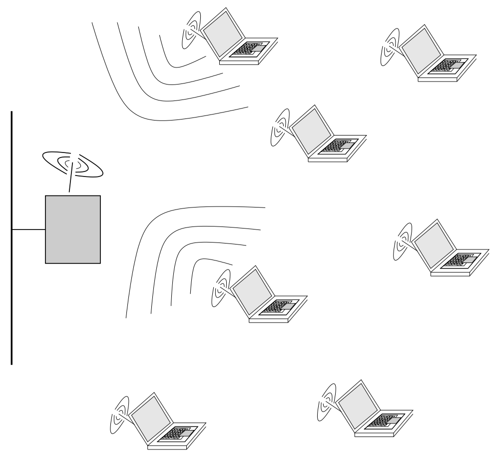
Bandwidth Provisioning
in
Contention-Based Wireless Access Networks

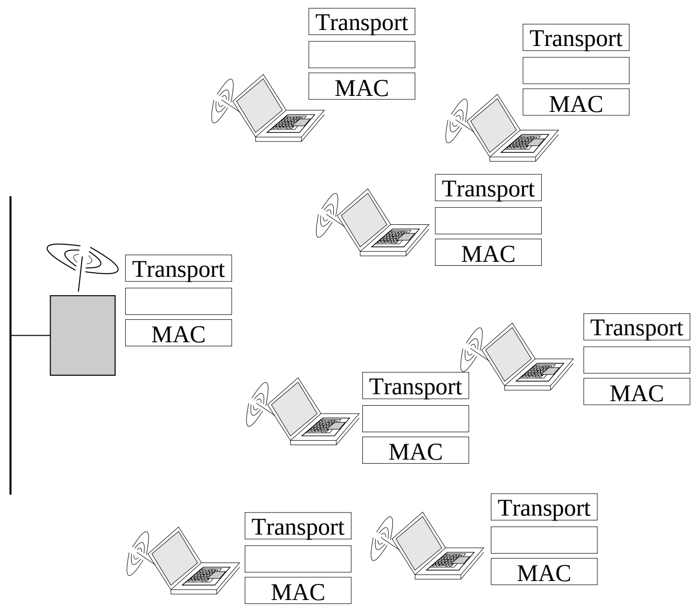
Joint Work with Clement Yuen

Wireless LAN



- Contention-Based Access: Collisions and Retransmissions
- No Reservations - No QoS Guarantees
- Questions:
  - Stability?
  - Service Differentiation?

Rate Control and Scheduling



- MAC Layer: Scheduling $->$ Delay
- Transport Layer: Rate Control $->$ Throughput

Protocol Design

- MAC Layer
  - Packet Retransmissions
    - Slotted Aloha
    - CSMA/CD
  - Stability Region?
- Transport Layer
  - Keep Arrival Rate within the Stability Region

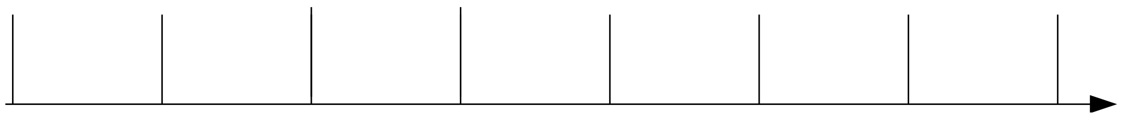
Cross-Layer Interaction?

Outline

- Slotted Aloha
- Slotted Aloha with Rate Control
- Service Differentiation
- Cross-Layer Interaction
- Case Study
- Conclusions

Model - Slotted Aloha

- Time is divided into slots
- Transmission Delay: 1 time unit



- Poisson arrivals with (aggregated) rate of λ packets/time unit
- Collision or Perfect Reception
- Immediate Feedback: $0, 1, e$
- Retransmission Probability: q
- Infinite number of hosts

Notation

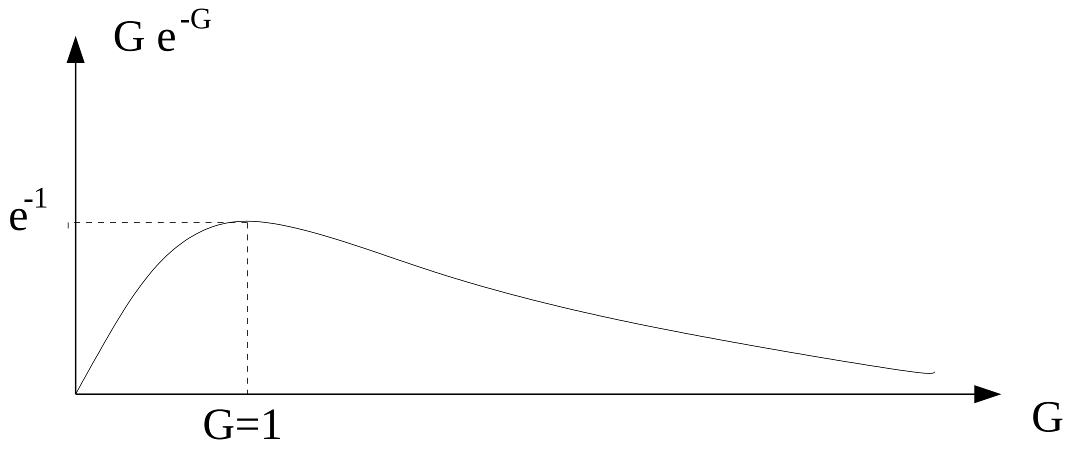
- λ: aggregated arrival rate
- n: number of backlogged packets
- $G(n) = \lambda + nq$: average number of arrivals per time slot

Want to compute

- Probability of successful transmission as a function of $G(n)$
- For small q, we have

$$P_{succ} \approx G(n)e^{-G(n)}$$

Model - Slotted Aloha



- Static q: System is not Stable
- q should dynamically change:

$$G(n) = 1$$

$$q(n) = \frac{1-\lambda}{n}, \qquad \lambda < e^{-1}$$

Slotted Aloha and Rate Control

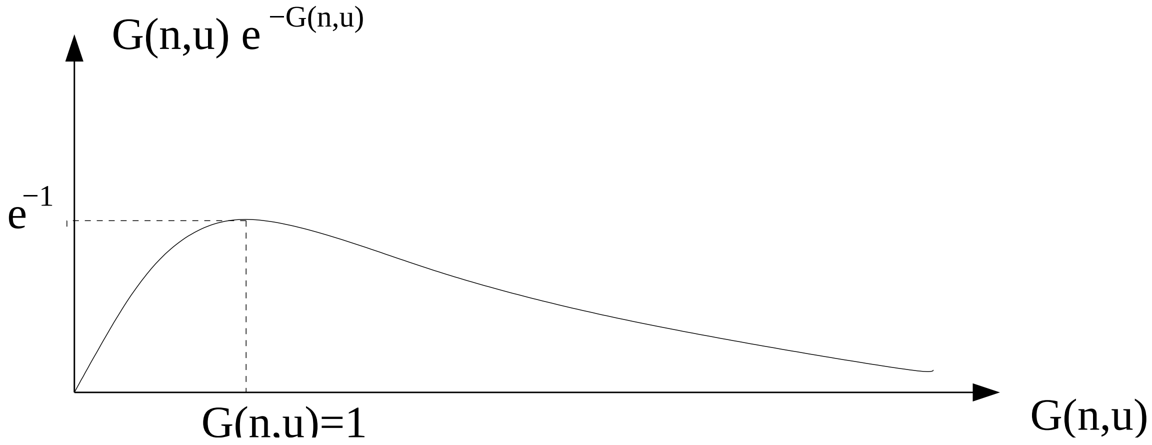
- Price Signal u
- Aggregated Transmission Rate $\lambda(u)$
- Collision: Increase Price
- Idle Slot: Decrease Price
- Price Adaptation: $\alpha < 0$, $\gamma > 0$

$$u_{t+1} = \Big[u_t + \alpha I[z_t = 0] + \beta I[z_t = 1] + \gamma I[z_t = e]\Big]^+$$

- Offered Load: $G(n, u) = \lambda(u) + nq$

Questions

- Is System Stable?
- Operating Point $G^* = G(n^*, u^*)$?



- How to choose α,β,γ?

Analysis

Dynamics

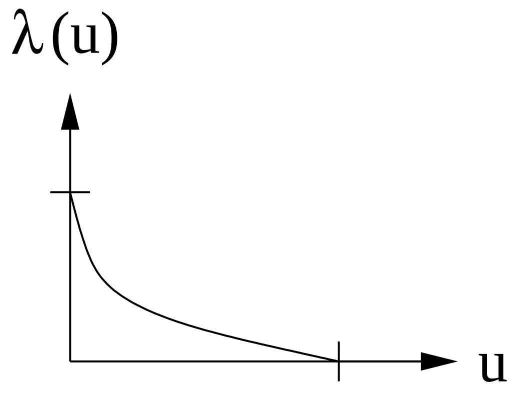
$$n_{t+1} = n_t + y_t - I[z_t = 1],$$
$$u_{t+1} = \big[u_t + \alpha I[z_t = 0] + \beta I[z_t = 1] + \gamma I[z_t \geq 2]\big]^+,$$

Poisson Approximation

$$\mathbf{P}\big(z_t = k \,\big|\, n_t = n, u_t = u\big)$$
$$= \begin{cases} e^{-G(n,u)}, & k = 0 \\ G(n,u)\, e^{-G(n,u)}, & k = 1 \\ 1 - e^{-G(n,u)}\big(1 + G(n,u)\big), & k \geq 2. \end{cases}$$

Analysis

Assumption 1 *There exist positive constants* λ_{max} *and* u_{max} *such that* $\lambda : \mathbb{R}_+ \rightarrow [0,\lambda_{max}]$ *is strictly decreasing, with* $\lambda(u) = 0$ *when* $u \geq u_{max}$.

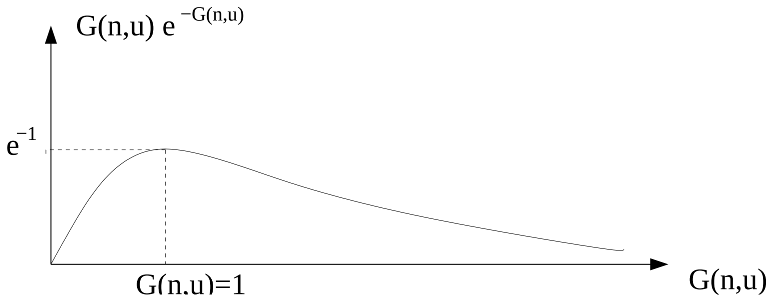


Stability: Is the Markov chain positive recurrent?

- Idea: Use Lyapunov function and drift criteria to show positive recurrence.

Results

- Yes, system is stable.
- There exists a unique operating point $G^* = G(n^*, u^*)$



- We can set $G^* = \lambda^* + n^* q$ by choosing α,β,γ.
  - Throughput $\lambda^* = G^* e^{-G^*}$
  - Backlog n^*
  - Average Delay $D^* = n^* / \lambda^*$
  - $\beta = \frac{\gamma}{G^*}\left(G^* + 1 - e^{G^*}\right) - \frac{\alpha}{G^*}$

Service Differentiation

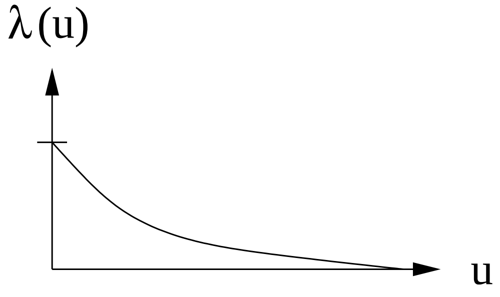
- m Nodes
- Throughput Differentiation: $\lambda_m(u)$

$$\lambda(u) = \sum_m \lambda_m(u)$$

- Delay Differentiation: $q_m \in (0, 1)$
- Results
  - System is Stable
  - Unique Operating Point G^*
  - $\beta = \frac{\gamma}{G^*}\left(G^* + 1 - e^{G^*}\right) - \frac{\alpha}{G^*}$

Dynamic Retransmission Probabilities

- Use Price u: $\quad q_m(u) = \frac{a_m}{(b_m - u)^{r_m}}$, $r_m > 1$
  - Assumptions:
    (a) $\lambda(u)$ is bounded and $\lim_{u \to \infty} \lambda(u) = 0$.



  - System is Stable
- Use Backlog n: $\quad q_m(n) = \frac{c_m}{n}$
  - System may not be Stable
- **Cross-Layer Interaction**

Case Study

User	Bandwidth	Delay
1	tolerant	tolerant
2	tolerant	intolerant
3	intolerant	tolerant
4	intolerant	intolerant

- Operating Point $G^* = 1$
- Throughput $\lambda^* = 0.368$
- $\alpha = -1$, $\beta = 0.28$, $\gamma = 1$

Case Study

- Throughput Differentiation: $\lambda_h^*/\lambda_l^* = 100$

$$\lambda_m(u) = \frac{c_m}{(1+u)^{1.5}}, \qquad c_m \in \{0.1, 10\}$$

- Delay Differentiation: $D_h^*/D_l^* = 10$

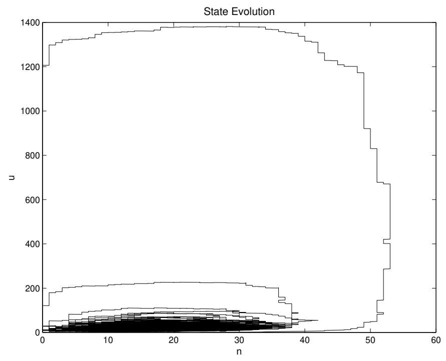
$$q_m \in \{0.022, 0.22\}$$

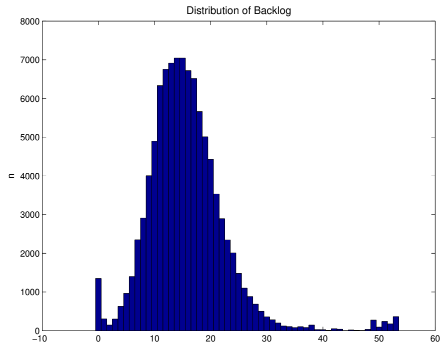
$$q_m(u) = \frac{c_m}{(1+u)^{1.1}}, \qquad c_m \in \{0.4, 4\}$$

$$q_m(n) = \frac{c_m}{(1+u)^{1.1}}, \qquad c_m \in \{0.1, 1\}$$

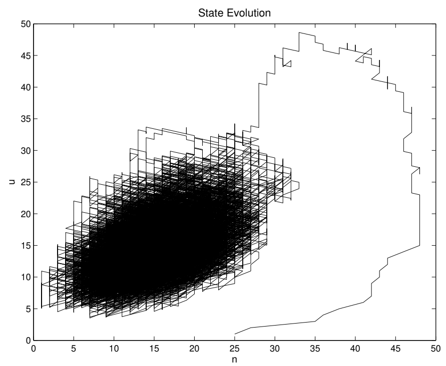
Case Study

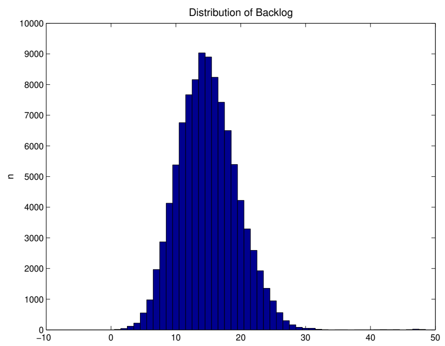
Fixed Retransmission Probabilities: q_m





Dynamic Retransmission Probabilities: $q_m(u)$





Case Study

Fixed Retransmission Probabilities: q_m

$$\lambda = 0.343, \qquad D = 45.00$$

User m	User 1	User 2	User 3	User 4
λ_m	0.0016	0.0017	0.1685	0.1711
D_m	78.11	10.43	79.77	10.72

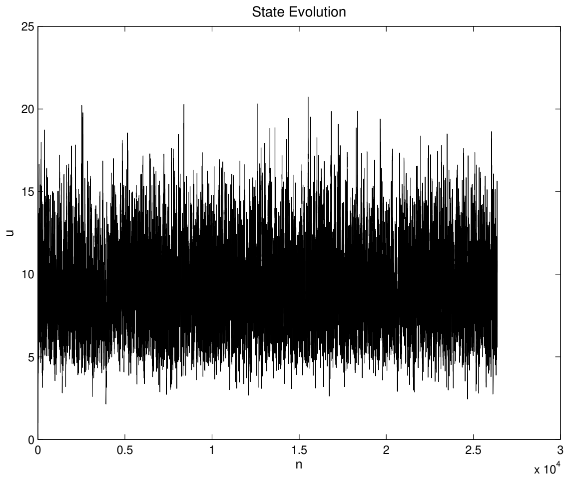
Dynamic Retransmission Probabilities: $q_m(u)$

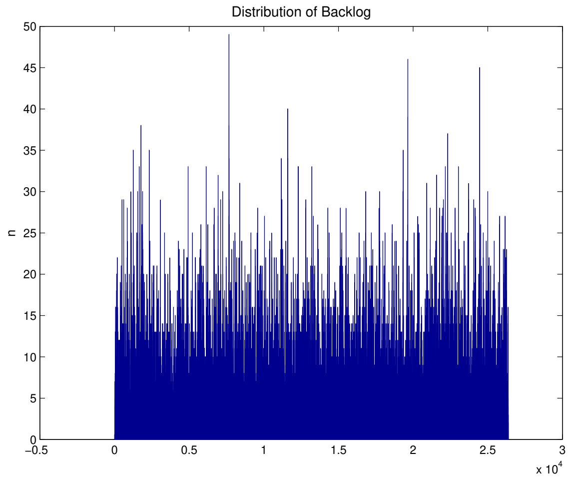
$$\lambda = 0.36, \qquad D = 48.78$$

User m	User 1	User 2	User 3	User 4
λ_m	0.0021	0.0018	0.1774	0.1799
D_m	75.55	8.88	88.30	9.89

Case Study

Dynamic Retransmission Probabilities: $q_m(n)$





System is not Stable

Conclusions

- "Slotted Aloha Never Dies"
- Slotted Aloha with Rate Control
- Service Differentiation
  - Transport Layer: Throughput Differentiation
  - MAC-Layer: Delay Differentiation
- Cross-Layer Interaction