Calculate length of DCF needed at each span*

-200ps/nm/km

$$1020/200 = 5.1\text{km}$$

5.1km of DCF is needed per span

# 2024 - Quantum

Thursday 13 November 2025 19:21

**a) With respect to quantum information systems, provide an answer to the following questions:**

**- What are the key differences between a classical bit and a Qubit?**

Classical Bits:

1. Can only be in one definite state (0,1)
2. Operations are deterministic
3. Measurement reveals the state of the classical bit without changing anything about it

Qubits:

1. Represented as a superposition of basis states:  $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$  where  $\alpha$  and  $\beta$  are complex numbers satisfying  $|\alpha|^2 + |\beta|^2 = 1$
2. Qubits can exist in superposition, not just simply 0 or 1.
3. Measurement of qubits collapses the qubit into 0 or 1 with the probability  $|\alpha|^2$  and  $|\beta|^2$ .
4. Qubits have a phase, which affects interference
5. Multiple qubits can be entangled, not possible in classical bits

**- How does the measurement of a qubit relates to its superposition state?**

If a qubit is in the state  $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$  after measurement, it collapses to whichever value was obtained by the probability  $|\alpha|^2$  and  $|\beta|^2$ .

It cannot remain in superposition once measured.

Measurement is probabilistic and destroys the original superposition.

**- Suppose you have 1000 pairs of qubits prepared in the exact same state. How do you know if the qubit pairs are entangled?**

A single pair cannot tell you if it is entangled because a single measurement destroys the state.

With many identically prepared pairs you can:

**1. Perform Correlation Measurements in Different Bases**

e.g. measure qubit A and qubit B in the Z basis

Then measure both in the X basis

Compare their outcomes

2. If their correlations violate a classical bound e.g. the Bell inequality then the pairs must be entangled.
  3. Non-entangled states cannot produce the same correlations
- Choose measurement settings on qubit A and qubit B
  - Repeatedly measure the 1000 copies
  - Compare results
  - If correlations exceed classical limits, the state is entangled

**b) With respect to quantum cryptography:**

**- Describe the two main categories of classic cryptography and then describe in which ways can quantum key distribution solve the issues of classical cryptography.**

Symmetric Key Cryptography:

- Uses the same key for encryption and decryption
- An issue in classical cryptography about how to get the shared key known between Alice and Bob without anyone else knowing what it is
- Quantum Key Distribution provides a physical method for creating a shared key which does not rely on mathematical assumptions which may one day be broken by quantum computing.

Asymmetric Key Cryptography:

- Each user has a public key which they openly share and a private key which they never share.
- Uses mathematically difficult problems to create keys, this has already been broken by quantum computing.
- Quantum Key Distribution relies on quantum physicals and not computational difficulty.
- Eavesdropping in quantum key distribution will change the quantum states and thus reveal the presence of the eavesdropper.

Quantum Key Distribution does not replace symmetric or asymmetric key cryptography, it replaces the key-exchange mechanisms with a quantum layer of security

**- Provide a comprehensive description of the BB84 quantum key distribution protocol, how it works, and why it is secure against eavesdropping.**

1. Alice Prepares a Qubit
  - a. Alice randomly chooses a bit value for the information she wants to transfer (0,1)
  - b. Alice randomly chooses a basis which to encode that data bit
2. Bob Measures the Qubit
  - a. Bob chooses his own random basis to measure the qubits with
3. Compare Bases
  - a. Alice and Bob publicly compare which bases they used to encode and decode the information.
  - b. They never compare the actual transferred information itself
  - c. Any non-matching bases are dropped
  - d. Only the matching information is maintained as the key. These are called sifted bits.
4. Eavesdropping Detection
  - a. Alice and Bob publicly reveal a small sample of their sifted bits
  - b. If the sample agrees then the channel is safe and they can use their quantumly distributed keys
  - c. If the sample of sifted bits appears to have a high error rate, someone has interfered with the system. Discard this pass and restart

Eve introduces errors as she must also randomly select a basis which to assess the qubits. If she selects the incorrect base, then she will disturb the qubits, causing bit flips which are detectable by Alice and Bob.

BB84 is secure because of the laws of quantum and classical mechanics:

No-Cloning Theorem: Eve cannot make a perfect copy of a qubit to measure later.

This would destroy the qubit

Measurement Disturbance: Measuring a qubit in the wrong basis changes its state

Random Bases: Eve does not know which basis Alice has used to encode her information bits, this introduces visible, detectable errors

Bit Error Rates: If Eve is present, the bit error rate will rise above acceptable thresholds and the process will abort.

# 2023 – Short Questions

Thursday, October 30, 2025 10:05 AM

**Which one among the following functionalities does not belong to the OSI Data Link layer?**

- a) Medium access
- b) Routing
- c) Error control
- d) Frame synchronisation

Ans: B – Routing, done at layer 3

**Which one among the following effects is modelled in the time-selective fading component of a wireless channel model?**

- a) Distance between transmitter and receiver
- b) A hill preventing line of sight between transmitter and receiver
- c) Sparks in passing cars
- d) User mobility

Ans: D – user mobility causes fading.

Distance between transmitter and receiver causes path loss

A hill in the line of sight causes shadowing

Sparks in passing cars causes interference

User mobility causes fading

**In the Kendall's notation a/b/m/K, what does 'K' indicate?**

- a) Service time distribution
- b) Number of servers
- c) Maximum number of customers allowed
- d) Type of arrival process

Ans – C: Maximum number of customers allowed

Kendall's notation is used for denoting the parameters of a queuing system

In Kendall's notation:

a: the type of arrival process the queuing system uses

b: the service time distribution, how the customers in the service and queue are processed

m: the number of servers available to serve the customers in the queuing process

K: the maximum number of customer's allowed in the queueing process

**Which one among the following options, cannot be considered a 'meter' for a cognitive radio system?**

- a) Transmitted power
- b) Interference level
- c) Signal-to-noise ratio
- d) Bit error rate

Ans: D – bit error rate

Meters in cognitive radio is what the system is capable of sensing, allowing it to perceive its environment

Transmitted power can be perceived by the cognitive radio

The level of interference is able to be perceived by the cognitive radio

The SNR is able to be perceived by the cognitive radio

The bit error rate is just a byproduct of transmission and cannot be considered a meter.

Knobs in a cognitive radio are the elements that the cognitive radio is able to control, whereas meters are the cognitive radio's measure of its surroundings

**If a transmission system suffers from nonlinear impairments, which of the following actions would you take to improve performance?**

- a) Increase transmission power

- b) Decrease transmission power**
- c) Use dispersion shifted fibre**
- d) Use multi-mode fibre**

Ans: B – decrease transmission power.

Nonlinear impairments are the result of increasing transmission power to the system, even if dispersion is not present in the system.

To mitigate this, decrease the transmission power

**Which of the following statements is false for a chain of amplifiers?**

- a) For the same span length, reducing the number of amplifiers increases the OSNR**
- b) For the same overall distance a shorter span length gives a higher OSNR**
- c) A system with amplifiers with lower noise figures has higher OSNR**
- d) A system with a larger number of channels has a higher OSNR**

Ans: D – a system with a larger number of channels has a higher OSNR.

This is false.

The total optical power is spread across more channels, which means less power per channel. It can also introduce cross-channel impairments like four wave mixing.

The same span length with less amplifiers, each amplifier will span a longer distance but introduces less noise into the system, which increases (positive) the OSNR.

Shortening the span length means that amplifiers do not have as much distance to amplify. This results in less amplified spontaneous emission per span, which positively increases the OSNR.

Amplifiers carry noise, so amplifiers with a lower noise figure will raise the OSNR.

**Which of the following statements is false with respect to broadband access networks?**

- a) Shortening the copper link length provides higher data rate**
- b) Doubling the bandwidth has the same effect as doubling the signal to noise ratio.**
- c) Typically higher capacity copper transmission technology uses higher bandwidth**
- d) Vectoring can double the capacity of a copper transmission system**

Ans – B: Doubling the bandwidth has the same effect as doubling the SNR.

The bandwidth is directly proportional to the capacity and the SNR is logarithmically proportional to the capacity

# 2023 – Shannon/System Design Question

Thursday, October 30, 2025 1:53 PM

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In the following equation:

$$C = m \cdot B \log_2 \left( 1 + \frac{S}{N} \right) \quad (2)$$

C represents the channel capacity [bps], B the system bandwidth [Hz], S the useful signal power [W], N the noise power [W], and  $m = R_s \cdot O_m \cdot R_c$ , where  $R_s$  is the multiple antenna spatial rate,  $O_m$  is the modulation order [bits / modulated symbol], and  $R_c$  is the channel coding rate. Assume that  $\frac{S}{N} = 1$ .

**(a)** Assume the following system components are available:

**(b)**

- Multiple antenna schemes: spatial diversity-only mode with a spatial rate of 1, hybrid diversity-spatial multiplexing mode with a spatial rate of 2, spatial multiplexing-only mode with a spatial rate of 3;
- Modulation schemes: BPSK, QPSK, 8-PSK;
- Channel coding rates: 1/4, 1/2, 3/4;
- Bandwidth: 50 MHz, 100 MHz, 150 MHz.

One wants to achieve a throughput equal to 300 Mbps or higher. Outline two systems obtaining that by using the above-mentioned system components.

$$M = R_s \cdot O_m \cdot R_c$$

$$R_s = \{1, 2, 3\}$$

$$O_m = \{1, 2, 3\}$$

$$R_c = \{0.25, 0.5, 0.75\}$$

$$B = \{50\text{M}, 100\text{M}, 150\text{M}\}$$

**System 1:**

$$R_s = 2, O_m = 2, R_c = 0.5, B = 150\text{M} = 300\text{MHz}$$

This is a balanced system which uses a moderate antenna scheme, moderate coding rate and moderate modulation, pushed with a high bandwidth.

This system would be good for general purpose broadband, video streaming, everyday tasks, etc.

**System 2:**

$$R_s = 3, O_m = 3, R_c = 0.75, B = 50\text{M} = 337.5\text{MHz}$$

This is a resource-intensive system which requires many antennas, a high coding rate meaning that the SNR must be quite high to prevent loss, and similarly a high modulation 8-PSK. This system is expensive but may be beneficial if a limited amount of bandwidth is available, as the lowest bandwidth option is available.

This system would be good for highly-optimized, spectrum limited systems e.g. microwaves operate in a very low portion of the bandwidth

This is a system for broadcast or digital TV which operates around the 50-150MHz band

(c) Considering equation (2) above, now suppose that an adaptive system can switch among the below configurations A, B and C, where:

- A = {spatial rate = 1, BPSK modulation, channel coding rate = 1/4}, if the user is positioned close to the cell edge;
- B = {spatial rate = 2, QPSK modulation, channel coding rate = 1/2}, if the user is positioned in an intermediate region between the base station and the cell edge;
- C = {spatial rate = 3, 8-PSK modulation, channel coding rate = 3/4}, if the user is positioned close to the base station.

Assuming that a uniform probability distribution for the three user position regions, calculate the average spectral efficiency of the adaptive system.

$$A(m) = 1 \times 1 \times 0.25 = 0.25 \text{ MHz}$$

$$B(m) = 2 \times 2 \times 0.5 = 2 \text{ MHz}$$

$$C(m) = 3 \times 3 \times 0.75 = 6.75 \text{ MHz}$$

$$\text{Average spectral efficiency of the adaptive system: } (0.25 + 2 + 6.75) / 3 = 3 \text{ MHz}$$

(d) In case you want to provide better coverage to mobile users close to the base station, what values (choosing between 'high' and 'low') of coding rate, modulation order and multiple antenna spatial rate should you choose? What will be the impact of the above choice on the system's spectral efficiency? Motivate your answers.

Users near the base station experience a really high SNR, as there is little interference between them and the base station such that the effects of path loss, shadowing, multipath, etc. Are not felt as much by nearby users than users very far away from the base station.

To optimise the coverage to the nearby users, we can use high values for coding rate, modulation and antenna spatial rate.

High value of the coding rate means that less redundancy bits are added to the transmission, this is reliable when close to the base station.

Modulation order can be high too and pack more bits per symbol, increasing coverage to the users near the BS.

Multiple MIMO streams for users nearer the base station are less susceptible to crosstalk between the streams.

The overall impact of this on the wider spectral efficiency is that 6.75\*bandwidth MHz is being transmit to all users.

The throughput is maximised alongside the spectral efficiency for users closer to the base station. However, this is a really expensive system and will be sensitive to sudden drops in SNR due to the high modulation rate being used.

Users further away from the base station will have a much more degraded experience which may be impacted by shadowing, path loss and fading

# 2023 – Kendall's Notation

Wednesday, November 05, 2025 10:19 PM

In a single server system, arrivals can be modelled as a Poisson process with rate of  $3\text{min}^{-1}$  and the service times are exponentially distributed with mean 8 s.

**Note: Show your workings when answering the questions below.**

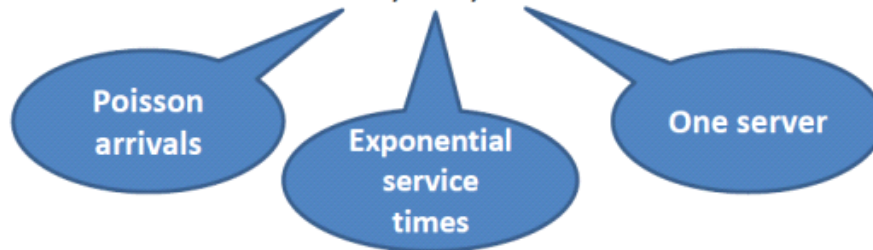
Describe this system using Kendall notation, motivating your choice.

Calculate the average number of customers in the system.

Calculate the average delay and the average waiting time.

Calculate the average number of customers in the queue.

Kendall's notation:  $M / M / 1$



Arrivals: 3 customers per minute.

0.05 customers per second ( $\lambda$ ).

Service takes 8s to service one customer.

$\mu$ =average number of customers that can be served per unit time.

Therefore, in 1 second you can serve 0.125 customers. ( $\mu$ )

**Traffic Intensity** = customers per second / service rate

Traffic =  $0.05/0.125 = 0.4$  ( $\rho$ )

**Average number of customers in the system** =  $0.4 / (1-0.4)$

= 0.66667 ( $\rho / (1-\rho)$ ) aka L

**Average delay** (time spent in the system) =  $0.66667/0.05 = 13.33334$

$1/(0.125-0.05) =$

Little's Law: ( $L / \lambda$ ) or ( $1/(\mu-\lambda)$ )

**Average number of customers in the queue** =  $0.4^2 / (1-0.4)$

= 0.26667

**Average waiting time** (time spent in the queue) =  $0.26667 / 0.05$

Number of customers in the queue /  $\lambda$

= 5.33334

Representing this in Kendall's notation

a: The type of arrival process the queuing system uses

b: The service time distribution

m: The number of servers

K: The number of customers allowed in the queuing process

a: M – Markov, the arrival of customers can be modelled exponentially

b: M – Markov, time it takes to serve a customer follows an exponential distribution

m: 1 – it is explicitly told that this is a single-server system

K: Irrelevant, there is no limits to the queue

**Calls arrive to a call-centre according to a Poisson process with intensity of 2 calls per minute.**

The call holding times are exponentially distributed with an average of 12 s.

Calls that find all operators busy are blocked.

Note: Show your workings when answering the questions below.

Describe this system using Kendall notation, motivating your choice.

How many operators are necessary to keep the blocking probability below 0.01?

Kendall's notation:

a: M, the arrival process is modelled in a Poisson distribution with a rate parameter of  $\lambda=1/30$  per second. This can be modelled as a Markov chain and is therefore a Markovian arrival system.

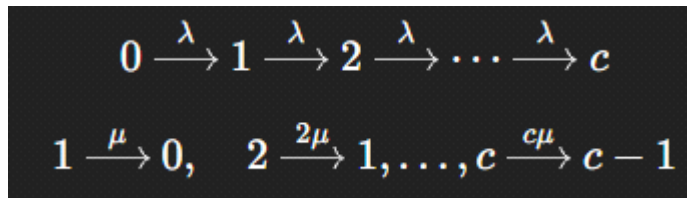
b: M, the service time distribution is modelled exponentially. Service time is not dependent on any previous services times and is memoryless. This can also be modelled by a Markov chain.

m: c, there is a limited number of servers available, indicated that there is some number of operators "c" which can become full

K: c, this system turns away any calls which cannot reach an operator, therefore the number of customers allowed into the system is equal to the number of operators

Kendall's notation: M/M/c/c

The Markov chain:



Intensity of 2 calls per minute.

1/30 of a call every second. =  $\lambda$

Service time distribution is exponential. 12 seconds to service a call.

1/12 calls are serviced in a second =  $\mu$

There are c servers and no queue, any arrival while all operators are busy is blocked.

The intensity of traffic is  $(1/30)/(1/12) = 2/5 = 0.4$

If there were infinite operators, we'd expect 0.4 calls to be serviced at any given time.

We need to find the probability that all call operators are full.

State	Meaning	Arrivals	Service Rate
0	No operators are busy	1/30 ( $\lambda$ )	0 (no service in progress)
1	1 operator is busy	1/30 ( $\lambda$ )	$\mu$ (service rate)
2	2 operators are busy	1/30 ( $\lambda$ )	$2\mu$ (service rate for 2 operators)
...	...	...	...
c	C operators are busy	1/30 ( $\lambda$ )	$c\mu$ (service rate for all operators)

$$B(A, c) = \frac{A^c / c!}{\sum_{k=0}^c A^k / k!}$$

The denominator will accumulate as we have to increase c

$P_1 = 0.4^1/1! / (0.4^0/0! + 0.4^1/1!) = 0.285714$  is the blocking rate, the chance that 1 operator is busy.

$P_2 = 0.4^2/2! / (0.4^0/0! + 0.4^1/1! + 0.4^2/2!) = 0.054$  is the blocking rate, the chance that 2 operators are busy

$P_3 = 0.4^3/3! / (0.4^0/0! + 0.4^1/1! + 0.4^2/2! + 0.4^3/3!) = 0.0072$  is the blocking rate, the chance that 3 operators are busy, this is less than the 0.01 desired

# 2023 - Describing Optical Networks

Wednesday 19 November 2025 21:21

**Q.4 a) With regards to Passive Optical Networks, describe why is the upstream scheduling more complex than downstream scheduling. Then describe how the upstream scheduling works.**

In passive optical networks, everyone shares the same fibre.

## **Downstream:**

Data flows down from the network **base station to the users**.

Only **one resource** is transmitting at a time.

All users select the part that is addressed to them.

**No** possibility of **collisions** because there is only one transmitter.

## **Upstream:**

Data flows from the **users back through the network**.

The users are **sharing** the fibre.

They must use different **time slots** to avoid collisions (TDMA).

**Scheduling** must account for the user's data arriving at **different times**.

## How Upstream Scheduling Works:

- Controlled time sharing of the fibre  
Each **user** tells the network **how much data** it has waiting
- The **network allocates time** for each user based on their traffic demand, ensuring no overlap, **adjusting for delays** in propagation
- Each user transmits only in their assigned slot
- **Timing compensation** is used so that signals far from far away and nearby users arrive in the correct order.

**Describe, making appropriate references to the Shannon-Hartley theorem, how the broadband access network has evolved from a pure copper-based telephone network to today's high-speed access.**

The Shannon-Hartley Theorem:  $C = B \times \log_2(1 + SNR)$

Capacity increases when bandwidth increases and when SNR increases.

### 1. **Copper**

- Copper was only designed for voice frequencies (kHz).
- Very small bandwidth
- Very small capacity
- Low SNR because copper heavily attenuates signals

### 2. **Improvements in Copper**

- A wider bandwidth on copper lines was introduced
- Advanced modulation was used to improve data rates
- Higher SNR was used where available

### 3. **Switch to Fibre**

- Fibre provides huge bandwidth (THz)
- Very high SNR because fibre has much lower loss
- Therefore fibre provides a higher B in the Shannon-Hartley Theorem and a higher SNR in the Shannon-Hartley Theorem which both in turn result in a higher capacity. Proving fibre's superiority over copper transmission.

**Provide a description of three access network sharing techniques.**

Time Division Multiple Access (TDMA):

Shares the medium by splitting user's access into time slots.

Used for upstream scheduling on shared fibres

Frequency Division Multiple Access (FDMA):

Shares the medium by allowing users to access different parts of the spectrum (different frequency bands)

Avoids collisions but divides available bandwidth

Wave Division Multiplexing (WDM):

Frequency division but using the optical wavelengths

Each user/service gets a different optical wavelength

Allows huge capacity because many wavelengths fit in fibre

# 2023 - WDM Calculations

Wednesday 19 November 2025 21:23

**Q.6 A Wavelength Division Multiplexing (WDM) transmission system uses 20 channels in the C band and needs to operate over a 400 km distance. Amplifiers have 18 dBm of power and noise figure of 8 dB, while the fibre has a nominal attenuation of 0.3 dB/km. The amplifier gain can be set to between 10 and 20 dB. Also consider that a margin of at least 5 dB is required.**

Given:

- 20 channels
- 400km total distance
- 18dBm amplifier power
- 8dB amplifier noise figure
- 0.3dB/km fibre loss
- 10-20dB amplifier gain range
- 5dB required margin
- 50Gbaud baudrate

**a) Assuming you need to support an overall capacity of at least 5.8 Tb/s, what is the maximum amplifier distance for the system to work without regenerators? (you can approximate to the closest smallest 5km multiple). Consider that the transceivers have a baud rate of 50 Gbaud and can work at modulation formats of 16QAM, 32 QAM and 64 QAM, which require, respectively, 18, 23 and 28 dB OSNR.**

*Loss in each span = 0.3\*SpanLength*

*Loss including margin = 5 + 0.3\*S*

*Gain (10dB-20dB) must satisfy 5 + 0.3\*S*

The minimum value that satisfies this is S=17 span length

$400/17 = 23.5294 \sim 24$  spans/amplifiers

Gain = 10.1dB

The maximum value that satisfies this is S=50 span length

$400/50 = 8$  spans/amplifiers

Gain = 20dB

50km is the maximum allows span length, this would use 8 amplifiers.

$OSNR = PowerTotal - NF - G - 10\log_{10}(numberChannels) - 10\log_{10}(numberAmplifiers) + 58 - M$

$OSNR = 18 - 8 - 20 - 10\log_{10}(20) - 10\log_{10}(8) + 58 = 25.95 \sim 26$ dB

16QAM	18
32QAM	23
64QAM	28

64 QAM cannot be used.

16QAM or 32QAM can be used.

32QAM encodes 5 bits per symbol

Channel baud rate = 50Gbaud

$50Gbaud * 5 = 250Gbaud$  per channel

$250Gbaud * 20$  channels = 5000Gbps.

This is 5Tbps and does not support the required **5.8 Tb/s**.

By using the minimum allowable gain = 10dB, using a span length of 17km and 24 amplifiers:  
 $OSNR = 18 - 8 - 10 - 10\log_{10}(20) - 10\log_{10}(24) + 58 = 57.2\text{dB}$   
 This allows the system to use 64QAM modulation which allows encoding of 6 bits per signal.  
 $50\text{Gbaud} * 6 = 300\text{Gbaud}$  per channel  
 $300\text{Gbaud}$  per channel \* 20 channels = 6000Gbps  
 This is 6Tbps and supports the required **5.8 Tb/s**.

It may be possible to increase the distance between amplifiers, as long as we are still able to use 64-QAM.  
 $OSNR = 18 - 8 - X - 10\log_{10}(20) - 10\log_{10}(X) + 58 = ?$

The minimum value that satisfies this is S=17 span length  
 $400/17 = 23.5294 \sim 24$  spans/amplifiers  
 Gain = 10.1dB.

**b) The system uses coherent transmission, so no dispersion compensating fibre (DCF) is required. The transceiver can work at a baud rate of either 33Gbaud (37.5 GHz bandwidth) or 66 Gbaud (75GHz bandwidth). The maximum tolerable dispersion by the digital filter is however 1ns. What is the total capacity you can achieve over the 20 channels if the available OSNR is > 28dB (assuming the modulation formats as defined in the previous problem)? Assume the average dispersion coefficient of the fibre to be 5 ps/nm/km (assume the following conversion ratio: 100 GHz = 0.8 nm).**

OPTIONS:

33Gbaud & 37.5 GHz bandwidth or 66Gbaud & 75GHz bandwidth.

TOLERABLE DISPERSION:

1ns

AVERAGE DISPERSION:

5ps/nm/km

OSNR:

> 28dB (16QAM, 32 QAM and 64 QAM can all be used here potentially)

DISTANCE THE SYSTEM HAS TO TRAVEL:

400km

**What is the total capacity you can achieve over the 20 channels?**

$100\text{GHz} = 0.8\text{nm}$

$1\text{GHz} = 0.008\text{nm}$

$37.5\text{GHz} = 0.008 * 37.5 = 0.3\text{nm}$

$75\text{GHz} = 0.008 * 75 = 0.6\text{nm}$

Overall dispersion in the entire system =  $400\text{km} * 5\text{ps/nm/km} = 2000\text{ps/nm}$

*Try 33GBaud:*

$2000\text{ps/nm} * 0.3\text{nm} = 600\text{ps}$

*Try 66GBaud:*

$2000\text{ps/nm} * 0.6\text{nm} = 1200\text{ps}$

The allowable dispersion is 1000ps. Only 33Gbaud stays within this limit

*Calculate the capacity*

OSNR allows 64-QAM to be used - encoding 6 bits per symbol.

$33\text{Gbaud} * 6 = 198\text{Gb/s}$  (per channel)

$198\text{Gb/s} * 20$  channels = 3960 Gb/s (overall capacity)

Total system capacity using a coherent system which can compensate for dispersion digitally instead of using DCF is  
3.96Tb/s

# 2022 – Short Questions

Thursday, October 30, 2025 1:08 PM

**Which one among the following functionalities does not belong to the OSI Physical (PHY) layer?**

- a) Frame synchronization
- b) Waveform selection
- c) Signal detection
- d) Power control

Ans – A: frame synchronisation is not a physical aspect of the system.

Waveform, signal and power are all physical components controlled by Layer 1.

**Which one among the following options, would likely be most suitable to comply with the requirements of enhanced Mobile Broadband systems?**

- a) Spatial multiplexing & coding rate of 1/3
- b) Spatial diversity & coding rate of 1/3
- c) Spatial multiplexing & coding rate of 2/3
- d) Spatial diversity & coding rate of 2/3

Ans – C: spatial multiplexing and a coding rate of 2/3

Mobile broadbands are designed to reach a large number of users.

Spatial multiplexing can be used to allow the signal to reach this.

Mobile broadbands can also experience a lot of shadowing and other impairments.

Using a coding rate of 2/3 means that 2/3 of the bits being transmitted are redundancy signals which helps to ensure that the real signals reach the end user.

**Which one among the statements about schedulers is incorrect?**

- a) Proportional Fair is the de-facto choice in modern cellular networks
- b) Maximum C/I is well suited for high throughput services
- c) Proportional fair is not in use in Wi-Fi systems
- d) The scheduling used by Wi-Fi is based upon the same principle as the scheduling used by cellular systems

Ans – D: the scheduling used by WiFi is NOT based upon the same principles as the scheduling used by cellular systems.

Cellular systems are designed to be nomadic, allowing the user to connect from different station to different station.

Wifi is infrastructure based and the user is connected only when in the range of the wifi station.

**Which of the following options is helpful in increasing a link reliability?**

- a) Using a higher order modulation
- b) Using a lower coding rate
- c) Increasing the spatial multiplexing gain
- d) None of the above

Ans – B: using a lower coding rate.

Higher order modulation packs in more bits per symbol but requires a higher SNR to be reliable.

Reducing the coding rate means that *more redundancy bits* are included in the transmission. This increases the systems ability to resist impairments.

Spatial multiplexing (MIMO) sends multiple data streams to increase the data rate but makes the link less reliable as it reduces the diversity gain. If reliability is the goal, spatial diversity is preferable to spatial multiplexing.

**Why is Dispersion Compensating Fibre only required for intensity modulated direct detection systems?**

- a) Because coherent systems do not suffer from inter symbol interference
- b) Because coherent systems make use of higher order modulations that do not suffer from dispersion

**c) Because intensity modulated systems tend to transmit at higher baud rate, since they use lower order modulations.**

**d) Because coherent system can make use of the additional phase information of the signal to compensate for dispersion digitally**

Ans – D: coherent systems can make use of the additional phase information of the signal to compensate for dispersion digitally.

*Coherent systems and cognitive radio are not the same thing. Cognitive radio is the one with the meters and knobs that has the ability to adapt its knobs to its environment.*

Coherent systems use a reference signal/local oscillator to detect amplitude and phase of the received signal, but it is not adaptive.

Coherent systems still experience inter symbol interference.

Coherent systems do use higher order modulations but higher order modulations still suffer from dispersion.

Baud rate differences have no impact on the need for dispersion compensating fibre.

**Which of the following is not a reason why broadband based on fibre is better than broadband based on copper?**

**a) Because the speed of light in fibre is higher than the speed of an electric current in copper**

**b) Because fibre has higher transmission bandwidth**

**c) Because fibre has higher signal to noise ratio**

**d) Because fibre has lower transmission loss**

Ans – A: the speed of light in fibre does NOT have a higher speed than an electric current in copper. Optical fibre is still used instead of copper because the fibre has a higher transmission bandwidth, a higher signal-to-noise ratio and a lower transmission loss

# 2022 – Shannon/System Design Question

Thursday, October 30, 2025 1:53 PM

**(a)** Assume the following system components are available:

- Multiple antenna schemes: spatial diversity-only mode with a spatial rate of 1, hybrid diversity-spatial multiplexing mode with a spatial rate of 2, spatial multiplexing-only mode with a spatial rate of 4;
- Modulation schemes: QPSK, 16-QAM, 64-QAM;
- Channel coding rates:  $1/3$ ,  $1/2$ ,  $2/3$ ;
- Bandwidth: 100 MHz, 200 MHz, 500 MHz.

One wants to achieve a throughput equal to 2 Gbps or higher. Outline two systems obtaining that by using the above-mentioned system components.

$$R_s = \{1, 2, 4\}$$

$$O_m = \{2, 4, 6\}$$

$$R_c = \{1/3, 1/2, 2/3\}$$

$$B = \{100, 200, 500\}$$

**System 1:**

$$2 \cdot 4 \cdot 0.5 \cdot 500 = 2000 \text{ MHz} = 2 \text{ GHz}$$

This is a balanced system which uses hybrid diversity-spatial multiplexing mode with a spatial rate of 2, a 16-QAM modulation and  $1/2$  coding rate, and 500MHz of bandwidth.

This is a relatively balanced system but does occupy a large portion of bandwidth.

This is a useful system if only a moderate amount of resources are available but a high bandwidth is available e.g. television broadcast signals

**System 2:**

$$4 \cdot 6 \cdot 2/3 \cdot 200 = 3200 \text{ MHz} = 3.2 \text{ GHz}$$

This system uses significantly less bandwidth than system 1. but it is more resource intensive, using a spatial rate of 4, 64-QAM modulation and  $2/3$  coding rate. The SNR for this transmission must be very high in order to achieve optimal results. This is a good system for where bandwidth is limited but the SNR is known to be stable and high. This is suitable for high-capacity indoor links e.g. wifi in an office block.

**(b)** Considering equation (1) above, now suppose that an adaptive system can switch among the configurations A, B and C, where:

- A = {spatial rate = 1, QPSK modulation, channel coding rate =  $1/3$ , 100 MHz bandwidth}, if Signal-to-Noise Ratio (SNR) is below 0 dB;
- B = {spatial rate = 2, 16-QAM modulation, channel coding rate =  $1/2$ , 200 MHz bandwidth}, if the SNR is greater or equal than 0 dB and below 10 dB;
- C = {spatial rate = 4, 64-QAM modulation, channel coding rate =  $2/3$ , 500 MHz bandwidth}, if the SNR is greater or equal than 10 dB.

Assuming that the probability distribution for the three SNR regions is uniform, calculate the average capacity of the adaptive system.

$$A(m) = 1 \cdot 2 \cdot 1/3 = 2/3$$

$$B(m) = 2 \cdot 4 \cdot 0.5 = 4$$

$$C(m) = 4 \cdot 6 \cdot 2/3 = 16$$

$$\text{Average capacity of the adaptive system: } (2/3 + 4 + 16)/3 = 6.88888$$

**(c)** In case you want to provide better coverage to mobile users far away from the base station, what values (choosing between 'high' and 'low') of coding rate, modulation order and multiple antenna spatial rate should you choose (justify your answer)? What will be the impact of the above choice on the system's spectral efficiency?

Coding rate – LOW : there should be a low coding rate for optimising coverage to mobile users far away from the base station. This is because users far away from the base station will experience the effects of path loss, shadowing, fading, etc. A lower coding rate means that more redundancy bits are added to the transmission, improving the chances that the far away user will receive the real signal.

Modulation order – LOW : Higher-order modulations require a very high SNR. We anticipate that the noise rate will be higher for users farther away from the base station, therefore it is better to use a lower-order modulation which will ensure that many bits (packed in higher-order modulation for example) are not lost in the fading or path loss.

Multiple antenna spatial rate – MID: Higher antenna spatial rate is more susceptible to cross talk between channels in a MIMO system. But antennas are still required to reach users which are far away from the base station. Therefore, use a moderate amount of antenna spatial rate such that crosstalk is not occurring but the far away users are still able to be reached by the MIMO.

The overall impact on the spectral efficiency is that the overall experience will be degraded for users closer to the base station. This is because of the lower order modulation, less bits are being packed in per symbol, which means it takes a longer duration of time before lots of symbols can reach the user.

# 2022 - Describing Optical Networks

Wednesday 19 November 2025 21:21

## Q.4

**(a) Considering an optical transmission system, describe how an eye diagram is generated and what information it can provide. Then draw an example of an eye diagram for a ON-OFF Key modulation transmission with large amount of noise and one for a PAM4 (Pulse Amplitude Modulation with 4 levels) modulation with small amount of noise.**

How an Eye Diagram is Generated:

1. Taking the received electrical signal after the optical receiver
2. Repeatedly overlaying many bit periods on top of each other
3. As more and more bits overlap, a pattern forms

What information it can provide:

Noise: vertical closure

Jitter: horizontal closure

Inter-symbol interference: Sloped or thickened traces

Amplitude distortion: flattened tops/bottoms

**(b) Describe what are Optical Signal to Noise Ratio (OSNR) margins in optical networks and why are they used. Then describe the pros and cons of using more conservative versus more aggressive margins**

OSNR is measured at the receiver.

Different bitrates/modulation formats need different minimum OSNR to operate correctly.

OSNR margin expresses how far you are from failure.

Large/Conservative Margins:

Large margins lead to reliable operation

Supports unexpected degradation

You must use a lower order modulation and thus may have to use a lower data rate

Network is more expensive as more amplifiers/regenerators are required

Small/Aggressive Margins:

Can use higher order modulation/more capacity

Reach longer distances

Less tolerant to degradation

# 2022 - WDM Calculations

Wednesday 19 November 2025 21:23

## Q.6

A Wavelength Division Multiplexing (WDM) transmission system with 40 channels needs to operate over a 1,000 km distance. Amplifiers have 15 dBm of power and noise figure of 6 dB, while the fibre has a nominal attenuation of 0.2 dB/km. The distance between amplifiers is 50 km. The signals all transmit at 33 Gbaud (occupying a 37GHz bandwidth). Also consider that a margin of at least 4 dB is required.

(a) What is the maximum useful data rate of your system, considering all channels, if the required OSNR for 16QAM, 32 QAM and 64 QAM modulations are, respectively, of 18, 23 and 28 dB? Notice that these rates can only be achieved using error correction codes, which have an overhead of 9% (i.e., they use 9% of the channel capacity).

Loss per span =  $0.2\text{dB/km} * 50 = 10\text{dB}$

Loss including network margins =  $10 + 4 = 14\text{dB}$

This is the gain of the amplifier as it is required to account for this loss

Number of Amplifiers =  $1000/50 = 20$

$\text{OSNR} = \text{Power} - \text{NF} - \text{G} - 10\log_{10}(\text{numberChannels}) - 10\log_{10}(\text{numberAmplifiers}) + 58 - M$

$\text{OSNR} = 15 - 6 - 14 - 10\log_{10}(40) - 10\log_{10}(20) + 58 - 4 = 19.969\text{dB} \sim 20\text{dB}$

Only 16QAM can be used under these OSNR requirements

16QAM encodes 4 bits per symbol

$33\text{Gbaud per channel} * 4 = 132\text{Gbps per channel}$

Error correction codes have an overhead of 9% of channel capacity

$132 * 9\% = 11.88$

$132 - 11.88 = 120.12\text{ Gbps}$

$120.12\text{Gbps} * 40\text{ channels} = 4804.8\text{Gbps}$

Maximum useful data rate of the system is 4.8Tb/s

(b) What is the chromatic dispersion of each channel if the average dispersion coefficient of the fibre is 17 ps/nm/km (assume the following conversion ratio: 100 GHz = 0.8 nm)? If the transmissions were carried out using direct detection receivers and the transmitters worked at the same Baud rate described above (i.e., 33Gbaud), how much dispersion compensating fibre (DCF) would be required at each amplifier location to compensate for dispersion? Assume the DCF has coefficient of -150 ps/km/nm.

Fibre dispersion is 17ps/nm/km

Per span (with a span being 50km as stated in the question)

$17 * 50 = 850\text{ps/nm}$

DCF is -150ps/km/nm

$850/150 = 5.6667\text{ km per span}$

# 2022 – Kendall's Notation

Wednesday, November 05, 2025 10:19 PM

**In a single server system, arrivals can be modelled as a Poisson process with rate of  $3 \text{ min}^{-1}$  and the service times are exponentially distributed with mean 15 s.**

**Give the Kendall's notation, justifying your choice.**

**Calculate the average number of customers in the system.**

**Calculate the average delay and the average waiting time.**

**Calculate the average number of customers in the queue.**

**What happens to the average number of customers in the system, if service times are exponentially distributed with mean 20 s? Why?**

Arrival rate = 3 customers per minute

Arrival rate = 0.05 customers per second ( $\lambda$ )

Service time = 15 seconds to serve a customer

( $\mu$ ) number of customers served per unit time.  $1/15$  customers can be served in 1 second.

**Traffic Intensity ( $\lambda/\mu$ ):**

$$0.05 / (1/15) = \frac{3}{4} \text{ (p)}$$

**Average number of customers in the system ( $p/1-p$ ):**

$$0.75 / 0.25 = 3 \text{ customers (L)}$$

**Average delay (time spent in the entire system) ( $L/\lambda$ ):**

$$3/0.05 = 60 \text{ seconds}$$

**Average number of customers in the queue ( $p^2/1-p$ ):**

$$0.75^2 / 0.25 = 2.25 \text{ customers (L}_q\text{)}$$

**Average waiting time (time spent in the queue) ( $L_q/\lambda$ ):**

$$2.25 / 0.05 = 45 \text{ seconds}$$

**Increase Service time to 20s**

$1/20$  customers can be served in 1 second.

$$0.05 / (1/20) = 1 \text{ traffic intensity}$$

When the traffic intensity is 1, the system is at full utilization, the average number of customers in the system ( $1 / 1-1$ ) becomes undefined and tends to infinity.

The system becomes unstable, the average number of customers grows without bound.

The service cannot keep up with the arrivals and the queue builds indefinitely.

Kendall's notation:

a: the type of arrival process

b: service time distribution

m: number of servers

K: maximum number of customers allowed in the system

a: M, arrivals are modelled according to a Poisson process of rate  $\lambda=3$ . This process can be modelled as a Markov chain such that the arrival of a new customer is memoryless and not dependent on how customers were previously received. The Markov chain changes from one state to another at the receipt of  $\lambda$ , and changes back to the former state at the receipt of  $\mu$ . In the case of arrivals,  $\lambda$  is the parameter which changes the Markov chain

b: M, service time is modelled exponentially which can also be modelled as a Markov chain. the servicing of a customer is memoryless and not dependent on how customers were previously served. The Markov chain changes from one state to another at the receipt of  $\lambda$ , and changes back to the former state at the receipt of  $\mu$ . In the case of service time distribution,  $\mu$  is the parameter which changes the Markov chain

m: 1, we are explicitly told that this is a single-server system

K: irrelevant, there is no limit on the amount of customers allowed in the system. There is a potentially infinite amount of customers waiting to be served

**In a certain system the arrivals, which can be modelled as a Poisson process, occur at a rate of one every 100 ms, and the service times are exponentially distributed with mean 2 s.**

**Also, there is no limit in the number of servers available.**

**Give the Kendall's notation, justifying your choice.**

a= M

b= M

m=  $\infty$

K =  $\infty$

This is a M/M/ $\infty$  queue.

The Poisson process and exponential distributions can both be modelled as a Markov chain. The arrival of a new customer and the servicing of a new customer are both memoryless and not dependent on how previous customers arrived/were served. The Markov chain changes from one state to a new state in receipt of an arrival  $\lambda$  and changes back to the previous state in receipt of a service  $\mu$ .

As there is no limit to the number of servers available, there is theoretically no limit to the number of customers which can be served by the M/M/ $\infty$  queue

**Calculate the average number of customers in the system.**

Arrivals: one customer arrives every 100ms, 1/100 customers arrive every ms, 10 customers arrive every second

Service: one customer is serviced every 2 seconds, 1/2 customers is served every second

$P = 10/(1/2) = 20$

Because the number of servers is theoretically infinite, the average number of customers in the system is simply equal to the traffic intensity.

**Calculate the average delay per customer.**

The average system-wide delay per customer is simply the service time of 2 seconds

**Calculate the average queuing delay. What do you notice? Why it is so?**

The average queuing delay is 0. As there is a theoretically infinite number of servers, no process should have to wait in the queue.

# 2021 – Short Questions

Thursday, October 30, 2025 1:08 PM

**Which one among the following options is a wireless channel mitigation technique?**

- a) Path loss
- b) Shadowing
- c) Multipath fading
- d) Code planning

Ans – D: code planning is a mitigation technique. Path loss, shadowing and multipath are all impairments

**Which one among the following functionalities does not belong to the OSI network layer?**

- a) Medium access
- b) Routing
- c) Handover
- d) Device location

Ans – A: medium access. This goes in Layer 2

**Which one among the following technologies is the least suitable for wireless wide area networks?**

- a) 5G
- b) 4G
- c) Terahertz
- d) LoRa

Ans – C: Terahertz.

4g and 5g have already been suitable used for wireless WANS.

LoRa is designed for long-range IoT and is therefore suitable for a wireless WAN.

Terahertz provides very high rate rates but suffers from severe path loss and poor propagation long-distance, making it unsuitable as a wireless WAN.

Terahertz is only very useful for low-range, line-of-sight, indoor applications.

**In the Kendall's notation a/b/m/K, what is 'b' indicating?**

- a) Service time distribution
- b) Number of servers
- c) Maximum number of customers allowed
- d) Type of arrival process

Ans – B: service time distribution

**What category of the Agent Based Modeling (ABM) cycle would the choice of modulation at your transmitter fit into?**

- a) Get stimulus
- b) Process stimulus
- c) Act
- d) None of the above

Ans – C: act.

ABMs follow the below process:

*Get stimulus*: sense or receive input from the environment

*Process stimulus*: analyse the information and make decisions based on rules, learning or optimisation

*Act*: affect the environment or system e.g. changing transmission parameters.

Therefore changing/affecting the choice of modulation at the transmitter falls under the acting step.

**Which one among the following options, would likely be most suitable to comply with the requirements of Ultra Reliable & Low Latency Communication systems?**

- a) Spatial multiplexing & 64-QAM

- b) Spatial multiplexing & QPSK**
- c) Spatial multiplexing & 16-QAM**
- d) Spatial multiplexing & 256-QAM**

Ans – B: QPSK

Ultra reliable communication: very low probability of packet loss

Low latency: minimal delay in delivery

Higher order modulations pack more bits per symbol but require a higher SNR to keep the Bit Error Rate low. If the channel fluctuates or SNR drops, the BER will rise which is not good in a URLLC system because those packets will definitely arrive and be wrong.

Therefore it is better to use a lower order modulation like QPSK which packs in just 2 bits per symbol. Yes this is slower than using higher order modulation but this doesn't matter because the channel is already low latency

Imagine sending critical emergency messages over a walkie-talkie:

- Using **high-order modulation** is like whispering a long, complicated sentence quickly — you might be misunderstood.
- Using **QPSK** is like speaking slowly and clearly — fewer words per second, but the message is guaranteed to be understood.

**Which one among the statements about schedulers is incorrect?**

- a) Round robin is simple in terms of implementation**
- b) Maximum C/I is well suited for HD video streaming**
- c) Proportional fair is not in use in 4G systems**
- d) WiFi scheduling is fundamentally different as compared to the scheduling used by cellular systems**

Ans – C: Proportional fair is not in use in 4G systems is false. Proportional fair is widely used in 4G systems.

Round robin is very simple to implement and it treats all users the same regardless of data.

Maximum C/I is well suited for HD video streaming because maximum c/i is suited for implementations with a very high throughput such as HD video.

Wifi scheduling is different altogether from cellular systems as cellular systems allows the user to be nomadic and move around while maintaining a connection, wifi requires that a user must connect to another wifi station if the user moves out of range of the previous wifi station.

**Which of the following options is helpful in increasing the data rate?**

- a) Using higher order modulation**
- b) Employing a frequency mitigation technique**
- c) Increasing the number of antennas used in the mobile phone**
- d) All of the above**

Ans – D: all of the above

**Why is chromatic dispersion an issue for optical fibre transmission in telecommunications networks?**

- a) Because it cannot be compensated**
- b) Because its effect is worse than modal dispersion**
- c) Because it increases the transmission loss**
- d) Because it creates inter-symbol interference**

Ans – D: because it creates ISI

**Which of the following statements is false about optical amplifiers?**

- a) They decrease the Optical Signal to Noise Ratio (OSNR)**
- b) They add thermal noise**
- c) They can be deployed in a chain configuration to reach longer distance**
- d) One amplifier can be used for multiple wavelength channels**

Ans – B: they add thermal noise

Amplifiers boost the signal but also add their own noise (ASE) which can decrease the OSNR.

Thermal noise is associated with electrical components, not optical amplifiers  
They are deployed in a chain configuration.  
Raman amplifiers can be used in wave division multiplexing

# 2021 – Shannon/System Design Question

Thursday, October 30, 2025 1:53 PM

**a)** The following system components are available:

- Multiple antenna schemes: spatial diversity-only mode with a spatial rate of 1, spatial multiplexing-only mode with a spatial rate of 2;
- Modulation schemes: 16-QAM, 64-QAM; 256-QAM;
- Channel coding: rate 1/3 code, rate 1/2 code;
- Bandwidth: 100 MHz, 200 MHz, 500 MHz.

One wants to achieve a throughput equal to 1 Gbps or higher. Outline two systems to achieve this performance using the components above.

$$R_c = \{1, 2\}$$

$$O_m = \{4, 6, 8\}$$

$$R_s = \{1/3, 1/2\}$$

$$B = \{100, 200, 500\}$$

### System 1:

$$1 * 6 * 1/3 * 500 = 1000 \text{ MHz} = 1 \text{ GHz}$$

This is a system which uses spatial-diversity only mode and a moderate modulation of 64-QAM. 1/3 of bits encoded are real, so there is a high redundancy associated with this system. It uses a significant amount of bandwidth.

This is a good system for when MIMO/antennas are a limited resource and can be compensated by a higher use of the bandwidth and higher order modulation. It does, however, require a decently high SNR to be present to compensate for the high modulation and 1/3 coding rate

### System 2:

$$2 * 8 * 1/2 * 200 = 1600 \text{ MHz} = 1.6 \text{ GHz}$$

This system uses much less bandwidth than system 1 but is very resource intensive with a 2 spatial rate and a 256-QAM packing 8 bits per signal. This would be a good system for users who are very close to a base station e.g. cellular service for a town which is situated near a cell tower. It is also a good system to use if bandwidth is a limiting factor but resources are abundant.

100-500

**b)** In case you want to maximise the performance of users that are on average far away from the base station, what values (choosing between 'high' and 'low') of coding rate, modulation order and MIMO spatial rate should you choose? (motivate your answer) What will be the impact of the choice above on the system's spectral efficiency?

Coding rate – LOW : there should be a low coding rate for optimising coverage to mobile users far away from the base station. This is because users far away from the base station will experience the effects of path loss, shadowing, fading, etc. A lower coding rate means that more redundancy bits are added to the transmission, improving the chances that the far away user will receive the real signal.

Modulation order – LOW : Higher-order modulations require a very high SNR. We anticipate that the noise rate will be higher for users farther away from the base station, therefore it is better to use a lower-order modulation which will ensure that many bits (packed in higher-order modulation for example) are not lost in the fading or path loss.

Multiple antenna spatial rate – MID: Higher antenna spatial rate is more susceptible to cross talk between channels in a MIMO system. But antennas are still required to reach users which are far

away from the base station. Therefore, use a moderate amount of antenna spatial rate such that crosstalk is not occurring but the far away users are still able to be reached by the MIMO.

The overall impact on the spectral efficiency is that the overall experience will be degraded for users closer to the base station. This is because of the lower order modulation, less bits are being packed in per symbol, which means it takes a longer duration of time before lots of symbols can reach the user.

c) In the following equation:

$$C = m \cdot B \log_2 \left( 1 + \frac{S}{N} \right) \quad (1)$$

C represents the channel capacity [bps], B the system bandwidth [Hz], S the useful signal power [W], N the noise power [W], and  $m = R_s \cdot O_m \cdot R_c$ , where  $R_s$  is the multiple antenna spatial rate,  $O_m$  is the modulation order [bits / modulated symbol] and  $R_c$  is the channel coding rate. Assume that  $\frac{S}{N} = 1$ .

Now suppose an adaptive system can switch among the configurations A and B below, depending on whether the Channel Quality Indicator (CQI) takes on the discrete values of 'good' or 'poor'.

- A = {spatial rate = 1, 16-QAM modulation, 1/3 channel coding rate, 100 MHz bandwidth};
- B = {spatial rate = 3, 256-QAM modulation, 2/3 channel coding rate, 500 MHz bandwidth}.

Assume that the receiver (user equipment) spends one third of the time close to the cell edge, and two thirds of the time close to the serving base station.

Calculate the average capacity of the adaptive system.

$$A(m) = 1 \cdot 4 \cdot \frac{1}{3} \cdot 100 = 133.3 \text{ MHz}$$

$$B(m) = 3 \cdot 8 \cdot \frac{2}{3} \cdot 500 = 8000 \text{ MHz}$$

$$(133.3 \cdot \frac{1}{3}) + (8000 \cdot \frac{2}{3}) = 5377.76 \text{ MHz}$$

# 2021 – Kendall's Notation

Wednesday, November 05, 2025 10:19 PM

In a single server, finite buffer system, arrivals can be modelled as a Poisson process with rate  $4 \text{ s}^{-1}$  and the service times are exponentially distributed with mean  $0.2 \text{ s}$

Describe this system using Kendall notation, motivating your choice.

Calculate the average number of customers in the system, assuming the maximum capacity of the system is 3 customers.

Calculate the blocking probability.

Calculate the rate of rejected customers

Arrivals: 4 arrivals per second

Service: 0.2 seconds to serve a customer

Service:  $1/0.2 = 5$  customers served per second

Kendall's notation: M/M/1/3

a: M, Poisson arrivals are Markovian

b: M, exponentially distributed service times are Markovian

m: 1, explicitly stated that there is one server

K: 3, explicitly stated that the maximum capacity of the system is 3 customers

**Traffic Intensity ( $\lambda/\mu$ ):**  $4/5 = 0.8$  ( $\rho$ )

Calculate the average number of customers in the system, assuming the maximum capacity of the system is 3 customers.

This is not an M/M/1 queue so we cannot use  $(\rho/1-\rho)$  to calculate the average number of customers in the queue

For an M/M/1/K system (finite capacity), the **steady-state probabilities** are:

$$P_n = \frac{(1 - \rho)\rho^n}{1 - \rho^{K+1}}, \quad n = 0, 1, 2, \dots, K$$

- Here  $K = 3$ , so  $n = 0, 1, 2, 3$ .

Denominator =  $1 - 0.8^{3+1} = 0.5904$

The average number of customers is:

$$L = \sum_{n=0}^K nP_n$$

$$P_0 = (1-0.8)*0.8^0 / 0.5904 = 0.33875$$

$$P_1 = (1-0.8)*0.8^1 / 0.5904 = 0.271$$

$$P_2 = (1-0.8)*0.8^2 / 0.5904 = 0.2168$$

$$P_3 = (1-0.8)*0.8^3 / 0.5904 = 0.17344$$

All of these probabilities should add up to 1 because they are the probabilities of how many customers the system is holding and we know that the system can hold a maximum of 3 customers.

$L = (0*0.33875) + (1*0.271) + (2*0.2168) + (3*0.17344) = 1.22492$  is the average number of customers in the system

Calculate the blocking probability.

The blocking probability is the probability that the system is at maximum capacity i.e. that there are 3 customers already in the system.

$$P_3 = (1-0.8)*0.8^3 / 0.5904 = 0.17344$$

Calculate the rate of rejected customers

Arrival rate \* blocking probability:  $4*0.17344 = 0.69376$

In a certain system the arrivals, which can be modelled as a Poisson process, occur at a rate of one every 150 ms, and the service times are exponentially distributed with mean 1.5 s. Also, there is no limit in the number of servers available.

**Describe this system using Kendall notation, motivating your choice.**

a= Markovian, the arrivals are modelled as a Poisson process.

b= Markovian, the service time is modelled exponentially

m = infinite, there is no limit to the number of servers available

K = infinite, as there is no limit to the number of servers available, there is no limit to the number of customers

M/M/∞/∞

**Calculate the average number of customers in the system.**

Arrivals  $\lambda$ : one arrival every 150ms = every millisecond 1/150 customers arrive

Service time  $\mu$  (: one customer is processed every 1.5 second = every second 2/3 customers are processed = every millisecond 1/1500 customers are processed

Traffic intensity  $\rho$ :  $(1/150)/(1/1500) = 10$

Because a theoretical infinite number of servers can be used, the average number of customers in the system is equal to the utilisation

**Calculate the average delay per customer.**

For a M/M/∞ queue, because a theoretical infinite number of servers can be used, the average delay per customer is simply the service time of 1.5s.

**Calculate the average queuing delay. What do you notice? Why is it so?**

The average queuing delay is zero. This is because of the infinite number of servers, no customer should need to wait

# 2021 - WDM Calculations

Wednesday 19 November 2025 21:23

**Q.6 An optical signal has a data rate of 20Gb/s and is transmitted over a single mode fibre with dispersion coefficient of 17ps/km/nm and a loss of 0.25 dB/km.**

**a) If the bandwidth of the signal is 40 GHz, what is the maximum distance allowed, if the maximum tolerable broadening of the pulse is 30% of the time slot duration? (Assume the following conversion ratio: 100 GHz = 0.8 nm)**

**b) Assume you need to design a link of 80 km length. Calculate the length of dispersion compensating fibre (DCF) required to keep the system dispersion within 10% of slot time duration. The DCF has coefficient of - 120ps/km/nm.**

# 2018 – Short Questions

Monday, November 10, 2025 10:25 PM

**Discuss the motivation behind the introduction of wireless local area networks (WLAN), and some examples of the application environment.**

**Describe the infrastructure-based and ad-hoc based modes of WLAN, and some examples of the application environment.**

**Describe the main characteristics, advantages and disadvantages of the IEEE 802.11a system**

**Describe the following wireless channel mitigation techniques:**

- a) Diversity.
- b) Directional antennas.
- c) Coding and modulation.

**Describe the critical systems and related challenges for 5G in dealing with IOT**

**Describe the main characteristics of the LoRa system.**

## **MCQ!!**

**Which one of the following statements is incorrect at frequencies above 60 GHz?**

- a) Propagation characteristics are poor.
- b) Size of antennas gets smaller.
- c) Interference with TV systems is an issue.
- d) RF hardware design is challenging.

Ans – C: Interference with TV systems is an issue.

At frequencies above 60GHz, path loss is high and signals are easily blocked by obstacles so propagation is poor.

Antenna size is inversely proportional to the frequency. Higher frequencies mean shorter wavelengths, hence smaller antennas.

TV broadcasting bands are well below 60GHz. Mostly below 1GHz. Frequencies above 60GHz should not have interference from TV broadcasting.

At very high frequencies, component tolerances and losses become critical, making design difficult.

**Given an OFDM transmission link in an environment which shows a channel gain which is independent of frequency, which of the following feedback schemes is the most efficient choice to provide channel state information to the transmitter?**

- a) The feedback channel only depends on the behaviour of the channel over time, so not enough information is provided to answer the question.
- b) The channel quality is reported for every subcarrier.
- c) The channel quality is reported for sub-channels of  $N$  subcarriers, where  $N_2$  is greater than one and smaller than the maximum allowed number of subcarriers.
- d) The channel quality is reported only once.

Ans – D: the channel quality is reported only once.

The channel has flat fading meaning all OFDM subcarriers experience the same gain.

The transmitter does not need separate channel state information for each subcarrier as each subcarrier has identical fading.

Grouping subcarriers helps if the channel varies slowly with frequency but this does not vary at all.

One report covers the entire band since the channel is flat (frequency-independent).

**Which of the following statements is incorrect?**

- a) Conventional radio design encompasses both baseband and RF design.

- b) Software radio adds provisions for easy upgrades to conventional radio.**
- c) Cognitive radio is like software radio, but does not necessarily provide easy upgrades to conventional radio.**
- d) Cognitive radio techniques impact RF design.**

Ans – C: cognitive radio is like software radio and provides easy upgrades to conventional radio. Conventional radios involve both an analog radio frequency design and digital baseband processing. Software defined radio moves much of the signal processing to software. Cognitive radio builds upon software defined radio. Cognitive radio often require wideband radio frequencies, spectrum sensing hardware

**With regards to a cellular automaton, which of the following statements is incorrect?**

- a) A cellular automaton represents necessarily a physical space.**
- b) The state at time  $t+1$  depends on the state at time  $t$  plus some of the neighbours.**
- c) The updates follow rules that are typically uniform for all cells.**
- d) A cellular automaton is useful to examine situations with some inherent structure.**

Ans - A

**Which of the following aspects is not among the benefits of license-exempt bands:**

- a) Facilitating market entry.**
- b) Providing guaranteed Quality of Service.**
- c) Providing certainty about spectrum access.**
- d) Reducing congestion in licensed bands.**

Ans - B

**Which of the following statements about 5G capabilities is incorrect?**

- a) It will mainly rely on contention-based access.**
- b) It will deliver a meaningful and efficient broadcast service.**
- c) It will make the realization of the tactile internet possible.**
- d) It will make use of massive antenna arrays at the base stations.**

Ans – D: 5G will not make use of massive antenna arrays at the base stations.

**The requirements for massive machine type communications (mMTC) include:**

- a) Architecturally sophisticated devices that use a high-complexity transmission mode.**
- b) Devices that can run on battery power for very long periods of time.**
- c) Main focus on short transmission ranges for devices in nearby locations.**
- d) Scalable networks that can connect only a large number of M2M devices, but not a small number of them.**

Ans - B

**How can we cope with the increasing capacity demand of modern networks?**

- a) Increasing radio link efficiency by more advanced physical layer techniques.**
- b) Increasing the amount of available radio spectrum.**
- c) Deploying a higher density of nodes in the wireless infrastructure.**
- d) All of the above solutions are considered by communication engineers to address the capacity crunch problem.**

Ans – D all of the above solutions are considered by communication engineers.

**In regular (i.e. non-dispersion-shifted) singlemode fibre, what is the limiting factor when pushing for higher bitrates and longer distances?**

- a) Modal dispersion.**
- b) Chromatic dispersion.**
- c) Polarization dispersion.**
- d) Non-linear effects.**

Ans – B: Chromatic dispersion

**What determines the wavelength of the light generated by a Fabry-Perot laser?**

- a) The colour filter on the partially reflective mirror.**

- b) Power: the highest frequency photons generated by stimulated emission will overwhelm the lower frequency photons and dominate the output.
- c) The resonance frequency of the lasing cavity, as determined by its length.
- d) Chance: stimulated emission is a probabilistic process that cannot be determined a-priori.

What is the sensitivity of an optical receiver?

- a) The ratio of the intensity of the generated current  $I_p$  and the power absorbed  $P_{in}$
- b) A measure of the effects of environmental factors such as temperature on accuracy of the receiver.
- c) The maximum amount of power the receiver can absorb before it saturates.
- d) The minimum amount of power needed to obtain a given BER for a given bitrate.

Ans – C: the maximum amount of power the receiver can absorb before it saturates

Why is ranging necessary in TDM or TWDM PONs?

- a) To charge customers proportionally to the length of fibre that was necessary to connect them to the network.
- b) To ensure that the latency experienced by the end-users is within an acceptable range for all customers.
- c) To avoid collisions in the shared upstream channel.
- d) To guarantee synchronization in the broadcast downstream channel.

Which of these technologies cannot be offered by an OLO with Local Loop Unbundling (LLU)?

- a) ADSL.
- b) VDSL2.
- c) Point-to-point fibre.
- d) None - these can all be implemented with LLU.

In Software Defined Networks (SDN), which of the following statements is false?

- a) The control plane and the forwarding plane are physically separated.
- b) The data plane can be programmatically controlled in a centralized fashion.
- c) Data can be switched on a per-flow basis.
- d) There is only one instance of the controller regardless of the size of the network.

Ans - D

What happens in an OpenFlow-enabled switch when a packet is received that does not match any of the known forwarding rules?

- a) The packet is discarded.
- b) The packet is broadcast on all ports; some other switch will know what to do.
- c) The packet header is forwarded to the controller so that it can instruct the switch on what to do.
- d) The packet is forwarded by reverting to traditional non-SDN routing protocols.

Network Function Virtualization (NFV) is:

- a) Just a different name for Software Defined Networking.
- b) The "softwarization" of typical network functions so that they can be run on commodity hardware and/or virtual machines.
- c) A polymorphism technique that allows operators to customize an abstract networking service by declaring some of its functions as virtual.
- d) Orthogonal to SDN: you can have one or the other, but not both.

# Optical Intro

Tuesday 11 November 2025 21:46

## Transmission distances

Early telephone networks used copper cables, good for short distances but limited for high-speed data.

Copper/coaxial cables: short range, high loss

Satellite: very long range but high delay

Optical Fiber: extremely long range and huge capacity

Mobile Networks: cover cities but limited by distance between towers

Fiber optics can send more data, faster and farther than any other

## Attenuation

Coaxial Cable: high attenuation, signal weakens quickly

Optical Fiber: very low attenuation, signal stays strong for many kilometers

Satellite: signal loss due to distance and atmosphere

Light in fiber stays strong much longer than electrical signals in copper.

## Differences Between Copper and Fiber

Aspect	Copper Cable	Optical Fiber
Signal type	Electrical signals	Light signals
Bandwidth	Low to moderate	Extremely high
Speed	Limited	Very high (Gbps–Tbps)
Distance	Short (few km max)	Very long (tens–hundreds of km)
Attenuation	High (signal weakens quickly)	Very low

# Optical Propagation

Monday, September 15, 2025 2:05 PM

## Optical Fibre

Uses the total internal reflection phenomenon – typical path loss 0.2dB/Km - 150km w/o amplification (very good)

Wavelength > obstacle – goes through  
Fibre – in infrared

## Radiation of copper wires

A static current on a wire produces a static electro-magnetic field.

Good at radiating = not good at propagating – losing power

Propagating near each other creates interference

An antenna is as good at transmitting as it is receiving

Twisting the copper helps reduce interference from external sources

Signal loss occurs in:

- Dissipation in the conductor

- Dissipation in the dielectric

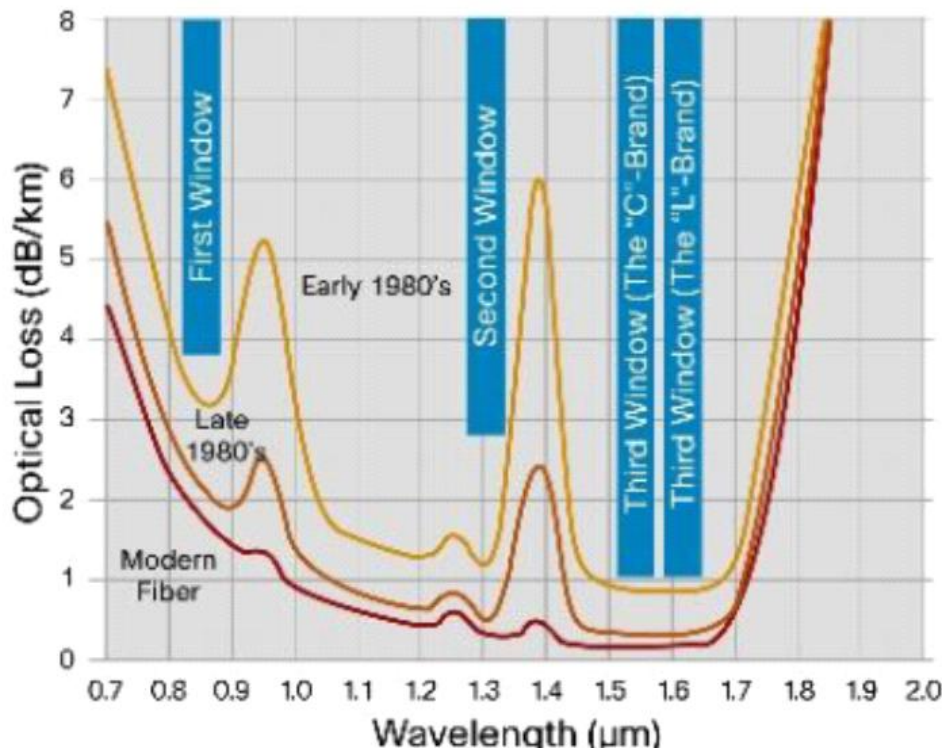
- Radiation (small)

## Optical Fibre

The aim is to transmit signals with minimum distortions

### Path Loss in Fibre

The amount of power lost depends on frequency/wavelength in transmission



## Fibre Fundamentals:

Transmit signals with the minimum distortion

1. Attenuation
2. Dispersion

3. Non-Linearity
4. Polarisation Distortion

**Path loss in fibre:**

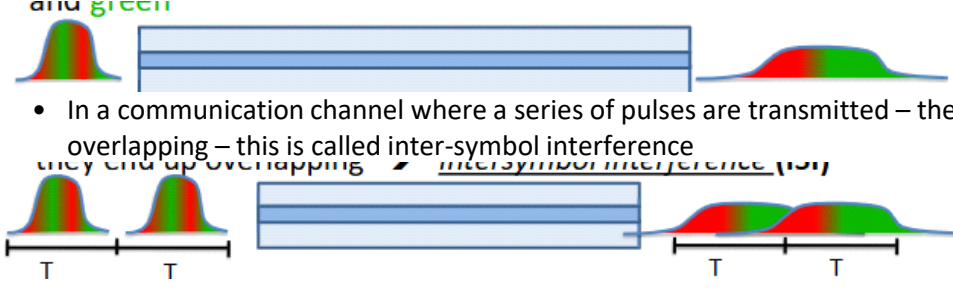
- Amount of power lost during propagation depends on the frequency or wavelength used in transmission

**Dispersion in Fibre**

- Dispersion in fibre is because the refractive index is not constant – value depends on the frequency of the signal
- **Modal Dispersion:** different modes propagate at different speed. Only occurs in multi-mode fibre.
- **Chromatic Dispersion:** difference frequencies within a single mode propagate at different speed
- **Polarization Mode Dispersion:** different spatial polarisation can propagate different speed

**Impairment caused by modal dispersion:**

- Transmit a pulse, it will be composed of a number of different modes. Because one is slower than the other, the pulse spreads and its peak power is decreased

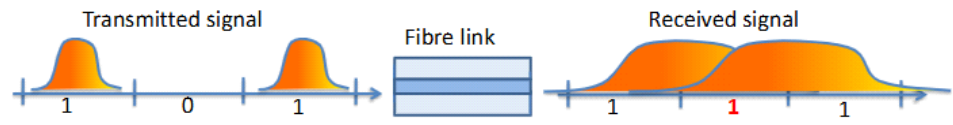


**Single-mode vs. Multi-mode fibre:**

- Multimode fibre has a larger core – multiple modes can coexist at the freqs used for optical communication
- Single-mode fibre has a smaller core – one propagation mode
- Modal dispersion is eliminated in single-mode fibre – most used in telecommunications. Modal dispersion only ever occurs in multimode

**Chromatic dispersion:**

- Optical comms = transmitting pulses
- Each pulse has finite spectral width (adjacent freqs)
- If lower freqs travel slower than higher – pulse spreads – signal overlaps



Dispersion = linear – cannot create new freqs – does modify the phase of a signal – when summed up the components will be out of phase which makes the pulse broader in the time domain. Pulses that are shorter in time have a larger bandwidth in the frequency domain – different for dispersion

**Modal dispersion – multi mode only:**

- Amount dispersion depends on data rate & length of fibre where signal propagates
- Has the biggest effects

**Dispersion shifted fibre:**

- Due to the material (this cannot be changed) and shape of the waveguide – shape of fibre cross-section – can be changed
- Can modify dispersion by changing distribution of refractive index

**Polarization mode dispersion:**

- Electric field in single-mode propagates with 2 orthogonal polarisation – not completely symmetrical – two orthogonal components of electric field have different propagation characteristics
- PMD is less severe than modal and chromatic dispersions

## Differences between single and multimode

The multimode fibre has a larger cladding

In singlemode fibre, modal dispersion is 100 times less

Modal dispersion is the largest dispersion impairment in multimode fibre

### In singlemode fibre

The dispersion characteristic can be changed by modifying the waveguide dispersion

Dispersion can cause inter-symbol interference

The absorption coefficient depends on the wavelength used

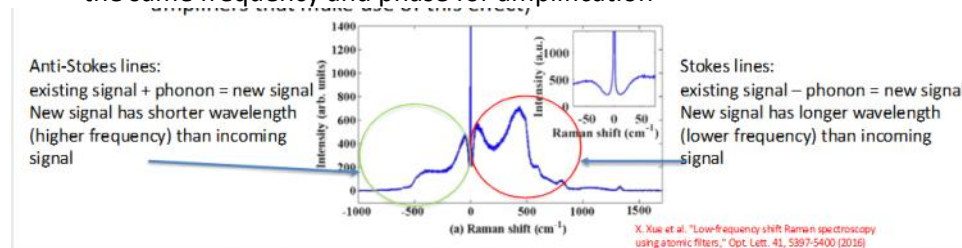
## Non-linear effects

If a transmission system is linear, then we can say that the transmitted signal has a constant rate of growth, as such, it remains roughly the same shape through transmission, only altering in terms of amplitude

Non linearity says the transfer function of the fibre depends on the signal being transmitted. Effects increase with the transmitted power.

### Raman Scattering:

- Light interacts with photons – generating photons with different frequency from the incoming signal
- If spontaneous, this can simply create signal with a different frequency and phase, creating noise.
- However, we can also stimulate our original frequency by making it interact with a phonon of the same frequency and phase for amplification



### Self Phase Modulation (SPM):

- The intensity of a light pulse changes the refractive index of the medium it travels through.
- This change in refractive index affects the phase of the pulse itself – broadens its spectrum

Light intensity  $\rightarrow$  refractive index change  $\rightarrow$  phase shift of the same light  $\rightarrow$  frequency spectrum broadening

### Cross Phase Modulation (CPM):

- If there are multiple wavelengths in a fiber, the modulation of other wavelengths produce changes in the refractive index that effects (re-modulates) the signal.

Both SPM and CPM produce broadening of the pulse – create additional dispersion and are problematic at high rates

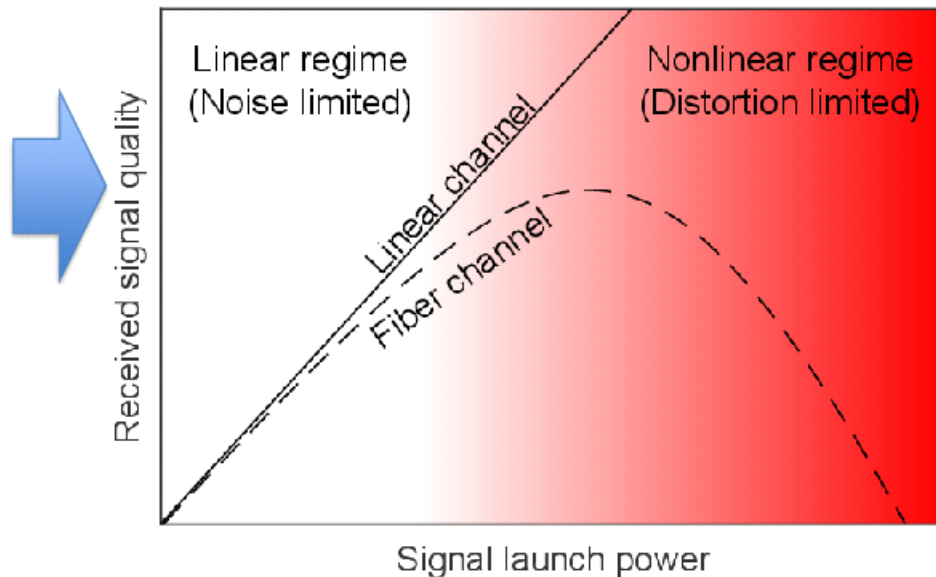
### Four Wave Mixing (FWM):

The refractive index nonlinearity generated new frequencies – the sum or difference of input signals.

This can generate noise in the form of smaller signals – becoming worse when the wavelength is smaller

### Shannon Capacity & Nonlinearity:

The capacity of a communication channel is proportional to the bandwidth of the signal and to the log of the signal to noise ratio SNR.



Shannon Capacity =  $C = B \log_2(1+s/n)$

----- PROF -----  
 GPT -----

### Optical Fiber > Copper

- Copper loses energy over long distances
- Copper can cause interference/leak out/mix
- Copper has limited bandwidth, transmitting less data per second
- Optical fiber uses light instead of electricity which travels farther, fast and cleaner
- Good optical fiber only loses about 0.2dB per kilometer. A signal can go ~150km before needing to be boosted

### Light?

- Electromagnetic radiation
- Typical radio waves: 10MHz
- Visible light: 100THz
- Light can carry hundreds of terabits per second, light waves vibrate incredibly fast

### How does copper radiate energy?

- DC current makes a fixed electromagnetic field
- AC current makes a changing field, radiating energy out like an antenna

Copper can both emit and pick up interference from other nearby signals

### Reducing Interference in Copper

Twisted pair cables: the wires are twisted together so that their fields cancel out. Used in phone lines and ethernet.

Coaxial cables: a wire in the center, surrounded by a metal shield that traps the radiation. Still, copper loses energy due to conductor loss, dielectric loss and radiation

### Optical Fiber

Carries light using total internal refraction

Core: center where light travels

Cladding: outer layer with a significantly lower refractive index

Light enters fibre at an angle, if the angle is steep enough it bounces back inside instead of escaping.

This keeps light trapped inside the core

### Dispersion in Optical Fiber

Parts of the light pulse travel at slightly different speeds

This causes the signal to spread out and overlap with the next one, causing intersymbol interference (SI)

1. Modal Dispersion: different **light paths take different times** (only in multi-mode fibers)
  - Light can travel in separate modes/angles
  - Each mode takes a slightly different route - this causes the pulse to stretch
  - Solution: use single-mode fiber which only allows one light path
2. Chromatic dispersion: different **frequencies travel at different speeds**
  - Each pulse is made up of a range of frequencies
  - If lower frequencies move slower than higher ones, the pulse spreads
  - This can cause bit errors and overlapping
3. Polarization dispersion: different **polarisation directions travel at different speeds**
  - Light can vibrate in two different directions e.g. horizontal and vertical
  - If the fiber isn't perfectly symmetrical, one direction travels faster. The two parts arrive at different times, making the pulse wider

### **Dispersion-shifted Fiber / dispersion compensating fiber**

Design the fiber's shape to move the wavelength of zero dispersion closer to the low-loss wavelength

### **Nonlinear effects**

If the signal power gets very strong, the fiber stops behaving linearly and starts generating new frequencies or interacting between channels

- Raman Scattering: light interacts with vibrations, creating new frequencies
  - Can be random (noise) or useful (Raman amplifiers)
- Self-Phase Modulation: the light changes its own phase because the fiber's refractive index varies with signal strength
- Four Wave Mixing: three signals mix to create a fourth, unwanted frequency
- Cross-Phase Modulation: one signal changes the phase of another when multiple wavelengths are sent

Nonlinear effects all:

- Get worse with more power
- Cause distortion and noise
- **Are stronger when wavelength spacing is small**

There is an optimal power level for maximum capacity before nonlinear effects start to occur

# Optical Transmitters & Receivers

Tuesday, October 07, 2025 4:57 PM

Optical communication systems send data using light, not electricity

We need a **transmitter** to create and modulate light (turn data into a light signal) (**lasers**)

We need a **receiver** to detect that light and turn it back into electrical data (**photodetectors**)

## Light Amplification by Stimulated Emission of Radiation (LASER)

Creates coherent light (all light waves have the same frequency and phase)

This makes the beam very sharp and precise

Lasers produce focused, perfectly synchronised light, perfect for communication

Because coherent light doesn't spread much, it's perfect for sending signals through optical fibers

## Tunable Laser

Change its output wavelength (colour) across a small range

Useful in communication systems because you can pick any wavelength in a **Wavelength Division Multiplexing (WDM)** system

## Direct Modulation

Change the current going into the laser. Simple and cheap.

Causes a small frequency chirp inside each pulse

Chirp worsens chromatic dispersions

## External modulation

Laser shines continuously

A separate device blocks or passes the light based on data, avoids chirps and keeps pulses cleaner

**PIN Photodiode**: simple, reliable, standard detector

**APD**: uses high voltage to multiply electrons, each photon creates several electrons

APD detects weaker signals but adds more noise than PINs

## Amplitude Modulation (Direct Detection systems)

Low-cost optical systems use amplitude to send information

### Eye Diagram

Overlaps many signal waveforms to visualise quality

## COHERENT SYSTEMS

Coherent Detection also measures phase and polarisation of the light wave as well as just brightness (amplitude)

This enables:

- **Phase-Based Modulation**: PSK, QAM, pack more bits per symbol
- Better sensitivity
- **Digital Signal processing**: correct fiber impairments like dispersion

## MODULATION TYPES IN COHERENT SYSTEMS

- **Phase Shift Keying**: changes the phase of the signal to represent bits
  - 4-PSK = 2 bits per symbol
  - 8-PSK = 3 bits per symbol
- **QAM**: changes both amplitude and phase
  - 16-QAM = 4 bits per symbol
  - 64-QAM = 6 bits per symbol

More complex modulation = higher data rates but requires a much cleaner signal

## ADVANTAGES OF COHERENT SYSTEMS

1. Higher sensitivity
2. Digital compensation
3. Dynamic operation
4. Better spectral efficiency
5. Filtering

<b>Concept</b>	<b>Meaning</b>	<b>Summary</b>
<b>LASER</b>	Creates coherent light	Clean, high-power light for data
<b>Modulation</b>	Imprints data into light	Sends digital information through fiber
<b>Photodetector</b>	Converts light to electricity	Receives data
<b>PIN/APD</b>	Two types of detectors	Trade-off: cost vs. sensitivity
<b>Direct Detection</b>	Uses only amplitude	Simple but limited
<b>Coherent Detection</b>	Uses amplitude and phase	Higher data rates, better quality

Lasers send light, modulators add data, detectors read it, and coherent systems increase speed and reliability

# Link Design

Tuesday, October 07, 2025 4:57 PM

An optical link is a connection that sends data as light through optical fiber

The goal is to **meet a target Bit Error Rate**, meaning only a very **small number of bits should be received incorrectly**.

Three things are checked to make sure that the optical link is meeting the target Bit Error Rate

1. **Power Budget:** is the received signal strong enough
2. **OSNR:** is the signal clean enough
3. **Impairments:** are effects like dispersions or nonlinearities under control

## Power Budget

Every component (fibers, connectors, amplifiers) in a fiber link causes *some* loss

*Power - Losses - Margins >/ Receiver Sensitivity*

If this holds, the receiver has enough light to work properly

## OSNR

Even if the power level is ok, too much noise will still cause errors at the receiving end

Higher OSNR = cleaner signal = fewer bit errors

## Impairments

Dispersion, pulse spreading, nonlinearities degrade signals. To accommodate for this, increasing the power slightly can achieve the same BER. This extra power is called the *power penalty*. How much extra volume is needed to overcome distortions

## Typical Optical Link

Laser: light source

Modulator: adds data to light

Fiber: transmission path

Optical Amplifier: boosts signal after each *span*

Dispersion-Compensating Fiber: fixes spreading

Regenerator: resets and cleans the signal if it gets too bad

## Power Budget in Amplified Systems

In systems with amplifiers, you must add up all the gains and losses

*Power at the receiver = Power at the transmitter - L1 + G1 - L2 + G2 - ... - M*

L = loss in each span

G = amplifier gain

M = network safety margins

## Chained Amplifiers

Amplifiers are used in a row and each compensates for loss from the previous span

Chaining amplifiers adds some noise (ASE - Amplified Spontaneous Emission)

More amplifiers --> more ASE noise --> lower OSNR

So spacing between amplifiers must be chosen carefully

## Noise in Optical Systems

Amplifier Noise/ ASE: noise from **amplifiers**

Thermal Noise: random motion of electrons in the **receiver**

Shot Noise: randomness in **photon** arrival times

## Forward Error Correction

Can **repair wrong bits** after transmission. The FEC threshold is the maximum BER for which the FEC can handle, above that, error correction can't save the high BER.

### OSNR for a Chain of Amplifiers System

$OSNR = \text{Amplifier Power Output} - \text{Noise Figure} - \text{Gain} - 10\log_{10}(\text{no. wavelength channels}) - 10\log_{10}(\text{no. amplifiers}) + 58$

Shorter spans & fewer amplifiers = higher OSNR

### Network Margins

**How far away you are from the point where the BER suddenly skyrockets.**

A safety zone that mitigates uncertainty in the network e.g. miscalculations, under/over estimations  
Larger margins --> more safety --> less efficient use of power and capacity

### Signal Regeneration

If OSNR gets too low:

1. **End** the optical link session
2. Convert the signal to its **electrical** form
3. Check and **clean** the data
4. **Re-modulate** into a fresh optical signal for the next section

This restores the signal quality but costs a lot

### Dispersion Compensating Fiber

A special fiber with opposite dispersion to counteract the effects of dispersion in the system. It cancels out spreading but adds an extra loss, which needs to be included in the power budget. Coherent systems can fix dispersion at the receiver but this uses a lot of computing power

### Wavelength Division Multiplexing (WDM)

Sending multiple signals at different wavelengths/colours of light through one fiber. Each colour carries its own data stream.

**Amplifiers boost all wavelengths together but not perfectly evenly.**

Dispersion compensation also works for different wavelengths but again, isn't perfectly even.

**WDM packs many channels into one fiber using different colours of light.**

Concept	Meaning	Purpose
<b>Power Budget</b>	Checks signal strength	Ensures light is detectable
<b>OSNR</b>	Checks signal quality	Ensures low BER
<b>Amplifiers</b>	Boost signal / adds noise	Balance power vs. cleanliness
<b>Dispersion</b>	Pulse spreading (bad)	Causes bit overlap / high BER / ISI
<b>Wave Division Multiplexing</b>	Multiple colours / flexible spacing	Increases capacity
<b>Coherent Systems</b>	Smarter modulation/compensation	Enables high-speed links

# Tutorial

**A Wavelength Division Multiplexing (WDM) transmission system with 40 channels needs to operate over a 1,000 km distance. Amplifiers have 15 dBm of power and noise figure of 6 dB, while the fibre has a nominal attenuation of 0.2 dB/km. The distance between amplifiers is 50 km. The signals all transmit at 33 Gbaud (occupying a 37GHz bandwidth). Also consider that a margin of at least 4 dB is required.**

**(a) What is the maximum useful data rate of your system, considering all channels, if the required OSNR for 16QAM, 32 QAM and 64 QAM modulations are, respectively, of 18, 23 and 28 dB? Notice that these rates can only be achieved using error correction codes, which have an overhead of 9% (i.e., they use 9% of the channel capacity).**

Span length = 50km

Fibre loss = 0.2dB/km

Span loss =  $50 \times 0.2 = 10\text{dB}$

Include margin =  $10 + 4 = 14\text{dB}$

Amplifier gain = 14dB

Number of amplifiers =  $1000\text{km} / 50\text{km span length} = 1000 / 50 = 20$  amplifiers

$\text{OSNR} = 15 - 6 - 14 - 10\log_{10}(20) - 10\log_{10}(40) + 58 = 23.9 \sim 24\text{dB}$

32-QAM can be applied to this system because of the OSNR constraints.

32-QAM = 5 bits per symbol

$33\text{GBaud} \times 5 \text{ bits per symbol} = 33 \times 5 = 165\text{Gb/s}$

Forward error correction uses 9% of the channel's capacity

$165\text{Gb/s} \times 91\% = 165 \times 0.91 = 150.15\text{Gb/s}$

Total system capacity = channel capacity \* number of channels =  $150.15 \times 40 = 6,006$

Maximum useful system data rate = 6Tb/s

(b) What is the chromatic dispersion of each channel if the average dispersion coefficient of the fibre is 17 ps/nm/km (assume the following conversion ratio: 100 GHz = 0.8 nm)? If the transmissions were carried out using direct detection receivers and the transmitters worked at the same Baud rate described above (i.e., 33Gbaud), how much dispersion compensating fibre (DCF) would be required at each amplifier location to compensate for dispersion? Assume the DCF has coefficient of -150 ps/km/nm.

## Exercise 2

A Wavelength Division Multiplexing (WDM) transmission system uses 20 channels in the C band and needs to operate over a 400 km distance. Amplifiers have 18 dBm of power and noise figure of 8 dB, while the fibre has a nominal attenuation of 0.3 dB/km. The amplifier gain can be set to between 10 and 20 dB. Also consider that a margin of at least 5 dB is required.

(a) Assuming you need to support an overall capacity of at least 5.8 Tb/s, what is the maximum amplifier distance for the system to work without regenerators? (you can approximate to the closest smallest 5km multiple). Consider that the transceivers have a baud rate of 50 Gbaud and can work at modulation formats of 16QAM, 32 QAM and 64 QAM, which require, respectively, 18, 23 and 28 dB OSNR.

(b) The system uses coherent transmission, so no dispersion compensating fibre (DCF) is required. The transceiver can work at a baud rate of either 33Gbaud (37.5 GHz bandwidth) or 66 Gbaud (75GHz bandwidth). The maximum tolerable dispersion by the digital filter is

however 1ns. What is the total capacity you can achieve over the 20 channels if the available OSNR is  $> 28\text{dB}$  (assuming the modulation formats as defined in the previous problem)? Assume the average dispersion coefficient of the fibre to be  $5\text{ ps/nm/km}$  (assume the following conversion ratio:  $100\text{ GHz} = 0.8\text{ nm}$ ).

# Quiz 1 Sample

Tuesday, October 07, 2025 9:46 PM



NGN\_quiz\_  
sample

**CS4031/CS7NS3/EEU44C4 – Quiz no .1**

## **WIRELESS**

1.

**Which of the following statements is incorrect?**

**a) High velocity of transmitters corresponds to low coherence time**

Coherence time =  $1/f_d$  where  $f_d$  is the Doppler spread. Higher velocity increases Doppler spread. Thus reducing coherence time. This is true

**b) Significant multipath corresponds to low coherence bandwidth**

More multipath increases delay spread, lowering the coherence bandwidth. This is true.

**c) A completely static environment corresponds to an infinite coherence time**

In a static environment, the channel does not vary over time. Coherence time is effectively infinite. This is true.

**d) We can more easily deploy multiple antennas on a mobile phone at lower carrier frequencies**

Lower frequencies have longer wavelengths, making it harder to fit multiple antennas in a mobile phone. This is false

This question asks about wireless channel characteristics : time coherence, frequency coherence, antenna deployment.

Coherence time measures the time interval over which the channels response is constant. It is inversely related to the Doppler spread caused by motion.

Coherence bandwidth measures the frequency range over which the channel's frequency response is flat. It is inversely related to the multipath delay spread.

Multipath creates frequency selectivity.

A static channel has infinite coherence time – a fast-moving transmitter reduces it.

Multiple antennas require spacing to reduce correlation. Lower carrier frequencies have longer wavelengths, making compact multiple-antenna deployment harder.

2.

**Which of the following design choices is best in terms of energy efficiency in a Frequency Division Duplexing (FDD) system?**

**a) Uplink frequency should be higher than downlink frequency**

Higher uplink frequency increases path loss, forcing the mobile to use more power. This is false

**b) Uplink frequency should be lower than downlink frequency**

Lower uplink frequency reduces path loss, improving energy efficiency for the mobile. This is true

**c) Uplink frequency should the same as downlink frequency**

Equal uplink/downlink frequencies do not optimise uplink path loss. This is not optimised. This is false.

**d)The choice of uplink and downlink frequency is not relevant for energy efficiency**

Frequency choice affects path loss. This is false

Energy efficiency in frequency division duplexing wireless systems – focusing on how uplink and downlink frequency affects mobile transmit power.

Energy efficiency: minimising power required for efficient communication.

Frequency dependent path loss: higher frequencies experience greater path loss, requiring more transmit power to achieve the same received signal strength.

Uplink: transmission from a user device to the base station/network infrastructure. Carries user-originated signals e.g. voice/data uploads

Downlink: transmission from the base station/infrastructure to the user device. Carries network-originated signals e.g. calls/data downloads

Frequency division duplexing uplink vs. Downlink: uplink and downlink operate on separate frequency bands. Since the mobile device transmits the uplink, reducing uplink frequency reduces path loss and energy consumption.

**3.**

**Which one among the following options cannot be consider a “knob” in the cognitive radio sense?**

**a)Number of selected transmit antennas**

Number of transmit antennas can be adjusted for capacity/power/interference control. This is a physical layer knob

**b)Modulation technique**

This can be adjusted based on the channel quality. The radio can switch between modulation schemes. This is a physical layer knob.

**c)Medium access control protocol**

This can be adjusted in adaptive networks. The radio can switch based on traffic patterns, user density or interference conditions. This is a data link layer knob.

**d)All the above are possible knobs**

Assessing cognitive radio adaptability.

Cognitive radio is where the system senses its environment and adjusts operating parameters to optimise performance while minimising interference.

A knob is a controllable parameter.

Knobs can exist at multiple layers of the protocol stack.

Transmit antennas: physical-layer knob – affects power efficiency

Modulation technique: physical-layer knob – affects data rate and spectral efficiency

MAC protocol: data link-layer knob – controls channel access, collision avoidance and coordination

**4.**

**Which of the following statements is incorrect in a single link system?**

**a)Increasing the bandwidth is never detrimental to the data rate**

Increasing bandwidth can reduce the data rate if the total transmit power is fixed. As this spreads the same power thinner over the bandwidth. This is false

**b) In a spatial multiplexing system, the data rate increases linearly with the number of transmit or receive antenna**

The data rate increases approximately linearly with the number of transmit and receive antennas. This is true.

**c) The multi-user interference will lead to a decrease in the data rate**

Multi-user interference degrades signal quality and hence decreases the data rate. This is true

**d) The usage of frequency reuse is not relevant**

In a single-link system, frequency reuse is irrelevant. This is true

Factors influencing the data rate in a single-link wireless communication system.

This is where only one transmitter-receiver pair operates.

Cells: the fundamental coverage in a cellular communication network. The geographic area covered by a single base-station. Each cell uses a portion of the available spectrum. Neighbouring cells can reuse frequencies to minimise interference. As a user moves, the connection is handed over between cells.

A single-link system refers to just one transmitter-receiver pair without multiple cells or frequency re-use. A cellular system involves many links coordinated across cells.

Bandwidth: determines the range of frequencies used. Data rate increases with bandwidth if signal power scales accordingly. With a fixed transmit power, more bandwidth spreads the same power thinner, possibly lowering total capacity.

Spatial multiplexing: a MIMO technique where multiple antennas transmit independent data streams. The capacity grows roughly linearly with the number of antennas.

Multi-user interference: arises from multiple simultaneous transmitters. Even in a single link, its presence would reduce the data rate.

Frequency re-use: cellular systems sharing spectrum across cells. It has no relevance in a single link

5.

**In case you want to optimise both data rate and coverage, which of the following options is the best design choice?**

**a) 802.11g**

Higher data rate and a moderate range

**b) 802.11a**

Higher data rate but a shorter range due to higher frequency and poor penetrating power.

**c) 802.11b**

Low data rate, long range

**d) 802.11**

Very low data rate

802.11g is the best design choice as it balances the data rate and coverage most effectively.

Wifi standards selection to optimise the data rate and the coverage.

Data rate: maximum throughput achievable by the standard. Higher frequency and advanced

modulation increase the data rate.

Coverage: effective range of the signal. Lower frequency bands penetrate obstacles better and propagate further than higher frequency bands.

Trade-off: 5GHz (802.11a) gives a high data rate but a shorter range. 2.4GHz (802.11b/g) gives longer range with moderate data rates

## **OPTICAL**

6.

**In which of the following cases increasing network margins is not useful:**

**a)When the specification of active network components is not known**

Unknown component specification introduces uncertainty. Network margins mitigate this. This is useful.

**b)When there is possible estimation error in the fibre length of the spans**

Estimation errors in the fiber length introduces uncertainty. Network margins mitigate this. This is useful.

**c)When the network is running at maximum possible capacity**

Network margins cannot create new capacity, it only reduces useable resources. This is not useful

**d)When the amount of crosstalk introduced by ROADMs is under estimated**

Underestimating ROADM crosstalk introduces uncertainty. Network margins mitigate this. This is useful

A network margin is a design allowance added to account for uncertainties, degradation or aging in the system. It improves reliability and tolerance

Network Margin: extra allowance in design to account for uncertainties, signal degradation or impairments. Reliable operation under varying conditions

Useful Scenarios: unknown component specifications, estimation errors in fiber length, underestimating impairments can all be mitigated by adding margin.

Limitation: if the network is already operating at full capacity, adding margin does not improve throughput or performance. It cannot create additional resources.

Hence margin is ineffective when the system is resource-limited, rather than uncertainty-limited

ROADM: Reconfigurable Optical Add-Drop Multiplexer - a device in optical networks that selectively adds, drops or passes through wavelengths in a fiber without converting them to electrical signals.

Crosstalk: unwanted leakage of optical power from one wavelength channel into another

ROADM Crosstalk: occurs when switching or routing signals through the ROADM causes part of one wavelength to leak into another, degrading signal quality. This increases bit error rate, reduces signal-to-noise ratio and may limit network margin if not properly accounted for.

7.

**Which of the following statements is true with regards to capacity in optical fibre:**

**a)A higher order modulation format requires higher signal to noise ratio**

Higher-order modulation (16-QAM, 64-QAM) encodes more bits per symbol but requires higher SNR to maintain acceptable error rates. This is true

**b)Increasing the transmission power always increases capacity**

Increasing transmission power improves SNR only up to the point where nonlinear effects (self-phase modulation, four-wave mixing) start degrading the signal, potentially reducing capacity. This is

false

**c) A high dispersion coefficient in fibre leads to higher capacity**

High dispersion spreads pulses in time, causing inter-symbol interference which reduces capacity. This is false

**d) Amplifiers with higher noise figures lead to higher capacity**

Higher amplifier noise increases noise, lowering SNR and capacity. This is false

Factors affecting optical fiber channel capacity, which depends on signal-to-noise (SNR) ratio, modulation format, fiber characteristics, and amplifier performance.

Symbol: a unit of modulation that conveys one or more bits of information. Each symbol represents a specific state of the carrier e.g. amplitude, phase or frequency

Pulse: the time-domain waveform that physically carries a symbol through the channel. Each symbol is transmitted as a pulse of finite duration. Pulse shape and spacing determine bandwidth and susceptibility to inter-symbol interference

Modulation format: higher-order formats encode more bits per symbol, increasing spectral efficiency but requiring higher SNR to maintain lower error rates.

Higher-order modulation formats: encode more bits per symbol than lower-order formats, increasing spectral efficiency. Higher-order formats transmit more data in the same bandwidth. They require higher Signal-to-Noise ratio (SNR) to distinguish and maintain lower error rates. More sensitive to impairments like noise.

Transmission power: increasing power improves SNR but only until nonlinear effects limit performance. Beyond that, capacity can degrade

Dispersion: high dispersion spreads pulses, causing inter-symbol interference which reduces achievable data rate unless compensated

Amplifier noise figure: higher noise introduces more additive noise, lowering SNR and capacity

8.

**Which of the following is not an advantage of a coherent system over a direct detection:**

**a) It can provide higher data rates**

This is true. Coherent detection enables higher-order modulation and higher data rates.

**b) It does not require the use of dispersion compensating fibre**

Coherent systems let the receiver fix pulse spreading using software instead of adding extra fiber

**c) It can work with lower input power**

Coherent detection is more sensitive, allowing operation at lower input power. This is true

**d) It is simpler to build**

Coherent systems are more complex due to the use of local oscillators and advanced digital signal processing

Advantages of coherent optical communications systems over direct detection systems

Phase: describes the position of a cycle of the waveform. In optical communications, phase represents the timing offset of the electric field of light relative to a reference

Coherent Detection: uses a local oscillator to recover amplitude and phase of the optical signal. It allows advanced modulation formats

Advantages: higher data rates through multi-level modulation

Limitations: more complex and costly due to the use of local oscillators

9.

In a chain of optical amplifiers:

- a)The optical signal to noise ratio is independent on the number of amplifiers - FALSE
- b)Optical amplifiers are typically used for multi-mode fibres - FALSE
- c)The amplifiers provide digital regeneration of the signals - FALSE
- d)The optical signal to noise ratio depends on the span length - TRUE

10.

Which of the following statements is false about the Shannon-Hartley theorem?

- a)Capacity is directly proportional to bandwidth - TRUE
- b)Capacity is directly proportional to signal to noise ratio - FALSE
- c)Higher loss implies lower signal to noise ratio in copper medium - TRUE
- d)Capacity stays the same if signal and noise increase by the same factor. - TRUE

# Quantum Systems

Tuesday, November 04, 2025 1:27 PM

## Solution of the blackbody problem:

- An assumption that the source of radiations are oscillators that can only take discrete energy values
- When the oscillator moves from energy level  $E_1$  to  $E_2$  it releases a discrete quanta of energy
- The assumption was a principle of reality, energy is quantised.

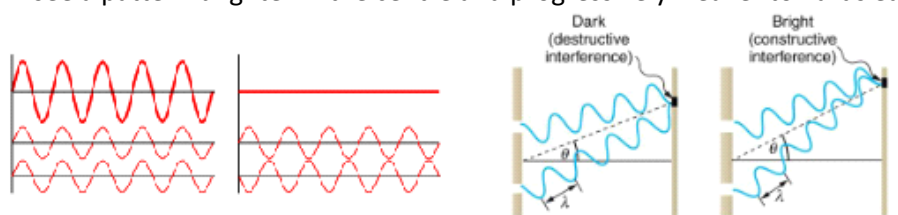
Other effects that could not be explained without quantum physics

- Below a certain frequency of light, there was no electron emission, no matter how bright the source. After that threshold the number of electrons were proportional to the source brightness
- Experiments shows discrete lines for absorption and emission, where a continuous spectrum was expected according to classical physics

## Double Slit Experiment

Light is a wave

- Selecting a slit difference and screen difference, there is an interference pattern
- Wave-like nature of light, depending on phase of the waves when they sum up result can be constructive or destructive
- If you close one of the two slits, you have one wave and there is no interference. You would see a pattern brighter in the centre and progressively weaker towards each side



## Quantum double slit experiment

- Attenuate the laser sources until you send one photon at a time
- If a photon is a particle then it either goes through one slit or the other. But it goes through both and creates the same interference pattern

## Interferometer Experiment

The light bouncing from mirror 1 and mirror 2 interfere at the beam splitter, creating constructive or destructive interference in the screen. Depends in the difference in length between the distance form beam splitter to mirror 1 and 2

## Quantum interferometer experiment

Now, imagine injecting one photon at a time:

In principle, if a photon is a particle, then there is equal and independent probability of exiting at each of the beam splitters. However interference experiments show the wave nature of photons, and the results are exactly the same as in the classical version.

However, if I try to make a measurement in one of the two arms, to see which arm did the photon pass by, the interference disappears and the photon appears at any of the two ports with equal probability

## Heisenberg's uncertainty principle

if you have an electron, you cannot determine at the same time exact position and momentum

----- PROF -----  
GPT -----

A blackbody is a perfect object that absorbs all light that hits it and only emits light based on temperature.

Solved by saying that energy isn't continuous, it comes in packets called quanta. Energy is quantised. Light and energy come in small chunks, not streams.

### Quantum Physics Stuff

Photoelectric Effect: when light shines on metal, it can knock out electrons if the light's frequency is above a threshold. Each photon must have enough energy to free an electron.

Atomic Spectra: when atoms emit/absorb light they produce specific lines of colour because electrons can only jump between *specific* energy levels, another sign that energy is quantised.

Light acts as both waves and particles.

### Observing Changes Reality

- If you try to detect which path a photon takes, the wave pattern vanishes.
- The photon suddenly behaves like a ball, one path or the other, no interference.
  - **If we don't look** light behaves like a wave
  - **If we do look** light behaves like a particle
- If you send one photon at a time, it behaves like a wave and "travels both paths" but if you try to measure which path it took, the interference disappears.
- You can't know the exact **position** and **momentum** of a particle at the same time. The more accurately you measure one, the fuzzier the other becomes.
- Experiments prove that quantum behaviour is truly random and depends on measurements, not hidden variables

Quantum effects are being used to build the next generation of communication

# Qubit

Tuesday, November 04, 2025 1:27 PM

Classical bits can be either 0 or 1

A quantum bit can be 0 or 1, but it can also be in a superposition of these two values

### 3 Phenomena that differentiate quantum communications and computing from its classical counterpart:

- Quantum superposition
- No cloning theorem
- Quantum entanglement

A qubit in the 0 state is represented as  $|0\rangle$  and in the 1 state as  $|1\rangle$

Superposition of 0 and 1, which is represented as a state:  $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$  where  $c_0$  and  $c_1$  are complex numbers with the property that  $|c_0|^2 + |c_1|^2 = 1$  (square them and sum them = 1)

They are a probability of being a 0 or 1. If they are equal then you just have 0.5 and 0.5 (normal bits).

This is not possible to see.

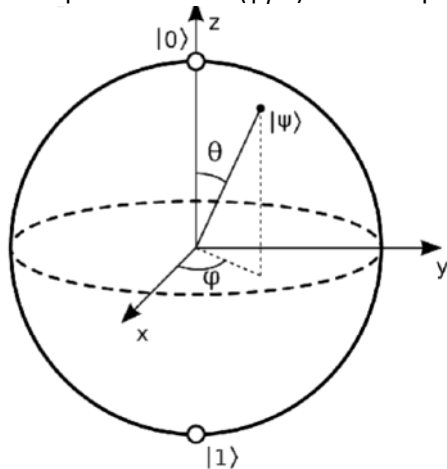
For 1 qubit, it doesn't matter because you always end up at 0 or 1 visually.

For multiple qubits, depending on the phase the result becomes different

### Bloch Sphere

The property that  $|c_0|^2 + |c_1|^2 = 1$  means that the state  $|\psi\rangle$  can be expressed as a vector within the surface of a sphere. Expressing them as the function of two angles.

The quantum state ( $|\psi\rangle$ ) can be represented as a point on the sphere.



All possible states can be represented as a point in the sphere surface with the conditions:

$$0 < \theta < \pi, 0 < \phi < 2\pi$$

The moment you measure you destroy the quantum state

#### - Quantum superposition

As a qubit evolves the value of its state moves around the Bloch sphere.

However, when measured, the qubit will always return a value of  $|0\rangle$  or  $|1\rangle^*$

The measurement process destroys the quantum states and "collapses" it into its  $|0\rangle$ ,  $|1\rangle$  base

The value  $|c_0|^2$  gives the probability that the outcome is a  $|0\rangle$  and the value  $|c_1|^2$  gives the probability that the outcome is  $|1\rangle$  (and their sum is always 1)

#### - No cloning theorem

it is not possible to copy the state of a qubit

You cannot send multiple copies of the same qubit in order to make a more robust communications system

if you send a qubit over a transmission medium and it is lost or corrupted, that information is lost forever

in a quantum system, two interacting qubits can be considered as part of one system

### – **Quantum Entanglement**

It is also possible to have different type of states

the value of each of the two qubits is not determined until a measurement is made.

Entangled states are non-separable. Cannot be represented as two separate qubits.

Both 00 or 01 or 10 or 11.

### **Multiple qubits**

#### **Generation of entangled photons (non-linear, things come out a different frequency)**

SPDC – spontaneous parametric down conversion.

A pump laser (high power laser, same as optical amplifiers) going through a nonlinear crystal (e.g. Beta Barium Borate).

One of the photons, hitting a specific parts of the material splits into two photons of different energy.

These two photons of different energies are entangled.

Two things can be entangled if both one or both zero or zero, one or one, zero.

When entangled, one is vertical and the other is horizontal. Or vice versa. Orthogonal.

Energy conserves, the energy of the splitted photons equals the energy of the original high power photon

$$|HV\rangle + |VH\rangle / \text{root}2$$

**SPDC** efficiency is low, one in a million probability.

Still can be created, physically possible.

### **Bell States**

There are 4 entangled states, maximally entangled. Each have equal probability of the first qubit to be measured as  $|0\rangle$  or  $|1\rangle$  but the result of measuring the second qubit is completely determined

$$- |\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

$$- |\Phi^-\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}$$

$$- |\Psi^+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

$$- |\Psi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

### **Bell state measurement**

Take entangled pair, measure it, get which Bell state the system was.

When two qubits enter the BSM, they are jointly measured, giving 4 possible outcomes (classical bits).

### **BSM with linear optics (frequency remains same)**

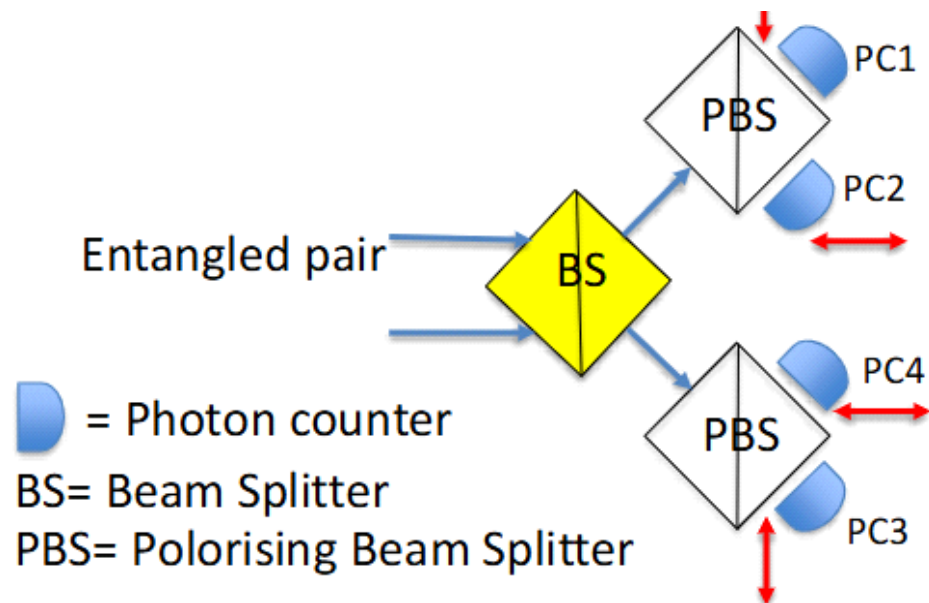
With photons, beam splitters, phase changers, etc.

The entangled pair: both vertical or one vertical, one horizontal.

Put it through the beam splitter. There are two directions now.

PBS looks at the directions. If diagonal, 50/50 chance is given, like BS.

The qubits are vertical or horizontal.



If two photons are entangled, they always come out at the same time.  
 Put a lot of light, can change the amount of photons per second

### Quantum Circuits

A quantum circuit shows how the state of qubits evolve as they go through quantum gates.

#### 1-qubit gates – qubit in, qubit out:

Pauli-X/NOT - flip around the Bloch x axis. Swaps the coefficient of  $|0\rangle$  and  $|1\rangle$

Pauli-Y – flip around Bloch y axis.  $|0\rangle \rightarrow i|1\rangle$  and  $|1\rangle \rightarrow -i|0\rangle$

Pauli-Z – flip around Bloch z axis  $|0\rangle \rightarrow |0\rangle$  and  $|1\rangle \rightarrow -|1\rangle$

Hadamard: turns the state  $|0\rangle$  into superposition  $|0\rangle + |1\rangle / \text{root}2$

and turns the state  $|1\rangle$  into superposition  $|0\rangle - |1\rangle / \text{root}2$

#### 2 qubit gates:

CNOT controlled not – if the control bit  $|x\rangle$  is  $|1\rangle$  then NOT is applied to  $|y\rangle$

All other gates seen also have a controlled version.

Example of circuit for creating entanglement.

One problem with quantum computers, a qubit can collapse if you are not watching it. When it interacts, it's like measuring it.

Difficult to keep a qubit as a qubit for a long time.

You can create a qubit out of anything as long as you can put it in a superposition.

Memory is just a device of keeping a qubit in its state for longer.

### Multi Partite Entanglement GHZ

Possible to have entanglement simultaneously on more than 2 qubits.

$$|000\rangle + |111\rangle / \text{root}2$$

The GHZ is maximally entangled

If you make a measurement on any of the 3 qubits, the result can be 0 or 1 with 50% probability

However once that qubit is determined, the other two are also determined: they are either all 0 or all 1

### Multi Partite Entanglement W

$$|001\rangle + |010\rangle + |100\rangle / \text{root}3$$

not as strong entangled

If any of the bit measured is 1, then the other two are also fully determined

### Quantum Bits

- Classical bits can be 0 or 1.
- Qubits can be 0, 1 or both at the same time (superposition)

Key principles of quantum systems:

1. Quantum Superposition: being in multiple states at once
2. No Cloning Theorem: you can't copy an unknown quantum state
3. Quantum Entanglement: two particles can be linked, sharing the same state instantly

### Representing Qubits

$|0\rangle$  means the qubit is in state 0

$|1\rangle$  means the qubit is in state 1

A general qubit is  $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$ , where  $c_0$  and  $c_1$  are complex numbers representing the quantum coordinates

$|c_0|^2$  and  $|c_1|^2$  must sum to 1, they are the probabilities that the qubit is in state  $|0\rangle$  or state  $|1\rangle$   
Therefore a qubit is a weighted mix of 0 and 1 until it is measured.

### Bloch Sphere

Every point on the sphere represents a possible qubit state.

At the poles  $|0\rangle$  North and  $|1\rangle$  South.

Anywhere inbetween is a superposition mix of both

The angles describe how much of a 0 and 1 are in the mix.

### Quantum Superposition

A superposition means a system exists in multiple states at once.

$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$  means the qubit is equally 0 and 1 at the same time

When we measure the qubit it collapses and becomes *either*  $|0\rangle$  or  $|1\rangle$

### Quantum Measurement

Measurement is probabilistic/based on chance.

If  $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$  then the probability of measuring  $|0\rangle$  is  $|c_0|^2$  and the probability of measuring  $|1\rangle$  is  $|c_1|^2$ .

E.g.  $|\psi\rangle = 0.3|0\rangle + 0.7|1\rangle$  means  $|0\rangle$  30% of the time and  $|1\rangle$  70% of the time.

You only know these probabilities after many measurements

### No-Cloning Theorem

In classical computing, you can copy data freely.

In quantum mechanics, you can't copy a qubit's state because measuring/trying to copy changes it.

- Lost qubits can't be recovered
- You can't make backup copies of quantum information
- Every qubit is unique, once it's lost it's gone.

### Two or More Qubits

When you combine qubits their states multiply together.

$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$

And

$|\psi'\rangle = c_0'|0\rangle + c_1'|1\rangle$

Then they form

$|\psi\rangle \otimes |\psi'\rangle = c_{00}|00\rangle + c_{01}|01\rangle + c_{10}|10\rangle + c_{11}|11\rangle$

The total probability must still equal 1.

Two qubits can make four possible combinations at once 00, 01, 10, 11

### Measuring Two Qubits

If you measure one qubit, the other's probabilities adjust automatically.

If the first qubit is measured as  $|1\rangle$ , only terms with "1" in the first position remain ( $c_{10}|10\rangle + c_{11}|11\rangle$ ).

Measuring one part of a system instantly affects the rest.

### Entanglement - Quantum Linking

Two qubits become entangled, they form one shared system.

When you measure one, the other's state is instantly decided, even across long distances.

e.g.  $|\theta\rangle = c_{00}|00\rangle + c_{11}|11\rangle$

If the first qubit is found to be 0, then the second qubit must always be 0.

Entangled qubits share one "joint" state.

### Bell States - Special Entangled Pairs

$$|\Phi+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

$$|\Phi-\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}$$

$$|\Psi+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

$$|\Psi-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

Bell States are the four "perfect" two qubit entangled combinations

### Bell State Measurements

Determines which Bell State two entangled qubits are in.

Gives one of four outcomes (00, 01, 10, 11)

This is essential for quantum teleportation, transferring a qubit's state from one place to another

### Generating Entangled Photons

Spontaneous Parametric Down Conversion:

1. A high energy photon from a laser hits a nonlinear crystal
2. It splits into two lower power energy photons that are entangled
3. Usually one photon is horizontally polarised  $|H\rangle$  and the other is vertically polarised  $|V\rangle$

Efficiency is low, about one in a million photons

But reliability is high, works every time

### Quantum Circuits

How qubits change through gates, operations that flip their state on the Bloch Sphere.

Quantum gates rotate or link qubits to perform logical operations

### Multi-Bit Entanglement

You can entangle 3 or more qubits.

GHZ State:

$$|\text{GHZ}\rangle = \frac{|000\rangle + |111\rangle}{\sqrt{2}}$$
 once you measure one you know the others

W State:

$$|\text{W}\rangle = \frac{|001\rangle + |010\rangle + |100\rangle}{\sqrt{3}}$$
 once you measure a qubit as a 1, all the other states are fixed immediately

Multi qubit entanglements show complex collective behaviours and can be used in advanced quantum networks

Concept	Meaning	Purpose
Qubit	Quantum Bit	Can be 0, 1 or both

<b>Superposition</b>	Being in multiple states at once	Enables parallel computation
<b>Measurement</b>	Collapsing to one outcome	Generates probabilistic results
<b>No-Cloning</b>	Qubits can't be copied	Ensures security in quantum
<b>Entanglement</b>	Linked particles share their states	Basis of quantum teleportation
<b>Quantum Gates</b>	Rotate or entangle qubits	Perform logic in quantum

# Quantum Key Distribution

Tuesday, November 04, 2025 1:28 PM

- Most encryption today is based on private-public key
- You encrypt using your public key, known to everyone
- You decrypt using your private key, known only to you
- The other way around is called Digital Signature (anyone can decrypt but only using my public key so everyone knows that the message came from me)
- Issue is with sharing keys privately (RSA algorithm is based on the factorisation of prime numbers so private keys are made up of two large prime numbers)
- It would take a classical computer 300 trillion years to break

## Breaking RSA with quantum computing

- A quantum algorithm can break RSA with polynomial complexity - a quantum computer would take 10 seconds
- Qubits are noisy and require quantum correction (uses physical noisy qubits to produce a logical qubit)
- Estimate: RSA could be broken in 8 hours using a quantum computer with 20million physical qubits. (Today we have 1000)

## Symmetric Key Encryption (Safe from Quantum for today)

- Instead use the same key to encrypt/decrypt. Classical algorithms break in exponential complexity
- No known quantum algorithm that can break it in polynomial complexity. (yet)
- Senders and receivers need to share a secret key (big problem, why RSA is used)

## Quantum Key Distribution (to safely distribute keys)

- So we can keep using symmetric key encryption!
- QKD would enable encryption through one-time (the key is the same length as the object to be encrypted)
- Cannot be broken as it randomises each individual bit with no dependence on other bits
- High rates for QKD (not available today)

Pros	Cons
Act in advance to make sure new, safe encryption is widespread before quantum computers arrive	Post-quantum/new encryption algorithms are not based on prime factorisation
Asymmetric & symmetric are not demonstrably secure. A classical algorithm could break at some point	Many years before quantum can break RSA
QKD could implement one-time pad, communication provenly secure	Many keys would be needed to break several keys consistently
Every letter encrypted using a totally random character - bit level	

## Measurement Basis / Measuring Polarisation

Logical states  $|0\rangle$  and  $|1\rangle$  are mapped to some physical property - use photons as communication mediums

A photon can vibrate:

- Horizontally
- Vertically
- Diagonally
- Anti-diagonally

These directions act as "0" and "1" depending on the chosen measurement basis.

A photon only passes through a filter if its direction matches the filter.

- Horizontal photon + horizontal filter → gets through
- Horizontal photon + vertical filter → blocked
- Horizontal photon + diagonal filter → 50% chance of getting through

This randomness is what makes eavesdropping detectable.

We use two different “coordinate systems” to read photons:

1. **H/V basis** (Horizontal/Vertical) → often called **0/1**
2. **D/A basis** (Diagonal/Anti-Diagonal) → often called **+/-**

If the basis is wrong, the result is random.

You only get predictable results if sender and receiver use the same basis.

If they use different bases, you get a random answer.

This randomness exposes eavesdroppers.

#### **Example - the first protocol BB84 QKD:**

1. Alice sends photons to Bob
2. For each photon she chooses a random basis (H/V) or (D/A).
3. She encodes a data bit in that basis.
4. Bob measures using his own random basis.
5. They compare which basis they used and keep only the cases where their bases matched.
6. This becomes their shared key

#### **Alice's encoding in BB84**

- a. 0 in H/V basis --> horizontal
- b. 1 in H/V basis --> vertical
- c. 0 in D/A basis --> diagonal
- d. 1 in D/A basis --> anti-diagonal

#### **Bob's decoding in BB84**

- a. Choose a random basis for every photon
- b. If his basis matches Alice's --> he gets the correct bit
- c. If not, his result is random
- d. The two publicly compare basis but not bit values
- e. Alice and Bob publicly announce which basis was used for each photon
- f. They discard all cases where their cases were different
- g. The remaining matched bits becomes the shared key

#### **Eavesdropping in BB84**

- a. An eavesdropper must choose a basis
- b. If it is wrong, it disturbs the photon
- c. When Bob measures, he gets errors
- d. Alice and Bob notice errors by comparing a subset of bits
- e. Disturbed key --> attack detected
- f. An eavesdropper cannot send new identical photons --> No-Cloning Theorem
- g. Photons can only be measured (destroys information) or attempt to recreate it (25% error rate because of the bases) and this can be detected easily by Alice & Bob

#### **Retrieving the Key**

If the basis is the same, Bob measures the exact same bit Alice sent

If the basis is different, there is a 50% probability that Bob measured the same bit that Alice sent, thus these are discarded.

Statistically, Bob will pick the same basis 50% of the time so it will just use half the bits sent by Alice

#### **Why is it Secure Against Eavesdropping**

Eve can intercept the qubits and read them the same way as Bob

The photons cannot be split, they go to Eve or Bob

Eve gets the key and Bob doesn't, therefore Alice and Bob won't use that key

#### **Spoofing Qubits**

Alternatively, Eve produces new qubits and sends them to Bob.

But Eve cannot replicate the state of the qubit (no-cloning theorem). The best eve can do is resend a new qubit based on the measurement (destroys info)

Statistically introduces a 25% error rate on the measurements in the correct basis

Alice and Bob exchange a few bits of the key and realise there is an error rate, inferring there was an eavesdropper

Alice's Bits	0	0	1	0	1	1	0	1
Alice's Base	0/1	-/+	-/+	0/1	-/+	0/1	0/1	-/+
Logical Encoding	0>	->	+>	0>	+>	1>	0>	+>
Eve's base selection	0/1	0/1	-/+	-/+	0/1	-/+	0/1	-/+
Eve's measurement	0>	0> (p)	+>	+> (p)	1> (p)	-> (p)	0>	+>
Eve's new encoding	0>	0>	+>	+>	1>	->	0>	+>
Bob's base selection	0/1	-/+	0/1	-/+	-/+	-/+	0/1	0/1
Bob's measurements	Yes,  0>	Yes*  ->	No	No	Er,  ->	No	Yes,  0>	No

### The BBM92 Protocol - using the property of entanglement

Instead of Alice preparing photons:

- A source creates entangled photon pairs (**Bell pair / maximally entangled**)
- One goes to Bob, one goes to Alice
- They randomly choose bases and measure
- Entanglement ensures perfect correlations in matching bases.
- Alice does not prepare the states, increasing security
- They're only going to keep the key if they choose the same basis

$$|\Psi^+\rangle = \frac{|HV\rangle + |VH\rangle}{\sqrt{2}}$$

- If the chosen basis is HV then the state remains the same and due to correlation Alice and Bob measure always the opposite state (because entanglement). Bob can then invert all the bits to get Alice's key.
- Same principle for DA
- If Alice uses HV and Bob uses DA, Bob gets a 50/50 random result, no correlation, throw it away

BB84	BBM92
Sender must create the photons to be sent	Third party can generate entangled photons
Introduces insecurity in the system	Neither Alice or Bob prepares the qubits

### Identity Verification

Alice and Bob need an authenticated channel to exchange information about the chosen basis.

It is public so Eve can listen, Alice has to be sure that she knows that the exchange of information is occurring with Bob.

If Eve pretends to be Bob then Alice will sift the key so Eve can then decrypt all information sent by Alice.

This requires Alice and Bob to have some pre-shared key before applying QKD.

### Random Deletion Errors

Loss of qubits is very common especially in fibre.

Result is a lot lower than the transmission rate.

### Practical Issues - Errors

Fibre birefringence, the fibre modifies the polarisation during transmission.

If Alice sends a qubit to Bob who picks the right basis, they expect the bit to be correct. Otherwise they suspect an eavesdropper.

Most systems don't use polarisation but differential phase encoding.

For using polarisation, the system needs to be tuned, so that you periodically adjust for the change in polarisation.

Also can use classical error correction systems where you part of the key as redundant bits and implement forward error correction. This reduces useful key rate.

Fibres lose photons.

Detectors are imperfect.

The protocol handles this by:

- Simply discarding missing photons
- Sending more photons until the key is long enough

This is normal and expected

Optical fibres twist the polarisation as light travels.

So the qubit may not arrive in the same orientation.

This creates false “errors” that mimic eavesdropping.

Solutions:

- Continuous calibration using classical light
- Or use **phase-based** encoding instead of polarisation

Detectors sometimes “click” even with no photon (thermal noise).

These “dark counts” introduce errors.

Solution:

- Use error-correction codes
- Discard enough bits to ensure the final key is safe

If a pulse contains more than one photon:

- Eve can steal one photon
- Bob gets the other
- Alice and Bob won’t notice

This reduces security.

Real systems therefore try to send **one photon per pulse**, but that is hard.

A common method is:

- Use a laser
  - Dim it until the average number of photons per pulse is small
- This makes photon number random (Poisson distribution).

But still:

- Many pulses are empty
  - Some pulses contain more than one photon
- So security must account for this.

### **Decoy State Protocols**

To make QKD secure with real lasers:

- Alice uses **different types of pulses**
  - normal
  - weaker
  - stronger
  - zero (empty)
- Eve cannot know which type is which
- By comparing statistics later, Alice and Bob can detect if Eve tampered with multi-photon pulses

This allows using higher average photon numbers (e.g., 0.3–0.5), which increases key rate.

# Quantum Networks

Tuesday, November 04, 2025 1:28 PM

A quantum network is not about sending qubits through fibre - qubits/quantum states are fragile and can't be copied.

Fibre losses are huge for single photons  
Only 1/1000 qubits survive to its destination

## Quantum Networks is not about sending qubits/quantum states but instead sending entanglements.

The quantum state can get teleported through quantum circuits but you are transmitting *entanglements*.

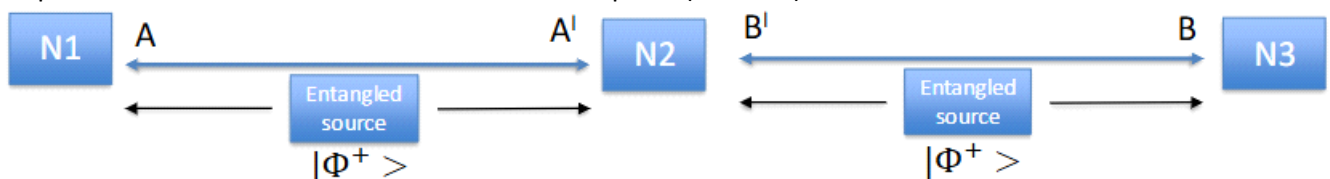
Quantum teleportation allows you to transfer a quantum state  $|\psi\rangle$  from Alice to Bob **without physically sending it**. Share a quantum state between two pre-shared entangled qubits without having to transmit the actual state.

1. A pair of entangled qubits shared between Alice and Bob beforehand
  - a. Alice has a given state  $|\psi\rangle$  that she wants to teleport to Bob
  - b. First they share an entangled pair e.g.  $|\Phi^+\rangle = \frac{|HH\rangle + |VV\rangle}{\sqrt{2}}$
2. A Bell-State Measurement at Alice's side
  - a. Alice carries out a bell state measurement between  $|\psi\rangle$  and  $|\Phi^+\rangle$  These turn them into *classical* bits
  - b. A BSM can be done in linear optics, through a polarisation beam splitter
3. Two classical bits sent from Alice to Bob
  - a. The BSM destroys the initial state  $|\psi\rangle$  and Alice's entangled qubit.
  - b. After the BSM, Alice's state is instantaneously teleported into Bob's entangled qubit
  - c. Alice transmits to Bob the results of the measurement (00, 01, 10, 11) over a classical channel.
4. Bob applies a unitary transformation to his entangled qubit
  - a. The entangled qubit becomes equal to the original state sent by Alice  $|\psi\rangle$
  - No fragile qubit needs to survive 100's of km of fibre
  - Only the entangled pair needs to be distributed once.
  - The actual state  $|\psi\rangle$  never travels in the fibre

## Entanglement Swapping

Direct consequence of teleportation.

Node 1 and Node 2 share an entangled pair A-A<sub>i</sub>.  
Node 2 and Node 3 share an entangled pair B-B<sub>i</sub>.  
N2 performs a Bell State Measurement on its local qubits (A<sub>i</sub> and B<sub>i</sub>)



This destroys the qubits A<sub>i</sub> and B<sub>i</sub> at N2 but automatically entangles the qubits at N1 and N3.

- Then N2 needs to communicate the result of the BSM to N1 or N3. At the end both N1 and N3 need to know that the operation was successful.
- N2 must send classical bits to N1 or N3
- They apply the right correction
- They end up sharing one of the Bell states

The result of the BSM is used to decide which unitary operation to carry out by N1 or N3. After that N1 and N3 share entanglement

- Exchange of classical information is required in order for N1 and N3 to know their shared Bell state --> this introduces latency
- Entanglement swapping is like teleportation, where the BSM of  $A_i$  and  $B_i$  at N2, teleport the state  $A_i$  into N3 (where B was). Since A and  $A_i$  are entangled already, this makes N1 and N3 sharing entanglement

### **Entanglement Distribution Networks**

Because qubits cannot be copied, amplified, or sent long distances efficiently, a quantum network is an entanglement distribution network, NOT a qubit-transmission network.

1. Entangled Photon Sources - spontaneous parametric down conversion
2. Optical Fibres - for sending one photon of each entangled pair to a destination node
3. Quantum Memories - to store entanglement until both ends are ready
4. Classical Communication Channels - to measure results, synchronise nodes, etc.

Once entanglement is distributed, teleportation and entanglement swapping let you build:

- quantum repeaters
- long-distance quantum key distribution
- distributed quantum computation
- quantum internet protocols

# Introduction

Monday, September 15, 2025 2:05 PM

## **Impairments:**

Path loss  
Shadowing  
Fading  
Multipath  
Noise  
Interference

**Path Loss:** signal attenuates with distance

**Shadowing:** models attenuation from obstacles

**Fading:** Quick variations in received power due to time-varying channel characteristics

**Multipath:** reflections and scattering, multiple versions of the transmitted signal may arrive at the receiver

**Noise:** Unwanted signals added to the message signal. May be due to signals generated by natural phenomena e.g., lightning, or man-made sources

## **Interference:**

- **Sources of interference:**
  - Another mobile in the same cell
  - A call in progress in the neighbouring cell
  - Other base stations operating in the same frequency band
  - Non-cellular system leaks energy into the cellular frequency band
  
- **Two major kinds of cellular interference:**
  - Co-channel interference (CCI): caused by signals at the same frequency
  - Adjacent channel interference (ACI): caused by signals from neighbouring frequencies

## **Mitigation:**

Diversity  
Directional Antennas  
Coding & Modulation  
Spread Spectrum  
System-Level Mitigation

**Diversity:** Combine independently received versions of the desired signal.

Spatial, frequency, temporal, polarization diversity

**Directional Antennas:** By appropriately weighing the elements, one can maximize the gain in one direction while minimizing it in other directions. Can be used to reduce interference

## **Coding & Modulation:**

## Coding and modulation

e.g., to achieve same Bit Error Rate (BER), QPSK uses less power than 16-QAM (lower SNR needed to get same error performance)

- Digital modulation schemes vary in...
  - ✓ Power efficiency - how much power is needed to transmit
  - ✓ **Spectral efficiency** - bits/second/Hz
  - ✓ Robustness - to multipath fading, noise, interference
- Multi-carrier modulation splits the bit stream into several lower bit rate streams, each sent using an **independent carrier frequency**
  - ✓ Frequency selective fading only affects some subcarriers, not the entire signal
- Forward error correction mitigates the effect of channel errors

**Spread Spectrum:** Spread spectrum signals are distributed over a wide range of frequencies and then

collected back at the receiver

**System-Level Mitigation:**

----- **PROF** -----  
**GPT** -----

### Impairments:

1. Path Loss - signals get weaker with distance - even in open space.  
The further away the receiver, the weaker the signal  $1/d^2$  where  $d$  is the distance
2. Shadowing - buildings/hills/walls block signals  
Shadowing behaves randomly as objects appearing is a random event
3. Fading - rapid signal strength drops due to movement or reflections  
Fading can be no clear direct path, many reflections  
Fading can be one strong direct path which happens to contain reflections  
The signal's strength changes quickly over time e.g. phone signal dropping and coming back when you're in the car
4. Multipath - copies of the signal arrive late due to reflections  
The faded signal is essentially echoed at different times
5. Noise - random unwanted signals from nature or other resources  
Effects all frequencies equally
6. Interference - other users or systems using nearby frequencies  
Can be co-channel interference - transmitters are in the same frequency  
Can be adjacent-channel interference - nearby frequencies can cross over and interfere

Wireless signals are constantly weakened, blocked and mixed with unwanted energy

### Mitigation Techniques

1. Diversity - use multiple signals, frequencies or antennas
  - Spatial Diversity: use several antennas spaced apart
  - Frequency Diversity: send the same data on different frequencies
  - Time diversity: send the same data again at a different time
  - Polarisation diversity: change the orientation of the antenna
2. Directional Antennas - focus energy where needed  
Antennas increase **gain** in one direction and reduce interference from other directions
3. Coding & Modulation - send information in smarter, more error tolerant ways

QPSK, 16-QAM, OFDM

4. Spread Spectrum - spread the signal across many frequencies

**Direct Sequence Spread Spectrum:** multiply the data by a fast "chipping" code that spreads it across a wide band

**Frequency Hopping:** jump quickly among frequencies in a known pattern

5. System-Level Techniques - carefully plan how frequencies and codes are reused.

**Direct Sequence Spread Spectrum:**

Each data bit is combined with a fast random-looking sequence

This widens the signal's bandwidth, making it more resistant to noise

Small spreading factor = narrower bandwidth, less protection

Bigger spreading factor = wider bandwidth, more protection

# Overview of Wireless Networks

Tuesday, September 16, 2025 11:11 AM

## Nomadic & Mobile Networks

### **Mobile e.g. Cellular (5G), land mobile radio:**

Seamless Roaming  
Wireless telephony  
Mobile Data Services  
Vehicular ad hoc networks  
Location aware-services

### **Nomadic e.g. IEEE 802.11 (WiFi) & Bluetooth:**

User changes point of connection to the network  
Wireless ISPs  
Hot spots

### **OSI Stack:**

1. Physical Layer
2. Data Link Layer
3. Network Layer
4. Transport Layer
5. Session Layer
6. Presentation Layer
7. Application Layer

### **1 Physical Layer – Frequency selection, modulation, signal detection, encryption**

Handles communications impairments (noise, interference, fading, shadowing, path loss, etc.) through coding, diversity, power control, waveform selection, etc.

### **2 Data Link Layer – Medium access, error control**

Responsible for mediating access to the wireless medium  
Frame synchronization  
Reliable point-to-point or point-to-multipoint connection

### **3 Network Layer (IP) – Routing, handover, network-wide addressing, device location**

Network-wide addressing, and redirection to deal with mobility  
Handoff (handover) between different networks  
Routing through multiple hops in ad-hoc networks

### **4 Transport Layer (TCP) – Reliable delivery, error recovery, congestion control**

Reliable end-to-end transmission  
Flow and congestion control

### **7 Application Layer – Application specific exchange of messages**

Application layer protocols may need to be tuned to support the constraints of mobile devices (small screen, low power, ...)  
Wireless Application Protocol (WAP)  
Location-aware services  
Wireless web access

### **Harmonization:**

Some degree of harmonization (more rational/efficient re-organization) of spectrum utilization world-wide is desirable

Not easy: a lot of legacy systems

But necessary, both for interference avoidance (inter-operability) and for economic reasons

### **Dynamic Spectrum Access:**

Allows operation in licensed bands as long as you don't interfere with the holder of the license

The 1GHz region of the spectrum is best suited for TV transmission because transmissions at lower frequencies attenuate with less distance which makes this band ideal for long range transmissions such as TV.

Wireless and optical networks are complementary.

Optical fibre does not reach everyone but provides large bandwidth.

Wireless networks potentially can reach everyone but provide bandwidth-constrained transmission, susceptible to impairments



### **Wireless networks**

Mobile: move around while staying connected e.g. 4G/LTE

Nomadic: you can move around locations but you must re-connect each time e.g. WiFi

### **Frequency Allocations**

Different wireless systems use different parts of the radio frequency spectrum

TV: below 1GHz

Wi-Fi: 2.4GHz and 5GHz

5G: around 3.5GHz

Microwaves: tens of GHz

### **Broadcast Radio & TV Frequencies**

FM Radio: 88-108MHz

Very High Frequency TV: 54-88MHz and 174-216MHz

Ultra High Frequency TV: 470-806MHz

These are all below 1GHz so they travel far and don't weaken quickly. Low frequencies travel far which is ideal for something like TV broadcasting.

The spectrum is regulated to prevent interference

**Harmonization** makes global communication and manufacturing easier

### **Dynamic Spectrum Access**

Some licensed frequencies are barely used but regulators aren't able to just claim them back.

So devices can temporarily use these frequencies as long as they don't interfere with the owner.

Enabled by **Cognitive Radio** and **Self-Organising Networks**

# Mobile Architectures

Tuesday, October 07, 2025 4:58 PM

Evolution from 2G and 3G

## LTE (4G)

- 100Mbps peak down-link, 40Mbps peak up-link
- Reduced latency & scalable bandwidth
- Uses existing spectrum

### Latency:

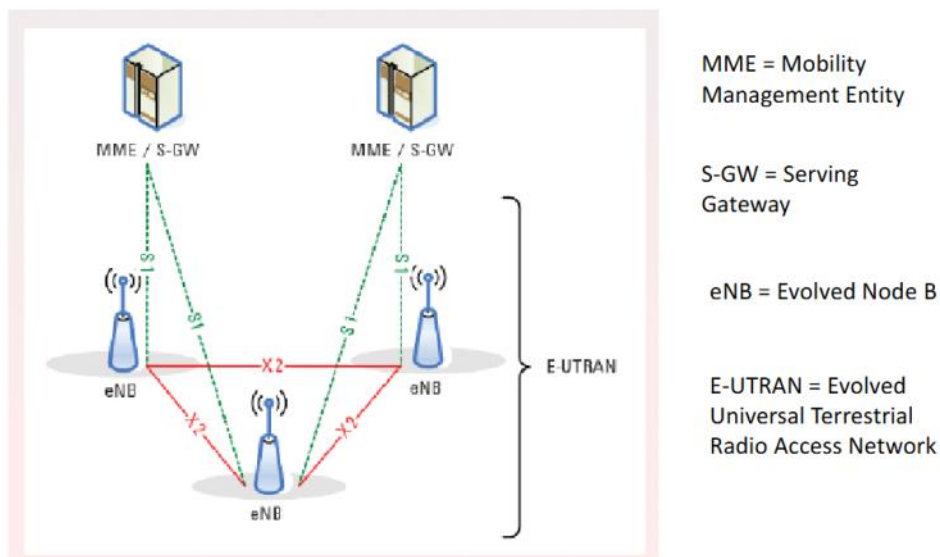
The time that passes from a user sending a piece of a data request to the time the user gets a response

Measured by time taken for IP packet to travel through network to the internet server and back

### LTE (4G) Features:

- **OFDM – Orthogonal Frequency Division Multiplexing**
- **OFDMA – Orthogonal Frequency Division Multiple Access**  
Increased spectral efficiency & increased data rates

## Architecture



### Protocol Layers:

- Packet Data Convergence Protocol – Layer 2  
IP header compression  
Cyphering & integrity protection
- Radio Link Control – Layer 2  
Segmentation & concatenation  
Retransmission handling  
In-order deliver to higher layers
- Medium Access Control – Layer 2  
Uplink & downlink scheduling at eNB  
Hybrid automatic repeat request
- Physical Layer – Layer 1  
Coding/decoding  
Modulation/demodulation  
Multi-antenna use

Scheduler in eNB allocates resource blocks to users for predetermined amount of time  
Slots consist of 6 or 7 OFDM symbols

Number of available subcarriers changes depending on transmission bandwidth

### [What is OFDM?](#)



#### **OFDM**

OFDM uses a large number of narrow sub-carriers for multi-carrier transmission  
OFDM symbols are grouped into resource blocks

#### **Multi Antenna Techniques:**

Transmit diversity

Beam-forming

Spatial multiplexing/multi-layer transmission

Multi-user MIMO (multiple input multiple output)

----- **PROF** -----  
**GPT** -----

#### **Motivation for 4G**

- **Faster data** particularly for video
- Companies needed to **handle more users** at one time
- Latency had to shrink so pages could load faster
- Operators wanted lower running costs

#### **LTE Performance Goals**

- 100 Mbps **download speed** and 50 Mbps **upload speed**. X10 faster than 3G
- Lower latency (10ms)
- Scalable bandwidth (channel sizes up to 20MHz)
- Backward compatible with older systems

Faster, more flexible, backward compatible

#### **Key LTE Technologies**

OFDM: Orthogonal Frequency Division Multiplexing splits data into lots of parallel signals --> less interference, higher efficiency

All IP Network: Everything uses Internet Protocol --> simpler management, cheaper operation

Spectrum Flexibility: can use any frequency band and combine pieces of the spectrum to get more capacity.

#### **Spectrum Flexibility in LTE/4G**

LTE can re-use 2G and 3G's spectrum e.g. 900MHz

LTE can also use new frequencies up to 3GHz

LTE works with both narrow and wide channels. (20MHz - 5MHz)

LTE can operate almost anywhere in the radio spectrum.

LTE juggles small pieces of radio spectrum between users.

#### **LTE Components / Architecture**

- **eNB**: evolved node B - the base station in 4G - connects phones to the network. Acts like a traffic controller. Divides the airwaves into resource blocks which are given to users for short periods of time depending on demand and signal quality.
- **MME**: Mobile Management Entity - handles user movement and control
- **S-GW**: serving gateway - routes data through to the internet

### Physical Layer Details

- Downlink (tower --> user) uses OFDMA
- Uplink (user --> tower) uses SC-FDMA, more power efficient for smaller devices
- Frame length = 10ms, divided into smaller slots
- **Modulation types**:
  - **QPSK**: Low speed, very reliable, used for broadcasts
  - **16-QAM / 64-QAM**: higher speeds but needs a cleaner signal
- LTE balances speed and reliability by switching between modulation techniques

### OFDMA

- Divides data into hundreds of sub-signals, sent on a slightly different frequency
- Each resource element carries a few bits of data depending on the modulation type used.

Many small signals sent together give high total speed and efficiency

### Multi-Antenna Techniques (MIMO)

Multiple Input Multiple Output uses several antennas for:

- **Transmit Diversity**: same message from multiple antennas --> higher reliability
- **Beamforming**: direct the signal towards each user --> better connectivity
- **Spatial Multiplexing**: send multiple data streams --> higher speed
- **Multi-user MIMO**: serve several users at once --> reduce latencies

More antennas = more speed, reach, reliability

### LTE-A(Advanced) Improvements

1 Gbps down / 500Mbps up / latency < 50ms to connect / latency < 5ms to send a packet

Advanced MIMO

Much better edge case handling e.g. people living near base stations

More bits per Hz --> more efficiency

Aggregates several spectrum blocks

### 5G New Radio

- **eMBB**: enhanced mobile broadband has very high data rates for phones
- **mMTC**: massive machine type communication: connecting huge numbers of sensors
- **URLLC**: Ultra reliable low latency communication has near instant responses for robots/cars/medical systems

Generation	Technology	Features	Speed
2G	TDMA	Voice & Text	~100kbps
3G	CDMA	Mobile Data	~1-10Mbps
4G	OFDMA + All-IP	High-Speed Internet	~100Mbps-1Gbps
5G	OFDMA + Massive MIMO	Ultra-fast, ultra-reliable, connects everything	1Gbps+

# Wireless LANs - WiFi

Tuesday, October 07, 2025 4:58 PM

## Wireless LAN

Easy to install/manage  
Planning is ad hoc/no new cabling  
Support for nomadic users  
Spontaneous deployment  
Cost

### Limitations:

Quality – lower than wired  
Regulatory issues – transmit power/ operate in ISM bands  
Multiple different standards  
Overlapping frequency bands  
Easy to eavesdrop

## 1. Overview

WiFi IEEE 802.11 is the main standard for wireless local area networks.  
802.11 is the family of Wi-Fi standards enabling wireless networking

## 2. Motivations for WLAN

- Easy installation, simple, no cables
- Supports users who are nomadic
- Works even when infrastructure fails
- Users can form ad-hoc networks quickly
- Cheaper than using wired networks

Wi-Fi is flexible, mobile and cost-effective

## 3. Limitations of WLAN

- Quality of Service (QoS) is slower than wired networks
- Regulations restrict transmit power, uses bands shared with other devices
- Many WiFi standards exist, this overlap in frequency --> interference
- It is easy to eavesdrop or attack on WiFi if data is not encrypted

WiFi is easy but can be slower and less reliable than cables

WiFi shares the airwaves, interference and security are persisting issues

## 4. Goals of WLAN

- Global operation on license-free bands, using the same tech worldwide
- Lower power saves battery and reduces emissions
- Robustness: must handle wireless impairments and user movements
- Interoperability: work with wired, cellular and personal networks
- Protect data and resist denial-of-service attacks
- Adapt to context/location-aware apps, remain transparent to others.

WiFi must be power-efficient, robust and universally available

WiFi must connect smoothly with everything else, safely and flexibly

## 5. Infrared vs. Radio

**Infrared:** short-range, often requires line-of-sight, uses LED/lasers

**Radio:** travels through walls, covers longer ranges, higher data rates

Infrared is for short-range point links; radio is for modern Wi-Fi networks

Infrared	Radio
Cheap, license-free	Long-range, higher data rates

No interference with electronics	Penetrates walls
Easily blocked by obstacles	More interference possible

Clear that radio is the one used in WLAN/WiFi systems.  
Radio wins for practical wireless networking

## 6. Infrastructure vs. Ad Hoc Networks

### Infrastructure-Based:

- central access points connects users and external networks
- Managed and stable.
- Access Point bridges wireless and wired networks, managing connections.
- The Access Point is the hub in typical WiFi setups

### Ad-Hoc:

- devices communicate directly, suitable for temporary or emergency situations
- Flexible and decentralised
- Devices connect peer to peer without an access point, may use routing protocols for multi-hop.
- Ad hoc mode is used when no fixed network exists

Wi-Fi alliance ensures devices from different brands work together. It certifies the interoperability of 802.11 products

### Orthogonal Frequency Division Multiplexing

- Splits data into multiple subcarriers spaced apart precisely
- Reduces interference
- Improves reliability
- Used in digital TV too

OFDM boosts efficiency by parallelizing data transmission

### IEEE802.11b

- 2.4GHz band
- Channels spaced 5MHz apart in 2.4GHz band
- Only 3 non-overlapping channels
- Uses direct sequence spread spectrum
- Data Rates: 1, 2, 5.5, 11Mbps
- Cheap
- Long-range
- Slow
- Interference-prone
- Reliable for simple use

Slow but long range and cheap. Overlapping causes interference, careful planning needed

### IEEE802.11a

- 5GHz band
- Shorter range
- Up to 54 Mbps using OFDM
- 12 non-overlapping channels
- Not compatible with 802.11b/g
- Several groups of channels across 5GHz
- Fastest
- Supports many users
- Less interference

Faster, cleaner spectrum but shorter reach. Higher frequency, more channels, less interference, short range

### IEEE802.11g

- 2.4GHz band

- Up to 54Mbps with OFDM and error correction
- Back compatible with 802.11b
- Long range, faster than b, supports more users
- Shares 2.4GHz interference
- Practical middle ground

Best mix of speed and compatability

Standard	Band	Max Rate	Typical Rate	Modulation
802.11	2.4GHz	2 Mbps	1.2 Mbps	DSSS
802.11a	5GHz	54 Mbps	32 Mbps	OFDM
802.11b	2.4GHz	11 Mbps	6-7 Mbps	DSSS
802.11g	2.4GHz	54 Mbps	32 Mbps	OFDM

2.4GHz = longer range, 5GHz = faster but shorter range

#### IEEE802.11n

- Uses MIMO/multiple antennas for higher data rates
- Up to 600Mbps data rate
- Operates in both 2.4GHz and 5GHz

Major step in speed and reliability using MIMO

#### IEEE802.11ad (WiGig)

- 60GHz band
- Up to 7Gbps, short range
- Ideal for high-speed indoor transfers e.g. HD video

Ultra fast, short range WiFi

#### IEEE802.11ax (Wi-Fi 6)

- 2.4 + 5 GHz, total bandwidth ~ 14Gbps
- Targets crowded places, stadiums, airports,
- Supports IoT, offloads mobile networks
- Uses OFDMA

Efficient in dense environments, better speed sharing

#### IEEE802.11be (Wi-Fi 7)

- Up to 320MHz bandwidth, 4096-QAM
- Multi link operation across 2.4, 5, and 6 GHz
- 16 spatial streams, very low latency

Multi-band, ultra low latency, next gen WiFi

# Wireless LANs – Hnet. Etc,

Tuesday, October 07, 2025 4:58 PM

## 1. Improving Capacity

To make a network faster and handle more users:

- Add more antennas/cells e.g. adding more WiFi routers
- Use new frequencies (like moving to 5G)
- Use smarter technologies (MIMO, beamforming, coding rate etc.)

**Improving capacity** can be achieved by **HetNets**, **mmWave** and **THz** Communications

## 2. Cell Densification

Adding more small base stations in one area.

- Big Towers = Macro Base Stations
- Tiny Towers = Pico Base Stations

More cells --> more coverage --> more capacity

Also

More interference

## 3. HomNet vs. HetNet.

- **HomNet** = all cells are the same type e.g. all macro base stations
- **HetNet** = mix of big and small cells, macro & pico
  - Hetnet gives better coverage and capacity but causes more interference.

Sometimes adding more cells helps but not always. Too many can cause interference and waste energy.

When multiple cells use the same frequency, their signals clash.

Solutions to this:

- **Fixed Spectrum Allocation:** assign each cell its own frequency
- **Flexible Re-Use:** cells share frequencies intelligently

## 4. Propagation Models

Signals behave differently depending on obstacles

- **Line of Sight:** direct view, fast, clean signal
- **Non-Line of Sight:** blocked by walls/buildings --> weaker signal.

## 5. mmWave (millimeter wave)

- Very high frequency signals (30-300 GHz)
- Super fast because of lots of bandwidth
- Short range / can't go through walls easily.
- Used in 5G, Wifi and short range networks like personal area networks

## 6. Terahertz Communication

Even higher frequencies (0.1-10THz) - between radio and infrared light.

- Super high speed potential
- Still experimental
- Not in real world use yet

## 7. Ultra-Dense Networks

Setups where there are *more base stations than users* (tiny cells everywhere)

This is ultra-dense because the network is packed with cells.

## Summary:

- Densifying networks --> more capacity
- HetNets --> flexible but interference prone
- mmWave --> ultra-fast, short range
- THz --> future, ultra high speed tech
- **Smart spectrum** use + **MIMO** = **dense, high-frequency, intelligent**

# Cognitive Radio, Integrated Sensing & Communication

Tuesday, October 07, 2025 4:59 PM

**Cognitive Radio (CR):** radios that can think and adapt to their surroundings

**Integrated Sensing & Communication (ISAC):** future systems like 6G that use the same signals both to communicate and sense what's around them

Wireless signals are getting smarter, they can sense, decide and re-use signals

## Evolution of Radios:

1. Traditional Radios: fixed hardware; each designed for one purpose
2. Software-defined radios: use software to control how signals are processed, flexible, upgradeable
3. Cognitive radios: software radios that can also learn and adapt
4. Cognitive networks: many cognitive radios coordinating together

## Software-Defined Radio:

- Hardware and software that can be reconfigured by code.
- Instead of buying new hardware for every network, the same radio can switch between functions (e.g. WiFi today, 4G tomorrow) by loading new software

SDR = radio controlled by software instead of fixed electronics

## Cognitive Radio:

- Learns, observes, makes decisions
- Sense the radio environment (what frequencies are busy, how strong the signals are)
- Adjust itself automatically

## What is it aware of?

- **Radio Environment**: which frequencies are free/noisy?
- **Itself**: power level, battery level, processing limits
- **Rules**: government or network policies, who's allowed to transmit
- **Goals**: maximise speed, save power, etc.
- **Other Users**: their priorities, permissions

Monitors both the outside world and its own limits

## What can it change?

- **Transmit power**: how strong it sends a signal
- **Waveform**: the shape or pattern of the signal
- **Frequency**: which band it uses to send data
- **Routing**: which path data takes through the network
- **Negotiation**: agreeing with others on which rules/formats to use

Tuning setting to match conditions

## How it learns?

- **Experience tables**: remembering what worked before
- **Machine Learning algorithms**

Cognitive Radio = Software Defined Radio + Intelligence

## Elements of a CR

- **Cognitive Engine**: decides what to do
- **Policies**: rules it must follow
- **Meters**: sensors that measure signal strength, interference, etc.
- **Knobs**: adjustable settings like power, frequency, waveform

The radio senses through meters and reacts through its knobs

### What can they do?

- Use dynamic spectrum access
- Borrow unused parts of the spectrum temporarily
- Switch among available networks automatically e.g. Wi-Fi, 4G
- Choose which antenna or signal pattern works best
- Improve coordination between different systems

### Sharing Spectrum

**Underlay:** transmit at a lower power such that you do not disturb others on the spectrum

**Overlay:** use parts of the spectrum that others are not currently using

CR allows mobile networks to expand without having to constantly buy new spectrum

### Femtocells

- Home/office base stations that reuse mobile frequencies (4G/5G)
- Mass produced and must configure themselves automatically

### Self-Organising Networks

Networks that can automatically

- Reconfigure themselves
- Extend coverage
- Optimise performance

CR means that this can happen in wireless systems

Self-organising networks is the automatic setup and optimisation using smart radios

### Integrated Sensing And Communication (ISAC)

Combining sensing and transmitting into one system

1. Shared hardware and spectrum - same **sites & equipment**
2. Shared waveforms - use the same **signal type** for sensing/communication
3. Full reuse - use **already transmitted** communication signals to detect surroundings

# Self-Organising Networks

Tuesday, October 07, 2025 4:59 PM

Devices can coordinate automatically to keep the system working efficiently, without a central controller telling every part what to do, like how birds can fly in perfect shapes even though there is no leader bird telling each one what to do.

Self-Organising Networks manage themselves through simple, local rules, not top-down control.

When devices communicate they use small exchanges, handshakes, data transfers. To predict network behavior, we need models that show how parts interact

## Cellular Automata

- Each cell has a simple rule
- Each cell can be in a state e.g. "on" "off"
- At each time step, a cell looks at its neighbours in the grid and changes state according to the simple rule e.g. if most of your neighbours are on then you turn on.
- When repeated many times across the grid, complex patterns can emerge
- **Von Neumann neighbourhood:** up, down, left, right neighbours only
- **Moore neighbourhood:** includes diagonals

Who the cells pay attention to affects how they behave and allows different patterns to emerge

At a time  $t+1$ , considerations are made to the current state of the cell  $N$  at time  $t$ , and the neighbours of cell  $N$  at time  $t$

In a network e.g. mobile cell towers, a rule might be "don't use a frequency near your neighbour", this is applied widely and eventually settles out with a solution that avoids interference without a central manager.

## Agent-Based Modelling:

- No grid, agents are individual decision makers
- An agent can be anything in the network that makes a choice.
- Agents have their own goals, behaviours and work in parallel and don't need a central controller.
- The many small decisions of the individual agents allows larger effects to emerge
- Each agent follows a simple rule like "avoid collisions".

## Agent Cycle

1. Get Stimulus: observe surroundings
2. Process It: decide what to do with your observations given the rule that you must follow
3. Act: do something with the information you have that allows your rule to be followed

Example of this was a bird flocking simulation where the agents (birds) were instructed not to bump into each other, fly in the same direction and move close together.

## ABM in Networks

- Each device, phone, antenna, server can be seen as an agent in the network

Combining cellular automata and agent-based modelling, engineers can model entire networks

# 5G&6G

Tuesday, November 04, 2025 11:02 AM

## 5G Capabilities

Better video, smarter offices, 50Mbps everywhere, create your own private network, flexible capacity, works on planes/trains/cars, IoT compatibility, ultra-reliable for emergencies

## 4G --> 5G Evolution

4G focused on mobile internet for humans

5G extended it to connect *everything*

Most innovation before 5G came from apps, not networks, over-the-top innovation. The network did not adapt, just deliver different innovations of the data.

Before 5G networks were just pipes for the data, but 5G makes them smarter

## Tailored Networks

- Different industries need different things
- 5G allows customised mini-networks for each purpose
- 5G adapts to what users/businesses need

## Network Slicing

Each slice of 5G can be customised depending on the use case

Take a network and build it so flexibly that it can be:

- Shared by different user-types
- Architecture is tailored to support user-type needs
- Resources allocated granularly
- Billed granularly
- 5G as a service

A network slice is a connectivity service defined by a number of customizable software-defined functions that govern geographical coverage area, duration, capacity, speed, latency, robustness, security and availability

Network slices make 5G flexible *and* profitable

- Every slice can be monitored and billed separately.
- Companies only pay for what they use.
- Networks can adapt automatically to new needs.

## 6G

6G (still being researched) will build on everything 5G started.

**Faster speeds:** potentially up to **1 terabit per second**

**Better sensing:** networks can detect objects and environments (useful for smart cities, cars, or drones)

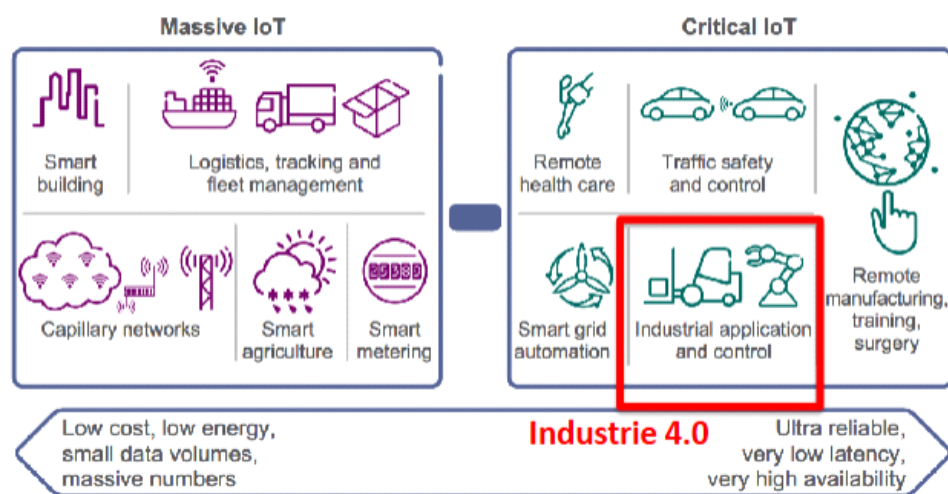
**Sustainability:** high performance but low energy use.

6G = networks that are not only fast, but also intelligent, sensing, and global.

# IoT / Machine Type Communication

Tuesday, November 04, 2025 11:02 AM

Internet of Things, Machine Type Communication, Industrial Internet of Things, Machine-2-Machine are all variations on a theme.



Industry 4.0 IoT will have very high reliability and availability and very low latency. The opposite ends of Machine Type Communication are Massive MTC and Critical MTC.

## MTC Requirements

Requirements vary considerably

### Massive MTC:

monitoring building infrastructure, smart agriculture, logistics, tracking, fleet management. Must be *architecturally simple*, have *low-complexity* transmission, have an *ultra long battery life*, *long range* transmission, *scalability*

### Critical MTC:

traffic safety & control, control of critical infrastructure, wireless connectivity for industrial processes. Monitoring often happens in real time. Low cost and energy consumption are of less importance for critical MTC devices.

## Massive IoT/MTC

Services that span a very large number of devices, usually *sensors* and *actuators*.

Sensors are extremely low cost, consume low amount of energy to sustain long battery life.

Very low latency is not a critical requirement.

## Critical IoT (and the challenges for 5G)

Applications such as traffic safety/control. Critical infrastructure.

Industries that can benefit from this vary from *automotive* (control from/to/between cars), *energy utilities*, and controls and communications in *factories*.

Monitoring and control occur in real time.

**E2E latency requirements are in the milliseconds**, the need for **reliability is high**.

Very high reliability and availability needed in terms of wireless connectivity.

Low device cost and energy consumption are not as important for critical IoT as it is for massive IoT applications.

5G has the aim of supporting these new classes of users.

Rather than depending on mobile networks solely for data communications, they are also looking for wireless control.

The automation of energy distribution in a smart grid exemplifies the critical MTC/IoT case. The energy sources are volatile and distributed. The grid needs to match the dynamics of volatile energy supply with demand, to protect the grid against faults.

## Supporting both Massive and Critical IoT (the bigger challenge for 5G)

There is much to gain from a network being able to handle as many different applications as possible (massive/critical) by means of the same wireless-access technology within the same spectrum. Avoids spectrum fragmentation, allows operators to offer support for new IoT services without having to deploy a separate network.

Network slices that support the IoT need for scalability can be optimized and reduce signaling. But 4G and 5G are not ready for this yet.

## Low Power Wide Area Networks (LPWANs)

- Technology that supports **small messages with specific duty cycles**
- Supports **low power end nodes** (hence long battery life)
- Suited to accessing sensors in awkward spots (in-building, rural)
- Cost points that suit the end applications
- Supports the creation of public networks that serve multiple uses and users

### LPWAN Aims

- Support vast number of cheap devices that transmit **bursty, small, infrequent messages**
- Similar topology to mobile networks
- Better range and penetration, lower frequencies, more robust signals
- **50k to 100k devices per square kilometer** per cell in non-line-of-sight urban areas.
- Operate in **sub 1GHz**
- Bill of materials (because long battery life) very low if deployed at scale

### LoRa

- Operates in the **868MHz** band which gives favourable propagation characteristics to travel long distances by line of sight or to penetrate non-line of sight situations.
- Anyone can deploy a base station to service their needs in different scenarios. Similar innovation potential to WiFi
- LoRa achieves a large link budget (range/penetration) by using spread spectrum based PHY
- Spread spectrum very robust to noise
- Bidirectional
- **250bps to 50kbps**
- Up to **154dB link budget**
- Battery based end devices

### LoRa Setup:

Things/sensors/end devices --> gateway/base station --> network server --> application enabling platform & device management  
-----> DATA  
DECREASING COST AND COMPLEXITY <-----

Low Power Wide Area Networks (LPWAN) is:

- A technology that supports small messages with specific duty cycles
- A technology that supports high power end nodes and hence long battery life  
LPWAN focuses on **low power**, not on high power
- A technology that is suited to accessing sensors over a short range  
LPWAN focuses on a **wide area**, not a short range

----- **PROF** -----  
**GPT** -----

### Massive IOT / MTC

- Huge numbers of simple, low-cost sensors e.g. smart cities, smart agriculture sensors, tracking vehicles
- Low complexity
- Cheap

- Simple
- Low power / batteries must last for years to keep the system up and running e.g. water meters
- Scalable / one network should handle millions of devices
- Each sensor sends a tiny amount of data e.g. temperature reading
- Latency doesn't matter much / ok if data arrives slightly late

**Critical IOT / MTC**

- Life-or-death, time sensitive applications that need ultra-reliable, realtime communication
- Traffic control / autonomous cars
- Smart energy grids
- Very low latency / extremely high reliability
- Moderate data volumes but must arrive instantly

**How 5G Enables Critical IOT**

Ultra-low latency / high reliability / network slicing / edge computing

A 5G network must support Massive IOT and Critical IOT which is difficult because their needs are opposite.

But running both of these on the same network (5G) avoids building multiple separate systems, saves spectrum, avoids costs.

**Low Power Wide Area Networks (LPWAN)**

- Send tiny messages occasionally
- Low power use --> battery life ~10 years
- Long range --> 30km in rural areas
- Works well indoors / hard to reach places
- Operates well in low frequency bands (< 1GHz) for better coverage

**LoRa (Long Range - a popular LPWAN)**

- 868MHz band
- Uses unlicensed spectrum - anyone can deploy
- Uses spread spectrum signals --> low interference
  - Uses different spreading factors for shorter vs. longer ranges.
  - Automatically adjusts this spreading factor based on its Adaptive Data Rate
- Long range and indoor coverage
  - The radio uses pure ALOHA, can transmit whenever ready no scheduling
  - Can cause collisions if many devices are sending at once
- Quality of Service can be questionable because of the unlicensed spectrum

Aspect	Performance
Data Rate	250bps - 50kbps (simple)
Range	15km rural, 3km urban
Battery	Years of life (scalable)
Communication	Bidirectional

IoT Type	Focus	Example	Key Feature
Massive IoT	Many simple devices	Smart meters	Long battery life
Critical IoT	Real-time control	Factory automation	Low latency / high reliability
LPWAN	Cheap, long range links	Smart cities	~10 year batteries
LoRa	Unlicensed LPWAN	Smart agriculture	Easy deployment / shared spectrum
5G IoT	Unified network	All of the above	Network slicing / edge case computing

# Queuing Systems

Tuesday, November 04, 2025 11:02 AM

Improve a situation where you have multiple users accessing a shared resource.

If you don't have to share anything, there is no queue.

Analytical models based on queuing theory used to predict effects of some change in **load/design**.

Capture one of two situations:

- More or less users
- Change in the resource e.g. removing/adding chips

## Examples

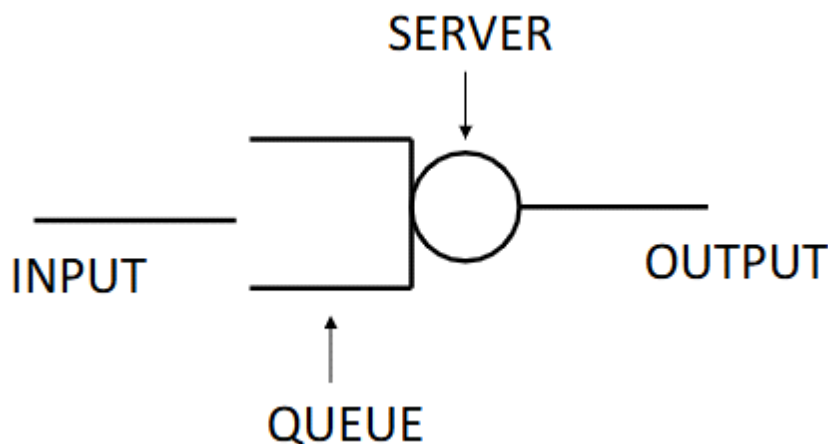
- **Time shared resources** on a computer e.g. CPU, disk, IO.
- Different programs has its own dedicated resources and polling to a common resource too. E.g. using a printer, you have your number in the queue
- **Channel/Packet based** queueing e.g. trying to call someone on New Years Eve, everyone is also trying to do that.
- Channel based: calls, channels
- Packet based: links
- **Multiple access networks** use queues e.g. using the same ethernet LAN, frames are queued.
- Wireless networks e.g. airport wifi has lots of people queuing
- **Web access** uses queues e.g. when a website crashes, too many people are in the queue trying to access from the server.

## Queuing Theory:

**Number of users** (do they come in bursts, arrive consistently), **arrival characteristics, service characteristics** (do we have priority, a policy? Can't model arrival/service deterministically, we use a model), **resources** (service point, are some faster, some slower, are they interdependent) --> **inputs**  
**Performance** (how the combination of inputs resulted, how much time do users have to wait, do we have the situation of limitations where some users have to be blocked/turned away, when does that happen, can we leave it there), **waiting time, blocking** --> **outputs**

Unless there is an infinite amount of servers, you queue.

Could turn away *everybody* else. You are the only thing trying to access the resource at a given time. How much time did you spent in the system, how many rejections were there



If all servers are busy, arriving customer/input joins a queue until a server is available.

The queue (waiting room) can be empty/full/partially full.

The queue can be finite or infinite. Can accommodate up to N waiting resources. Or could be an infinite buffer but this can cause waiting forever.

How to choose the customers you are going to serve, introduces a bias. Do you use LIFO, FIFO,

priority queue.

Delay in when you access system vs. Access service = queuing time

Total delay is the queuing time plus however long it takes for you to be served

Ideally minimise both delays

## KENDALL'S NOTATION (EXAM QUESTION EVERY YEAR!!!)

a/b/m/K notation

### **a= type of arrival process**

Can be modelled according to an **exponential process**

**Markov denotes Poisson arrivals**, the interarrival times (average time between arrivals) are **iid**, **exponential random variables**.

**Past behaviour does not count**. Future can be inferred from present only.

Noise, normal phone calls are well modelled by this.

Can represent the arrival process as a Markov chain.

### **b= service time distribution**

*Markov denotes exponentially distributed.*

Time it takes to serve a customer follows an exponential distribution. Can also be modelled as a Markov chain. The probability of 5 customers, can find the probability of 4 customers

### **Deterministic denotes constant service times**

For things that are more constrained. Knows exactly how long the service takes.

A certain fixed time e.g. Round Robin scheduling, a fixed packet length.

### **General denotes iid service times following some general distribution**

Any service process is general, the service times are independently and identically distributed but we don't necessarily know what that distribution is e.g. doesn't have to be exponential/Poisson like the Markov version

### **m= number of servers**

### **K= maximum number of customers allowed in the system.**

Might not be there sometimes. If there is no maximum on users, there is an infinite buffer, just wait. Between those that I serve and those that I make queue

Identify the queuing model for the following system (capital M for Markov, lowercase m for number of servers):

- Inter-arrival times are independent and identically distributed, exponential RV

a= M

- Service times are constant

b= D

- More than one server is available

m=m

- The first being served is the last that arrived

k=LIFO policy

# M/M/1 Queue

Tuesday, November 04, 2025 11:02 AM

## Memoryless arrivals and services

This means that this is one server  
Potentially infinite users in the buffer/queue  
You could be waiting forever

Poisson assumptions for the arrival of customers to a queue makes the analysis a Markov chain.

**Arrivals** according to Poisson process of rate  $\lambda$ .

Arrivals in a certain time interval is Poisson

Time between arrivals is exponential

Services time exponential.  $1/\text{serviceRate}$

## Markov Chains:

**Memoryless property of exponentials as Markov chains.** A sequence of states with transitions from state to state.

Every time new arrival, move to new state.

Every time user served, move to the state on the left.

The chain is infinitesimally long.

## Utilisation ( $\rho = \text{arrival}/\text{service}$ ):

A number.  $\lambda/\mu < 1$

**Must be  $< 1$  to ensure that there's not more users coming in than going out**

Determine the probability mass function for the number of customers currently in the system.

## Average number in the system:

Customers in the system =  $\rho / (1-\rho)$

**Little's Law:** the expected number in the system is the product of the arrival rate and the average time spent in the system (queue). Get the average delay

$\rho^2 / (1-\rho)$

**Arrival:** 1 message per 4ms

= 1/4 messages per 1ms ( **$\mu$** )

= 250 messages per second

**Service:** 3ms to service one message

= 1ms to service 1/3 message ( **$\lambda$** )

= 333.3333 services per second

**Customers:**  $(1/3)/(1/4) = 3/4$  ( **$\rho$** )

$1 / (1/3 - 1/4) = 12$

**Delay:**  $(3/4)^2 / (1/4) = 2.25$

## Other M/M/... Queues

Thursday 20 November 2025 12:33

Queuing systems are similar to the M/M/1 queue

**M/M/1/N**: finite buffer (system capacity= N)

**M/M/c**: c servers (rather than 1)

**M/M/∞**: infinite number of servers (no queuing)

**M/M/c/c**: c servers without queuing

### **M/M/1/N** Queue

Finite capacity of N customers in the system

Terminates with N in the system.

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

Blocking probability is an important performance measure for systems with finite capacity

The blocking probability is the probability that an arriving customer will find the system full, i.e., that there are already N customers in the system

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

### **M/M/∞** Queue

The M/M/∞ queue is a special case of the M/M/m queue with an infinite number of servers

Every arriving customer is put into service

No queuing delay, only service time

### **M/M/c** Queue

c identical servers.

If all servers busy --> customers join a single queue.

Widely used for call centres

“Erlang C” Formula (widely used in telephony and circuit switching systems)

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

### M/M/c/c Queue

The M/M/c/c queue is known as the “m-server loss system”  
 Queuing is not allowed, so a customer that arrives at a system with all servers busy is lost

The blocking probability is  $P_m$ , the probability that all m servers are busy

Suppose that messages arrive according to a Poisson process at a rate of one message every 4 ms, and that message transmission times are exponentially distributed with mean 3 ms.

The system maintains buffers for 4 messages, including the one being served.

What is the blocking probability?

What is the average number of messages in the system?

### M/M/1/N system with N=4

$\lambda$ : 1/4 messages every ms

$\mu$ : 1/3 messages every ms

System utilisation ( $\rho = \lambda/\mu$ ) = 3/4

**What is the blocking probability?**

$$P_N = P_4 = \frac{(1-\rho)(\rho^N)}{1-(\rho^{N+1})} = \frac{\left(1-\frac{3}{4}\right)\left(\frac{3}{4}\right)^4}{1-\left(\frac{3}{4}\right)^{4+1}} \approx 0.1$$

**What is the average number of messages in the system?**

$$E[n] = \frac{p}{1-p} - \frac{(N+1)p^{N+1}}{1-p^{N+1}} = \frac{(4+1)\frac{3^{4+1}}{4}}{1-\frac{3^{4+1}}{4}} \approx 1.44$$

Suppose that messages arrive according to a Poisson process at a rate of one message every 3 sec, and that message transmission times are exponentially distributed with mean 2 sec.

The system serves 3 users at a time.

What is the mean time a 4<sup>th</sup> user will spend in the queue?

**M/M/c** system with  $c=3$

$\lambda$ : 1/3 messages every s

$\mu$ : 1/2 messages every s

Because there is more than 1 queue, this must be considered when calculating the utilisation

**System utilisation ( $\rho = \frac{\lambda}{c\mu}$ ) = 2/9 per server**

$$m\rho = \frac{3 \times 2}{9} = \frac{2}{3}$$

$$P_0 = \left[ \sum_{n=0}^{m-1} \frac{(m\rho)^n}{n!} + \frac{(m\rho)^m}{m!(1-\rho)} \right]^{-1}$$

**What is the mean time a 4th user will spend in the queue**

$$P_0 = \frac{\binom{2}{3}^0}{0!} + \frac{\binom{2}{3}^1}{1!} + \frac{\binom{2}{3}^2}{2!} + \frac{\binom{2}{3}^3}{3!(1-\frac{2}{9})} = \frac{17}{9} + \frac{4}{63} = \frac{41}{21}$$

$\left(\frac{41}{21}\right)^{-1} = \frac{21}{41} = 0.512$  The probability that the system is empty

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

$$\frac{\left(\frac{2}{3}\right)^3}{3!(1-\frac{2}{9})} \times 0.512 = 0.0325 \text{ seconds}$$

**Calls arrive to a call-center according to a Poisson process with intensity of 2 calls per minute. The callholding times are exponentially distributed with an average of 5 minutes. Calls that find all operators busy are blocked.**

**Give the Kendall notation of the system.**

M/M/c/c queue

2 calls per min  $\lambda$

1/5 call per min  $\mu$

$$\rho = 2/0.2 = 10$$

**How many operators are necessary to keep the blocking probability below 75%?**

$$\frac{\rho^m / m!}{\sum_{n=0}^m \frac{\rho^n}{n!}}$$

$$\frac{\left(\frac{10^1}{1!}\right)}{\left(\frac{10^1}{1!} + \frac{10^0}{0!}\right)} = 90\% \text{ NO}$$

$$\frac{\left(\frac{10^2}{2!}\right)}{\left(\frac{10^2}{2!} + \frac{10^1}{1!} + \frac{10^0}{0!}\right)} = 82\% \text{ NO}$$

$$\frac{\left(\frac{10^3}{3!}\right)}{\left(\frac{10^3}{3!} + \frac{10^2}{2!} + \frac{10^1}{1!} + \frac{10^0}{0!}\right)} = 73\% \text{ YES}$$

# M/G/1 Queue

Déardaoin 4 Nollaig 2025 11:25

Arrivals still random/Poisson Process

Service times are General - can follow any distribution, not necessarily exponential. Allows anything.

Can't use Markov chains for this. Service times *are not memoryless*. We need to know how much time is left when someone is being serviced: number of people, how long the current job has already taken so far.

## PK Formula

Gives expected waiting time in the queue only using:

Average service time

Second moment of service time

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

## Utilisation in M/G/1

It is NOT  $\frac{\lambda}{\mu}$  as per M/M/... Queues.

$\rho = \lambda \bar{X}$  where  $\bar{X}$  is the average service time

## M/G/1 Example

- Poisson arrivals  $\rightarrow$  M
- service time distribution = general  $\rightarrow$  G
- 1 server  $\rightarrow$  1
- average service time = 5 seconds
- arrival rate = 3 per second

Average service time = 5s = 0.2 services per second

Utilisation ( $\rho$ ) =  $\lambda \bar{X} = 3 \times 5 = 15$

The utilisation ( $\rho$ )  $> 1$

The server can only serve 0.2 services per second but 3 arrivals are being made every second!

$\rho > 1$  means that the server is completely unsustainable

## A valid M/G/1 Queue

- Poisson arrivals  $\rightarrow$  M
- service time distribution = general  $\rightarrow$  G
- 1 server  $\rightarrow$  1
- average service time = 1 second
- arrival rate = 0.5 per second
- Suppose service times are:
  - X = 0.5 seconds with probability 0.5
  - X = 1.5 seconds with probability 0.5

Two customers are arriving every second

One customer can be serviced every second.

$$\text{Average service time} = E[X] = (0.5 \times 1.5) + (0.5 \times 0.5) = 1$$

$$\text{Second moment of service time} = E[X^2] = (0.5 \times 1.5^2) + (0.5 \times 0.5^2) = 2$$

$$\text{Utilisation } (p) = \lambda E[X] = 0.5 \times 1 = 0.5 = p$$

**Use the PK formula to find the waiting time in the queue**

$$W_q = \frac{\lambda E[X^2]}{2(1-p)} = \frac{0.5(2)}{2(1-0.5)}$$

*= 1 second*

**Total time in the queue**

$$T = W_q + E[X] = 1 + 1 = 2$$

**Average number in the queue**

$$N_q = \lambda W_q = 0.5(1) = 0.5$$

**Average number in the system**

$$N = T\lambda = 2(0.5) = 1$$

# QUEUES FORMULA CHEAT SHEET

Thursday 27 November 2025 11:35

## M/M/1

Potentially infinite users in the queue, could be waiting forever.

System Utilisation:  $\frac{\lambda}{\mu} = p$

Average number of users in the system:  $\frac{p}{(1-p)} = L$

Average number of users in the queue:  $\frac{p^2}{(1-p)} = L_q$

Average time spent in the system (delay):  $\frac{L}{\lambda}$

Average time spent in the queue (waiting time):  $\frac{L_q}{\lambda}$

## M/M/1/N

Terminates with N users in the system.

The blocking probability is the probability that an arriving customer is turned away because the server *and* the queue are both full.

Traffic Intensity:  $\frac{\lambda}{\mu} = p$

Steady state probabilities is the probability of the system containing n users (with a maximum of N):

$$P_n = \frac{(1-p)p^n}{1-p^{N+1}}$$

In the scenario where the system is operating at full capacity ( $p = 1$ ) then the probability of finding any amount of users in the system is  $P_n = \frac{1}{N+1}$

A customer is blocked when the system is full, which is just the probability that the system contains

N users at that time:  $P_{block} = P_N = \frac{(1-p)p^N}{1-p^{N+1}}$

Arrivals are rejected when the system is full:  $\lambda_{eff} = \lambda(1 - P_{block})$

Average users in the system:  $L = \sum_{n=0}^N nP_n$

If the system is at full utilisation then the average number of users in the system is  $\frac{N}{2}$  as there is no possible queue which is growing past N

Average delay:  $\frac{L}{\lambda_{eff}}$

Average users in the queue:  $L_q = L - \frac{\lambda_{eff}}{\mu}$

## M/M/∞

No queue ever forms as there is always a server for everyone.

Traffic intensity:  $\frac{\lambda}{\mu} = p$

No one is ever turned away so the effective arrival rate is:  $\lambda_{eff} = \lambda$

Average users in the system is equivalent to the average number of customers being served:  $L = \frac{\lambda}{\mu}$

Average delay only deals with the servicing time because there is no queue:  $\frac{1}{\mu}$

## M/M/m aka Erlang C

Waiting room is infinite but customers only wait if all servers are busy.

For  $n < m$ : some servers are idle

For  $n > m$ : all servers are busy and users are waiting

Traffic:  $a = \frac{\lambda}{\mu}$

Utilisation per server:  $p = \frac{\lambda}{m\mu}$

Probability of zero customers:  $P_0 = \left[ \sum_{n=0}^{m-1} \frac{a^n}{n!} + \frac{a^m}{m!(1-p)} \right]^{-1}$

Probability that an arriving customer must wait:  $P_w = \frac{a^m}{m!(1-p)} P_0$

Average number of users in the queue:  $L_q = \frac{P_w \times p}{1-p}$

Average number of users in the system:  $L_q + a$

Average waiting time:  $W_q = \frac{L_q}{\lambda}$

Average delay:  $W = W_q + \frac{1}{\mu}$

## M/M/m/m aka Erlang B

No waiting room, if all servers are busy, new arrivals are blocked and lost.

Traffic:  $a = \frac{\lambda}{\mu}$

Probability of n users in the system:  $P_n = \frac{\frac{a^n}{n!}}{\sum_{k=0}^m \frac{a^k}{k!}}$

Blocking probability is just the probability that all servers are busy:  $P_{block} = P_m$

Effective arrival rate:  $\lambda_{eff} = \lambda(1 - P_{block})$

Average number of users in system:  $L = \sum_{n=0}^m nP_n$

Average delay:  $\frac{1}{\mu}$

# SYSTEMS SEEN IN CLASS

Dé Céadaoin 10 Nollaig 2025 11:58

Use this when answering Q3 in the exam

1.01:

## **LAN - Local Area Network**

- Access points are deployed close to each other
- Interference

## **WAN - Wide Area Network**

- Base stations are far apart but coverage area is large.
- Path loss, noise

1.02:

## **Broadcast TV - Very High Frequency**

- 54-88MHz
- 174-216MHz

## **Broadcast TV - Ultra High Frequency**

- 470-806MHz

## **FM Radio**

- 88-108MHz

## **Digital TV**

- 54-88MHz
- 174-216MHz
- 470-806MHz

## **2G**

- 800-900MHz

## **3G**

- 746-794MHz
- 1.7-1.85GHz
- 2.5-2.7GHz

## **4G**

- 800MHz
- 1.8GHz

## **5G**

- 3.4-3.8GHz

## **Personal Communication Service**

- 1.85-1.99GHz

## Wireless LAN

### **Wireless LAN (IEEE802.11b/g)**

- 2.4GHz

### **Bluetooth**

- 2.45GHz

### **Wireless LAN (IEEE802.11a)**

- 5GHz

### **Local Multipoint Distribution Services**

- 27.5-31.3GHz

## WiFi

**IEEE 802.11**

- 2.4GHz

**IEEE 802.11b**

- 2.4GHz

**IEEE 802.11a**

- 5GHz
- Not compatible with IEEE 802.11b or IEEE 802.11g because of the difference in bands
- This has a shorter range due to the higher frequency band

**IEEE 802.11g**

- Trying to combine IEEE 802.11a and IEEE 802.11b
- 2.4GHz
- Interoperable with IEEE 802.11b

**IEEE 802.11n**

- Uses MIMO
- 2.4GHz and/or 5GHz

**WiGig**

- Speeds of 7Gbps
- 60GHz band
- Range is only a few meters e.g. HD Video

**WiFi 6 / IEEE 802.11ax**

- Theoretical bandwidth of 14Gbps
- Back compatible with 802.11n
- Uses MIMO
- 2.4GHz and/or 5GHz

**WiFi 7 / IEEE 802.11be**

- 4096-QAM: 12 bits/symbol
- Simultaneously operate in 2.4GHz and 5GHz
- MIMO with 16 spatial streams

Wireless LAN**mmWave**

- 30-300 GHz
- Super short range

**Terahertz / THz**

- 0.1-10THz
- Super high speed potential

**LoRa**

- < 1GHz
- 868MHz
- Unlicensed spectrum