Mobile Network 2017 - Cheat Sheet

1 Wireless communication and mobility

Wireless networks in comparison to fixed networks:

- ▷ Higher data loss-rates due to interferences
- ▷ Restrictive regulations of frequencies
- ▷ Lower transmission rates
- ▷ Lower security, Higher jitter
- ▷ Fluctuation quality of the links
- ▷ Unknown location of the mobile station

2 Wireless Network Models

Need to satify **coverage requirements** & **service requirements**
Resources to be managed/conserved: **frequency spectrum**, **power consumption**, **infrastructure and terminal cost**
Interference often limites the performance of the system
Technical measures of a wireless network: number of subscribers served, overall bandwidth provided, BER, delay, user data rate, coverage, outage probability, ...
Common Service types

- ▷ **Best Effort traffic**: guarantee maximum throughput. Utilize all available throughput at any time
- ▷ **Guaranteed service traffic**: constant data rate and delay

Network/infrastructure deployment: how many, where, what infrastructure and how much spectrum?
Radio Resources allocation: Given a set of base stations, allocate spectrum, power, ...
Interference Models: Propagation conditions on link (i, j) given by G_{ij} where G is the link gain matrix.
SINR of uplink, downlink:

$$\Gamma^u_{i_0 j} = \frac{P_j G_{i_0 j}}{\sum_{m \neq j} P_m \theta_{0,m} G_{i_0 m} + N_{i_0}}$$

$$\Gamma^d_{i_0 j} = \frac{P_{i_0} G_{i_0 j}}{\sum_{b \neq i_0} P_b \theta_{0,b} G_{i_0 b} + N_j}$$

with θ the normalized cross-correlation term.
Guaranteed service quality → boundaries on $\Gamma^u_{i_0 j}$ and $\Gamma^d_{i_0 j}$
M terminals active, Y terminals served, $Z = M - Y$ assignment failure.
Assignment failure rate:

$$v = \frac{E[Z]}{E[M]} = \frac{E[Z]}{\omega A}$$

with ω the terminal per unit area and A the area.
Capacity: the maximum allowed traffic load in order to keep the assignment failure rate below some threshold.
Resource Management Strategies

- ▷ **Static assignment**: based on statistical information during planning phase of the network
- ▷ **Perfect dynamic channel assignment**: based on instantaneous values. Traffic and interference adaptive assignment
- ▷ **Random assignment**: DS-CDMA, ALOHA, ...

3 Medium Access Control

MAC protocols handle channel sharing between multiple terminals.
Challenges for wireless networks

- ▷ Signal experiences reflection, diffraction, ...
- ▷ Broadcast nature of the medium
- ▷ Half-duplex: sending data usually prevents receiving

Performance Measures

- ▷ **Delay**: between arrival time and time the message sent to receiver
- ▷ **Quality** of data received:
  - ▷ **BER**: Bit Error Ratio
  - ▷ p_{BER}: Bit Error Probability
  - ▷ **Packet Error Rate** $= 1 - (1 - p_{BER})^N$
- ▷ **Throughput**: expected number of messages delivered to the receiver per time unit.
- ▷ **Normalized link delay**: 1 / throughput

3.1 Contention-free MAC protocols

Each terminal sends packets using predetermined time slots, frequency bands, or codes. A central scheduler coordinates the transmissions of different terminals, and **there will be no collisions** in the network.
Static resource partitioning

3.1.1 TDMA - Time Division Multiple Access

- ▷ All terminals are synchronized
- ▷ Flexible in handling different rate requirements

3.1.2 FDMA - Frequency Division Multiple Access

- ▷ Not efficient for traffic with different rate requirements
- ▷ Need guard bands between adjacent bands → lower thrghput

3.1.3 OFDMA - Orthogonal Division Multiple Access

- ▷ Like FDMA but uses orthogonal sub-carriers
- ▷ Doesn't need guard band between adjacent frequency bands
- ▷ Allows overlapping adjacent spectrum bands → more spectrum efficient
- ▷ Easy to implement and used in 4G

3.1.4 CDMA - Code Division Multiple Access

- ▷ Terminals send on whole frequency bandwidth
- ▷ Each sender has a unique code → XOR the signal with it
- \- Higher complexity of the receiver
- \- All signals should have the same strength at the receiver
- \+ Huge code space compared to frequency space
- \+ More robust to jamming and eavesdropping
- ▷ Used in 3G and Wifi

3.1.5 SDMA - Space Division Multiple Access

- ▷ Uses the spatial separation to reuse frequency spectrum
- ▷ Useful when terminals are located far from each other
- ▷ Use intelligent signal processing and antenna arrays so it can reuse frequency spectrum within the same cell.
- ▷ Often combined with other partitioning methods.

Dynamic resource partitioning
Network resources can be dynamically allocated using a central scheduler to achieve better network performance.

- \+ Good performance in heavy traffic
- \+ QoS guarantee
- \- Higher complexity and cost
- \- Not scalable

3.1.6 Poll-based access protocol

- ▷ Designate device as a channel access administrator
- ▷ Admin queries other terminals to see if they have packets
- ▷ If so, they transmit packets in the following several time slots
- ▷ Higher overhead as polling consumes a lot of bandwidth and turnaround time increases time overhead.

3.1.7 Token-based access protocol

- ▷ Token is passed in a orderly fashion between the terminals.
- ▷ Terminal holding the token has the channel access.

3.2 Contention-based MAC protocols

- ▷ Terminals access channel randomly when they have packets to send.
- ▷ No terminals is superior to another station
- ▷ Terminals decide when to send based on a procedure defined by the protocol
- ▷ Allows packet collisions
- \+ Good performance in low-traffic networks
- \+ Low complexity

3.2.1 Pure ALOHA

1. If there is a message to send, send it
2. ▷ If the transmission succeeded → step 1
   ▷ If the transmission failed, wait a random time → step 1

- ▷ Poor performance with high traffic

3.2.2 Slotted ALOHA

- ▷ Terminals are synchronized and can send packets only at the beginning of a time slot
- ▷ The average number of messages arriving to the system has to be equal to the average number of departing messages.
- ▷ Mathematical model
  - ▷ M: # terminals
  - ▷ $\lambda_i = \lambda / M$: message arrival rate
  - ▷ σ_i: message retransmission rate
  - ▷ $\delta_i = \lambda_i + \sigma_i$: message attempt rate
  - ▷ $q = e^{-M\delta_i}$: successful transmission probability
  - ▷ $\Rightarrow \lambda_i = q\delta_i$: for stable equilibrium
  - ▷ $p = 1 - e^{-\delta_i}$: transmission probability
  - ▷ Overall network thrghput:

$$\lambda = \sum_{i=0}^{M} \lambda_i = M\delta_i e^{-M\delta_i}$$

3.2.3 CSMA - Carrier Sense Multiple Access

- ▷ Abort transmission as soon as a collision is detected
- ▷ **Non-persistent CSMA**:
  1. If the channel is sensed idle → send
  2. Otherwise → wait a random amount of time and → step 1
- ▷ **1-persistent CSMA**:
  1. If the channel is sensed idle → send
  2. Otherwise sens until idle → send
- ▷ **p-persistent CSMA**:
  1. If the channel is sensed idle → send with prob p
     Otherwise → delay its transmission by one time slot
  2. If channel busy → continue sensing until idle → step 1

3.2.4 CSMA/CD - with Collision Detection

- ▷ If collision during transmission → stop and signal collision
- ▷ If collision occurs several time → increase time window (exp)
- ▷ **Not appropriate for wireless networks**
- ▷ **Hidden Terminal Problems**: Senders sense idle but receiver in the middle get both messages at the same time.
- ▷ **Exposed Terminal Problem**: Senders sense channel busy while the receivers actually isolated

3.2.5 CSMA/CA - with Collision Avoidance

1. At new transmission → choose backoff counter randomly
2. Sense the channel:
   - ▷ if idle for DIFS (Duration Inter-Frame Space) → step 3
   - ▷ Otherwise → continue sensing
3. Count down using backoff counter while channel remains idle.
   - ▷ If the channel sensed busy → step 2.
   - ▷ If the counter is zero → transmit data immediately.

- ▷ **Request To Send (RTS)**, **Clear To Send (CTS)** packets, carrying data length solve exposed & hidden terminal issue

3.2.6 CRA - Conflict Resolution Algorithms

Resolves conflicts → users are scheduled using distributed algo.

- ▷ Each terminal is uniquely numbered
- ▷ When conflict occurs → enters *conflict resolution mode* until the conflict has been resolved → check last digit on IDs

3.2.7 Reservation-Based Protocols

- ▷ Very costly to loose one long data packet when collision
- ▷ Reserve resources (time, frequency, ...) for data transmission
- ▷ Two phases: 1. reservation phase, 2. data transmission phase
- ▷ **Scheduling-based**: Central scheduler first collects networks information and then schedule the resources
- ▷ **Contention-based**: Short reservation pckt w/ ALOHA, CRA

3.2.8 Bit-map protocol

- ▷ Terminals are numbered
- ▷ Send short reservation packet in the corresponding time slot
- ▷ Send data in the data phase folling order in resrvation phase.
- ▷ Station see all 1-bits resrvation transmitted during resrvation phase. Station know which stations want to transmit.
- ▷ After the resrvation phase, stations that asserted to transmit sends its frame in the order of station number.
- ▷ Efficiency: $\frac{d}{(d+N)}$, d # bits in the packet, N # terminals

3.2.9 Bianchi's model

- ▷ Semi-analytical model to express performance of networks.
- ▷ Use 2D Markov C. of $m + 1$ backoff stages in which each stage represent the backoff time counter of a node. Transitions take place upon collisions and successful transmissions
- ▷ In each stage, CW is the maximum value for the contention window and is equal to $2^i(CW_{min} + 1)$
- ▷ If a correct transmission takes place, a random backoff will be chosen between 0 and $CW_0 - 1$ with probability $\frac{1-p}{CW_0}$
- ▷ In the case of a collision, a random backoff will be chosen between 0 and $CW_i - 1$ with probability $\frac{p}{CW_i}$
- ▷ State are represented as $\{s(t), b(t)\}$, $b(t)$: counter, $s(t)$: stage
- ▷ This model assumes that packets collide with probability p
- ▷ With π the probability to send a packet: $p = 1 - (1 - \pi)^{N-1}$
- ▷ Stationary distribution of the chain:

$$b_{i,k} = \lim_{t \to \infty} P(s(t) = i, b(t) = k), i \in \{0, m\}, k \in \{0, CW_i - 1\}$$

- ▷ Transmission occurs when backoff time counter = 0, therefore:

$$\pi = \sum_{i=0}^{m} b_{i,0}$$

- ▷ Close form of $b_{i,k}$

$$\begin{cases} b_{i,0} &= p^i b_{0,0} \qquad 0 < i < m \\ b_{m,0} &= \frac{p^m}{1-p} b_{0,0} \\ b_{i,k} &= \frac{CW_i - k}{CW_i} b_{i,0} \qquad 0 \leq i \leq m, 0 < k < CW_i - 1 \end{cases}$$

Imposing normalization condition, we obtain $b_{0,0}$ as function of p:

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W_{min}+1) + pW_{min}(1-(2p)^m)}$$

$$\pi = \frac{b_{0,0}}{1-p} = \frac{2}{1 + W_{min} + pW_{min}\sum_{k=0}^{m-1}(2p)^k}$$

- ▷ **Saturation throughput**: average information payload transmitted in a slot time over the average duration of a slot time:

$$\tau = \frac{P_s P_{tr} L}{P_s P_{tr} T_s + P_{tr}(1 - P_s)T_c + (1 - P_{tr})T_{id}}$$

with

$$P_{tr} + 1 - (1 - \pi)^N \text{ and } P_s = \frac{N\pi(1-\pi)^{N-1}}{1 - (1-\pi)^N}$$

T_{id}: duration of the idle period, T_c: average time spent in collision, T_s: average time needed to transmit a packet of size L

4 Scheduling

4.1 Reservation-based access protocol w/ centr. sched.

- ▷ Most used access protocol in wireless cellular networks
- ▷ High efficiency and flexibility in managing wireless resources.
- ▷ **Physical Downlink Control Channel (PDCCH)**: → conveys control information for each user.
- ▷ **Physical Downlink Shared Channel (PDSCH)**: → multiplex the data of all terminals.
- ▷ Reservation phase: PDCCH. Data phase: PDSCH
- ▷ During the reservation phase, one can estimate channel and adapt scheduling in consenquence.
- ▷ Wireless scheduling suffers from **supporting a mix of classes** of traffic desiring different QoS.
  - ▷ Conversational: Preserve time relation.
  - ▷ Streaming: Preserve time relation
  - ▷ Interactive: Request response pattern, preserve payload
  - ▷ Background: Destination is not expecting data within a certain time, preserve payload
- ▷ **Channel Variation**: Channel is unstable, hard to predict, capacity of the link varies w.r.t. time and locations.
- ▷ Difficult to estimate the amount of resources needed. Thus, it is needed to use an adaptive procedure to assure QoS.
- ▷ For M uplink users, the sum of the data rates is bounded

$$\sum_{i=1}^{M} r_i \leq W \log_2\left(1 + \frac{\sum_i P_i g_{i0}}{N_0 W}\right)$$

with W: frequency bandwidth, P_i: transmission power, g_{i0}: power gain of the channel and N_0: noise spectral density

- ▷ In the downlink, the base station sends independent data streams to multiple users.
- ▷ Assuming $g_{01} \leq g_{02} \leq \ldots$, the capacity region is:

$$r_m \leq W \log_2\left(1 + \frac{P_m g_{0m}}{\sum_{i=m+1}^{M} P_i g_{0m} + N_0 W}\right), \forall m$$

4.2 Wireless Packet Scheduling Algorithms

- ▷ Increase flexibility in adaptation to QoS and channel
- ▷ Significant performance improvement
- ▷ Model contains M users served on a single channel, TDMA; each user has a buffer to store the packets to be sent.
- ▷ Queue modeling: At timeslot t, queue of user i updates:

$$q_i[t+1] = q_i[t] + d_i[t] - n_i[t]$$

$d_i[t]$: new bits arriving, $n_i[t]$: # bits scheduled to transmit

S_i: long-run throughput for user i can be predicted using

$$\hat{S}_i[t] = (1 - \frac{1}{\tau})S_i[t-1] + \frac{1}{\tau}\hat{r}_i[t]I[i]$$

where $\tau >> 1$ scheduler's constant, $\hat{r}_i$: expected data rate

4.2.1 Round-robin scheduling

- ▷ One of the simplest scheduling algorithms
- ▷ Users are scheduled in round robin
- ▷ All users scheduled the same amount of resources

4.2.2 Max throughput scheduling

- ▷ Schedule the minimal in each time slot → total network throughput is maximized.
- ▷ Most aggressive packet scheduler
- \- unfairness and coverage limitations. i.e. terminals in unfavorable positions may never be served.

4.2.3 Proportional Fair Scheduling

- ▷ Compromised policy to balance the competing interests of maximizing total network throughput and providing all terminals with at least a minimum level of service.
- ▷ Meets the **Proportioanl fairness criterion** → When the scheduling result is already proportional fair, changing the scheduling such that the throughput of any user is increased by a percentage, the cumulative decrease of the throughputs of the other users will be higher.

4.2.4 Max-Min Scheduling

- ▷ Objective: maximize the minimum user throughput
- ▷ Scheduling result is max-min fair iff increase of thrghput of one user results in decrease of a user with a smaller thrghput

4.2.5 Max Utility Scheduling

- ▷ All previous schedulers do not consider QoS
- ▷ Utility ≡ satisfaction of each user given allocated resources
- ▷ Model the QoS perception of users
- ▷ Objective: maximize the sum utility of all users

$$\max \sum_{i=0}^{M-1} U_i(S_i)$$

- ▷ Utility function determined based on traffic characteristics
- ▷ Different utility functions can be designed:
  - ▷ Max-throughput: $U_i(S_i) = S_i$
  - ▷ Proportional fair: $U_i(S_i) = \ln(S_i)$
  - ▷ **Alpha Fair Utility**: Contains a parameter a which mesures how fair the scheduler is. Get max throughtput when $a = 1$ and is propotional fair when $a = 0$

$$U_\alpha(S) = \begin{cases} \frac{S^{1-\alpha}}{1-\alpha} & \alpha \geq 0 \text{ and } \neq 1 \\ \ln(S) & \alpha = 0 \end{cases}$$

4.2.6 Scheduling in OFDMA Systems

- One more dimension of resources: subcarrier allocation
- Different users experience: different gains because of frequency selectivity in channels
- Scheduling of subcarriers in an adaptive way based on the instantaneous channel qualities.
- Use adaptive subcarrier assignment, power allocation, modulation and coding to exploit the diversity in multiple users and frequency to improve the network performance.
- Usually combined w/ modulation and coding to improve perf.
- Additional signal overhead is necessary so the base station can inform all users the resource allocation results
- Round-robin, max-throughput, PF, max-min and max-utility scheduling can all be done for OFDMA
- **Power adaptation**: Each subcarrier should be assigned to the user with the highest Y (ratio between the channel gain and the interference) as the rate increase by using any amoung of power on any subcarrier will be maximized if the subcarrier has the hightest Y.
- Scheduling in OFDMA is usually based on optimization techniques to compute how much power should be used on each subcarrier. Generally no closed-form expressions.
- Expected overall throughput

$$R[t] = \sum_{i=1}^{M} R_i[t] = \sum_i \sum_j W \log_2 \left(1 + \frac{p_{ij}[t] y_{ij}[t]}{\theta}\right) \underbrace{I(i,j)}_{\text{assignement}}$$

$y_{ij}[i]$: ratio between channel gain and interference

- Without power adaptation (max-thrput)

$$I^*(i,j) = \begin{cases} 1 & \frac{p_{ij}[t] y_{ij}[t]}{\theta} \geq \frac{p_{mj}[t] y_{mj}[t]}{\theta}, \forall m \\ 0 & \text{otherwise} \end{cases}$$

- With power adaptation (max-thrput)

$$I^*(i,j) = \begin{cases} 1 & y_{ij}[t] \geq y_{mj}[t], \forall m \\ 0 & \text{otherwise} \end{cases}$$

- Base station defines power allocation p_{ij} to maximize thrput

5 Principles of cellular systems

- Cellular networks contain a set of fixed base stations
- Signal power decreasing with the distance → terminals connect to the closest base station

$$SNR = \frac{c_t P_t}{r^\alpha N}$$

r: distance, c_t: antenna constant, α: propagation constant

- Considering **shadow fading** → received SNR becomes random - G lognormal distribution. To preserve the same cell coverage area, need an extra **fade margin** M at the transmitter

$$P\left(\frac{c_t G P_t M}{r^\alpha N} \leq y_0\right) \leq p_{out}$$

- W/ known radius, # cells required to cover the service area is the ratio between total area and cell area.
- The **decibel**: dimensionless unit → power ratio. Express the magn. of a physical quantity relative to a reference level
- A value expressed in dB is computed as

$$10 \log_{10}(P/P_{\text{ref}})$$

- **Capacity of a wireless network (or radio capacity)** is measured as the average number of simultaneous radio links supported by the system.
- **Area capacity**: # users per cell per unit area ratio.

$$\text{area capacity} = (C/(KA_{\text{cell}})) \tag{1}$$

- Trade off between quality (SINR) and capacity in the network → i.e.: with large clusters, the reuse distance is larger and thus the quality of the connections is increased
- Queueing modelling: **Blocking probability**

$$P_{block} = \frac{\rho^\eta/\eta!}{\sum_{k=0}^{\eta} \rho^\eta/k!}, \rho = \frac{\lambda}{\mu}$$

- Outage probability ≡ average over the pdfs of t
- # assignment failures in a network with n channels, M mobiles is given by $Z = max(0, M-n) + Q$ with Q: # mobiles having a channel but bad SINR
- **Assignment failure rate**:

$$v_p = \frac{E[Z]}{E[M_c]} = \sum_{k=\eta}^{\infty} (k-\eta) \frac{(\omega A_c)^{k-1}}{k!} e^{-\omega A_c}$$

ω the number of calls (Poisson distributed) per unit area

- **Relative traffic load**:

$$\bar{\omega}_\eta = \frac{\omega A_c}{\eta}$$

- The system capacity can also be defined in terms of a combined blocking and signal outage, or **Grade of Service**

Other facts:

- Cellular networks are based on efficient spectrum reuse
- Directional antennas reduce interference, improve coverage
- Cell capacity depends on the cell size
- Small cells → better capacity
- Fading reduces the capacity of wireless networks

5.1 Coverage planning

- **Connection region** of a base station is the geometrical region where the received signal power from that base station is larger that from any other base station.
- **Coverage area** of each base station ≡ **cell**.
- **Coverage planning problem**: find the required number of base s to be used with the servie area
- Common model used is uniform hexagonal-shaped areas
- It is pretty easy to compute the radius of the cells and # of cells required to cover the service area
- channels / cells: C available channels, K groups

$$\eta = \left\lfloor \frac{C}{K} \right\rfloor$$

- **Normalized reuse distance**

$$\frac{D}{R} = \sqrt{3K}$$

with R the radius, D distance between cells

5.2 Frequency Planning

- SINR at any receiver located in cell k

$$\Gamma_k = \frac{c \frac{P_t}{r^\alpha}}{\sum_{i=1 \dots B} \frac{c P_t}{d_i^\alpha} + N}$$

5.3 Static channel allocation

- # simultaneous connections within the service area is often larger that # orthogonal waveforms. → usefull to reuse same frequency within the service area as often as possible
- The higher the propagation loss as a function of distance, the more often we can reuse the spectrum
- **Reuse distance** is the minimum physical distance between two transmitters using the same waveform, required to achieve a certain link quality
- In **Fixed channel allocation (FCA)**, each access port is assigned a certain fixed number of channels. This allocation is achieved by dividing the C available channels into K (reuse factor) groups (clusters) of equal size. The access port has the right to use these channels freely to communicate with its terminals, but cannot use any channel from another group.
- To maintain a sufficiently high SINR, the channels in a group cannot be reused in a cell that is too close to the first cell

5.4 Best-effort data services

- **bandwidth** of each channel: $W = W_s/K$ with W_s the total bandwidth
- **Instantaneous data rate** within a cell at distance $d = D/D_0$ from the base station

$$R(d) = \min(R_{max}, cW \log_2(1 + \Gamma(d)))$$

with D_0 the radius of the cell and $\Gamma(d) = \frac{\Gamma(D_0)}{d^\alpha}$

- The data rate at the center of the cell is limited by peak rate R_{max}

5.5 Directional antennas and sectorizations

- directional receiving antenna → reduce interference → ↓ the number of base station sites → ↓ infrastructure costs

6 More on cellular networks

6.1 Capacity of CDMA Cellular Networks

- Techniques to reduces interference:
  - Multi-sectorized antennas
  - Discontinuous transmission mode
- **Power Control**: for a single cell, all uplink signals should be received ≈ with the same power at the base station
- **Pilot signal**: transmitted by the base station: used by each mobile to set its own power
- Average energy per bit, compared to noise power density:

$$\left(\frac{E_b}{I_0}\right)_i = \frac{W}{R} \frac{G_{ii} P_i}{\sum_{k \neq i} G_{ki} P_k} + N_0 W = \frac{W}{T} \Gamma_i$$

with $R = 1/T_s$: data rate, W: interference bandwidth, N_0: additive noise power density.

- single cell case:

$$SNR = \frac{S}{(N-1)S} = \frac{1}{N-1}$$

with S: power from single user, N: # users

- bit energy to noise ratio

$$\frac{E_b}{N_0} = \frac{S/R}{(N-1)(S/W)} = \frac{W/R}{N-1}$$

with W:available bandwith, R: bitrate, N_0: noise spectral density

- taking thermal noise η into account

$$\frac{E_b}{N_0} = \frac{W/R}{(N-1) + (\eta/S)} \Rightarrow N = 1 + \frac{W/R}{E_b/N_0} - (\eta/S)$$

- To increase this number, switch off user while not talking and antenna sectorization:

$$\frac{E_b}{N_0} = \frac{W/R}{(N_s - 1)\delta + (\eta/S)} \Rightarrow N_s = 1 + \delta \left[\frac{W/R}{E_b/N_0}\right]$$

with N_s: # users per sector

6.2 Femtocells

- Home base stations for mobile networks
- Licensed spectrum, low-power, low-range, better thrghput, better coverage, ...
- Susceptible to security attacks

6.3 Frequency management

- In all countries of the world, the licensed spectrum is managed by the government and leased to private operators
- Auction or beauty contest based on very detailed dossiers
- Currently trying to allocate more frequencies for more bandwidth in mobile communication → a new total auction
- Mobile network is doubling every 9-12 mounths.
- Auctions is a transparent procedure and let the market determines the value of frequencies
- With auction of small frequency blocks, the market decides on the scope of the licences
- More rules to prevent people to abuse the auction

7 Association and Handover

- To each active terminal, in order to maximize system utility, we need to assign transmit power, waveform, base station
- Association on the move : **handover**

7.1 Mobility management

- *While inactive*: track the location of the terminal and wake it up when necessary (e.g. to update location area)
- *While connected*: handover → timely selection of base stations based on signal quality measurements.

7.2 Handover types

- **Involved networks**
  - Horizontal handover: within a single network of homogeneous radio access technology (RAT)
  - Vertical handover: between different networks, heterogeneous RATs
- **Hard handover**: only one base stations serving at a time
- **Soft handover**: multiple base stations can simultaneously serve a mobile terminal. Can lead to a better usage of radio resources, at the expense of higher complexity

7.3 Handover phases

1. Measurement and decision
2. Resource management
3. Execution (handshaking)

7.4 Performance metric

- Handover failure probability
  - Handover attempts fail
  - Prob. that signal quality is below the required value
- Handover frequency

7.5 Handover decision criteria

- Received signal strength (cell boudaries)
- Signal to interference ratio

7.6 Handover resource management

- Resource reservation for handover
- Protection of ongoing services is more important than accepting new services
- Its significance depends on delay tolerance of the service

7.7 Handover execution

- System and mobile should reach agreement on which base station to pass, which waveform, authentification, ...
- Procedure has to be fast and reliable

7.8 Load balancing

- Traffic load fluctuates a lot over time
- neighbor cell may have much lighter load at the moment

8 F-Transport

8.1 Reminder TCP

- Reliable, in-order packets delivery
- Single path
- Congestion avoidance and control
- Three-way handshake
- Lost packet detection using sequence numbers and ACKs

Nowadays, hosts have several interfaces, or multiple addresses for a single interface. Addresses of mobile hosts can change as they move from one network to another. Current TCP is not designed to switch between interfaces as they come and go.
Link aggregation: combine multiple channels at different frequencies and use different radio technologies into a single link

8.2 Multipath TCP (MPTCP)

MPTCP is a modification of TCP presenting regular TCP interfaces to applications, spreading data across several TCP subflows. Achieve higher throughput, failover from one path to another and seamless mobility.

- First establish the intial subflow
- Then additional subflows can be established
- At least one of those need to differe between two subflows: Local IP, Remote IP, Local Port, Remote Port
- Use two levels of sequence numbers to prevent gaps in seq.
- Dseq: data sequence number (SQN) and seq is the additional SQN carried inside the TCP option. It ensures that the segments sent on any given subflow have consecutive SQNs.
- On linux, upon timeout expiration, re-evaluate whether packet could be retransmitted over another subflow
- Upon loss of a subflow, all the unacknowledged data are retransmitted on other subflows

8.2.1 MPTCP Congestion Control

- Each path runs its own congestion control, detect, respond
- MPTCP send all its traffic on its least-congested paths
- Users get at least as much thrghput as w/ single-path TCP

8.2.2 MPTCP Congestion Control Algorithm

- A connection consits of a set of subflows R
- Each subflow maintains a congestion window
- Specific rules on how to increase and decrease the windows
- Still experimental, but largely deployed on smartphones

9 Wireless Network Security

- In wireless networks, sending and receiving messages do not need physical access to the network
- Wireless communications have a broadcast nature, therefore, transmissions can be overheard by anyone in range
- Easy to, eavesdrop, replay messages, jamming, ...
- Security requirements
  - Confidentiality: use encrypted messages
  - Authenticity: origin of the message must be verified
  - Replay detection
  - Integrity: messages stay un-modified
  - Access control: access provided only to legitimate entities
  - Protection against jamming

9.1 Cellular Network Security

9.1.1 GSM (2G) - Global System for Mobile com.

- Provides subscriber authentication
- Uses long-term secret key to generate session keys
- Provides protection of the subscriber's identity from eavesdroppers
- Provides confidentiality of communications
- User devices have SIM card (Subscriber Identity Module)
  - Allows to authenticate on the network
  - Contains a secret key
  - Encrypted with a PIN (Personal Identification Number)
  - User permanent identity, **IMSI** (International Mobile Subscriber Identity)
  - If possible don't use IMSI but temporary TMSI
- weaknesses:
  - Unilateral authentication → fake base station can pretend to be legitimate network
  - No security within the wired network
  - Uses 1st generation of cryptography
  - SIM cloning

9.1.2 UMTS (3G) - Universal Mobile Telecom. Systems

- Provides protection against false base stations
- Key lengths were increased → stronger encryption
- Security mechanism within the networks
- However no end-to-end encryption

9.1.3 LTE (4G) - Long Term Evolution

- Even more secure
- Completely IP-based
- Security principles:
  - Permanent security association with home network
  - New key hierarchy
  - Reciprocal authentication mechanisms
  - Trusted environment (in isolation from the OS)
  - DoS protection of the network
  - User privacy
  - Authorization required for connection to core networks

9.1.4 WEP - Wired Equivalent Privacy

- Before association, the station needs to authenticate itself
- Default key is manually installed in every station and the AP
- Default keys need to be changed when a member leaves the group, practically impossible to change in every device simultaneously
- hence, supports **multiple default keys**: message header contains a key ID, tells which key should be used for decryption
- Weaknesses:
  - Authentication is one-way only
  - Same key is used for authentication and encryption
  - No session key is established during authentication
  - No replay messages protection
  - Broken authentication protocol

9.1.5 WPA/WPA2 - WiFi Protected Access

- Authentication process results in a shared session key
- Different functions use different keys
- Integrity protection is improved
- Weaknesses:
  - Weak passwords
  - TKIP (encryption algo) has been broken
  - PIN can be bruteforced easily in 2 hours

9.1.6 Wireless Pairings

- Used when there is no central authority distributing keys
- Devices pair by themselves and set up keys
- Use symmetric key techniques or Diffie-Hellman

9.1.7 Diffie-Hellman Protocol

- Enables secret key establishment in cleartext
- Fully resits passive attackers
- Not secure against active attackers, hence need authentication
- Based on the discrete logarithm problem:
  - A generates a, computes and send ($g^a \mod p$). B generates b, computes and send ($g^b \mod p$). They can both generate the key
    $$k = (g^b \mod p)^a = (g^a \mod p)^b$$
    with p a prime number and g a generator of Z_p^*

9.1.8 Other techniques

- **Short String Comparison**: Display hash of the key on the screen, visually compare
- **Seeing is Believing**: Uses optical channel (in which impossible to perform MitM attack) to validate key exchange.
- **Loud and Clear**: Human-assisted string comparison using voice communication
- **Shake Them Up**: Rely on the fact that the attacker does not know which device transmits at which time
- **Integrity Regions**: Distance-bounding protocols (proved that devices are at most at X cm from each others)

9.1.9 In practice

- Bluetooths's device pairing aims at creating one shared secret called the Link Key. This key is used both for authentication and encryption. Uses a PIN-based protocol called **Link Manager Protocol (LMP)**
- **Sound-Proof**: Sense ambient audio to verify proximity of the two devices

10 Privacy in Mobile Network

- **Privacy control**: ability of individuals to determine when, how, and to what extend information about themselves is revealed to others
- **Anonymity**: hiding who performed a given action
- **Untraceability**: making difficult for adversary to identify that given actions were performed by the same subject
- **Unlinkability**: hiding relationships between any item
- **Unobservability**: hiding of the items themselves
- **Pseudonymity**: use of a pseudo instead of real identity
- **Anonymity set**: subjects that might performed the action
- **Privacy metrics**:
  - **Anonymity set**: set of subjects that mights have performed the action
  - Measure of anonymity:
    $$-\sum_{\forall x \in A} p_x \log p_x$$
    A: anonymity set, p_x: prob. that x performed the action
  - Measure of unlinkability
    $$-\sum_{\forall R \subseteq I_1 \times I_2} p_r \log p_r$$
    p_r: prob real relationship between elements in I_1 and I_2
  - Measure of certainty:
    $$-\sum_{v \in V} p_v \log p_v$$
    V: set of possible values, p_v: prob that the value is v for a given user

10.1 Location privacy

- With location-based services, users upload location episodically on network
- Use pseudo is a solution for the location privacy problem
- However changing pseudo at each timestamp is ineffective against a global eavesdropper (can predict your next location and infer the new pseudonym)
- **Mix zone**: unobserved zone where the vehicles change pseudo
- Vehicles do not know where the mix zone is
  $\rightarrow$ need to change pseudo frequently
- **Model of the mix zone**:
  - p_{ij}: prob exiting at j and entering at i
  - D_{ij}: RV representing time that elapses between entering at i exiting at j
  - $d_{ij} = P(D_{ij} = t)$
  - $P($ exit at j at t and enter at i at $\tau) = p_{ij} d_{ij(t-\tau)}$
  - each possible mapping between exit and enter events is represented by a permutation π:
    $$m_\pi = (N_1 <> X_{\pi[1]}, ..., N_k <> X_{\pi[k]})$$
    $$P(m_\pi, \bar{X}|\bar{N}) = \prod_{i=1}^{k} p_{n_i x_{\pi[i]}} d_{n_i x_{\pi[i]}}(t_{\pi[i]} - \tau_i) = q_\pi$$
    $$H(\bar{N}, \bar{X}) = -\sum_\pi \frac{q_\pi}{\sum_{\pi'} q_{\pi'}} \log\left(\frac{q_\pi}{\sum_{\pi'} q_{\pi'}}\right)$$
- **Tracking game**: adversary picks a vehicle in the obeserved zone. When this vehicle enters a mix zone, estimates time to enter other obvesable zones. When a vehicule enter oversable zone, compute probability of vehicle to be the one.
- Level of privacy is the success probability of the adversary
- **Location-Privacy Meter (LPM)**: open source software tool to quantify location privacy
- **Adversary model**: using observation and knowledge such as users' mobility profiles, the adversary can infer location by computing some probability distribution.
- **Inference Attack**: TODO -> uses de-anonymization and de-obfuscation

10.2 IMSI catchers

- **IMSI**: International Mobile Subscriber Identity
- Fake mobile towers acting between the target mobile phone and the service provider's real towers
- Used to track users, eavesdropping calls, geotargeting ads
- Used by law enforcement and intelligence agencies
- Use lack of mutual authentication, lack of encryption in the current mobile network implementations (mainly GSM, 2G)
- We can catch them using the constant parameters broadcasted by the cell towers

11 Hands-On Exercise 1

- **Distributed coordination function (DCF)** is the basic medium access mechanism of IEEE 802.11, and uses a CSMA/CA algorithm.
  - Basic access method: is channel busy, a backoff time is randomly chosen in $[0, CW]$. This timer is decremented by one as long as the channel is sensed idle for a *distributed inter frame space* $DIFS = SIFS + 2 \times SlotTime$. CW is doubled after each unsuccessful transmission. When the backoff timer reaches zero, the source transmits the data packet. The ACK is transmitted by the receiver immediately after a period of time called *short inter frame space* SIFS. When a packet is transmitted, all other stations hearing this transmission adjust their *network allocation vector* NAV, maintaining a prediction of future traffic on the medium.
  - Optional channel access method with *request-to-send* RTS and *clear-to-send* CTS exchanged.
- **Point coordination function (PCF)** is a centralized, polling-based access mechanism which requires the presence of a base station that acts as an access point. An RTS frame should be transmitted by the source and the destination should accept the data transmission by sending CTS frame prior to the transmission of the actual data packet.

Exercices and Exams

HW 1

Ex 1.1

If two channels are mutually exclusive in terms of time, then the capacity of the link is
$$c = \frac{c_1 c_2}{c_1 + c_2}$$

Ex 1.2

For minimum acceptable SIR of 10 dB, with power la distance dependence model, solve the equation
$$\frac{S}{I} = \frac{cP_{t2}/d_2^\alpha}{cP_{t1}/d_{12}^\alpha} \geq 10$$

Ex 1.4

Given a gain matrix G for two access ports and three terminals, apply uplink and downlink formula to compute the different throughputs for the different combination of assignment.

HW 2

Ex 2.1 - Slotted ALOHA

Given arrival rate of packets modeled with a Poisson distribution
$$P(k) = \frac{G^k e^{-G}}{k!}$$
with G the channel load and knowing 94% of the slots idle:

- Compute channel load:
  $$P(0) = e^{-G} = 0.94$$
- Compute throught of the system
  $$S = P(1) = Ge^{-G}$$
- Compute fraction of busy slots
  $$1 - P(0)$$
- Compute fraction of busy slots with collisions amongs busy slots
  $$\frac{1 - P(0) - P(1)}{1 - P(0)}$$
- Calculate peak throughtput
  $$\frac{\delta S}{\delta G} = 0 \rightarrow e^{-G_{peak}} - G_{peak} e^{-G_{peak}} = 0 \Rightarrow S(G_{peak})$$

Ex 2.2

N stations on the same channels, transmit with probability p at each time slot.

- Throughput of the system
  $$S = Np(1-p)^{N-1}$$
- Compute p that maximizes the throughtput
  $$\frac{\delta S}{\delta p} = 0 \rightarrow p = \frac{1}{N}$$

Ex 2.3

Channel operating at 25 Mbps. M workstations at 100 meters aways from the acces point. Polling messages are 64 bytes long and packets are of constant length of 1250 bytes. When no more packets to transmit, notification with a 64-byte message.

- Compute maximum possible arrival rate (packets/secs) if stations are allowed to transmit unlimited number of packets per poll:
  $$\lambda_{max} = \frac{N}{T_{tot}}$$
  with
  $$T_{tot} = N \times T_{packets} + T_{poll} + T_{end} + 2t_{prop}$$
  with N the number of packets allowed to transmit and t_{prop} the propagation time. Given light speed c and distance d
  $$t_{prop} = d/c$$
  Then
  $$N \rightarrow \infty \Rightarrow \lambda_{max} = \frac{1}{T_{packet}}$$

Ex 2.4 - Frame headers - TODO

Ex 2.5 - Timing diagram CSMA-CA - TODO

HW3

Ex 3.2.1 - Network throughput

TDMA system with 4 terminals and data rate R_i.

- Compute throughput with **Max-min scheduling**:
  Try to assigns time slots such that
  $$x_i r_i = x_j r_j$$
  with x_i the percent of the slots and r_i the data rate. Each terminal will have same throughput so its easy to compute the total throughput S.
- Compute throughput with **Round-robin scheduling**:
  Each terminal we be assign the same percent of the slots. Easy to compute S.

Ex 3.2.2

Two terminals scheduled bu prop. faire scheduler. Rates are 64 and 128 kbps. The transmission continues for 2 time slots and $S_1[1] = 64$, $S_2[1] = 128$. The average throughput is update as follow:
$$S_i[t] = (t-1)/t \times S_i[t-1] + 1/t \times \hat{r}_i[t] i[t]$$
Calculate the average throughput of each terminal:
In the first slot
$$i[1] = \arg\max_i\left(\frac{64}{64}, \frac{128}{128}\right) = 1 \text{ or } 2$$
Both terminals can be schedule. Suppose terminal 1 is selected, then update and compute $S_1[2]$, $S_2[2]$. Update
$$i[2] = \arg\max_i\left(\frac{64}{64}, \frac{128}{64}\right) = 2$$
Update and compute $S_1[3]$ and $S_2[3]$.

Ex 3.3 Bianchi model TODO

HW 4 - Principles of Cellular Systems

Ex 4.1

System with C channels and minimum SIR of 19 dB using symmetric hexagonal plan. D is the distance between centers of nearest co-channel cells. R is the radius of a cell. 6 co-channels for each distances $\sqrt{3}D$, $\sqrt{4}D$, ...$\sqrt{(i+j)^2 - ij}D$. Assume propagation model $P_r = cP_t d^\alpha$ and all stations transmi with power P.

- Find expression for co-channel interference on downlink channel:
  $$\Gamma_A = \frac{\frac{cP}{R^\alpha}}{6 \times \left(\frac{cP}{D^\alpha} + \frac{cP}{(\sqrt{3}D)^\alpha} + ...\right)} = \left(\frac{D}{R}\right)^\alpha \frac{1}{6 \times \left(1 + \frac{1}{3^{\alpha/2}} + ...\right)}$$
  The sum at the denominator doesn't converge for $\alpha \Rightarrow \Gamma_A = 0$. In practice $\alpha > 2$ dut to obstables, fading, ...
- Compute the **radio capacity** η of this system for $\alpha = 4$:
  We know that
  $$K = \frac{1}{3}\left(\frac{D}{R}\right)^2$$
  So using the previous result
  $$\Gamma_A = \left(\frac{D}{R}\right)^4 C \geq 10^{1.9} (19dB) \Rightarrow K \geq \sqrt{\frac{10^{1.9}}{9C}}$$
  Also, given the symmetric hexagonal cell plan, K has to satisfy $K = (i+j)^2 - ij$. We can then compute K and η.

Ex 4.2 - Sectoring technique

We only consider the first tier of interferers (distance D). We have $K = 7$ and minimum SIR at 18.45 dB.

- Show that the system satisfies minimum requirement:
  $$\Gamma_A = \left(\frac{D}{R}\right)^4 \frac{1}{6} = \frac{3K^2}{2} > 10^{1.845}$$
- Use directional antennas dividing each cell into three sectors (120'). Compute radio capacity:
  Reduce number of co-channel interferes from 6 to 2. Therefore
  $$\Gamma_A = \left(\frac{D}{R}\right)^4 \frac{1}{2} \geq 10^{1.845} \Rightarrow K = \frac{1}{3}\sqrt{2(\Gamma)} \Rightarrow \eta = \left\lfloor \frac{C}{K} \right\rfloor$$
  The result is nearly twice the capacity of the system with omni-directional antennas.

H5 - Association and Handover

Ex 5.1

Assume straight highway of 8km with traffic density
$$\rho(x) = \begin{cases} x^2 & \text{if } 0 \leq x \leq 2 \\ 4 - \frac{x}{2} & \text{if } 2 \leq x \leq 8 \\ 0 & \text{otherwise} \end{cases}$$
and we are deploying two base stations covering the highway.

- Assume $0 \leq z \leq 2$ (z the handover point), show that we can't distribute traffic load between the two stations:
  Traffic load on both side should be equal: $\lambda_1 = \lambda_2$, we have
  $$\lambda_1 = \int_0^z x^2 \, dx = \lambda_2 = \int_z^2 x^2 \, dx + \int_2^8 \left(4 - \frac{x}{2}\right) dx$$
  Solving this we have $z = 2.6 > 2$.
- Find best location y for the right base station. We want to keep the overall power radiated to a minimum. To estimate the weight of the traffic of all terminals at both sides of the base station, we can integrate the product of the traffic intensity function and the square of the distance from y. We want the weights on both side to be equal.
  $$w_1 = \int_z^y \left(4 - \frac{x}{2}\right)(y-x)^2 \, dx = w_2 \int_y^8 \left(4 - \frac{x}{2}\right)(y-x)^2 \, dx$$

HW 6 - Transport Layer

Ex 6.1 - Sequence numbers in MPTCP

- Why a single sequence space is not enough in MPTCP: Because striping seq numbers across two paths will leave gaps in the sequence space seen on any single path. Some network middleboes will not allow a gap in sequence numbering space.
- TODO - illustration

Ex 6.2 - Congestion control in MPTCP

In MPTCP, connection consists of a set of subflows $r \in R$, with each their own congection window w_r. RTT_r the round trip time on subflow r. For each ACK on subflow r compute
$$\min_{S \subseteq R: r \in S} \frac{\max_{s \in S} w_s / RTT_s^2}{\left(\sum_{s \in S} w_s / RTT_s\right)^2}$$
then find the minimum and increase w_r by that much.
For each loss, decrease $w_r = w_r/2$

- What if each subflow was just running a regular TCP congestion control algorithm: It would be unfaire because MPTCP connections would get much more throughput than single path TCP.
- If only one subflow, behaves like regular TCP (super obvious)

HW 7 - Security

Ex 7.1

- Symmetric-key encryption: confidentiality, Authentication
- Asymmetric-key encryption: Confidentiality
- Hash functions: Data integrity, Authentication
- MACs: Data integrity, Authentication -> hash the data and include it in the message. Reciever can recompute MAC and check data integrity.
- Digital signatures: Data integrity, Authentication, Non-repudiation

Ex 7.2 - Diffie-Hellman

- **Key agreement protocal**: when both participants contribute information to the established key
- If non of the participtans knows the verification algorithm of the other, then an man-in-the-middle attack is possible.
- TODO

Ex 7.3 - GSM security

- In GSM security, why does the mobile station use 2 different keys (user's secret and ciphering key)?:
  Using secret key too often leaks some information about this key. Therefore it uses long-term secret key to generate a session ciphering key and use this new key to encrypt the data.

Ex 7.4

How can a rogue base station establish a session in GSM:
In GSM, only the mobile authenticates to the visited network. The rogue station only needs to reply with a random number after the authentication procedure by sending the IMSI number. Using crypto-analysis, the rogue station could infer the secret key of the mobile (might take a while)

HW 8 - Privacy protection

Consider a mix zone with $n \geq 2$ ports in which the transition probabilities $p_{i,j}$ (exiting at j when entering at i) are $\frac{1}{n}$. At time 0, 2 cars enter the mix-zone at ports 1 and 2 at time t_1 and t_2.

- Quantify the uncertainty of the adversary regarding the mapping between enter and exit event for the folloring distribution of the time spent in the mix-zone:

$$d_{1,1}(t_1) = 0.5, d_{1,2}(t_2) = 0.25, d_{2,1}(t_1) = 0.5, d_{2,2} = 0.5$$

  For event $(1 \to 1, 2 \to 2)$ we have likelihood:

$$p_{1,1}d_{1,1} \times p_{2,2}d_{2,2} = \frac{1}{4n_2}$$

  For event $(1 \to 2, 2 \to 1)$ we have likelihood:

$$p_{1,2}d_{1,2} \times p_{2,1}d_{2,1} = \frac{1}{8n_2}$$

  And the corresponding probabilities $p_1 = 2/3$ and $p_2 = 1/3$. The uncertainty of the adversary is captured by the entropy

$$H = -\frac{1}{3}\log_2\frac{1}{3} = \frac{2}{3}\log_2\frac{2}{3}$$

- Give a condition on the distributions $d_{i,j}$ that maximizes the uncertainty:
  The uncertainty is maximized when the time spent in the mixe zone brings no information about the path.
- Give a condition on the distributions $d_{i,j}$ that minimizes the uncertainty:
  The uncertainty is minimum when the time spehtn in the mix-zone determines with certainty the path.

Exam 2014

Question 2.1

- Express P_{tr}, the prob. that there is at least one transmission in a slot time as functions of π (prob transmission for a station) and N (# stations)

$$P_{tr} = 1 - (1-\pi)^N$$

- Express P_s the cond. prob. of a successful transmission if there is at least one transmission with π and N

$$P_s = \frac{N\pi(1-\pi)^{N-1}}{1-(1-\pi)^N}$$

Question 2.2

Express T_s (average time need to transmit packet of size L) as a function of $L, ACK, DIFS, SIFS, \ldots$ with σ the propagation delay:

- Basic transmission mode (without RTS and CTS):

$$T_s = DIFS + L + \sigma + SIFS + ACK + \sigma$$

- RTS/CTS transmission mode:

$$T_s = DIFS + RTS + \sigma + SIFS + CTS + \sigma + SIFS + L + \sigma + SIFS + ACK + \sigma$$

Question 3

A space craft equipped with a 2 GHz, 10W transmitter is at a distance to earth of $7.5 \cdot 10^9$ km. The receiving earth station has a parabolic antenna with a diamterer D_r. The receiver has a noise temperature T and we assume a free space path loss. Boltzmann's constant is given as k in J/K and the speed of light c.
Calculate the necessary diameter D_t of the space craft's antenna if we want to transmist at a rate R with a E_b/N_0 of 9.88 dB.
Assume the tow antennas have an efficiency of $\eta = 0.5$ and the gain of a parabolic antenna is $G = \eta\frac{\pi^2 D}{\lambda^2}$, where D is the antenna's diameter.
Answer: Let's express

$$\frac{E_b}{N_0} = \frac{P_r}{kTR} = \frac{P_t G_t G_r (\frac{\lambda}{4\pi d})^2}{kTR}$$

where $P + r$ is the received power, P_t is the transmit power, and d is the distance between the antennas. Knowing that $\lambda = c/f$, we get

$$G_t = \eta(\frac{\pi D_t f}{c})^2$$

$$G_r = \eta(\frac{\pi D_r f}{c})^2$$

We obtain

$$\frac{P_t \eta^2 \pi^2 D_r^2 D_t^2 f^2}{16c^2 d^2 kTR} \geq 9.73 \Rightarrow D_t \leq 11.36m$$

Question 4

Plan to cover area A_l with a cellular system. Total number of channels $C = 400$, propagation model follows $P_{rx}(r) = cP_{tx}r^{-\alpha}$. Assume FDMA with minimum acceptable SIR of $15dB$. We only consider first tier of interferes and distance between co-channel base station is equal to D.

- Calculate cluster size N:

$$\frac{S}{I} = \frac{(\sqrt{3N})^\alpha}{6} \geq 15dB \Rightarrow N \geq 5.27$$

  The closest possible cluster size is $N = 7$.
- Compute required number of base stations to cover the whole area:

$$R = \frac{D}{\sqrt{3N}}$$

  Derive surface of each cell and compute required #
- Compute total radio capacity:

$$m = \left\lfloor \frac{C}{N} \right\rfloor$$

Exam 2015

Question 3

Communication system operating a 9 GHz, identical antennas seperated by 10km. To meet the SNR requirement, the received power must be at least $P_r = 10\mu W$ in free space.

- Compute antennas' gain when transmitting power is 10W?
  Answer:

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{G_r G_t \lambda} = \frac{(4\pi d)^2}{G^2(c/f)^2}$$

$$\Rightarrow G[dB] = 10\log(G)$$

- What is the resulting effection radiated power of the transmitted signal?

$$P_t \cdot G_t$$

- Consider now received signal level is $-130dB$ with noise temperature of $1500K$ and Boltzmann's constant k. What is the maximum bit rate at which we can transmit if we want a bit error rate less than 10^{-5} (corresponds to $\frac{E_b}{N_0} = 9.88dB$)
  Answer:

$$\frac{E_b}{N_0} = \frac{S}{kTR}$$

$$\Rightarrow 9.88 = -130 - 10\log(k) - 10\log(T) - 10\log(R)$$

Question 4

System with $C = 100$, $\alpha = 4$ and minimum required SIR is 19 dB.

- Calculate the cluster size N_1:

$$\frac{S}{I} = \frac{(\sqrt{3N_1})^\alpha}{6} \geq 19dB = 80$$

  So we have

$$N_1 \geq 7.28 \Rightarrow N_1 = 9 \text{ to satisfy } N_1 = i^2 + ij + j^2$$

- Calculate radio capacity m:

$$m = \left\lfloor \frac{C}{N_1} \right\rfloor = 11$$

Question 6

- TCP relies on two assumptions that are valid for the wire-line Internet but not for wireless and mobile networks: Packet loss only due to congestion and packet loss is rare.

Exam 2016

Question 1 - Slotted ALOHA

N statsions with probability p of sending a packet. Let X be the random variable denoting the total number of packets emitted in one time slot:

- Compute X:

$$P[X = k] = \binom{N}{k} p^k (1-p)^k$$

- Compute the throughput S:

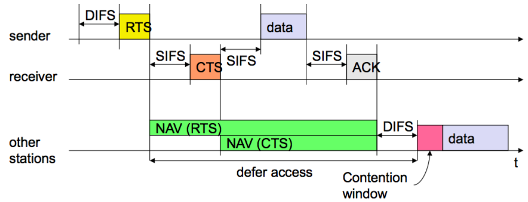
$$S = P[X = 1] = Np(1-p)^{N-1}$$

- Compute p that maximizes the throughput:

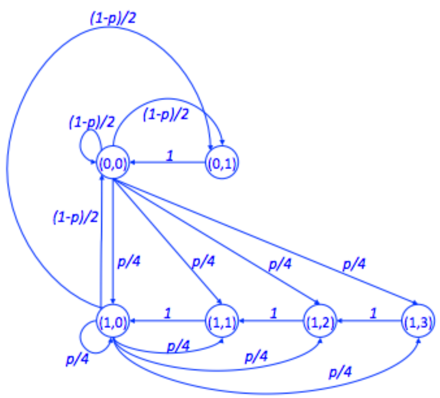
$$\frac{\delta S}{\delta p} = N(1-p)^{N-2} \cdot ((1-p) - p(N-1)) \Rightarrow p = \frac{1}{N}$$

Question 6 - Multipath TCP

- Name 3 benefits introduced by MPTCP
  1. Higher throughput
  2. Failover from over path to another
  3. Seamless mobility



Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	all terminals are active for short periods of time on the same frequency	every terminal has its own frequency, uninterrupted	all terminals can be active at the same place at the same moment, uninterrupted
Signal separation	cell structure, directed antennas	synchronization in the time domain	filtering in the frequency domain	code plus special receivers
Advantages	very simple, increases capacity per km²	established, fully digital, flexible	simple, established, robust	flexible, less frequency planning needed, soft handover
Dis-advantages	inflexible, antennas typically fixed	guard space needed (multipath propagation), synchronization difficult	inflexible, frequencies are a scarce resource	complex receivers, needs more complicated power control for senders
Comment	used in all cellular systems	standard in fixed networks, together with FDMA/SDMA used in many mobile networks	typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)	higher complexity



Bianchi model with 6 steates in total. p denote the probability that collision happens