Cellular Communication

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Cellular Communications

- Performance measure: with limited spectral width support maximum number of users
- Poor signal to interference ratio, higher transmission BER due to channel impairment result in a reduction of usable spectral width
- Parameters: wider spectrum, powerful transmitter, larger geographical coverage, high antenna, cell size, frequency reuse
- Cellular communications: dividing the total large geographical coverage area into many small contiguous area and
- using a low power transmission with low antenna in each small area

Cellular Communications: Terminology

- BS: small area is served by a transmit/receive unit
- user access the base station so called access point (AP)
- radio coverage by one base station is referred to as a cell or called a footprint
- forward channel (downlink) BS to user
- reverse channel (uplink) user to BS
- cells arrangement: square, triangular, hexagonal - no dead spot and no overlap
- due to difference in terrain and population densities, cells are amorphous in nature
- irregular structure or topology result into inefficient and limited growth

Cellular Communications: Other Issues

- support user roaming: continuous operation of an ongoing session and preserve end-to-end QoS; effective and efficient handoff management
- handoff operation: identification of a new base station, allocation of channel to support data and control signal
- MSC having larger computing power handles handoff operation
- MH (MS) is assigned a home network
- MH is identified by address, called home address
- an agent in home network, called home agent keeps track of MH's current location to facilitate delivery of messages destined for MH
- foreign territory and foreign network

Cellular Communications

- as MH migrates away from its home network, the association between MH and its home agent must be maintained so that
- the home agent can keep track of MH's current location for message delivery
- MH has to register with its home agent, through the foreign agent, to let the home agent know its current location
- When MH powers on, it registers with its home agent so when it moves to a foreign network, it has to register with its home agent via foreign agent
- requires association between the home agent and the foreign agent
- home agent needs to ensure the registration process through the foreign agent is the correct MH called as authentication process

Cell Cluster

- forward channel and reverse channel separated in time or in frequency for duplexing
- channel capacity is the total number of channels available which are finite
- also depends on how the available channels are deployed
- reuse for additional traffic and expand the system capacity
- different cells can reuse radio channels if cells are separated and minimum interference between cells; called cochannel cells and cochannel interference
- a group of cells that use a different set of frequencies in each cell is called a cell cluster
- N cluster size (number of cells) and K total number of available channels without frequency reuse

Cell Cluster

- N cells utilize all K available channels
- each cell in the cluster contains one-Nth of the total number of available channels
- N is referred to as the frequency reuse factor of the cellular system
- Let, each cell is allocated J channels and if K channels are divided among the N cells into unique and disjoint channel group $K = JN$
- decrease in the cluster size $N \rightarrow$ increase in the number of channels J per cell; increase capacity per cell
- cluster replicated say M times and C the total number of channels used in the entire cellular system with frequency reuse
- System capacity $C = MJN$

Cell Cluster

- replicate smaller cluster more times to cover the same geographical area with $K = JN$ constant and
- M is increased then C is increased
- when N is minimized, C is maximized
- minimizing N will increase cochannel interference
- Say 1001 radio channel available, area of a cell is
- $A_{cell} = 6\ \text{km}^2$ and the entire system is $A_{sys} = 2100\ \text{km}^2$
- Say if cluster size is $N = 7$ and $K = 1001$; $J = 1001/7 = 143$ channels/cell
- $A_{cluster} = N \times A_{cell} = 7 \times 6 = 42\text{km}^2$ so $M = A_{sys}/A_{cluster} = 2100/42 = 50$
- $C = MJN = 50 \times 143 \times 7 = 50,050$ channels

Cellular System Capacity

- Now, $N = 4$ $A_{cluster} = 4 \times 6 = 24$ km^2
- $M = A_{sys}/A_{cluster} = 2100/24 = 87.5$
- $J = 1001/4 \approx 250$ channels/cell
- Channel capacity $C = 87 \times 250 \times 4 = 87,000$ channels
- $N : 7 \rightarrow 4 \rightarrow M : 50 \rightarrow 87$
- results into $C : 50,050 \rightarrow 87,000$ channels
- decreasing the cluster size does increase the system capacity

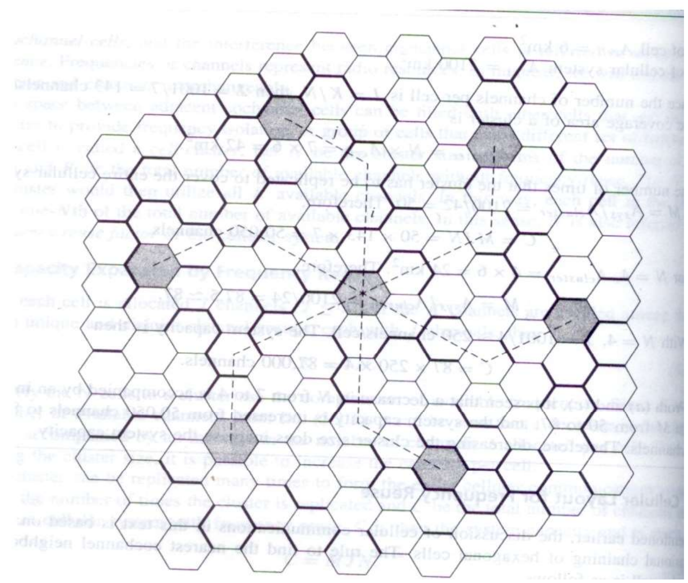
Increasing System Capacity

- cell splitting is another concept
- when traffic density starts to build up, frequency channels in cell no enough to support calls
- original cell split into smaller cells
- new radius is one half the original radius
- new cell area is one fourth the original cell area
- each new cell carry the same maximum traffic load of the old cell then
- in theory new traffic load/unit area = 4 x traffic load/unit area
- permanent splitting - installation of every new split cell to be planned
- number of channels, transmitted power, assigned frequencies, traffic load consideration
- dynamic splitting - based on using allocated spectrum efficiency in real time
- traffic jams at stadium, accidents, small cell sites to increase traffic capacity

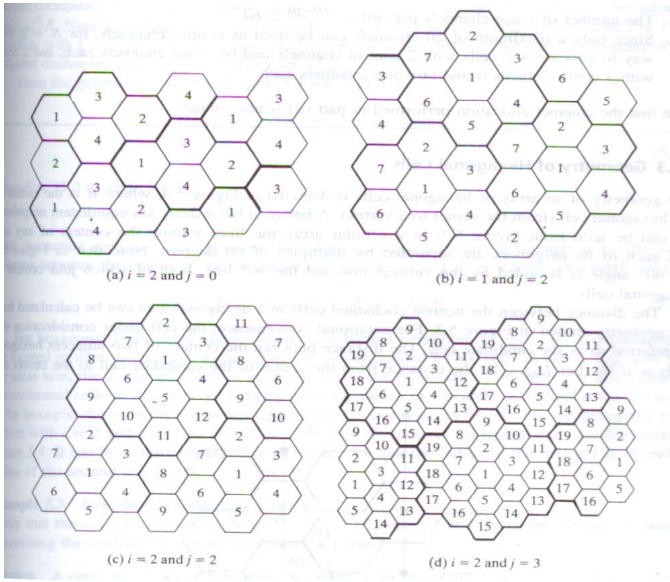
Cellular Layout for Frequency Reuse

- Rule for determining the nearest Cochannel neighbors
  - Move i cells along any chain of hexagons
  - Turn 60 degrees counterclockwise and move j cells
- each cell is numbered and cells with the same number use the same set of frequencies (Co-channel cells)
- must be separated by a distance such that the cochannel interference is below a prescribed QoS threshold
- i and j measure the number of nearest neighbors between cochannel cells; the cluster size $N = i^2 + ij + j^2$
- with $i = 1$ and $j = 2$, $N = 7$, *i.e*, the frequency reuse factor is $N = 7$ since
- each cell contains one-seventh of the total number of available channels

Cellular Layout for Frequency Reuse



Cellular Layout for Frequency Reuse



- feature: low power transmitter and frequency reuse
- distance between cochannel cells increase, cochannel interference will decrease
- Example: bandwidth 30 MHz, uses two 25 kHz simplex channels for fullduplex voice and control channels
- $N = 9$ and 1 MHz of total bandwidth for control channels
- Channel bandwidth $= 50$ kHz/duplex channel
- number of available channels $= 30000/50 = 600$
- number of control channels $= 1000/50 = 20$
- number of voice channels per cell $= (600 - 20)/9 \approx 64$
- 7 cells with 2 control channels, 64 voice channels
- 2 cells with 3 control channels, 66 voice channels

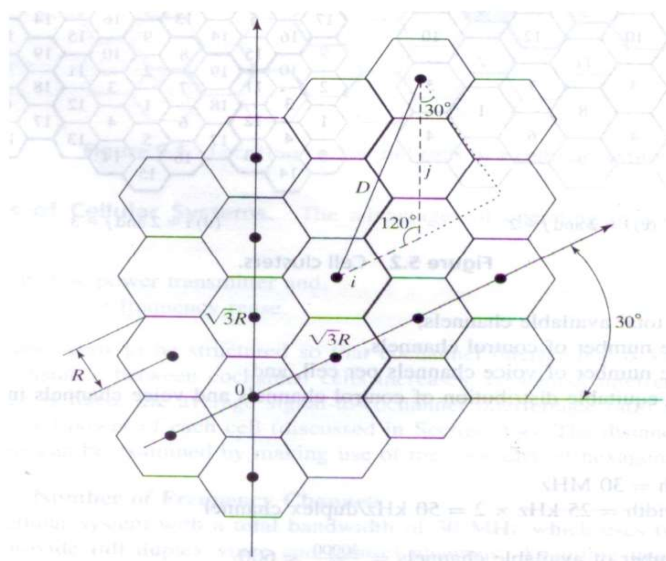
Hexagonal Cells

- R radius of hexagonal cell
- in a cellular array the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees
- distance between the centers of two adjacent hexagonal cells is $\sqrt{3}R$
- D_{norm} distance from the center of the candidate cell (cell under consideration) to the center of a nearest cochannel cell,
- normalized with respect to the distance between the centers of two adjacent cells, $\sqrt{3}R$
- normalized distance between two adjacent cells ($i = 1, j = 0$ or $i = 0, j = 1$) is unity
- D actual distance between the centers of two adjacent cochannel cells

$$D_{norm}^2 = j^2 \cos^2(30^\circ) + (i + j\sin(30^\circ))^2 = i^2 + j^2 + ij$$

- $D_{norm} = \sqrt{N}$ and $D = D_{norm} \times \sqrt{3}R = \sqrt{3N}R$

Cellular Layout for Co-channel Cell Location



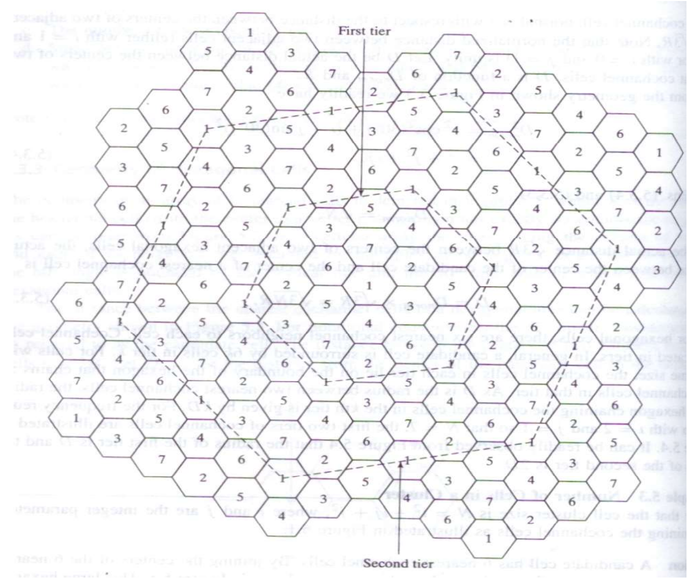
Cochannel Cells

- six nearest cochannel neighbors to each cell
- cochannel cells are located in tiers
- a candidate cell is surrounded by $6k$ cells in tier k
- cochannel cells in each tier lie on the boundary of the hexagon that chains all the cochannel cells in that tier
- D is the radius between two nearest cochannel cells, the radius of the hexagon chaining the cochannel cells in the kth tier is given by kD
- candidate cell has 6 nearest cochannel cells, join the centers of the 6 nearest neighboring cochannel cells gives large hexagon having radius D, is also cochannel cell separation

$$D = \sqrt{3}RD_{norm} = \sqrt{3(i^2 + ij + j^2)}R$$

- area of hexagon is proportional to square of its radius
- $A_{large} = \beta D^2$ and $A_{small} = \beta R^2$

Cochannel Cells



Frequency Reuse Ratio

- number of cells in the large hexagon $= 3(i^2 + ij + j^2)$
- from geometry, the large hexagon encloses the center cluster of N cells plus $1/3$ the number of the cells associated with six other peripheral large hexagons
- the total number of cells enclosed by the large hexagon is $N + 6\left(\frac{1}{3}N\right) = 3N$, *i.e.* $N = i^2 + ij + j^2$
- *frequency reuse ratio* $q \triangleq \frac{D}{R} = \sqrt{3N}$ *(cochannel reuse ratio)*
- *for example,* $(i, j) = (1, 1)$ $N = 3$ $q = 3.0$
- *q increases with N, a smaller value of N has the effect of increasing the capacity of the cellular system but increases cochannel interference*

Cochannel and Adjacent Channel Interference

- base station capacity: handle the services of many mobile users
- interference from transmission of other mobiles in the same cell, background noise, and interference from transmissions by mobiles in neighboring cells
- time domain or frequency domain separation between uplink and downlink transmission, interference from transmissions in the other link can be neglected
- interference from other mobiles at the cell-site receiver in the same cell is intracell interference
- interference from other cells is intercell interference
- intercell interference in the downlink affects the reception at the individual mobile hosts, may be more problem, than uplink interference at the base station (cell-site receiver)

Cochannel Channel Interference

- tradeoff: use of different sets of frequencies intercell interference is minimum, system capacity limited
- frequency reuse, system capacity increased
- cochannel interference should be at an acceptable level
- intercell interference dominated by cochannel interference
- Cochannel Interference
  - S power of the desired signal and I power of the cochannel interference at the output of the receiver demodulator
  - N_I number of cochannel interfering cells and I_i interference power caused by transmission from the ith interfering cochannel cell base station

Cochannel Channel Interference

- signal-to-cochannel interference ratio S/I at the desired mobile receiver
$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{N_I} I_i}$$
- average received received signal strength at any point decays as a power law of the distance between the transmitter and receiver
- D_i distance between the ith interferer and the mobile
- received interference, I_i at a given mobile due to the ith interfering cell is proportional to $(D_i)^{-\kappa}$, κ is the path loss exponent (determined by measurement, $2 \leq \kappa \leq 5$)
- desired received signal power S is proportional to $r^{-\kappa}$, r distance between the mobile and the serving base station

Cochannel Channel Interference

- if transmit powers from all base stations are equal and the path loss exponent is the same throughout the geographical coverage area, the cochannel interference the ith cochannel cell I_i $(\forall i)$, depends on D_i and κ
$$\frac{S}{I} = \frac{r^{-\kappa}}{\sum_{i=1}^{N_I} D_i^{-\kappa}}$$
- with hexagon shaped cellular system, 6 cochannel interfering cells in the first tier
- $N_I = 6$ neglecting second and higher tiers
- $r = R$ if mobile is located at the cell boundary and $D_i = D$

$$\frac{(D/R)^\kappa}{N_I} = \frac{q^\kappa}{N_I} = \frac{(\sqrt{3N})^\kappa}{N_I}$$

$$q = \left(N_I \times \frac{S}{I}\right)^{1/\kappa} = \left(6 \times \frac{S}{I}\right)^{1/\kappa}$$

Cochannel Channel Interference

- $S/I = 18$ dB, $\kappa = 4$, then
$$q = (6 \times 10^{1.8})^{1/4} \simeq 4.41 \text{ and } N = q^2/3 = 6.49 \simeq 7$$
- $S/I = 20$ dB, $\kappa = 4$, $q = (6 \times 100)^{1/4} = 4.9492 \rightarrow N = 8.165 \simeq 9$
- with $q = D/R$, given R; D can be determined and vice versa
- worst case - mobile at the cell boundary
$$\frac{S}{I} = \frac{R^{-\kappa}}{2(D-R)^{-\kappa} + 2D^{-\kappa} + 2(D+R)^{-\kappa}}$$
- $D/R = q, \kappa = 4$
$$\frac{S}{I} = \frac{1}{2(q-1)^{-4} + 2q^{-4} + 2(q+1)^{-4}}$$

Cochannel Channel Interference

- For a cellular system that requires S/I 18 dB
- $N = 7$ $q = \sqrt{3N} = 4.6$ $\kappa = 4$ worst case $\frac{S}{I} = 17.3$ dB
- to increase S/I, decrease I, can be achieved by increasing the frequency reuse factor N
- $N = 9$ $q = 5.20$ and $S/I = 19.8$ dB
- increase in N result into decrease in system capacity (9-cell reuse offers a spectrum utilization of 1/9 within each cell)
- Adjacent Channel Interference (ACI)
  - due to imperfect receiver filter; allows nearby frequencies to leak into the passband
  - near-far effect significantly increase ACI

Adjacent Channel Interference

- to reduce ACI
  - use modulation schemes which have low out-of-band radiation
  - carefully design the bandpass filter at the receiver front end
  - use proper channel interleaving by assigning adjacent channels to different cells
  - avoid using adjacent channels in adjacent cells
  - separate the uplink and downlink by TDD or FDD
- Signal-to-interference ratio determines the transmission bit error rate
- for a user: QoS is more than an acceptable transmission accuracy

Call Blocking

- two aspects
  - how successfully can a new user get a connection established?
  - after connection establishment, how successfully will the connection be maintained as the user moves from one cell to another?
- first aspect refers to the admission of new calls
- second aspect refers to the admission of handoff calls
- performance measure is the probability that a call (new or handoff) is blocked
- to find probability of call blocking, say radio cell has been allocated J channels having large population size of mobile users in the cell
- during connection time each user occupies one channel
- if number of active user during any epoch equals J, all channels will be occupied then with probability 1, a call will be blocked (denied)

Call Blocking

- if number of ongoing calls is fewer than J, a call will be blocked with probability smaller than 1, *i.e.*, to condition that the trunk traffic load in Erlangs is less than J
- One Erlang represents the amount of traffic load carried by a channel that is completely occupied, one call-hour per hour
- if channel is busy for 30 minutes during a one hour period, then the channel is said to carry 0.5 Erlangs of traffic
- Offered traffic refers to the amount of traffic sent by the users and carried traffic refers to the amount of traffic served
- say, base station (cell-site) bufferless system, no buffer, blocked calls are lost
- L users in the system

Arrival Rate and Service Time Modelling

- aggregate arrival traffic is Poisson distributed with rate λ
- duration of a call is exponentially distributed with parameter μ_1
- residence time of each user in a cell is exponentially distributed with parameter μ_2
- exponential random variable is memoryless
- the channel holding time is minimum of the call duration and the cell residence time, is also exponentially distributed with parameter $\mu = \mu_1 + \mu_2$ (mean channel holding time of call)
- it is corresponding to a mean service rate of μ for the call
- the service time of each of the servers is also exponentially distributed
- with Poisson arrival and exponential service times, the underlying queueing process is Markovian

Arrival Rate and Service Time Modelling

- base station (cell-site) receiver modeled as J-server system and each server serves traffic at a mean rate μ
- J-server system for a population of size L and aggregate arrival rate λ
- when system is in state j ($j = 0, 1, \ldots, J$), there are j ongoing calls and j servers, each with mean service rate μ are being engaged
- if system is in state $j = J$, all J servers are engaged and new requests will be blocked
- if $L \leq J$ than no blocking

Bernoulli Trials

- Random experiments has two possible outcomes, success and failure and respective probability p and q with $p + q = 1$
- Sequence of n independent experiment - sequence of Bernoulli trials
- S_n sample space of an experiment, $S_n - \{2^n$ tuples of 0's and 1's$\}$
- the probability of obtaining exactly k successes in n trials

$$p(k) = \binom{n}{k} p^k q^{n-k} \quad k = 0, 1, \ldots, n$$

$$\sum_{k=0}^{n} \binom{n}{k} p^k q^{n-k} = (p+q)^n = 1$$

Arrival Rate: Poisson distribution

- arrival of jobs to a computing center for the time interval $[0, t]$
- interval divided into n subintervals of very short duration $\delta = t/n$
- the probability of more than one event occurrence in a subinterval is negligible compared to the probability of observing one or zero events
- an event, occurs or not in a subinterval is independent
- probability of an event occurrence in each subinterval is p then the expected number of event occurrences in the interval $[0, t]$ is np
- events occur at a rate of λ events per second, the average number of events in the interval $[0, t]$ is λt, so $\lambda t = np$
- n interval constituting a sequence of Bernoulli trials with the probability of success $p = \lambda t/n$

Arrival Rate: Poisson distribution

- the probability of k arrivals in a total of n intervals

$$b(k; n, \frac{\lambda t}{n}) = \left(\begin{array}{c} n \\ k \end{array} \right) \left(\frac{\lambda t}{n}\right)^k \left(1 - \frac{\lambda t}{n}\right)^{n-k}$$

as $n \longrightarrow \infty$ the binomial distribution approaches a Poisson distribution with parameter λt

$$p(N(t) = k) = \frac{(\lambda t)^k}{k!} e^{-\lambda t}$$

- Application modeled as Poisson distributed
  - congestion, queuing, number of jobs arriving, the number of jobs completing service, the number of messages transmitted through a communication channel in a fixed interval of time

Service Time: Exponential Random Variable

- T time between event occurrences in a Poisson process
- The probability that the intervent time T exceeds t seconds is equivalent to no event occuring in t seconds

$$\begin{aligned} P[T > t] &= P[\text{no events in } t \text{ seconds}] = (1-p)^n \\ &= (1 - \frac{\lambda t}{n})^n \rightarrow e^{-\lambda t} \text{ as } n \rightarrow \infty \end{aligned}$$

- T is an exponential random variable with parameter λ
- the intervent times in a Poisson process from an *iid sequence of exponential random variables with mean* $1/\lambda$
- *sum of n* iid exponential random variables has an Erlang distribution; if T_j denote the iid exponential interarrival times

$$S_n = T_1 + T_2 + \cdots + T_n$$

Service Time: Exponential Random Variable

- Exponential random variable satisfies the memoryless property

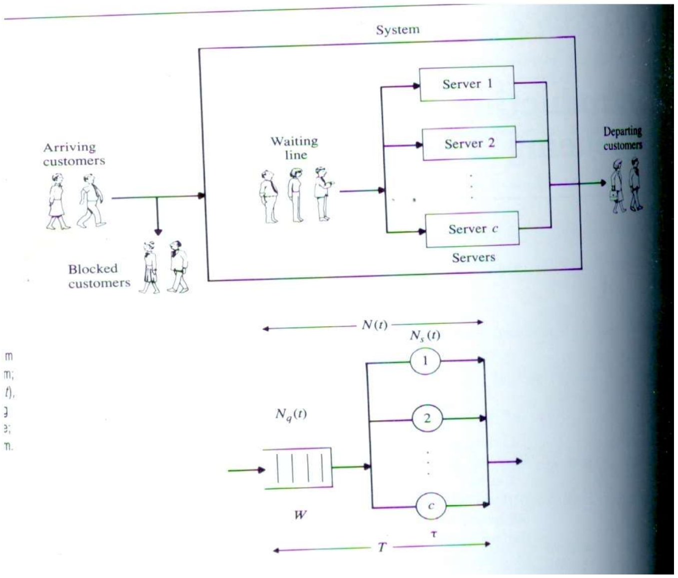
$$P[X > t + h | X > t] = P[X > h]$$

- left side is probability of having to wait at least h additional seconds given that one has already been waiting t seconds
- right side is the probability of waiting at least h seconds when one first begins to wait, i.e. the probability of waiting at least an additional h seconds is the same regardless of how long one has already been waiting
- Application of Exponential distribution
  - Time between two successive job arrivals to a computing server
  - Service time at a server in a queuing network
  - Time to failure (lifetime) of a component
  - Time required to repair a component that has malfunctioned

Queueing Theory

- Users - Resources - time period of resource use - queue
- Random nature of demand behavior of customers implies that probabilistic measures such as average delay, average throughput etc. are required to assess the performance of the system
- arrival time of the ith customer S_i and arrival rate is λ
- ith customer seeking a service will require τ_i seconds of service time
- a limited number of waiting spaces and if no room customers are turned away called "blocked" at rate λ_b
- Queue or service discipline specifies the order in which customers are selected from the queue and allowed into service
- Waiting time W_i; time elapses from the arrival time of the ith customer until the time when it enters service; total delay $T_i = W_i + \tau_i$

Queueing Process



Queueing Process

- performance of the system is given by the statistics of the waiting time W and T
- the proportion of customers that are blocked λ_b/λ
- the proportion of time that each server is utilized and the rate at which customers are services by the system, $\lambda_d = \lambda - \lambda_b$
- These are function of the number of customers in the system at time t and the number of customers in queue at time t
- $a/b/m/K$ is used to describe queueing system
  - a type of arrival process
  - b service time distribution
  - m number of servers
  - K maximum number of customers allowed in the system at any time

Queueing Process

- if a is given by M, then the arrival process is Poisson and the interarrival times are independent, identically distributed exponential random variables
- if b is given by M, then the service times are iid exponential random variables
- if b is given by D, then the service times are constant (deterministic)
- if b is given by G, then the service times are iid according to some general distribution

Thank You