TTM4105 Forkortelser og formler

Eskil Dybvik Dharshini Tharmarajan Anna Storlie Tveit
Erlend Håkegård Georg Skuggedal Iselin E. Eng

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Innhold

1 Forkortelser

1.1 A. General

- **CMTS**: Cable Modem Termination System
- **CO**: Central Office
- **DSL**: Digital Subscriber Line, for home access
- **DSLAM**: Digital Subscriber Line Access Multiplexer
- **FDM**: Frequency Division Multiplexing
- **ISP**: Internet Service Provider
- **MAC**: Medium Access Control
- **OLT**: Optical Line Terminal
- **ONT**: Optical Network Terminal
- **WLAN**: Wireless Local Area Network

1.2 B. Access networks

1.2.1 5G

- **BBU**: Base Band Unit
- **CPRI**: Common Public Radio Interface
- **CRAN**: Centralized Radio Access Network
- **CU**: Centralized Unit
- **DRAN**: Distributed Radio Access Network
- **DU**: Distributed Unit
- **FIFO**: First In First Out
- **NFV**: Network Function Virtualization
- **NGC**: Next Generation Core
- **NGFI**: Next Generation Fronthaul Interface
- **RAN**: Radio Access
- **RE**: Radio Equipment
- **REC**: Radio Equipment Control
- **RU**: Radio Unit
- **SDN**: Software Defined Network

1.2.2 B.1

- **VLF**: Very Low Frequency
- **LF**: Low Frequency
- **MF**: Medium Frequency
- **HF**: High Frequency
- **UHF**: Ultra High Frequency
- **SHF**: Super High Frequency
- **VHF**: Very High Frequency
- **EHF**: Extra High Frequency
- **Ground wave**: (<2MHz) Long wave
- **Sky Wave (<2-30MHz)**: Short wave
- **LOS (>30MHz)**: Line of Sight/Long wave
- **SNR**: Signal Noise Ratio
- **Transmission range**: Communication possible, low error rate.
- **Detection range**: Detection of the signal is possible. No communication.
- **Interference Range**: Signal may not be detected. Signals adds to background noise.
- **MPP**: Multipath Propagation
- **Short-term fading**: Quick changes of the power received.
- **Long-term fading**: Slow changes in average recipe power.
- **A/D**: Analog-to-Digital
- **D/A**: Digital-to-Analog
- **Source coding**: compression and decompression
- **Channel coding**: adding redundancy to combat errors
- **Modulation**: Shift the signals into different frequency bands.
- **Channel coding/channel encoding**: Channel encoding adds additional bits to improve transmission reliability.
- **Detection codes**: capable of detecting bit errors
  - **ARQ**: Automatic Repeat reQuest (retransmission, low coding redundancy)
    - **Parity check**
    - **CRC**: Cyclic-redundancy check
- **Correction codes**: capable of detecting and correcting bit errors

- **FEC**: Forward Error Correction (no retransmission, high coding redundancy)
  * **Convolution code**
  * **Turbo code**
  * **LDPC**: Low-Density Parity-Check code
  * **Polar code**

- **Multiplexing**: multiple use of shared medium
  - **Guard space**: The space between the interference ranges. Such guard space is needed in all five multiplexing schemes presented.
  - **SDM**: Space division multiplexing
  - **FDM**: Frequency division multiplexing
  - **TDM**: Time division multiplexing
  - **Time-and Frequency division multiplexing**
  - **CDM**: Code division multiplexing.
  - **PDM**: Polarization division multiplexing.
  - **CR**: Cognitive radio
  - **PU**: Primary users (users assigned to a specific spectrum by e.g. regulation)
  - **SU**: Secondary users (users with a CR to use unused spectrum)

- **Modulation**: is the process of converting data into radio waves by adding information to an electronic or optical carrier signal.
  - **DM (digital modulation)**: translate digital signals into (baseband) analog signals.
  - **AM (analog modulation)**: shift the baseband analog signals into passband signals
  - **AM**: amplitude modulation
    * **ASK**: amplitude shift keying
  - **FM**: frequency modulation
    * **FSK**: frequency shift keying
  - **PM**: phase shift keying
    * **PSK**:
  - **PLL**: Phase-Locked Loop
  - **MSK**: minimum shift keying
  - **GMSK**: gaussian minimum shift keying
  - **CPM**: continuous phase modulation
  - **BPSK**: binary PSK
  - **QPSK**: quadtratic PSK
  - **DQPSK**: differential quadtrature PSK
  - **QAM**: quadtrature amplitude modulation
  - **BER**: bit error rate
  - **HP**: high priority

- **LP**: low priority
- **MCM**: multi-carrier modulation
- **OFDM**: orthogonal frequency division multiplexing
- **COFDM**: coded OFDM
- **FTT**: Fast Fourier Transform
- **PAPR**: peak-to-average-power ratio

- **Spread Spectrum**: methods by which a signal (e.g., an electrical, electromagnetic, or acoustic signal) generated with a particular bandwidth is deliberately spread in the frequency domain, resulting in a signal with a wider bandwidth.
  - **DSSS**: Spreading Direct Sequence Spread Spectrum
  - **FHSS**: Frequency Hopping Spread Spreading
- **MIMO**: Multiple-Input Multiple-Output
  - **SISO**: Single Input Single Output
  - **SIMO**: Single Input Multiple Output
  - **MISO**: Multiple Input Single Output
  - **MIMO**: Multiple Input Multiple Output
  - **IF**: Interference Cancellation
  - **CSI**: Channel State Information

1.2.3 B.2

- **MAC**: Media Access Control
- **SDMA**: Space Division Multiple Access
- **FDMA**: Frequency Division Multiple Access
- **TDMA**: Time Division Multiple Access
- **CDMA**: Code Division Multiple Access
- **PDMA**: Polarization Division Multiple Access
- **OFDMA**: Orthogonal Frequency-Devision Multiple Access
- **TDD**: Time Division Duplex
- **CSMA**: Carrier Sensing Multiple Access
- **CSMA/CD**: Carrier Sensing Multiple Access with Collision Detection
- **CSMA/CA**: Carrier Sensing Multiple Access with Collision Avoidance
- **MACA**: Multiple Access with Collision Avoidance
- **RTS**: Ready To Send
- **CTS**: Clear To Send
- **MACAW**: MACA for WLANs
- **SAMA**: Spread ALOHA Multiple Access

1.2.4 B.3

- **WPAN**: Wireless Personal Area Networks
- **Bluetooth**
  - **Bluetooth 1.0 og 2.0**
  - **BR** Basic Rate
  - **EDR** Enhanced Data Rate
  - **Bluetooth 3.0**
  - **HS** High Speed
  - **AMP** Alternative MAC/PHY
  - **Bluetooth 4.0**
  - **BLE** Bluetooth Low Energy
- **SCO**: Synchronous Connection Oriented
- **FEC**: Forward Error Correction
- **ACL**: Asynchronous ConnectionLess
- **SCO**: Synchronous Connection Oriented
- **AT**: attention sequence
- **OBEX**: object exchange
- **TCS BIN**: telephony control protocol specification – binary
- **BNEP**: Bluetooth network encapsulation protocol
- **SDP**: service discovery protocol
- **RFCOMM**: radio frequency comm
- **FFD**: Full function device
- **RFD**: reduced function device
- **GTS**: guaranteed transmission services
- **FDD**: Frequency Division Duplex
- **BS**: Base Station
- **BSC**: Base Station controller, kontrollerer flere BS
- **AP**: Access Point, type base station
- **MS**: Mobile station
- **SS**: Subscriber Station, type mobile station
- **MT**: Mobile terminal, type mobile station
- **MN**: Mobile Node, type mobile station

- **MSC**: Mobile switching center, GSM
- **LR**: Location register
- **HLR**: Home Location register
- **GMSC**: Gateway mellom vanlig nett og NSS
- **VLR**: Visitor Location register
- **RSS**: Radio sub system, radio aspekter, består av BSC, BS
- **NSS**: Network and switching subsystem. gjør forwarding, handover og switching
- **OSS**: Operation subsystem, managment av nettverk.
- **AUC**: Autentication center. del av OSS. Genererer authentikasjon til VLR.
- **EIR**: Equipment identity register- Registrer GSM MS, Kan lokaliserer GSM MS. Del av OSS
- **OMC**: Operation and maintainance center. Del av OSS.
- **DL**: Downlink, BS til MS
- **UL**: Uplink, MS til BS
- **TA**: Time advance. GSM. Justerer distanse signalet går mellom MS og BTS. mellom 0-63. Multiplisert med 3.7 for antall μs MS må sende tidligere.
- **GPRS**: General packet radio service, 2.5G
- **EDGE**: Enhanced data rates for GSM, Forbedret GPRS.
- **UMTS**: Universial mobile telecomunication system.
- **UE**: User equipment
- **UTRAN**: UMTS terrestrial radio access network.
- **RNS**: Radio network subsystem
- **CN**: Core Network
- **USIM**: Universal subscriber identity module. Kryptering og autentikasjon ved en SIM
- **OVSF**: Orthogonal variable spreading factor. coding UMTS
- **RNC**: Radio network controller
- **RNS**: Radio network subsystem
- **CSD**: Circuit switched domain
- **PSD**: Packet switched domain
- **LTE**: Long term evolution. 3.9G
- **UE**: User equipment

- **MT**: Mobile termination, håndterer tråløs/ mobil komunikasjon.
- **TE**: Terminal equipment. handles data streams
- **UICC**: Unerversial integrated circuit card. Sim kort for LTE. USIM.
- **E-UTRAN**: Evolved UMTS terrestrial radio access network. Radio, BS. Mellom UE og EPC.
- **EPC**: Evolved packet core. Sentral database for subscribers.
- **PDN**: Packet data network
- **NVF**: Network function virtualisation. Virtualiserin av for eksempel MME, S-GV.
- **SDN**: Software defined networking
- **SDAN**: Software defined access networks
- **MTC**: Machine type communication.
- **IoT**: Internet of things
- **CIoT**: Cellular IoT
- **NB-IoT**: Narrow Band IoT
- **NGMN**: Next generation mobile networks.
- **RAT**: Radio access technologies
- **ARPU**: Average revenue per user.
- **NR**: New radio
- **NGCN**: Next generation core network.
- **LPWA**: Low power wide area network.
- **WPAN**: Wireless personal area network
- **LR-WPAN**: Low-rate WPAN. Zigbee.
- **6LoWPAN**: IPv6 over low poewer wpan.
- **ND**: neighbor discovery
- **IPHC eller HC1**: IP header compression
- **NHC eller HC2**: next header compression
- **CoAP**: Constrained applcation protocol
- **M2M**: Machine To Machine
- **SFP**: Small Form-Factor Pluggable Transceiver
- **DOCSIS**: Data-Over-Cable Service Interface Specification
- **SFC**: Service Function Chaining

1.3 Optisk transport

- **1R**: Regeneration by amplification. May be done transparently (using only optical components) using an EDFA.
- **2R**: Regeneration by amplification and reshaping. Currently done electronically, but may be possible to do optically in near future.
- **3R**: Regeneration by amplification, reshaping, and retiming. Done electronically, but may be possible to do optically in far future.
- **ADSL**: Asymmetric Digiatal subscriber line) - download speed is considerably faster than the upload speed.
- **AON**: Active Optical Network. The opposite of PON. For example using a powered switch to give several houses FTTH.
- **APS**: Automatic Protection Switching. Protection switching at multiple levels.
- **ASE**: Aplified Spontaneous Emission. Photons may be exited spontaneously, causing noise.
- **BGP**: Border-gate Protocol. Using between different ISPs to learn routes.
- **CR-LDP**: Constraint-Based LDP.
- **CSPF**: Constraint Shortest Path First.
- **CWDM**: Coarse Wavelength Divided Multiplexing. Multiplexing by using different wavelengths with ”large” spacing between them.
- **DCF**: Dispersion Compensating Fiber. Fiber with negative dispersion, which may be used to create a long link with no dispersion in total.
- **DGD**: Differential Group Delay.
- **DLP**: Dedicated Line Protection.
- **DPP**: Dedicated Path Protection.
- **DPRings**: Dedicated Protection rings.
- **DSLAM**: Digital Subscriber Line Access Multiplexer is a network device, often located in telephone exchanges, that connects multiple customer digital subscriber line (DSL).
- **DWDM**: Dense Wavelength Divided Multiplexing. Multiplex over wavelengths that are close to each other. Gives good channels, as wavelengths with less attenuation may be used.
- **EDFA**: Erbium Doped Fiber Amplifier. Uses a pump laser to exite erbium in fiber cables, which gives 1R without having extra components in the fiber cable itself.
- **EPON**: Ethernet PON. A standard for PON using TDMA. Used in the US and Japan, cheaper than GPON, standardized by IEEE. Less scalable than GPON.
- **ER-LSP**: Explicitly Routed LSP.
- **EVC**: Ethernet Virtual Connections.

- **FEC**: Forward Error Correction. Add extra bits to increase fault tolerance by making it possible for the receiver to fix bit errors.
- **FLP**: Fixed Length Packets.
- **FTFL**: Fault Type and Fault Location Channel.
- **FTTB**: Fiber-to-the-building.
- **FTTC**: Fiber-to-the-comb.
- **FTTH**: Fiber-to-the-home.
- **FTTS**: Fiber-to-the-sofa. (Very important!)
- **FSC**: Fiber-switch capable.
- **GCC**: General Communication Channel.
- **GMPLS**: Generalized MPLS. MPLS which uses wavelengths and timeslots as labels, making it more general than MPLS.
- **GPON**: Gigabit PON. PON access technology using TDMA. Alternative to EPON. A bit more expensive than EPON, but supports higher capacity links. Standardized by the ITU-T.
- **GST**: Guaranteed Service Transport.
- **IaDI**: Intra-domain Interfaces. Kommunikasjon internt i en operatør.
- **IEEE**: Institute of Electrical and Electronics Engineers. Standardizes Ethernet as 802.3, Wi-Fi as 802.11, and several other standards.
- **IHON**: Integrated Hybrid Optical Network. Technology to give lower latancy to prioritized packets.
- **IP**: You should know what this is at this point.
- **IP-WDM**: IP over Wavelength Divided Multiplexing. Buzzword about senting IP packets directly over fiber. Not used in practise (use SONET/SDH or OTN instead).
- **IrDI**: Inter-domain Interfaces. For communication between two operators.
- **IS-IS**: Intermediate System Intermediate System. Alternative to OSPF.
- **ITU-T**: International Telecommunication Union Telecommunication Standardization Sector. Standardizes different technologies within telecom.
- **KEOPS**: Broadcast and Select Switch (don't ask how).
- **L2SC**: Layer-2 Switch Capable.
- **LDP**: Label Distribution Protocol.
- **LSC**: Lambda Switch Capable.
- **LSP**: Label Switched Path.

- **MAC**: Medium Access Control. Multiplication method and algorithm.
- **MEF**: Metro Ethernet Forum. It's an organization defining how to achieve scalable predictable ethernet.
- **MEMS**: Micro-ElectroMagnetical System. Uses some magnetic magic to create optical switches with many ports.
- **MPLS**: MultiProtocol Label Switching. Mark packets with labels for use internally in operator networks. Avoid many lookups in routing tables, saving resources.
- **MPλS**: Old name for GMPLS.
- **NHLFE**: Next Hop Label Forwarding Entry.
- **NMS**: Network Management System
- **MTIE**: Maximum Time Interval Error.
- **OADM**: Optical Add Drop Multiplexer. OADM takes in signals at multiple wavelengths and drops fixedwave-lengths locally while letting others pass through. The wavelengths that hav ebeen dropped may be added back in the link.
- **OAM**: Operation, Administration, and Maintenance.
- **OBLSR**: Optical Bidirectional Line Switched Rings.
- **OBPSR**: Optical Bidirectional Path Switched Rings.
- **OBS**: Optical Burst Switching. Switch a burst of packets instead of a single one.
- **OCS**: Optical Circuit Switching.
- **OEO**: Optical-Electronic-Optical. A component that takes in fiber and outputs fiber, but converts the signal to an electrical signal in the middle. E.g. a 3R device.
- **OH**: Over-head.
- **OOK**: On-off-keying. Turn the signal on or off to signal 0 or 1.
- **OpMiGua**: Optical packet switched Migration capable network with service Guarantees.
- **OPS**: Optical Packet Switching.
- **OSPF**: Open Shortest Path First. Algorithm for finding routes internally in an operators network. Alternative to IS-IS.
- **OTN (G.709)**: Optical Transport Network. A protocol-like technology used to transfer arbitrary data over fiber links. May be used to send Ethernet packets, IP etc. Circuit switched. Alternative to SONET/SDH.
  - Electrical domain:
    - **OPU**: Optical channel Payload Unit.
    - **ODU**: Optical channel Data Unit.
    - **OTU**: Optical channel Transport Unit
  - Optical Domain:

    * **OCh**: Optical channel sublaye
    * **OMS**: Optical muliplex section - Multiplexing of OCh's.
    * **OTS**: Optical transmission section - The fiber itself.

- **OULSR**: Optical Unidirectional Line Switched Rings.
- **OUPSR**: Optical Unidirectional Path Switched Rings.
- **OXC**: Optical cross connects. Trengs for å realisere mesh nettverk. Har samme funksjonalitet som ROADM, men for større antall porter + kan gjøre wavelength conversion.
- **PBB**: Provider Backbone Bridges.
- **PCC**: Protection Communication Channel.
- **PDV**: Packet Delay Variation (jitter). Follows a statistical distribution. Use the expected value (empirically the average).
- **PLR**: Packet Loss Ratio.
- **PM**: Path Monitoring.
- **PMD**: Polarisation Mode Dispersion.
- **PPB**: Parts-per-billion.
- **PSC**: Packet Switch Capable.
- **QoS**: Quality-of-service. Such as uptime, prioritizing specific packets, service guarantees, data transfer speeds etc.
- **RN**: Remote Node.
- **ROADM**: Reconfigurable Optical Add Drop Multiplexer - Brukes mye i metropolitian area networks. Er samme som OADM, men kan rekonfigureres vha network management system.
- **RSVP-TE**: Resource reservation protocol with traffic engineering.
- **RTT**: Rount-Trip-time (ping). How much time it takes to transfer something between two nodes and back. Usefull for measuring delays with TCP.
- **SCMA**: Sub-carrier multiple access.
- **SCWP**: Scattered Wavelength Path.
- **SHWP**: Shared Wavelength Path
- **SLA**: Service Level Agreement.
- **SLP**: Shared Line Protection.
- **SM**: Statistical Multiplexing.
- **SPP**: Shared Path Protection.
- **SONET/SDH**: Synchronous Optical Networking and Synchronous Digital Hierarchy. Standards for transferring data over fiber. OTN is the more modern solution.

- **SOP**: State of modulation.
- **T-MPLS**: Transport-MPLS.
- **TCM**: Tandem Monitoring.
- **TCP**: Transmission Control Protocol.
- **TDEV**: Time Deviation.
- **TDM**: Time Divison Multiplexing.
- **TE**: Traffic Engineering.
- **UDP**: User Datagram Protocol.
- **VDSL**: Faster type of DSL. Its only made for short distances.
- **VLAN**: Virtual LAN.
- **VLP**: Variable Length Packets.
- **WDM**: Wavelength Divided Multiplexing.
- **WDM-PON**: Wavelength Divided Multipexing Passive Optical Network.

2 Formler

2.1 Access part

Frequency

- $\lambda = \frac{c}{f}$
- λ: wavelength, c $= 3 * 10^8$ m/s (speed of light), frequency f
- $f = \frac{1}{T}$, T: Periode

Channel capacity

- Forkortelser:
  - C: Channel Capacity
  - B: Channel Bandwidth
  - $\log_2 M$: Spectral Efficiency
  - SNR: Signal Noise Ratio
  - P: received signal power
  - N_0: Noise spectral density
- Noise free channel
$$C = 2Blog_2M \tag{1}$$
- Noisy channel (bps):
$$C = Blog_2 \cdot (1 + SNR) \tag{2}$$

- Spectral efficiency *(bps/Hz)*:

$$C = log_2 \cdot (1 + SNR) \tag{3}$$

- AWGN Channel (Additive White Gaussian Noise) - (bps):

$$C = Blog_2 \cdot \left(1 + \frac{P}{N_0 B}\right) \tag{4}$$

Signal to Noise Ratio (SNR):

- The signal strength divided by the noise level. Higher is better. Often denoted in the logarithmicly scaled decibel units:

$$SNR_{dB} = 10log_{10}SNR \tag{5}$$

$$SNR = 10^{SNR_{dB}/10} \tag{6}$$

Frequency Reuse

- Forkortelser:
  - N: Frequency reuse factor, antall celler i en cluster(?)
  - D: Reuse distance, avstand mellom celler som bruker samme frekvens.
  - r: Celle radius
- Formel

$$\frac{D}{r} = \sqrt{3N} \tag{7}$$

Free-path loss

- Forkortelser:
  - P_t: power transceiver
  - P_t: power receiver
  - d: distance
- Formel

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2} \tag{8}$$

Coding rate

$$\text{coding rate} = \frac{\text{data bits}}{\text{transmitted bits}} \tag{9}$$

Fourier representation of a real signal

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t) \tag{10}$$

2.1.1 5G

- Continuous-time birth/death Markov Process

$$p_k = p_0 \prod_{i=0}^{k-1} \frac{\lambda_i}{\mu_{i+1}}$$

  - **k** is the number of customers in the system

- Normalizing condition

$$\sum_{k=0}^{\infty} p_k = 1$$

- Little's formula

$$\overline{N} = \overline{\lambda} \cdot \overline{W}$$

  - $N(t)$ number of customers in the system at time t, with the average $\overline{N}$.
  - W_i is the sojourn time in the system for customer i, with the average $\overline{W}$.
  - $\overline{\lambda}$ is the average arrival intensity.

- Average system traffic and time

$$\overline{k} = \sum_{k=0}^{\infty} k p_k = \sum_{k=0}^{\infty} k(1-\rho)\rho^k = \overline{k} = \frac{\rho}{1-\rho}$$

  - This average tends to increase as the system utilization increases, as expected.
  - To find the average time T spent in the system we apply the Little's result:

$$\overline{T} = \frac{\overline{k}}{\lambda} = \frac{1/\mu}{1-\rho} = \frac{\overline{\Theta}}{1-\rho}$$

    * $\overline{\Theta}$ is the average service time equal to $1/\mu$
  - $\overline{T}$ exhibits an asymptotic behavior in correspondence with $\rho = 1$. In order to limit the delay, a limit on service utilization must be put.

- Probability functions of queuing delay η

  - Consider a queue with FIFO queuing discipline
  - M/M/1/∞
  - Let η indicate the waiting time in the queue

$$F_\eta(\eta) = P(\text{waiting time} \leq \eta)(\text{Cumulative distribution})$$

$$f_\eta(\eta) = \frac{dF_\eta(\eta)}{d\eta}(\text{probability density function})$$

  - The cumulative distribution function results in

$$F_\eta(\eta) = 1 - \rho e^{-(1-\rho)\mu\eta}$$

- This gives the complementary distribution:

$$\overline{F_\eta}(\eta) = P(\text{waiting time} > \eta) = \rho e^{-(1-\rho)\mu\eta}$$

$$\overline{F_{\eta|\text{waiting}}}(\eta) = e^{-(1-\rho)\mu\eta}$$

- The equation above represents the probability that the waiting time is $> \eta$ when the customer waits in the queue for the service, ρ being the probability of waiting for the service.

- M/M/m/0 queue:
  - Pure loss queuing system

$$p_k = p_0 \prod_{i=0}^{k-1} \frac{\lambda_i}{\mu_{i+1}}$$

$$\sum_{k=0}^{\infty} p_k = 1$$

  - λ_i and μ_{i+1} are determined in relation to queueing system characteristics.
  - We have for M/M/m/0 queue:

$$\lambda_k = \lambda, \quad k < m$$

$$\lambda_k = 0, \quad k = m$$

$$mu_k = k\mu, \quad k \leq m$$

  - Offered traffic: $A_0 = \lambda/\mu$

- Loss system performance: Erlang B formula
  - The probability that the system is in time congestion is:

$$p_\Omega = p_m = \frac{\frac{A_0^m}{m!}}{\sum(m, A_0)}$$

  - When an arrival happens when the system is in the time congestion, we have a loss (call congestion). The probability Π_p of this to happen is:

$$\Pi_p = P(\text{Time congestion}|\text{arrival}) = P_\Omega = B(m, A_0)$$

    * Consequence of independent arrivals
  - The B Erlang formula:

$$B(m, A_0) = \frac{\frac{A_0^m}{m!}}{\sum(m, A_0)}$$

- Waiting system M/M/m/∞
  - k is the number of customers in system
  - h is the number of customers in service
  - l is the number of customers in queue

– We have:

$$\lambda_k = \lambda, \quad \forall k$$
$$\mu_k = k\mu, \quad k < m$$
$$\mu_k = m\mu, \quad k \geq m$$
$$p_k = p_0 \prod_{i=0}^{k-1} \frac{\lambda_i}{\mu_{i+1}} = p_0 \frac{\lambda^k}{k!\mu^k}, \quad k < m$$
$$p_k = p_0 \frac{\lambda^k}{\mu^k m! m^{k-m}} = k \geq m$$
$$\sum_{k=0}^{\infty} p_k = 1$$

– We can obtain the statistical description by calculating p_k

- Erlang C formula
  - The probability to wait in the system is defined by

$$\Pi_r = prob(Time\, congestion|arrival) = C(m, A_0)$$

  - Where time congestion is defined by:

$$S_r = prob(k \geq m)$$

  - Being the system state and arrival process independent we have $\Pi_r = S_r$

$$\Pi_r = \sum_{k=m}^{\infty} p_k = \sum_{k=m}^{\infty} \frac{\frac{A_0^k}{m!m^{k-m}}}{\sum(m-1, A_0) + \frac{A_0^m m}{m!m-A_0}} = \frac{\frac{A_0^m m}{m!m-A_0}}{\sum(m-1, A_0) + \frac{A_0^m m}{m!m-A_0}}$$
$$= C(m, A_0),\ where\ A_0 = \frac{\lambda}{\mu}$$

2.2 Optical transmission

- **Snells Law**
$$n_{kjerne} \cdot \sin\theta_{kjerne} = n_{kappe} \cdot \sin\theta_{kappe}$$

- **Critical angle of total refraction**
$$\theta_{kritisk} > \sin^{-1}\left(\frac{n_{kappe}}{n_{kjerne}}\right)$$
Where n are material constants, and θ is entry angle.

- **Refractive index:**
$$n_{materiale} = \frac{c_{vakum}}{c_{materiale}} \to n_{luft} \approx 1 \tag{11}$$

- **Number of modes in multimode fiber**
$$V = \frac{2\pi}{\lambda} \cdot a \cdot NA \qquad V \geq 10 \to m \approx \frac{V^2}{2}$$
der m er antall modes, normalisert frekvens V, kjernediameter a, og bølgelengde λ.

- **CWDM/ DWDM link attenuation:**
  - Forkortelser:
    * A_{tf}: Attenuation in transmission fibre at the transceiver wavelength
    * $A_{linkmux}$: Link attenuation in the MUX/DMUX pair
    * A_p: Attenuation in patch-cord
    * N: Number of patch-cords
$$L_i = A_{tf} + A_{linkmux} + (N \cdot A_p) \tag{12}$$

- **Elaton based adjustable filter - Finesse**
  - Forkortelser:
    * FSR: Period between repetition of pass-band.
      · In some filters, the transfer function, or the shape of the filter passband, repeats itself after a certain period
$$Finesse = \frac{FSR}{\text{Width of channel } (\Delta \text{ f})} \tag{13}$$

- **Packet Loss Ratio (PLR)**
$$\frac{\text{Number of packets dropped}}{\text{Number of packetes transmitted}} \tag{14}$$

3 Eksempler

3.1 CDMA Example

Assign '0' = -1 and '1' = +1

- Sender A:
  - sends $A_d = 1$
  - Key A_k = 0 1 0 0 1 1
  - sending signal: $A_s = A_d \cdot A_k = -1 + 1 - 1 - 1 + 1 + 1$
- Sender B:
  - sends $B_d = 0$
  - Key A_k = 1 1 0 1 0 1
  - sending signal: $A_s = A_d \cdot A_k = -1 - 1 + 1 - 1 + 1 - 1$
- Both signals superimpose in space $A_s + B_s$ = -2 0 0 -2 +2 0
- Receiver wants to receive the sign from sender A:

  Key A_K applied bit-wise (inner product): $A_r = (A_S + B_S)A_K$ = (-2 0 0 -2 +2 0) $\cdot(-1 + 1 - 1 - 1 + 1 + 1) = +6$
- $result > 0 \rightarrow$ bit was '1'

  Key B_k applied bit-wise (inner product): $B_r = (A_S + B_S)B_K$ = (-2 0 0 -2 +2 0) $\cdot(+1 + 1 - 1 + 1 - 1 + 1) = -6$
- $result < 0 \rightarrow$ bit was '0'

3.2 Case Study: Single Server Queue (M/M/1/∞)

- m = 1
- $\lambda_k = \lambda \quad \forall k$
- $\mu_k = my \quad k > 0$
- Stability condition is $\rho < 1$ and system utilization $\rho = \frac{\lambda}{\mu}$
- State probabilities are

$$p_k = (1-\rho)\rho^k$$

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

3.3 M/M/1: Average time behaviour

- With $\overline{\Theta}$ being the average service time

$$\overline{T} = \frac{\overline{k}}{\lambda} = \frac{1/\mu}{1-\rho} = \frac{\overline{\Theta}}{1-\rho}$$

3.4 Exercise: Statistical multiplexer

- A statistical multiplexer has N inputs and 1 output and a queue with infinite capacity
- The arrival process from each connected input is Poisson with arrival rate $\lambda = 15$ packets/min and the service process has exponential distribution, with average service time $E[\Theta] = 0.2s$
- Calculate the maximum number N so that the average delay $E[T] <= 0.5s$
- Solution:
  - M/M/1/∞

$$E[T] = \frac{\Theta}{1-\rho} = \frac{0.2}{1-\rho} \leq 0.5s$$

$$\rightarrow (1-\rho) \geq 0.4 \rightarrow \rho \leq 0.6 = A_0 = NA_{0T}$$

$$\rightarrow N \leq \frac{0.6}{0.05} = 12$$

3.5 Finite queue length system (M/M/1/L)

- The system capacity in this case is given by $K = L + 1$, where L is queue length.

$$\lambda_k = \lambda, k < K$$

$$\lambda_k = 0, k = K$$

$$\mu_k = \mu, k > 0$$

$$p_k = p_0 \prod_{i=1}^{k-1} \frac{\lambda_i}{\mu_{i+1}} = p_0 A_0^k, \; k \leq K$$

$$p_k = 0,\ k > K$$

$$p_0 = \frac{1}{1+\sum_{k=0}^{K}} A_0^{K+1} = \frac{1}{1+\frac{A_0(1-A_0^K)}{1-A_0}} = \frac{1-A_0}{1-A_0^{K+1}}$$

$$p_k = A_0^k \frac{1-A_0}{1-A_0^{k+1}},\ k \leq K$$

$$p_k = 0,\ k > K$$

$$A_0 = \frac{\lambda}{\mu}$$

- Loss probability in the M/M/1/L queue

$$\Pi_p = p_{L+1} = A_0^{L+1} \frac{1-A_0}{1-A_0^{L+2}}$$

  - When L = 0 (K = 1)

$$p_0 = \frac{1}{1+A_0},\ k = 0$$

$$p_1 = \frac{A_0}{1+A_0},\ k = 1$$

  - And $p_k = 0, \quad k > 1$
  - p_1 also represents the loss probability in this queue and coincides with the $B(1, A_0)$
  - In an infinite queue model the loss can be calculated as $P(k \geq L+1) = A_0^{L+1}$

3.6 Exercise 2: Loss in a Statistical multiplexer

- A statistical multiplexer has N inputs and 1 output and a queue with L = 3 packet
- The arrival process from each connected input is Poisson with arrival rate lambda = 15 packets/min and the service process has exponential distribution, with average service time $E[\Theta] = 0.2s$
- Calculate the packet loss probability with N = 12 using 2 different models: M/M/1/L and M/M/1/∞
- Solution

$$A_{0T} = 0.25 \cdot 0.2 = 0.05$$

$$A_0 = 0.05 \cdot 12 = 0.6$$

  - M/M/1/L model:

$$\Pi_p = p_{L+1} = A_0^{L+1} \frac{1-A_0}{1-A_0^{L+2}} = 0.056$$

  - M/M/1/∞

$$\Pi_p = A_0^{L+1} = 0.13$$

3.7 Exercise 3: Statistical multiplexer

- A statistical multiplexer as N inputs and 1 output and a queue with infinite capacity
- The arrival process is Poisson with arrival rate lambda = 15 packets / min and the service process has exponential distribution, with average service time $E[\Theta] = 0.2s$
- Calculate the maximum number N so that the probability that a packet waits for more than 2s is less than or equal to 0.001.
- Solution: M/M/1/∞

$$prob(waiting\,time > \eta)|waiting = e^{-(1-\rho)\mu\eta}$$

$$\rho = \frac{\ln \Pi + \mu\eta}{\mu\eta} = \frac{-6.91 + 10}{10} = 0.309$$

- This represents the limiting value of the total load to have a probability of delay > 2s, less than or equal to 0.001

$$A_{0T} = 0.05 \rightarrow N \leq \frac{0.309}{0.05} = 6.18(6 \text{ terminals as maximum})$$

3.8 Exercise 1 &2 : SNR

- Consider a wireless channel of spectrum between 2.412GHz and 2.432GHz. Assume the channel experiences white Gaussian noise and the received signal-to-noise ratio (SNR) is 25dB, what is the maximum achievable date rate?
- Solution:
  - Bruker formel 5:

$$SNR = 25dB = 10^{\frac{25}{10}} = 316$$
$$C = B * log_2(1 + SNR) = 20 * log_2(1 + 316) = 166\text{Mbps}$$