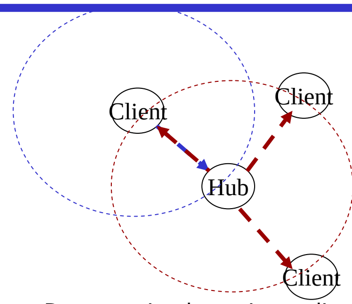
Lecture 5

ALOHA protocols

ALOHAnet

- Aloha was a pioneering computer networking system developed at the University of Hawaii in 1970's.
- The idea was to use radio to create a computer network linking the far-flung campuses of the University.
- The original version of ALOHA used two distinct frequencies in a hub/star configuration, with the hub machine broadcasting packets to everyone on the downlink channel, and the various client machines sending data to the hub on the uplink channel.



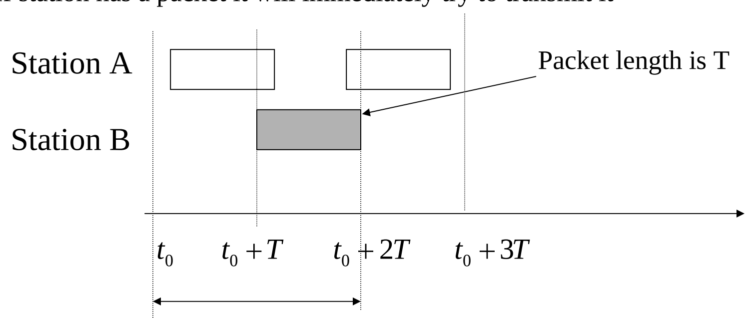
- Data received was immediately re-sent, allowing clients to determine whether or not their data had been received properly.
- Any machine noticing corrupted data would wait a short time and then re-send the packet.

Infinite user population

- Users will generate packets according to Poisson process
- The aggregate packet arrival rate generated by the users is λ

Pure Aloha

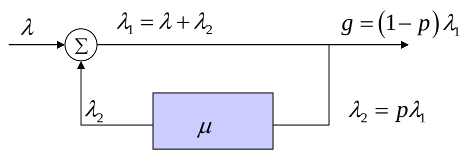
If station has a packet it will immediately try to transmit it



The packet generated by station B collides if any station generates a packet on the time interval $t_0 < t < t_0 + 2T$

Pure Aloha

- Packets arrive to the system with intensity λ
- Packets collide with probability p
- In case of collision, the packet will be retransmitted after random back-off time
- Aggregate of new packets and failed packets returning to the transmitter buffer is still a Poisson process with intensity $g = (1-p)\lambda_1 = \lambda$



Pure Aloha

- Packets arrival process is Poisson with intensity g packets per second.
- Transmission time of the packet is T
- Probability that *k* packets arrive in time window Δt

$$\Pr\{k \text{ arrivals in } \Delta t\} = e^{-g\Delta t}\frac{(g\Delta t)^k}{k!}$$

- Probability that there is no collision is equal to the probability that no other packets arrive during the time interval $t_0 < t \le t_0 + 2T$:

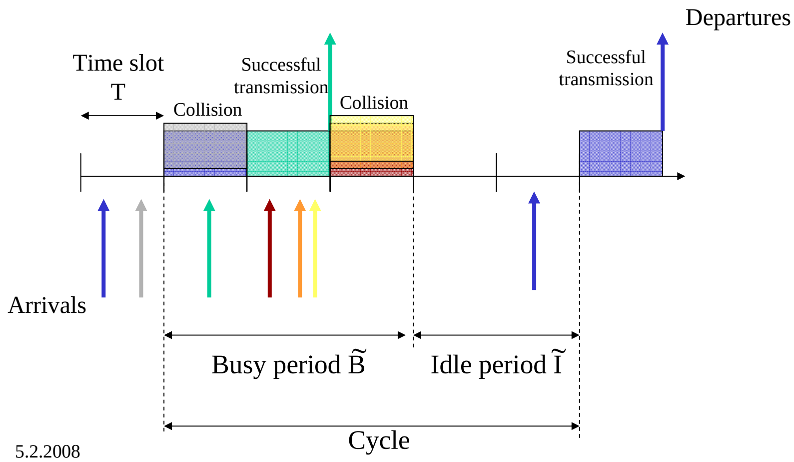
$$\Pr\{\text{no collision}\} = \Pr\{0 \text{ arrivals in } 2T\} = e^{-g2T}$$

- Normalized load, average number of arrivals in time T $G = gT$
- Throughput per time T

$$\boxed{S = Ge^{-2G}}$$

Slotted Aloha

If station has a packet it will immediately in the beginning of the next slot



Slotted Aloha

- The pdf for the length of the *idle period* $\tilde{I}$ is given by

$$\Pr\{\tilde{I}=1\} = \Pr\{\text{Some packets arrive during the first idle slot}\}$$

$$= 1 - \Pr\{\text{No arrival during the first slot}\} = 1 - e^{-G}$$

$$\Pr\{\tilde{I}=k\} = \Pr\{\text{No arrivals during k-1 firs slots and some arrivals at slot k}\}$$

$$= \left(1-e^{-G}\right)^{k-1} e^{-G}$$

- Expected length of the idle period

$$I = E\{\tilde{I}\} = \sum_{k=1}^{\infty} k \Pr\{\tilde{I}=k\} = \sum_{k=1}^{\infty} k\left(1-e^{-G}\right)^{k-1} e^{-G} = \frac{1}{1-e^{-G}}$$

Slotted Aloha

- The pdf for the length of the *busy period* is given by

$$\Pr\left\{\tilde{B}=1\right\}=\Pr\left\{\text{No arrival during the fist busy slot}\right\}=e^{-gT}$$

$$\Pr\left\{\tilde{B}=k\right\}=\Pr\left\{\text{No arrival during the fist k-1 busy slots and some arrivals at slot k}\right\}$$

$$=\left(e^{-G}\right)^{k-1}\left(1-e^{-G}\right)$$

- Expected length of the busy period

$$B=E\left\{\tilde{B}\right\}=\sum_{k=1}^{\infty}k\Pr\left\{\tilde{B}=k\right\}=\sum_{k=1}^{\infty}k\left(e^{-G}\right)^{k-1}\left(1-e^{-G}\right)=\frac{1}{e^{-G}}$$

Slotted Aloha

- Let Ũ denote the number of useful slots during the busy period. That is, the number of slots during which there were no collisions.
- The probability that a slot in busy period is successful is

$$\Pr\left\{\text{Busy slot is useful}\right\}=\Pr\{\text{Number of arrivals }=1|\text{Number of arrivals>0}\}$$

$$=\frac{\Pr\left\{\text{Number of arrivals=1, Number of arrivals >0}\right\}}{\Pr\left\{\text{Number of arrivals>0}\right\}}$$

$$=\frac{\Pr\left\{\text{Number of arrivals =1}\right\}}{\Pr\left\{\text{Number of arrivals>0}\right\}}=\frac{Ge^{-G}}{1-e^{-G}}$$

- Expected number of useful slots is

$$U=\Pr\left\{\text{Busy slot is useful}\right\}\bullet B=\frac{G}{1-e^{-G}}$$

Slotted Aloha

- Throughput

$$S=\frac{U}{B+I}=\frac{\frac{G}{1-e^{-G}}}{\frac{1}{e^{-G}}+\frac{1}{1-e^{-G}}}=Ge^{-G}$$

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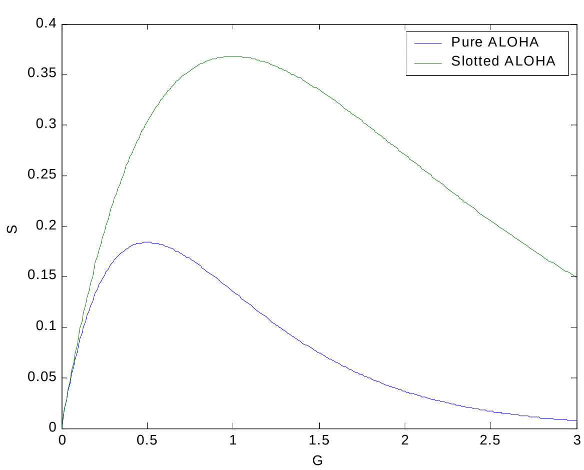
Slotted Aloha



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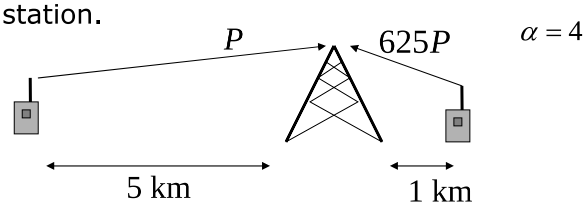
Radio channel

- Consider a radio transmission system in which large number of transmitters are sending packets to a base station.



P_{tx} Transmit power

$$P_i = \frac{1}{r_i^{\alpha}} P_{tx}, \quad i = 1, 2, \quad 2 \le \alpha < 5 \quad \text{Received power}$$

- *Power capture phenomena*: The received signal-to-interference ratio (SIR) from one of the colliding packets is large enough so that it can be decoded successfully.

Radio channel

- Packet is received correctly if the Signal-to-Interference Ratio (SIR) is larger β

$$SIR_i = \frac{\frac{1}{r_i^{\alpha}} P_{tx}}{\sum_{j \ne i} \frac{1}{r_j^{\alpha}} P_{tx}} > \beta$$

- Assume that capture occurs only if up to two packets collide and the SIR of the other packet is greater than β:

$$P_{capture} = \Pr\{P_2 \ge \beta P_1\} + \Pr\{P_1 \ge \beta P_2\} = 2\Pr\{P_2 \ge \beta P_1\}$$

$$P_{capture} \approx 2\Pr\left\{r_1 \le \beta^{-\frac{1}{\alpha}} r_2\right\} = \beta^{-\frac{2}{\alpha}}$$

Radio channel

- Probability of successful transmission

$$\Pr\{\text{success}\} = \Pr\{0 \text{ arrivals in T}\} + P_{capture} \Pr\{1 \text{ arrival in T}\}$$

$$= e^{-G} + P_{capture} G e^{-G}$$

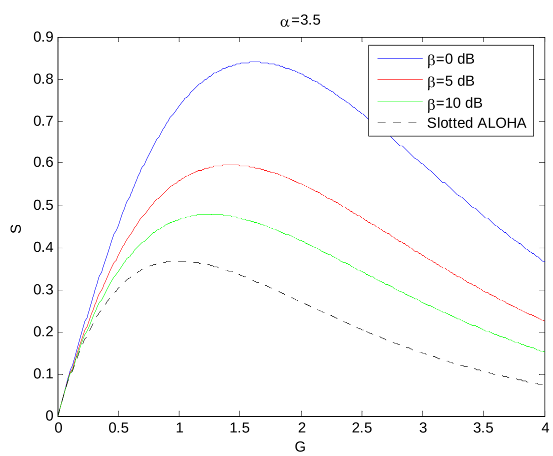
$$= e^{-G} + \beta^{-\frac{2}{\alpha}} G e^{-G}$$

- Throughput per time interval T:

$$S = G \Pr\{\text{Success}\} = G\left(e^{-G} + \beta^{-\frac{2}{\alpha}} G e^{-G}\right)$$

$$= G e^{-G}\left(1 + \beta^{-\frac{2}{\alpha}} G\right)$$

Radio channel



Finite user population

- M users share the channel
- An user can be in two states
  - Thinking
    - The user has no packets in the transmission buffer.
    - The user generates a packet in a given slot with probability σ
    - Once a packet is generated, its transmission is attempted immediately
  - Backlogged
    - If the packet transmission was unsuccessful, the user enters the backlogged state
    - In a given slot a backlogged user tries to retransmit with probability ν
    - This could be interpreted as defining geometrically distributed backoff time in case of collision

Slotted Aloha – Finite number of users

- Slots are numbered sequentially k=0,1,…
- Let N(k) denote the number of backlogged users at the beginning of slot k.
- N(k) defines the state of the system
- The action of an user depends on the current state of the system, but not on the past states. Hence, the system can be modeled as a Markov chain.

Slotted Aloha – Finite number of users

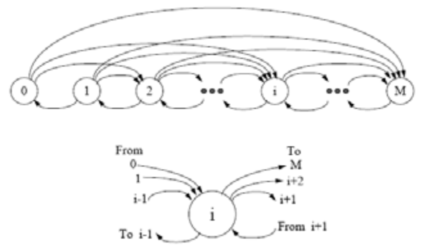
- In steady state, the state probabilities converge to
  $\pi_j = \lim_{k\to\infty} \Pr\left\{\tilde{N}(k) = j\right\}$
  and the state transition probabilities converge to
  $p_{ij} = \lim_{k\to\infty} \Pr\left\{\tilde{N}(k) = j \,\middle|\, \tilde{N}(k-1) = i\right\}$
- The probabilities fulfill

$$\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P}$$

$$\sum_{i=0}^{M} \pi_i = 1$$

$$\boldsymbol{\pi} = \begin{pmatrix} \pi_0 & \pi_1 & \dots & \pi_M \end{pmatrix}$$

$$\mathbf{P} = \left[p_{ij} \right]$$



R. Rom and M. Sidi, Multiple Access Protocols, Springer-Verlag, 1989

Slotted Aloha – Finite number of users

- Let us define

$$B(i,j) = \Pr\{i \text{ backlogged users attempt transmission} \mid N = j\} = \binom{j}{i} \nu^i (1-\nu)^{j-1}$$

$$T(i,j) = \Pr\{i \text{ thinking users attempt transmission} \mid N = j\} = \binom{M-j}{i} \sigma^i (1-\sigma)^{M-j-1}$$

- Transition from state i to j<i-1 is not possible, since only one packet can be transmitted in a slot. Hence p_{ij}=0 for j=0,1,…,i-2
- Transition from stat i to itself, p_{ii} can happen in two ways
  - No new packet is generated
  - No new packet in generated by a thinking user and the transmission of the backlogged users result in collision

$$p_{ii} = B(0,i)T(0,i) + \sum_{k=2}^{i} B(k,i)T(0,i)$$

Slotted Aloha – Finite number of users

- Transition from state i to j=i+1, can happen if one new packet is generated and there is collision

$$p_{ii+1} = \sum_{k=1}^{i} B(k,i) T(1,i)$$

- Transition from state i to j>i+1 happens if j-i thinking users generated packet causing collision. The behavior of the backlogged users does not matter in this case.

$$p_{ij} = T(j-i,i), \quad j > i+1$$

- The transition from state i to state j=i-1 occurs if no thinking users generate packet and there is no collision

$$p_{ii-1} = \left(1 - T(0,i)\right) B(1,i)$$

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Slotted Aloha – Finite number of users

- Finally, we get

$$p_{ij} = \begin{cases} 0 & j < i-1 \\ \left[i\upsilon (1-\upsilon)^{i-1} \right] (1-\sigma)^{M-i} & j = i-1 \\ \left[1 - i\upsilon(1-\upsilon)^{i-1} \right] (1-\sigma)^{M-i} + \left[(M-i)\rho(1-\sigma)^{M-i-1} \right] (1-\upsilon)^{i} & j = i \\ \left[(M-i)\rho(1-\sigma)^{M-i-1} \right] \left(1 - (1-\upsilon)^{i} \right) & j = i+1 \\ \binom{M-i}{j-i} \rho^{j-i} (1-\sigma)^{M-j} & j > i+1 \end{cases}$$

- Now, the state probabilities can be solved from

$$\boldsymbol{\pi} = \boldsymbol{\pi} \mathbf{P}$$

$$\sum_{i=0}^{M} \pi_i = 1$$

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Slotted Aloha – Finite number of users

- Probability of successful transmission when the number of backlogged users is i

$$P_{suc}(0) = T(1,i)$$
$$P_{suc}(i) = T(1,i)B(0,i) + T(0,i)B(1,i)$$
$$= (M-i)\sigma(1-\sigma)^{M-i-1}(1-\upsilon)^{i} + (1-\sigma)^{M-i} i\upsilon(1-\upsilon)^{i-1}$$

- Total throughput

$$S = E\{P_{suc}(i)\} = \sum_{i=0}^{M} P_{suc}(i)\pi_i$$

- In a special case where ν=σ , we get

$$S = E\{P_{suc}(i)\} = M\sigma(1-\sigma)^{M-1} = G\left(1-\frac{G}{M}\right)^{M-1}, \quad G = M\sigma$$

clearly

$$\lim_{M\to\infty} G\left(1-\frac{G}{M}\right)^{M-1} = Ge^{-G}$$

Slotted Aloha – Finite number of users

- The throughput defines the departure rate
- In state i there are M-i thinking users generating packets with the rate (M-i)σ.
- In stable system the input and output rates must be equal. Thus we must require that

$$S = E\{(M-i)\sigma\} = (M-N)\sigma$$

where N is the average number of backlogged users

$$N = \sum_{i=0}^{N} i\pi_i$$

Slotted Aloha – Finite number of users

- Let b denote the rate packets join the backlog
- Since packets depart from the system at rate S then a fraction of (S-b)/S of the packets are newer backlogged and suffer a delay of 1 time slot.
- The fraction of b/S of the packets that are backlogged will first have to wait in the backlog for w=N/b (b=Nw) slots and thus see an overall delay of N/b+1 slots.
- Hence the average delay in the system is

$$\hat{D} = \frac{S-b}{S} + \frac{b}{S}\left(\frac{N}{b}+1\right)$$

- Recall that. $S = (M-N)\sigma$ Hence $N = M - \frac{S}{\sigma}$ and

$$\hat{D} = \frac{S-b}{S} + \frac{b}{S}\left(\frac{M-\frac{S}{\sigma}+b}{b}1\right) = 1 + \frac{M}{S} - \frac{1}{\sigma}$$

Slotted Aloha – Finite number of users

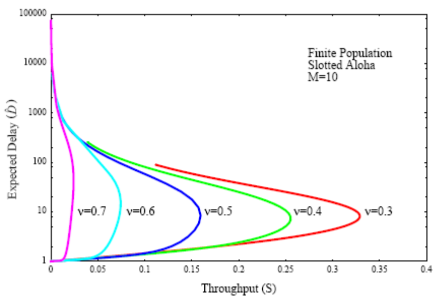
- In a special case where $\nu=\sigma$, we get

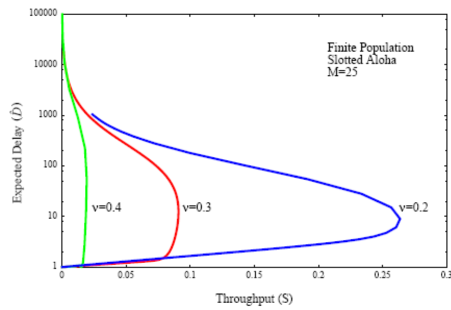
$$\hat{D} = 1 + \frac{1-(1-\sigma)^{M-1}}{\sigma(1-\sigma)^{M-1}}$$

  - When $M\to\infty$, also $D\to\infty$ so in the infinite population case, the Aloha protocol becomes unstable
  - When $\sigma\to 0$, we have $D\to M$. This implies that although most packets get through with delay 1, some packets still collide and see very large delays. On average the packet delay becomes equal to M.

Slotted Aloha – Finite number of users

- The curve is parameterized with respect to σ





- Delay increases monotonically as a function of σ
- Throughput increases up to a point after which it starts to decrease again

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Slotted Aloha – Capture phenomenon

- If $M\nu \ll 1$ and $0 \ll \sigma < 1$, then capture phenomena is manifested
- Throughput

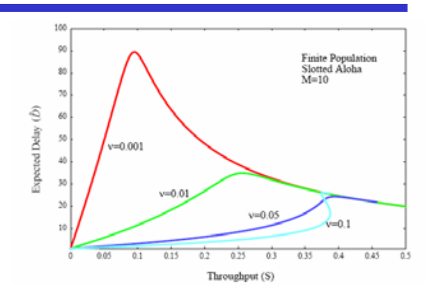
$$S \approx \frac{M\sigma}{M + (M-1)\sigma}$$

increases as a function of σ!

- Delay

$$D \approx M + \frac{M-1}{\sigma}$$

decrease as a function of σ!



R. Rom and M. Sidi, Multiple Access Protocols, Springer-Verlag, 1989

The system eventually becomes backlogged, but the probability that a backlogged user transmits is small. Hence, it is very likely that a new packet gets transmitted right away. One user captures the channel for a while until there is collision again

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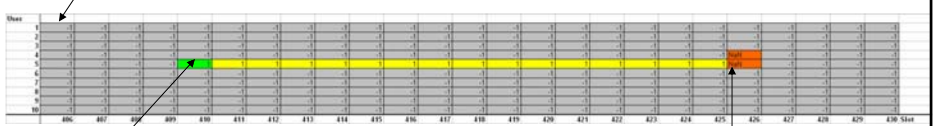
Slotted Aloha – Capture phenomenon

- Example packet trace
  - M=10
  - σ=0.7
  - ν=0.01

Backlogged state, no transmission
Collision
Successful transmission from backlogged state
Successful transmission from thinking state

Due to high transmission probability, all users eventually become backlogged



Capture

Collision

Backlogged user has low transmit probability, but when it finally transmits and becomes thinking, she can capture the channel for long time due to high σ

(In)Stability

- Stability condition, for the infinite number of users case:

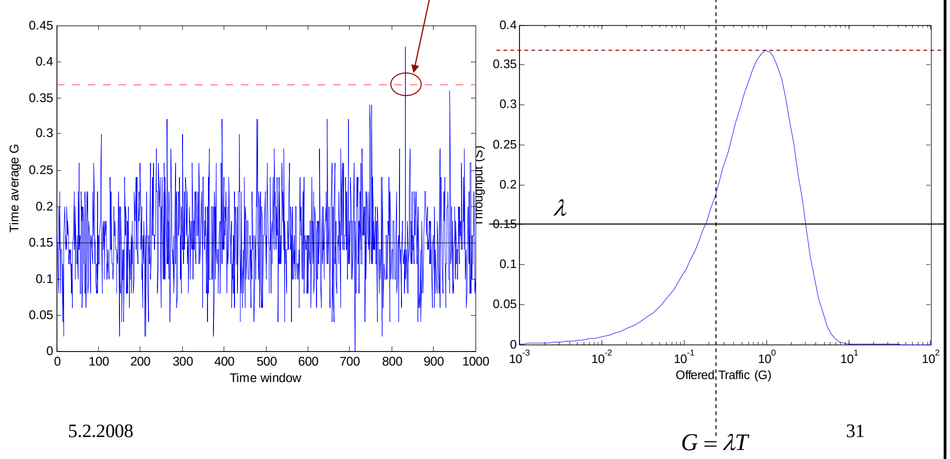
  $S=Ge^{-G} \geq G$

  $\Rightarrow G \leq e^{-1} \approx 0.3679$
- In practice the assumption that the aggregate rate of new packets and backlogged packets is Poisson does not hold.
- Consider the case, in which the traffic source is generating packets with arrival rate λ
- The arrival rate is only an average rate. The actual arrivals will fluctuate around this mean.
- If the time average of the mean rate exceeds e^{-1} the throughput starts to degrease and the number of backlogged users growing without bound.
- This will happen with probability 1! That is, *the ALOHA protocol is instable*.

(In)Stability

Arrival rate exceed e^{-1} and thus the queues start to grow without bound.

Time average over 50 slots



Stabilizing Aloha

- Arrival process

$$a_i = \Pr\{i \text{ new packets arrive at slot}\} = a_i$$

$$\lambda = \sum_{i=0}^{\infty} i a_i$$

- Backlogged users

$$b_i(n) = \Pr\{i \text{ backlogged users transmit at slot} \mid n \text{ backlogged users}\}$$

- Number of backlogged users at slot *k* when $\tilde{N}(k) = i$

$$\tilde{N}(k+1) = \begin{cases} i-1 & \text{with probability } b_1(i)\, a_0 \\ i & \text{with probability } [1 - b_1(i)]\, a_0 + b_0(i)\, a_1 \\ i+1 & \text{with probability } [1 - b_0(i)]\, a_1 \\ i+j,\ j \geq 2 & \text{with probability } a_j \end{cases}$$

Stabilizing Aloha

- Expected change in system state during one time slot

$$E\left\{\tilde{N}(k+1)-\tilde{N}(k)\middle|\tilde{N}(k)=i\right\}=(i-1)b_1(i)a_0+i\left[\left(1-b_0(i)\right)a_0+b_0(i)a_1\right]+\sum_{j=2}^{\infty}(i+j)a_j-i$$
$$=\lambda-b_1(i)a_0-b_0(i)a_1$$

- System is stable if

$$E\left\{\tilde{N}(k+1)-\tilde{N}(k)\middle|\tilde{N}(k)=i\right\}=\lambda-b_1(i)a_0-b_0(i)a_1\leq 0$$
$$\Rightarrow \lambda<b_1(i)a_0+b_0(i)a_1$$

Stabilizing Aloha

- Assume that we somehow know how many packets are backlogged and choose the retransmission probability based on the state n

$$b_i(n)=\binom{n}{i}\left[\upsilon(n)\right]^i\left[1-\upsilon(n)\right]^{n-i}$$

- The maximum arrival rate under which the system is stable is given by

$$\lambda=\limsup_{n\to\infty}\left\{b_1(n)a_0+b_0(n)a_1\right\}$$

- The stability limit yields

$$\lambda<e^{\log a_0+\frac{a_0}{a_1}-1}$$

Stabilizing Aloha

- Define

$$S_n(\upsilon) = b_1(n)a_0 + b_0(n)a_1 = [1-\upsilon(n)]^n a_1 + n\upsilon(n)[1-\upsilon(n)]^{n-i} a_0$$

- Maximizing the above with respect to ν yields

$$\nu^*(n) = \frac{a_0 - a_1}{na_0 - a_1}$$

- The maximum throughput for given n is thus

$$S_n^*(\upsilon^*) = a_0 \left[\frac{n-1}{n - \frac{a_1}{a_0}}\right]^{n-1}$$

- The maximum arrival rate must correspond to the system throughput

$$\lambda < \lim_{n\to\infty} S_n^*(\upsilon^*) = e^{\ln a_0 + \frac{a_0}{a_1} - 1}$$

Stabilizing Aloha

- For Poisson arrival of packets, we have

$$a_i = \frac{(\lambda)^i}{i!} e^{-\lambda} \qquad \frac{a_1}{a_0} = \lambda$$

- Hence the stability condition becomes

$$\lambda < e^{\ln a_0 + \frac{a_0}{a_1} - 1} = e^{-1}$$

- And the probability for backlogged user to transmit becomes

$$\nu^*(n) = \frac{1 - \frac{a_1}{a_0}}{n - \frac{a_1}{a_0}} = \frac{1-\lambda}{n-\lambda} \approx \frac{1}{n} \quad \text{for small } \lambda$$

Stabilizing Aloha

- The merit of ALOHA is being very simple protocol
- Its major drawback is that is instable
- Stabilization of the protocol requires knowledge on the system state *n* which requires
  - Coordination between the transmitters

  Or
  - Some form of feedback mechanism to be applied

  $$\nu_{k+1} = f\left(\nu_k, \text{Feedback of slot } k\right)$$

Stabilizing Aloha

- In practice, the number of retransmission attempts is limited. If the maximum number of transmission attempts is reach the packet is rejected.
- In this manner the system can be stabilized, but the we have to cope with occasional packet drop.
- For simplicity, let us consider the case in which $\sigma=\nu$.
- The probability of successful transmission is

$$P_{suc} = E\left\{P_{suc}(i)\right\} = M\sigma\left(1-\sigma\right)^{M-1} = G\left(1-\frac{G}{M}\right)^{M-1} = S$$

- Maximum number of transmission attempts is r. Probability that packet is rejected is R. If retransmission attempts are independent $R=(1-S)^{r+1}$
- Offered traffic $G = RM\sigma$

Reverse engineering ALOHA

Strategic games
One shot random access game

Stategic games

- Game theory is a form of interactive decision theory
  that provides a rigorous mathematical formulation for how decision-makers behave when they interact.
- Players in a strategic game choose their actions *simultaneously* and *independently* without knowing the selections done by others nor past outcomes of the game.

<u>Definition:</u> A strategic game is the tuple $G = \langle N, \{A_i, i \in N\}, \{u_i, i \in N\} \rangle$
where
- *N denotes the set of players*
- *For every i∈N, A_i is the set of actions available to player i.*
- *For every i∈N,* $u_i : x_{j \in N^{A_j}} \rightarrow R$ *is the utility function of player i showing his preference over the set of action profiles A*

Stategic games

- If the set of actions for every player is finite, then the game is finite
- An action profile $\mathbf{a}=(a_i)$ $i \in N$ is an *outcome.* That is, it defines the actions taken by the players.
- An action profile $\mathbf{a} \in A$ is preferred over action profile $\mathbf{b} \in A$ only if $u_i(\mathbf{a}) \geq u_i(\mathbf{b})$
- Let $\Delta(A_i)$ denote the set of all probability distributions σ_i on A_i (σ_i is the probability that action a_i is selected)
- There are two types of strategies available for the users
  - *Pure strategy*: Player chooses an action $a_i \in A_i$ with probability 1.
  - *Mixed strategy*: Player chooses an action $a_i \in A_i$ with probability $\sigma_i(a_i)$

Stategic games

<u>Definition</u>: *The mixed strategy profile σ^* in a strategic game with is a* mixed strategy **Nash equilibrium** *if, for each player i and every mixed strategy σ_i of player i, the expected payoff to player i of (σ_i^*, σ^*_{-i}) is at least as large as the expected payoff to player i of (σ_i, σ^*_{-i}). That is,*

$$\sigma_i^* = \arg\max_{\sigma_i \in \Delta(A_i)} u\left(\sigma_i, \sigma_{-i}^*\right)$$

Furthermore, the mixed strategy Nash equilibrium is said to be fully mixed *if σ_i non-degenerate. That is for all i* $\sigma_i(a_i) \neq 1$

One shot random access game

- Each player can choose from two actions:
  - a_i=1: Transmit
  - a_i=0: Stay idle
- The utilities are given by

$$u_i(\mathbf{a}) = \begin{cases} 0 & a_i = 0 \\ 1 & \sum_{i \in N} a_i = 1 \\ -c & \sum_{i \in N} a_i > 1 \quad \text{Cost induced by unsuccessful transmission} \end{cases}$$

One shot random access game

- According to Inealtekin and Wicker (2005), the one shot random access game witn n players has 2^n-1 Nash equilibrium points:
  - *n* pure strategies in which only one node transmits
  - There is one fully mixed nash equilibrium (FMNE) with

$$\sigma_i(a_i) = \begin{cases} \left(\frac{c}{c+1}\right)^{\frac{1}{n-1}} & a_i = 0 \quad \text{Stay idle} \\ 1 - \left(\frac{c}{c+1}\right)^{\frac{1}{n-1}} & a_i = 1 \quad \text{Transmit} \end{cases}$$

  - The rest are combinations of pure and mixed strategies where some of the players choose to stay idle all the time and the remaining n’ users use mixed strategy

One shot random access game

- The throughput of the FMNE is given by

$$S(n) = n\left(\frac{c}{c+1}\right)\left[1-\left(\frac{c}{c+1}\right)^{\frac{1}{n-1}}\right]$$

- Throughput is maximized if

$$c^* = \frac{\left(1-\frac{1}{n}\right)^{n-1}}{1-\left(1-\frac{1}{n}\right)^{n-1}}$$

- The optimal throughput is given by

$$\lim_{n\to\infty} S^*(n) = e^{-1}$$

which corresponds to the maximum channel utilization of the slotted ALOHA.

Reverse engineering ALOHA

- Furthermore, when $n \to \infty$ the number of players choosing to transmit converge to Poisson distribution
- For given c, the throughput S converges to

$$S = \lim_{n\to\infty} S(n) = -\frac{c}{1+c}\ln\left(\frac{c}{1+c}\right)$$

- The throughput of slotted aloha in case of infinte user population is

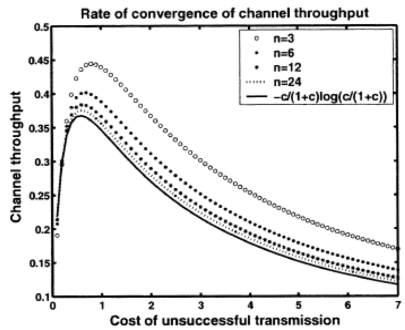
$$S = Ge^{-G}$$

- The throughput becomes the same if $\frac{c}{1+c} = e^{-G}$. That is,

$$c = \frac{e^{-G}}{1-e^{-G}}$$

Reverse engineering ALOHA

- Convergence of the channel throughput



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Applications of ALOHA

- ALOHA is utilized in applications where carrier sensing is difficult or not possible. E.g.
  - In Frequency Division Duplexing (FDD), systems transmission and receiving takes place simultaneously on different frequency bands
  - In under water acoustic communications, the propagation delays are very long (long time would be needed for carrier sensing in order to detect on-going transmissions)