Design and Evaluation of New Power Management Methods to Reduce Direct and Induced Energy Use of the Internet

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Agenda

- Introduction
- Reducing direct power consumption
- Reducing induced power consumption
- Contributions

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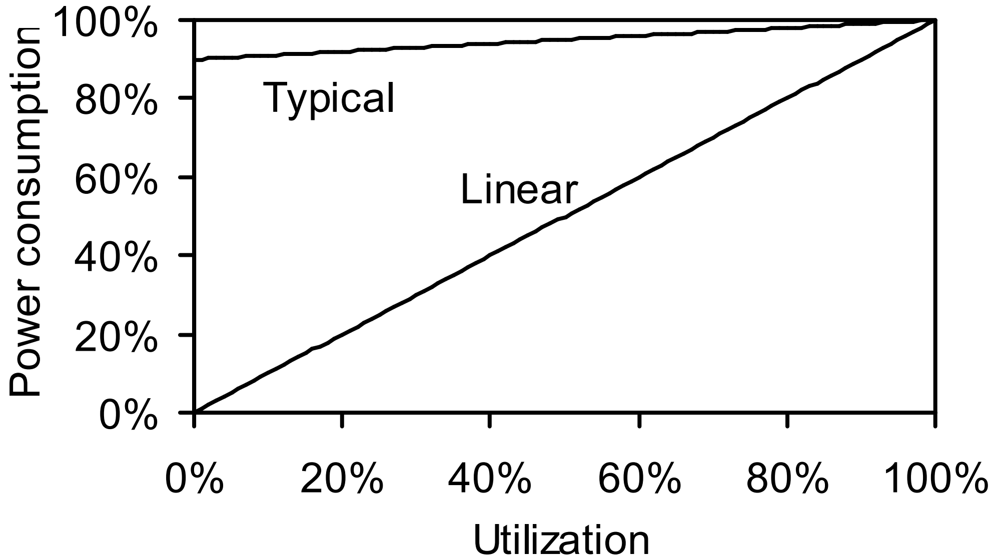
Introduction

- **This is the first investigation into reducing the power consumption of Ethernet links and network hosts**

- **Power consumption can be classified as:**
  - ***Direct* power consumption**
    - Power consumed by the network infrastructure of the Internet (e.g., links, switches, and routers)
  - ***Induced* power consumption**
    - Power consumed by network hosts that are inactive, but remain fully powered-on in order to maintain network connectivity

Direct power consumption

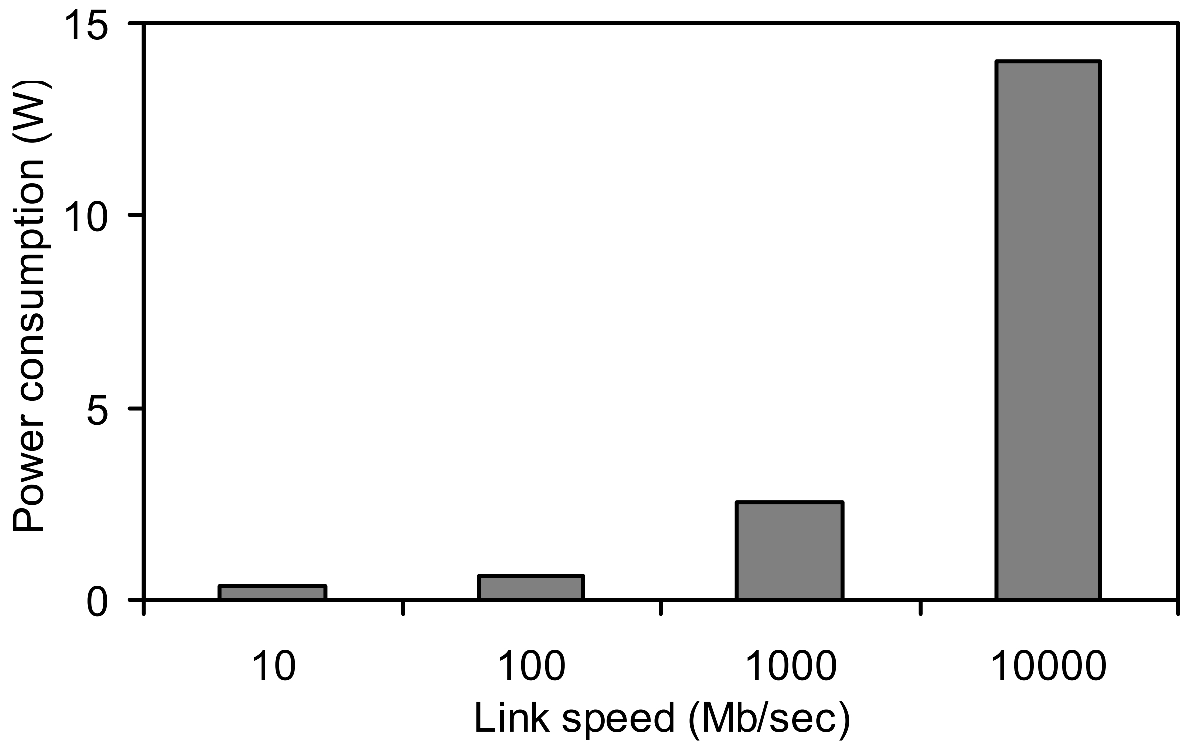
- **The Internet is a major consumer of electricity**
  - Estimated to be 7.5 TWh/yr in 2005 [108]
- **Average network utilization is low**
  - Typically less than 5% for edge Ethernet links
- **Power consumption is not linear with utilization**



Not in dissertation

Direct power consumption continued

- **Power consumption is increasing super-linearly**
  - Measurements of Ethernet NICs (average power consumption)



Induced power consumption

- **Network hosts are a major consumer of electricity**
  - Estimated to be 74 TWh/yr in 2001 [81]
- **Most desktop PCs in offices are powered-on 24/7**
  - Office desktop PCs are idle most of the time
  - 5% or less had power management enabled [105, 126]
- **Use of power management would save 17 TWh/yr**
  - Majority of savings would come from desktop PCs

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- **Reducing direct power consumption**
- Reducing induced power consumption
- Contributions

Adaptive Link Rate (ALR)

New contribution

- **Match Ethernet link rate to link utilization**
  – Energy is saved by operating at low link data rate
  – Consists of a *mechanism* and *control policy*

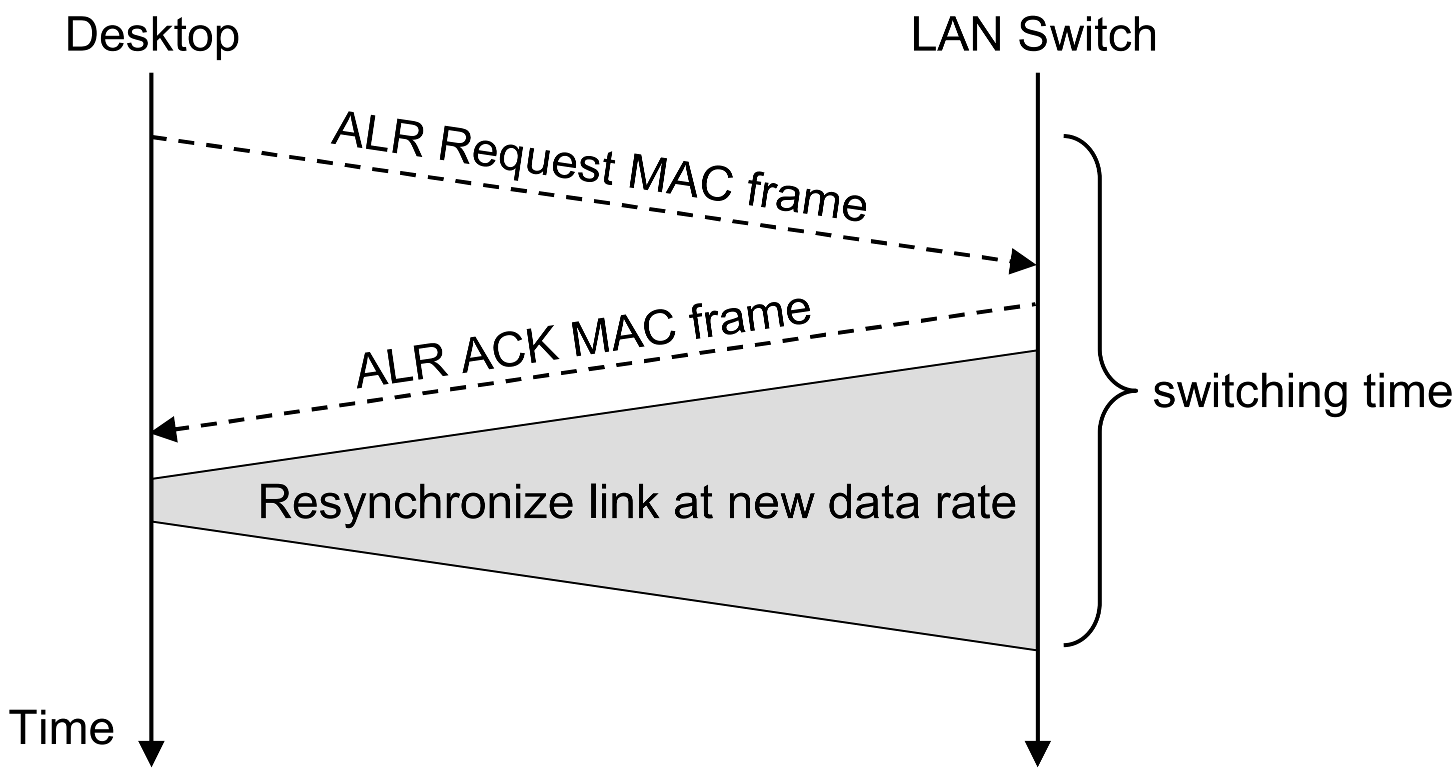
- **Mechanism**
  – How to switch link rate

- **Control policy**
  – When to switch link rate

- **ALR has a fundamental trade-off**
  – Packet delay vs. energy saved

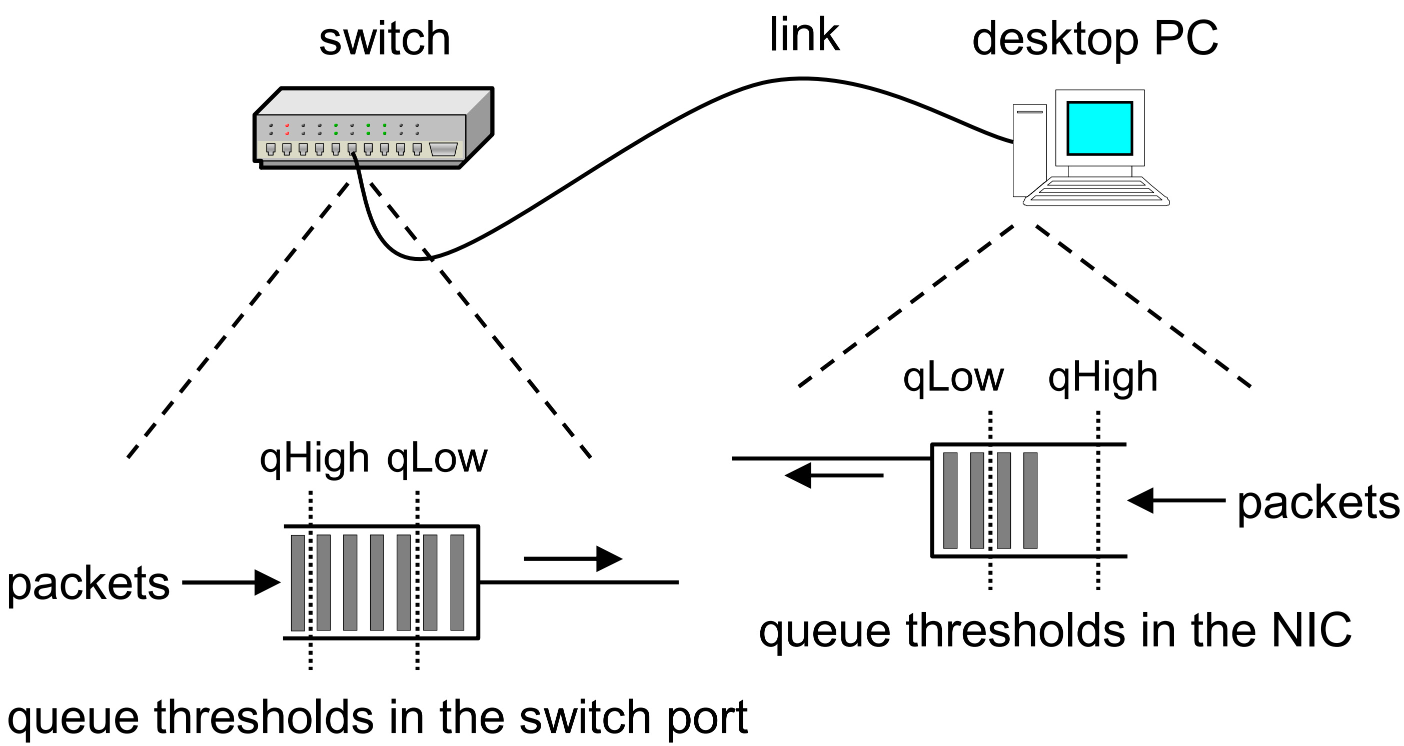
ALR mechanism

- **Mechanism implements link rate switching**
  - ALR must be implemented in both ends of an Ethernet link



ALR policy

- **Dual-threshold policy**
  - If queue is above qHigh then switch to high rate
  - If queue is below qLow then switch to low rate



Evaluation of dual-threshold policy

- **Control variables**
  - Threshold values
  - Utilization
  - Time to switch between link rates
- **Response variables**
  - Mean response time (mean packet delay)
  - Percentage of time in low data rate (energy saving)
  - Frequency of rate switches
- **First, Markov models were created**
  - Poisson arrivals and exponential service times assumed
- **Next, simulation models were created**
  - Actual traced Ethernet traffic used

Markov models

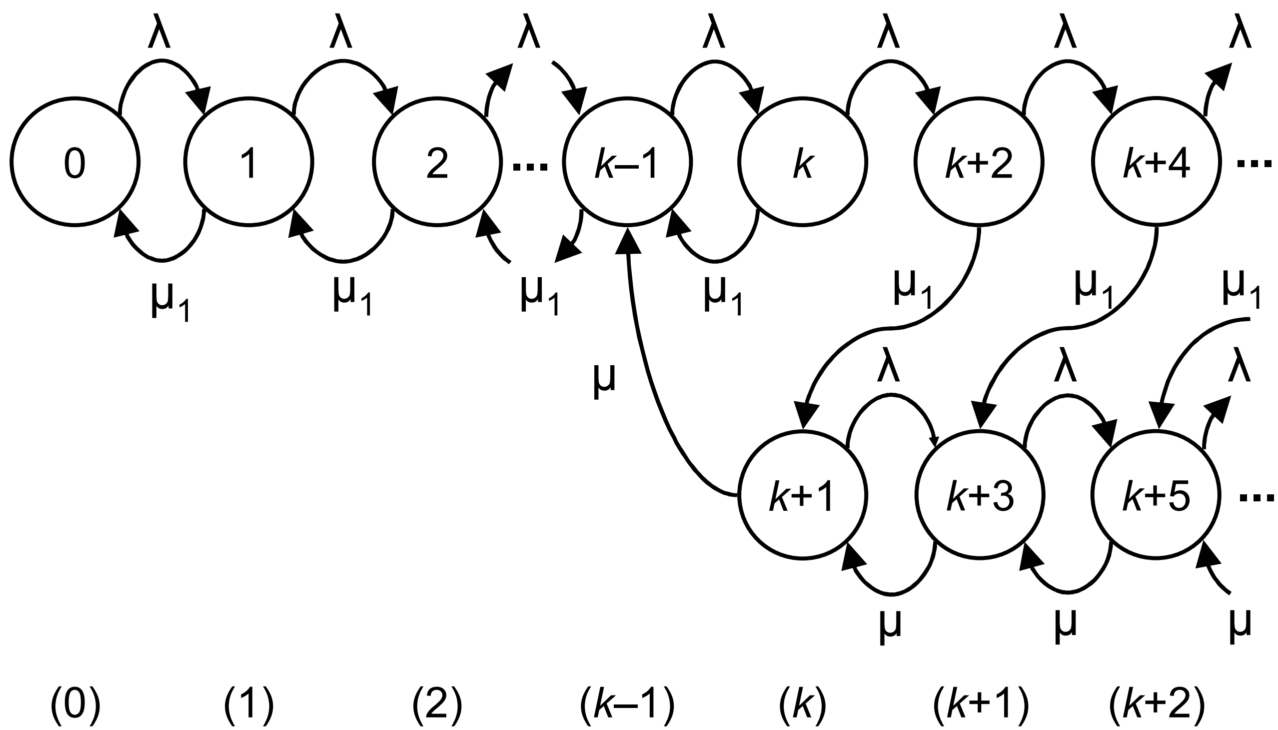
- **The following was modeled**
  - One and two thresholds
  - Rate switch *during service* and at *completion of service*
    - Rate switching time is zero

- **Switch at *completion of service* models packets**
  - Rate cannot switch until current packet is fully transmitted

- **Four Markov models**
  - #1: Single-threshold, rate switch during service
  - #2: Dual-threshold, rate switch during service
  - #3: Single-threshold, rate switch at completion of service
  - #4: Dual-threshold, rate switch at completion of service

Markov model #3

- **Single threshold, rate switch at completion of service**
  - Discovered later that same model was developed by Chong and Zhao [22] for CPU control



Markov model #3 continued

- **Model can be solved directly using global balance**
  - Requires two recursive equations and many steps
- **Dr. Suen identified a key relationship**

$$\pi_k = \left(\frac{\lambda}{\lambda + \mu_1} \right) \pi_{k-1}$$

- **This relationship enabled a solution with less steps**
  - Requires one recursive equation and fewer steps
- **This solution method "scales" to the next model**
  - Dual thresholds (Model #4)

Markov model #3 continued

- **Direct solution is novel**
  - Mean number in system (*L*) is solved numerically

$$P_n = \begin{cases} P_0 \rho_1^n & (0 \le n < k) \\ \dfrac{P_0 \rho_1^{k-1}}{\rho + \rho/\rho_1 - 1} \left(\rho^{n-k+2} - \left(1 - \dfrac{\rho}{\rho_1}\right) \left(\dfrac{\rho_1}{1+\rho_1} \right)^{n-k+1} \right) & (n \ge k) \end{cases}$$

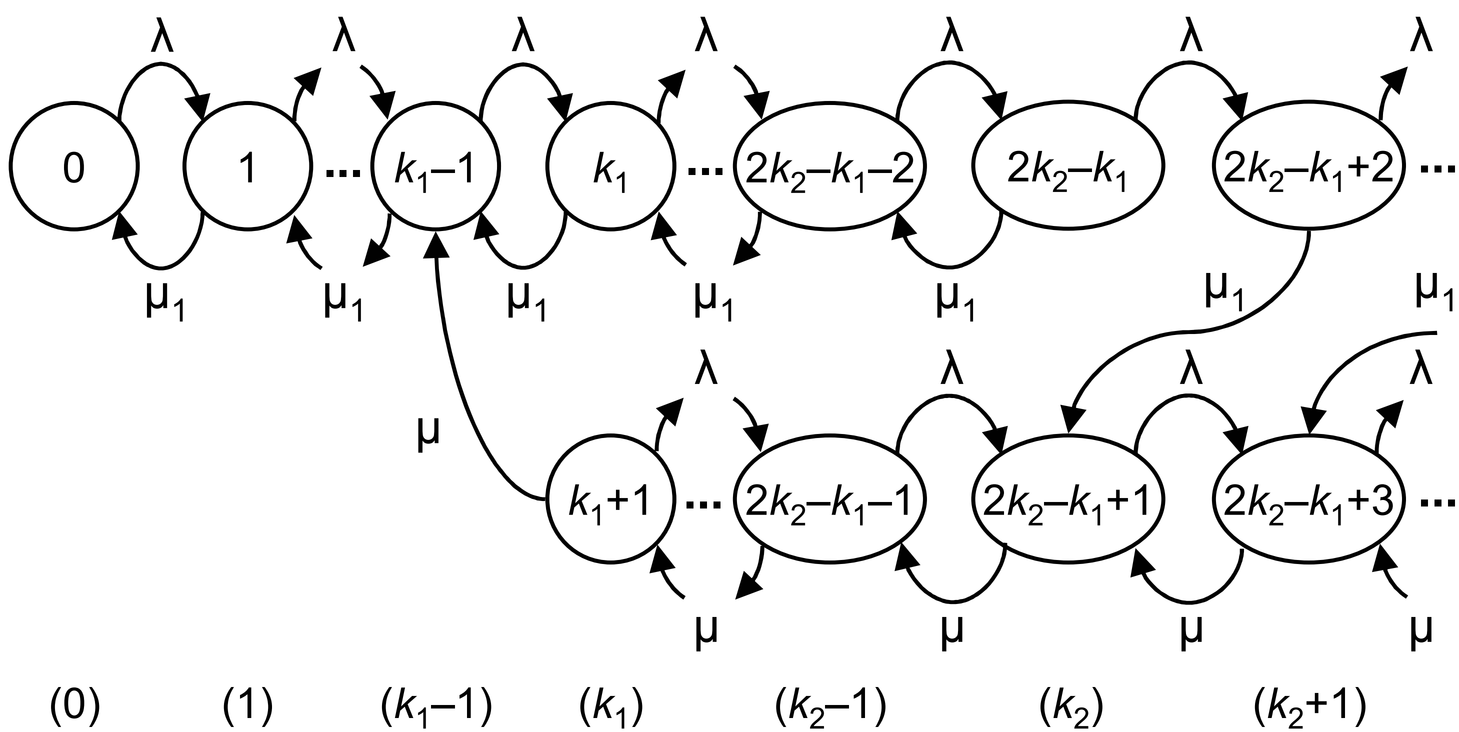
$$P_0 = \left(\frac{1-\rho_1^k}{1-\rho_1} + \frac{\rho_1^k}{1-\rho} \right)^{-1}$$

Derivation is in Chapter 5

Markov model #4

New contribution

- **Dual-threshold, rate switch at completion of service**



Markov model #4 continued

Derivation is in Appendix A

- **Direct solution was achieved**
  - Solved similarly to previous model
  - Mean number in system (*L*) is solved numerically

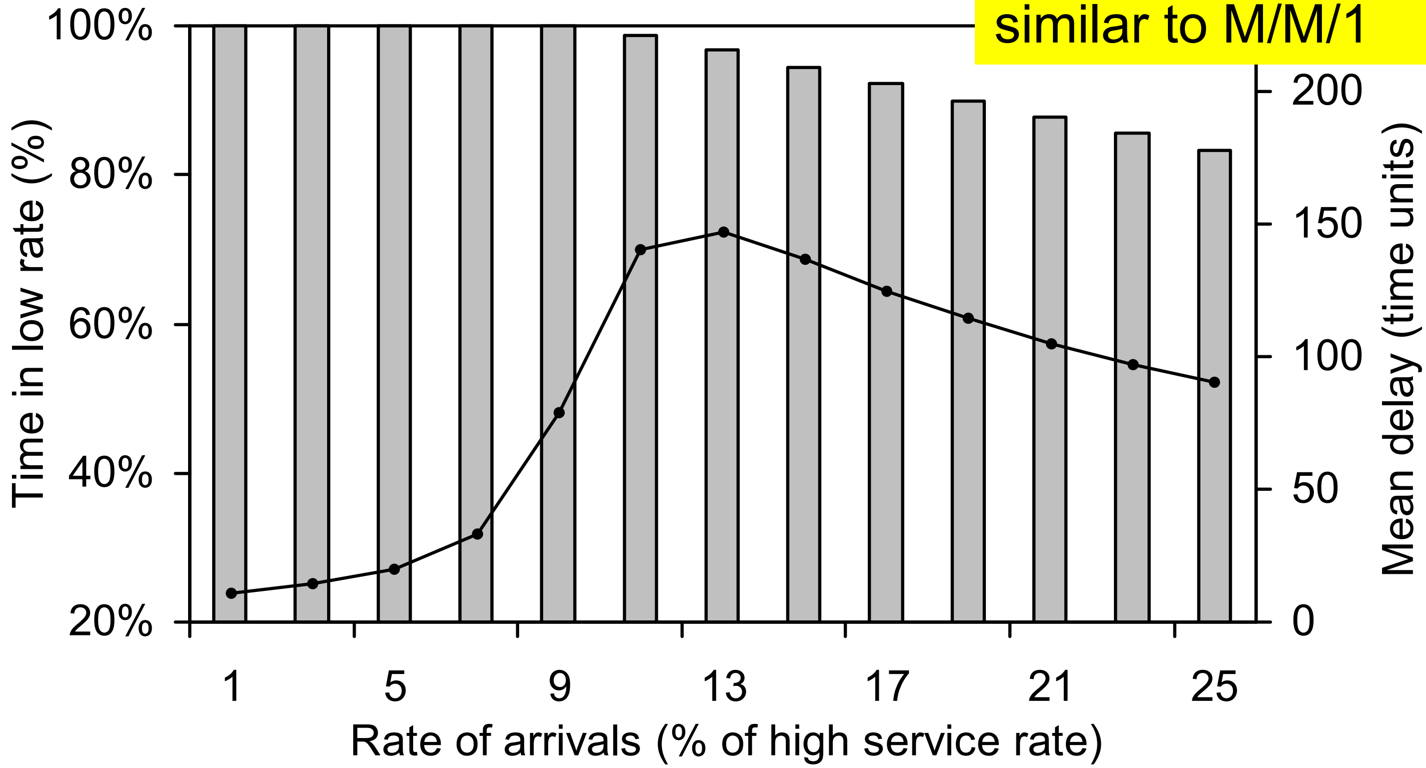
$$
P_n = \begin{cases}
P_0 \rho_1^n & (0 \le n < k_1) \\[2ex]
\dfrac{P_0 \rho_1^{k_1-1}\left(1 - 1/\rho_1\right)}{1 - 1/\rho_1^{k_2-k_1+2}} \left(\dfrac{1 - 1/\rho_1^{k_2-n+1}}{1 - 1/\rho_1} + \dfrac{\rho\left(1-\rho^{n-k_1+1}\right)}{1-\rho} \right) & (k_1 \le n < k_2) \\[2ex]
\dfrac{P_0 \rho_1^{k_1-1}}{1 - 1/\rho_1^{k_2-k_1+2}} \left(\rho^{n-k_2+1} \left(\dfrac{\left(1-1/\rho_1\right)\left(1-\rho^{k_2-k_1}\right)}{1-\rho} - \dfrac{1-1/\rho_1^2}{1-\rho-\rho/\rho_1} \right) + \dfrac{\left(1-1/\rho_1^2\right)\left(1-\rho/\rho_1\right)}{1-\rho-\rho/\rho_1} \left(\dfrac{\rho_1}{1+\rho_1} \right)^{n-k_2+1} \right) & (n \ge k_2)
\end{cases}
$$

$$
P_0 = \left(\frac{1-\rho_1^{k_1}}{1-\rho_1} + \frac{1}{1-\rho_1^{k_2-k_1+2}} \left(\frac{\rho_1^{k_2} - \rho_1^{k_1}}{\rho_1 - 1} + \frac{\rho_1^{k_2}\left(\left(k_2 - k_1\right)\left(\rho_1 - \rho\right) + \rho_1^2 - 1\right)}{\rho - 1} \right) \right)^{-1}
$$

Results from Markov model #4

- **Numerical results for switching time of zero**
  - "time unit" = mean service time at high rate

At low utilization, behavior similar to M/M/1

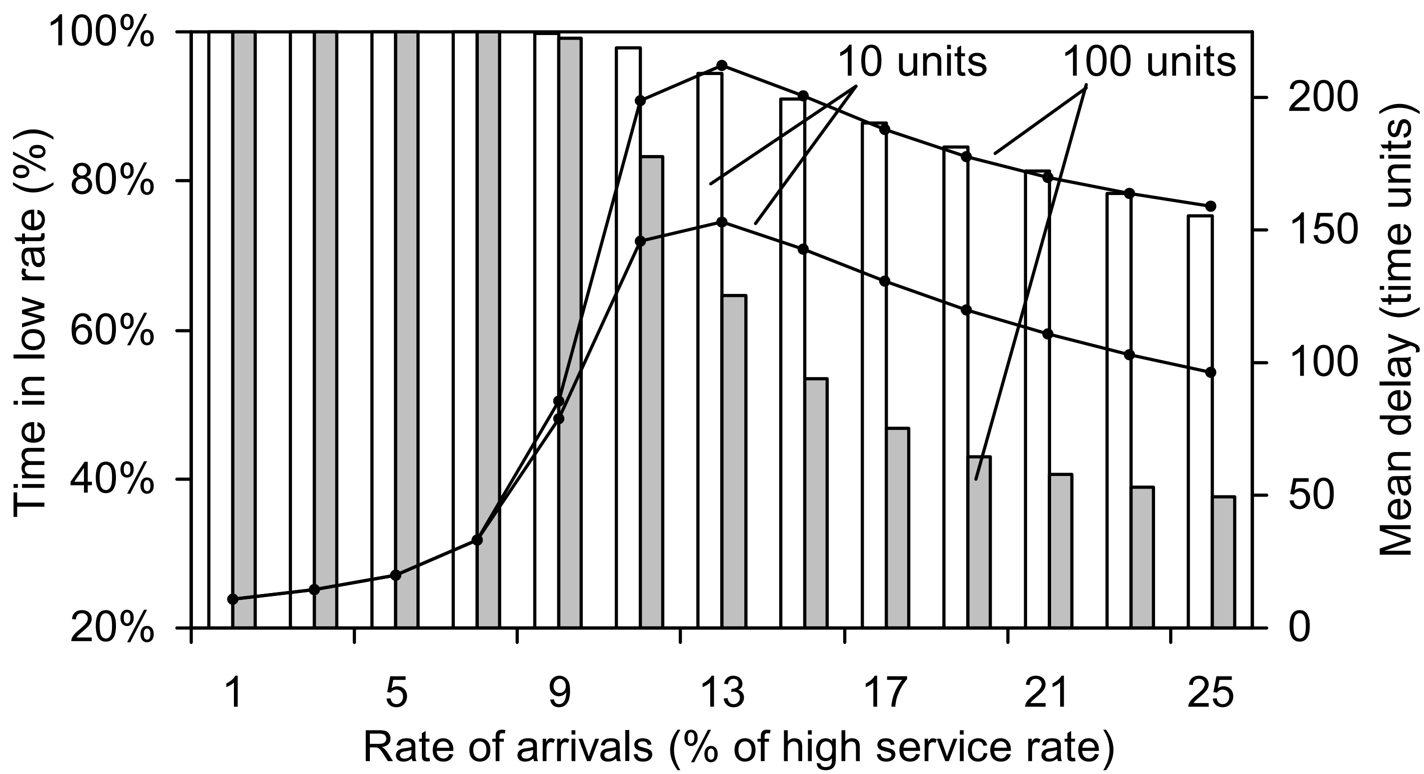


Simulation model

- **Evaluate ALR with a simulation model**
  - Built a queueing model using CSIM19
    - Validated against numerical results from Markov model
  - Can use Poisson and trace traffic inputs
  - Can model non-zero rate switching time

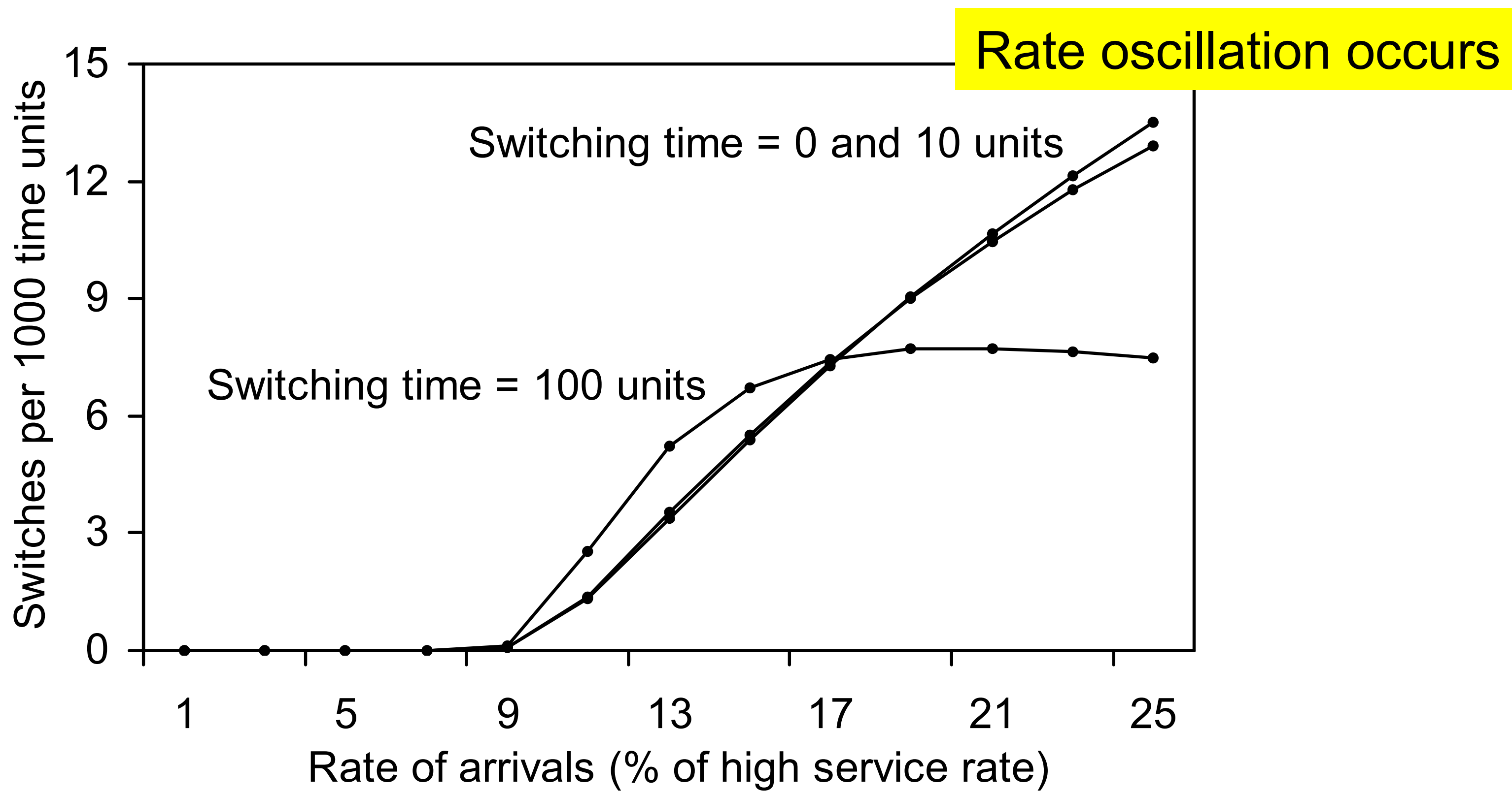
Results using Poisson traffic

- **Simulation results for non-zero switching time**
  - "time unit" = mean service time at high rate



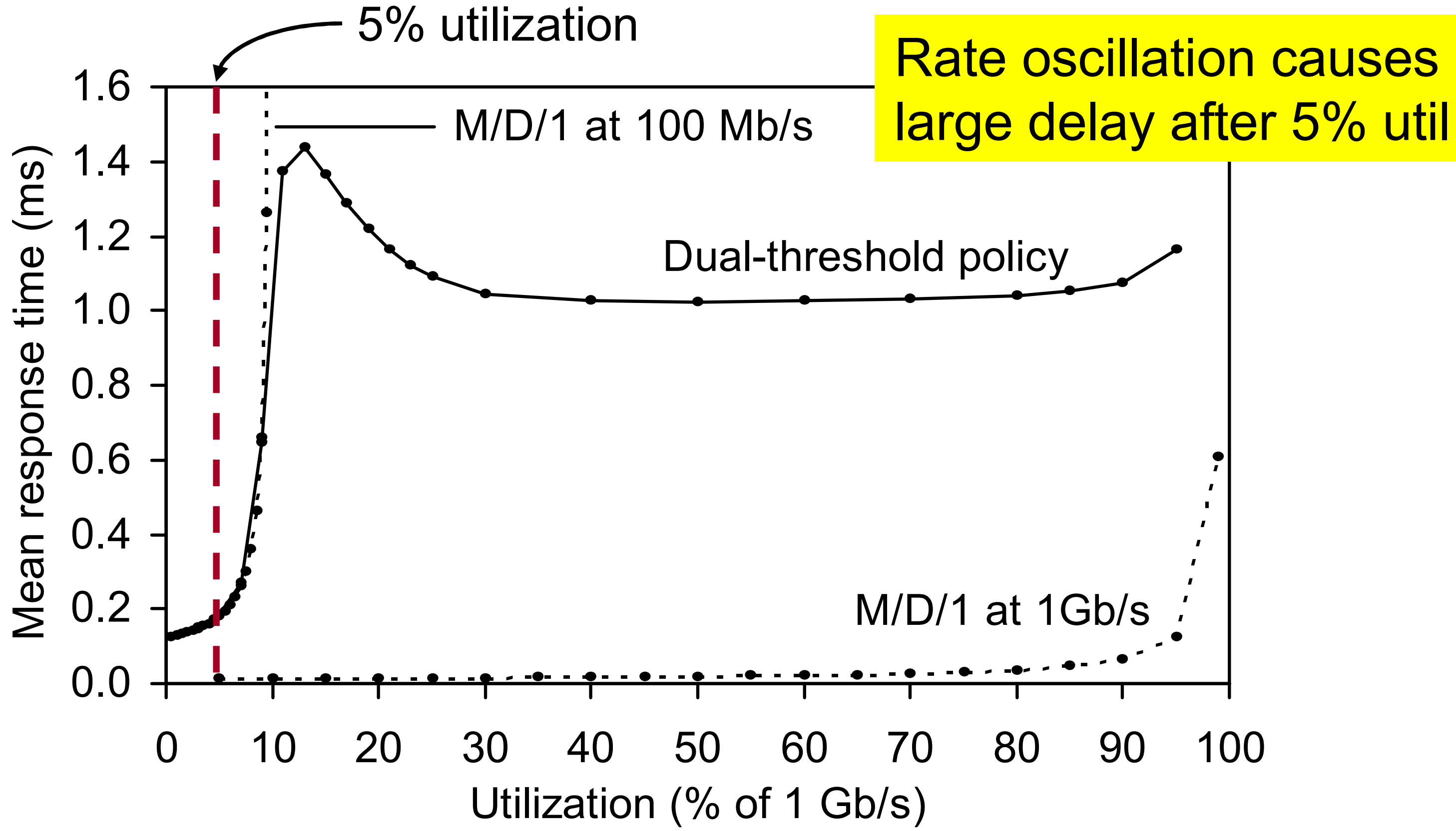
Results using Poisson traffic <u>continued</u>

- **Simulation results for non-zero switching time**



Results using Poisson traffic <u>continued</u>

- **More results for non-zero switching time**
  - Poisson arrivals, fixed length packets (M/D/1), 1 ms switch time



Results using trace traffic

- **Characteristics of trace traffic**
  - Note very low average utilization

Trace	Duration	Description	Avg util.
USF #1	0.5 hours	Link to "busiest" user in USF	4.11 %
USF #2	0.5	Link to 10th busiest user	2.63
USF #3	0.5	Link to an average user	0.03
PSU #1	2.0	Link to a desktop PC	0.13
PSU #2	2.0	Link connecting two switches	1.01
PSU #3	2.0	Link connecting switch to router	1.03

Results using trace traffic <u>continued</u>

- **Results for all traces without and with ALR**
  - Showing mean packet delay

Trace	10 Mb/s	100 Mb/s	ALR	
USF #1	7.60 ms	0.09 ms	2.79 ms	99.42 %
USF #2	3.95	0.08	1.81	99.81
USF #3	196.29	0.05	1.48	99.99
PSU #1	33.51	0.18	5.63	99.98
PSU #2	2321.31	0.12	9.55	99.12
PSU #3	1147.83	0.51	4.07	99.83

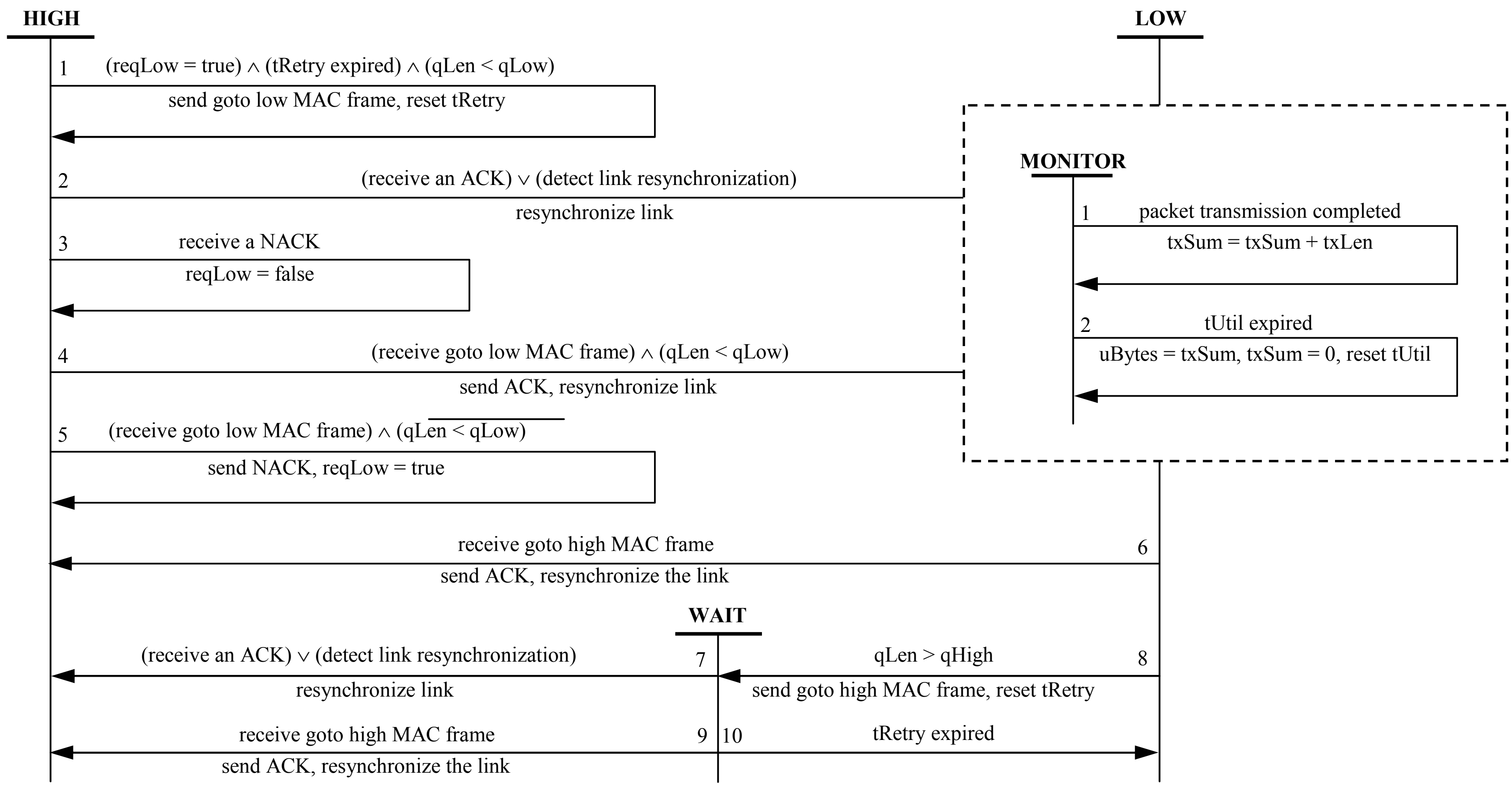
Time in 10 Mb/s

Improved ALR policy

- **ALR policy must prevent oscillation between rates**
  - Oscillation causes excessive packet delay
- **Utilization-threshold policy**
  - Use high threshold to increase link rate
  - Use explicit utilization measurement to reduce link rate

ALR utilization-threshold policy

- **Detailed FSM (Figures 6.1 and 6.2 in dissertation)**



Not in dissertation

ALR utilization-threshold policy continued

- **Simplified description**

Executes on receiving a frame

```
if (link rate is low)
  if (buffer size exceeds qHigh threshold)
    handshake for high link rate
```

Executes periodically at end of dampening time period (tUtil)

```
if (link rate is high)
  if (buffer size less than qLow threshold)
    if (bytes sent less than byte count threshold)
      handshake for low link rate
```

Comparison of ALR policies

- **Link data rate oscillations are compared**
- **Number of data rate oscillations can be calculated**
  - For dual-threshold policy – given by (5.27)

$$N_{dual} = \mu\pi_{k_1+1} + \sum_{n=1}^{\infty} \mu_1 \pi_{2k_2-k_1+2n}$$

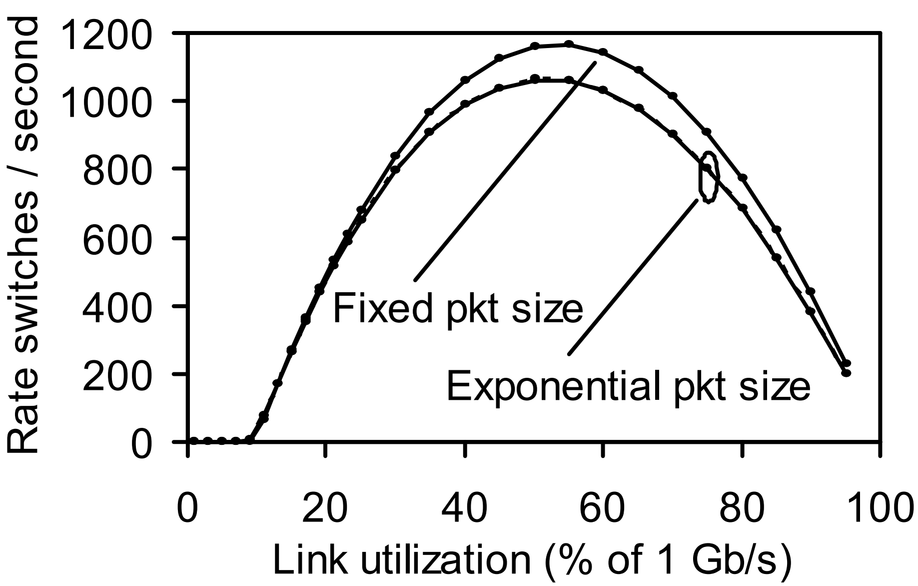
  - For utilization-threshold policy – given by (6.1) and (6.2)

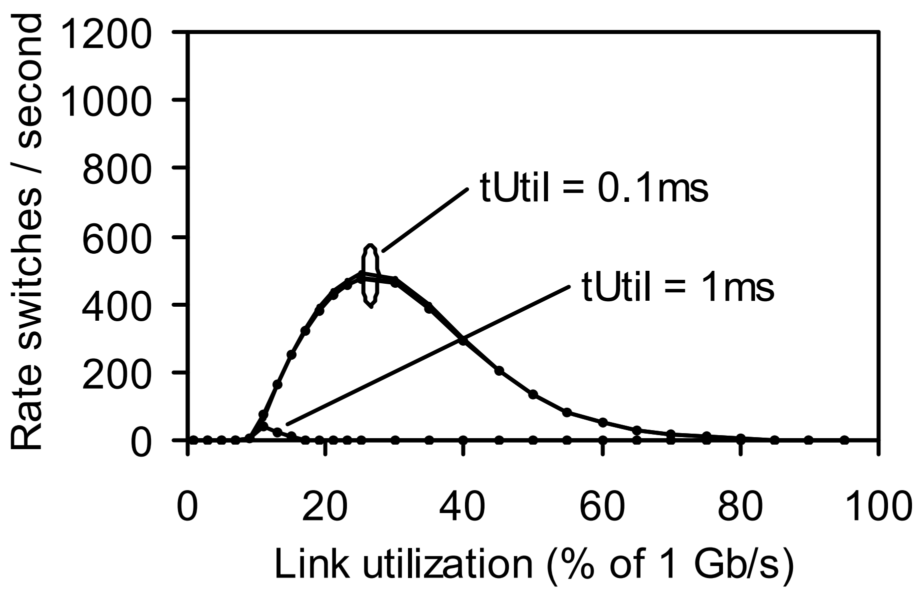
$$N_{oscilUtil} = 2\left(T_{passLow} + T_{passHigh} + \frac{tUtil}{q\sum_{n=0}^{k_1-1}\pi_n} \right)^{-1}$$

Comparison of ALR policies <u>continued</u>

- **Link date rate oscillations for both policies**
  - From calculations and simulations

- **Utilization-threshold policy has lower oscillations**
  - Poisson arrivals, service rates correspond to 1Gb/s and 100Mb/s





Evaluation of utilization-threshold policy

- **Control variables**
  - Threshold values
  - Utilization
  - Utilization sample time (tUtil timer)
  - Utilization byte count threshold value (uThresh)
- **Response variables**
  - Mean response time (mean packet delay)
  - Percentage of time in low data rate (energy saving)
- **Dual-threshold model was modified**
  - Developed realistic synthetic traffic generator

Traffic generator

New contribution

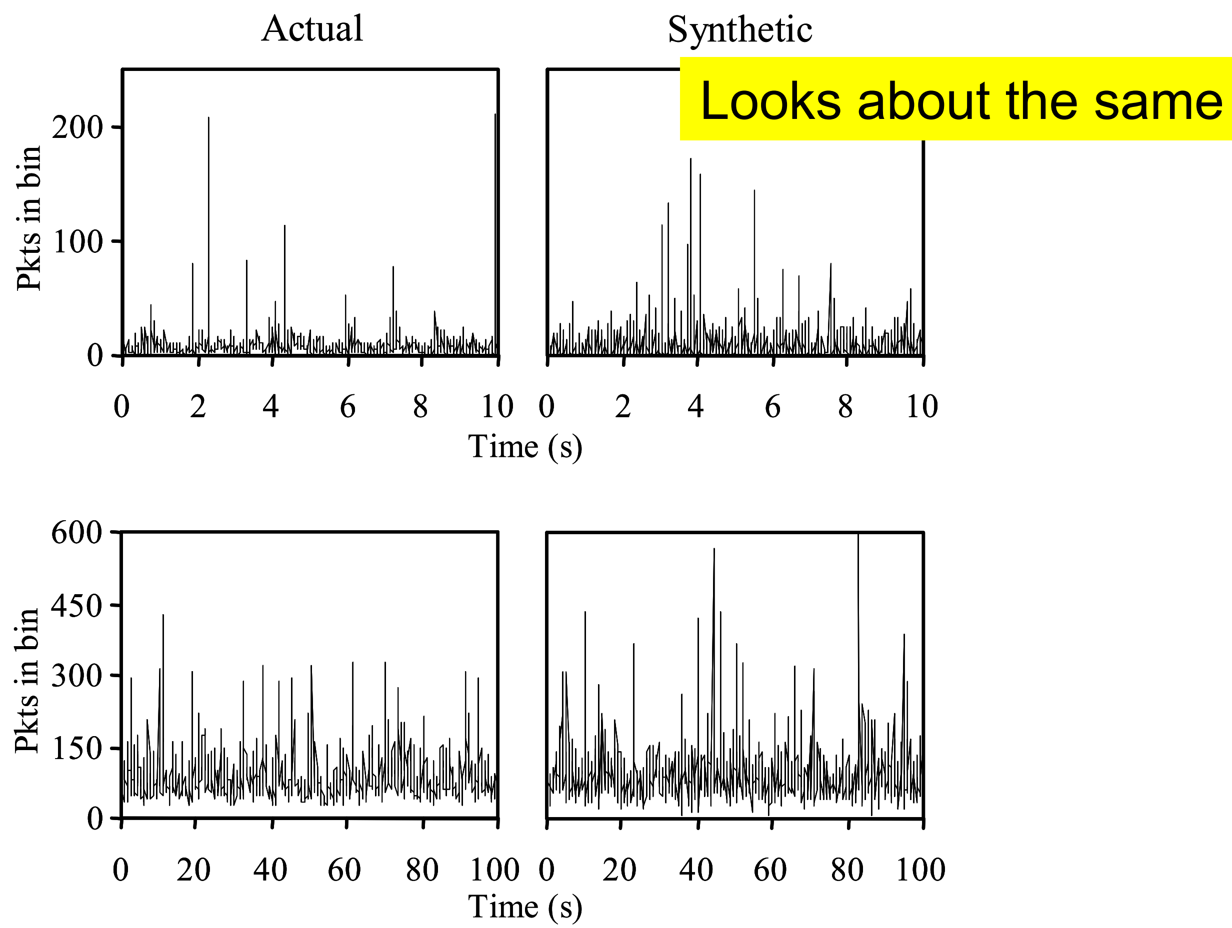
- **Developed a synthetic traffic generator**
  - Able to match most characteristics of traced traffic
    - Including utilization, burst length, CoV, and Hurst parameter

- **Generates synthetic bursty traffic**
  - Pareto burst size and exponential inter-burst time

- **Key parameters of traffic generator**
  - Data rate (100 Mb/s, 1 Gb/s, and 10 Gb/s)
  - Minimum and maximum burst size
  - Pareto index for bursts
  - Burst intensity
  - Packet length distribution
  - Mean utilization

Traffic comparison

- **Subjective visual comparison to traced traffic**



Traffic comparison <u>continued</u>

- **Objective measurement comparison to traced traffic**
  - Synthetic versus traced for 100 Mb/s

Close to the same

Characteristic	Actual	Synthetic
Mean inter-packet time (ms)	1.10	1.06
CoV of inter-packet times	1.76	3.81
Mean packet size (bytes)	577	526
CoV of packet size	1.16	1.15
Hurst parameter of packet counts	0.66	0.64
Utilization (% of 100 Mb/s)	4.11	3.95

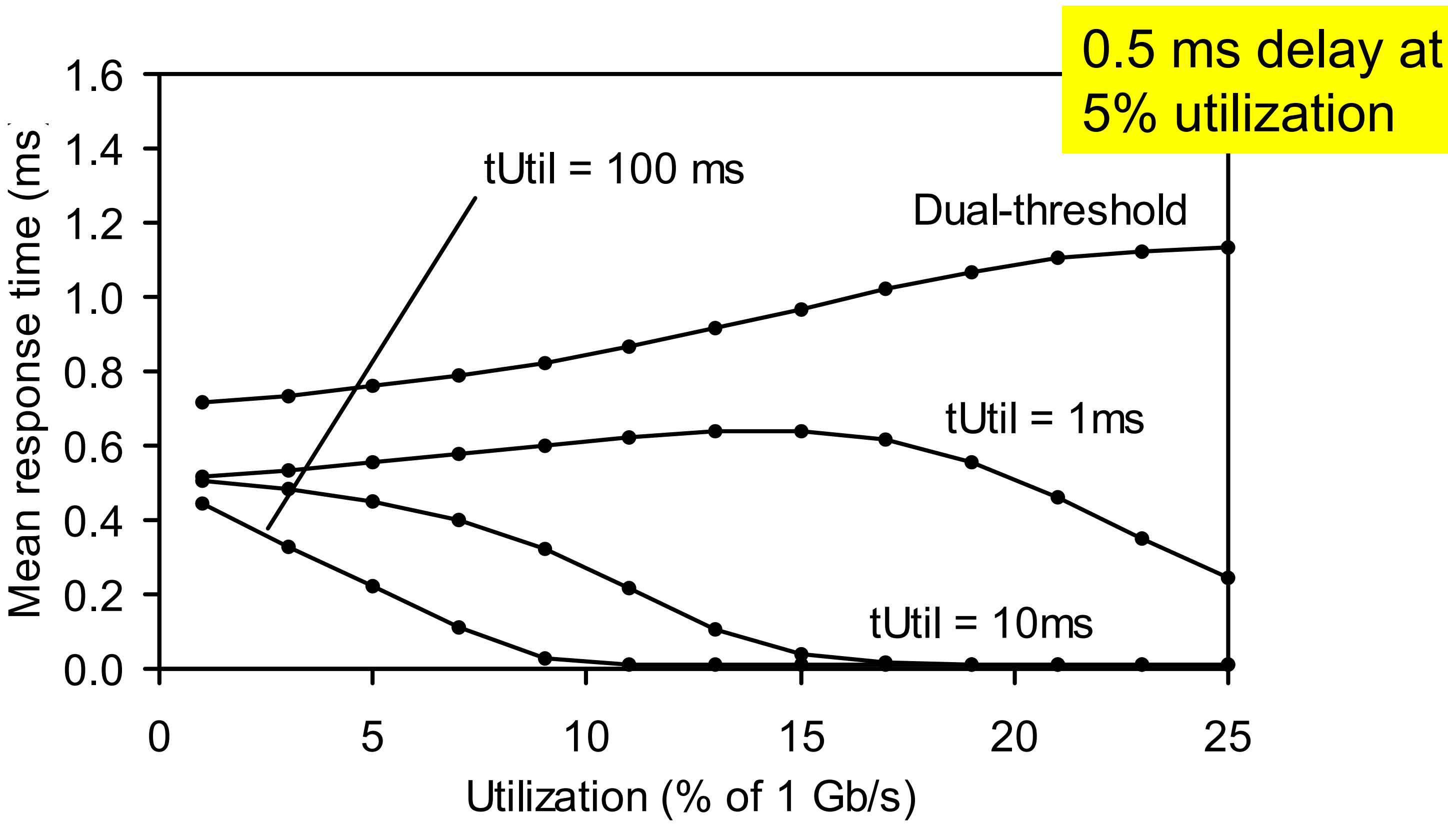
Simulation experiments

Rate switch time is 1 ms in all cases

- **Smooth traffic experiment**
  – Poisson arrivals, fixed length packets, utilization is varied
- **Single burst experiment 1**
  – One burst (Poisson) at 80% utilization and 0.4 s duration
- **Single burst experiment 2**
  – One burst (Poisson) at 80% utilization, length is varied
- **Bursty traffic experiment**
  – Bursty (mean burst = 8.4 KiB), utilization is varied
- **LAN switch experiment**
  – Use bursty traffic as input to a LAN switch model
  – Power consumption figures from Cisco Catalyst 2970
    - With no links = 46 W, each 100 Mb/s link is 0.3 W, 1 Gb/s 1.8 W
    - Measurements made at University of Florida

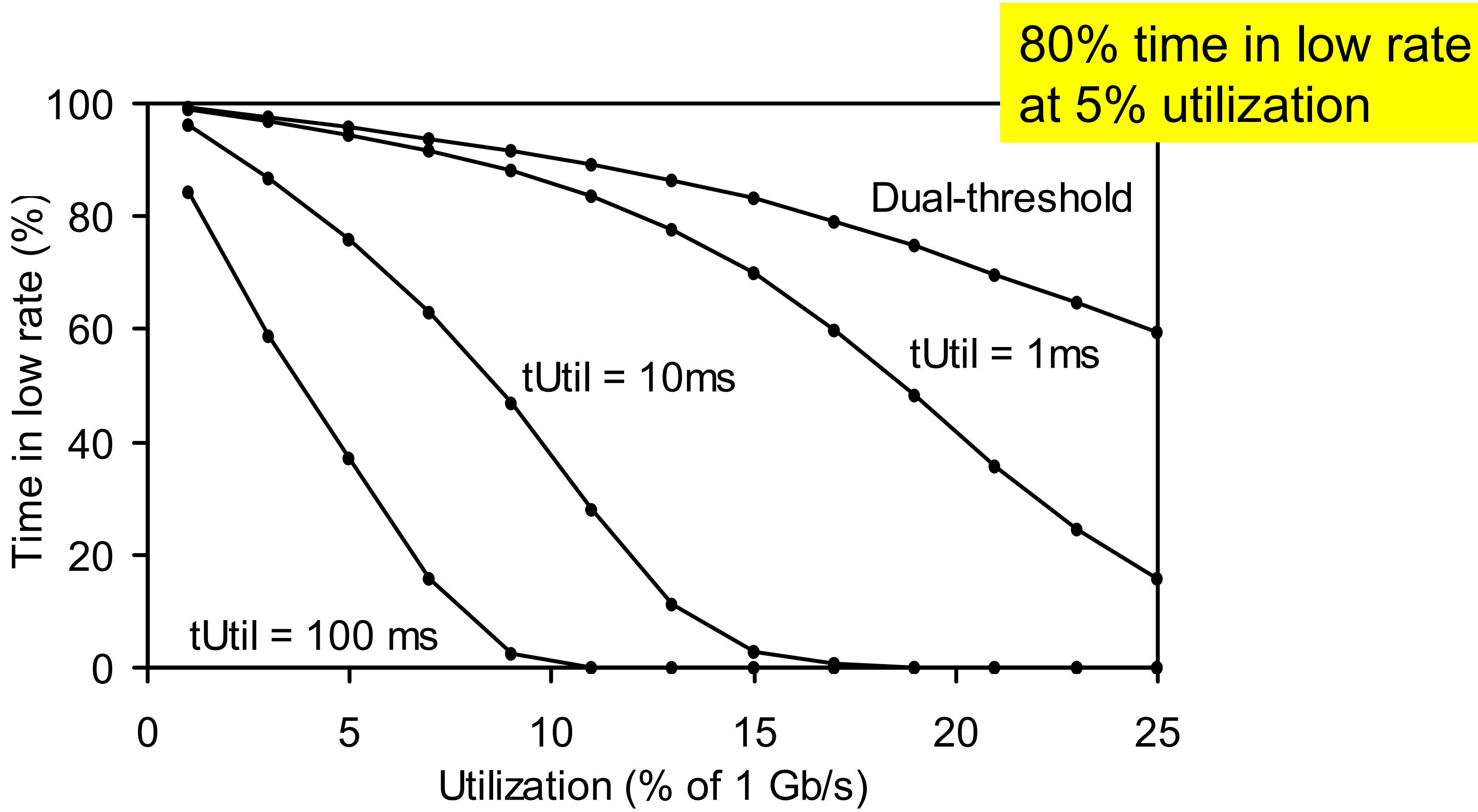
Bursty traffic experiment results

- **Mean response time (packet delay)**



Bursty traffic experiment results <u>continued</u>

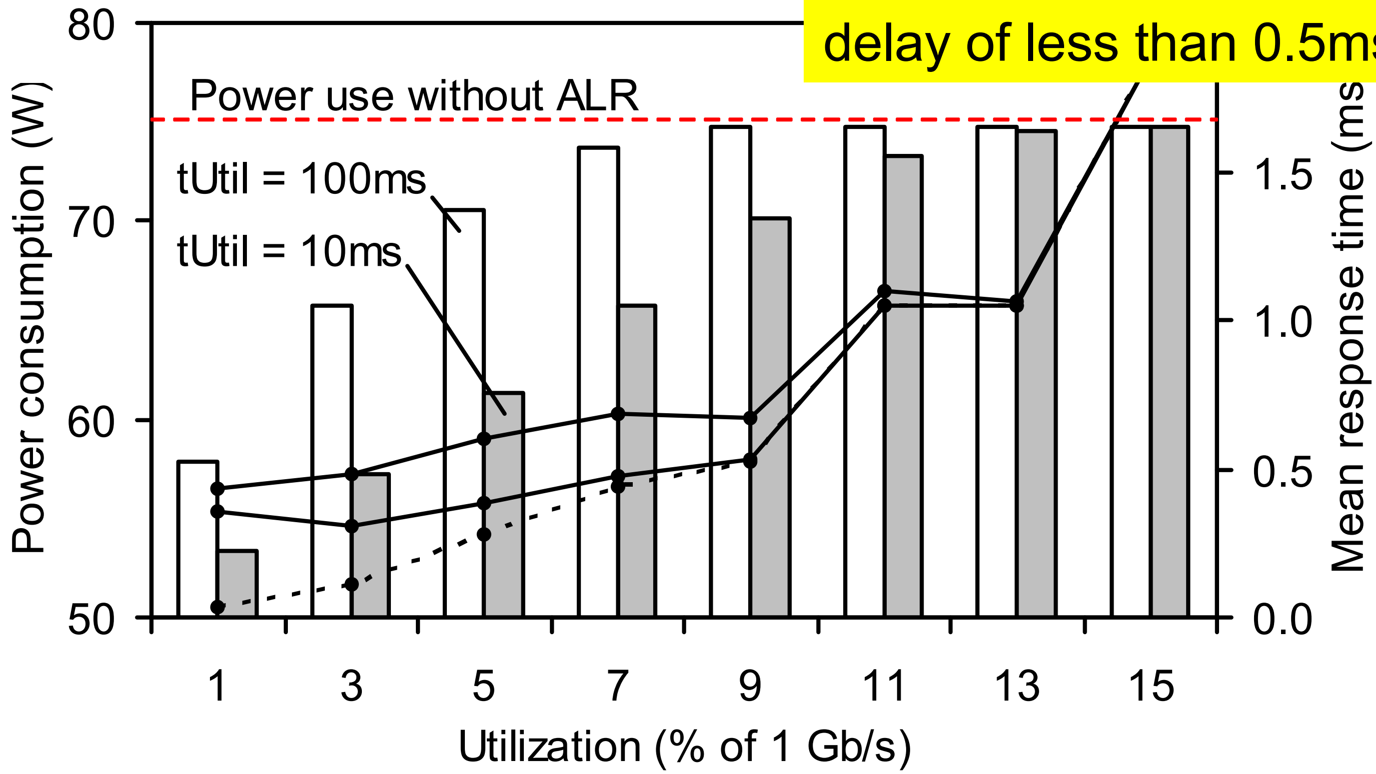
- **Time in low data rate (energy saving)**



LAN switch experiment results

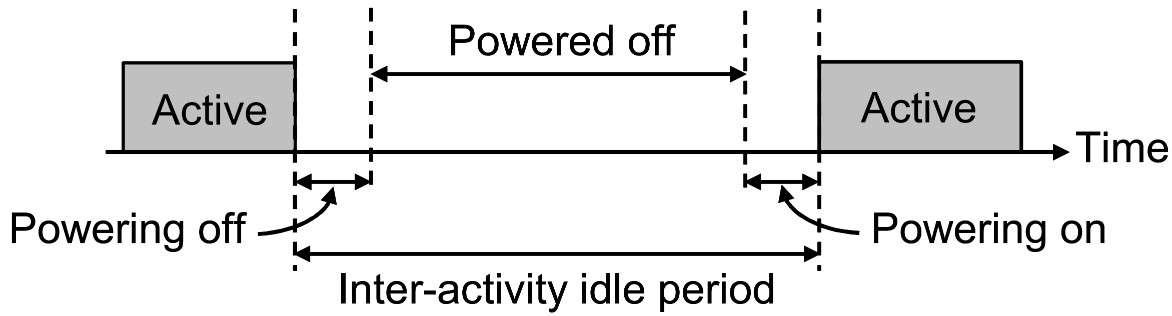
- **Power use and delay in one graph**
  - Shows trade-off

20% energy savings at 5% utilization with an added delay of less than 0.5ms



Powering off during idle periods

- **Energy can be saved by powering off when idle**
  – Key is detecting "long enough" idle periods



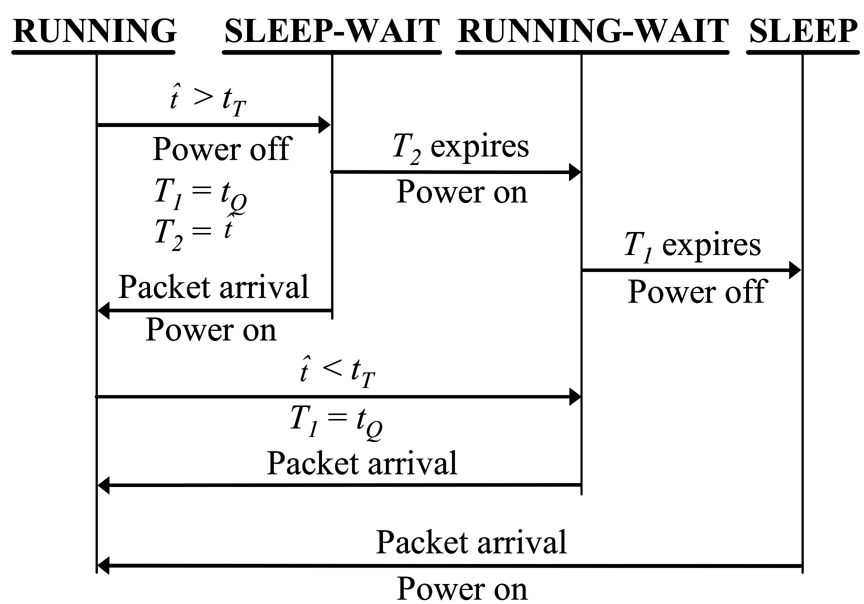
- **In networks, a few idle periods have most idle time**
  – In 3 of 4 traces, 10% of idle periods have over 50% of idle time

Powering off during idle periods

New contribution

- **Quantiles used to detect "long" idle periods**
  - If idle period extends beyond a threshold, then sleep
  - Quantile estimation is used to determine threshold t_Q
  - Powers on when request arrives

- **Performance evaluation**
  - Less powered off time than Hwang and Wu [59]
  - But, performance is better when forced wake-up is considered



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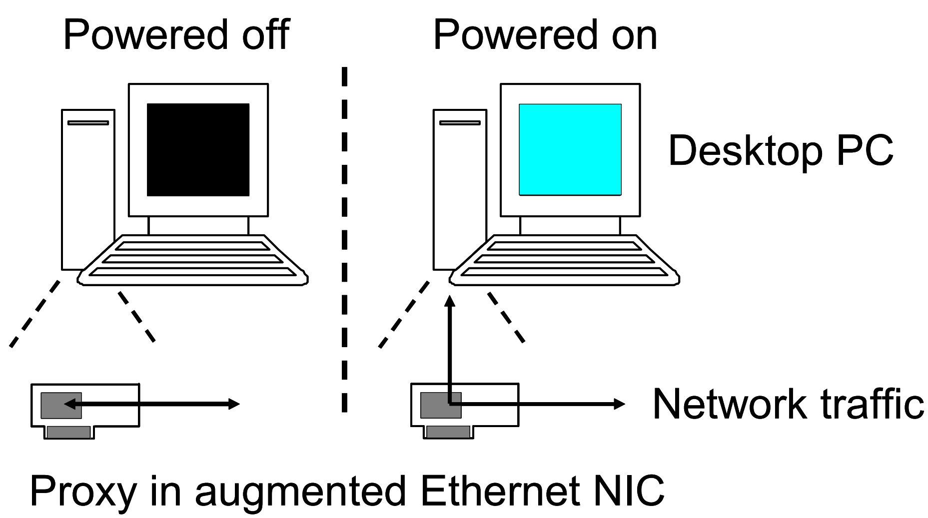
A first look at protocol proxying

New contribution

- **Proxy capability in NIC to allow host to goto sleep**
  - Respond to ARP, ICMP messages when host is powered off
    - Maintain “network presence”
  - Wake up the PC when is services are needed



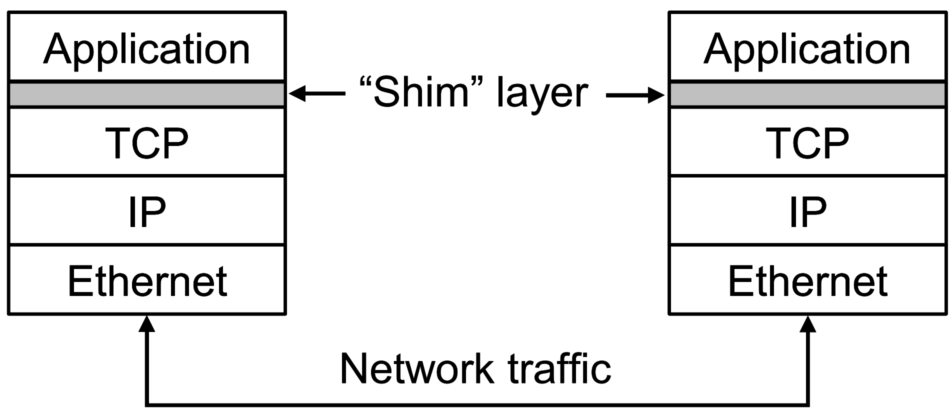
A first look at protocol proxying <u>continued</u>

- **Built a prototype proxy for a Web server**
  - Demonstrated feasibility of the idea

A first look at TCP connections

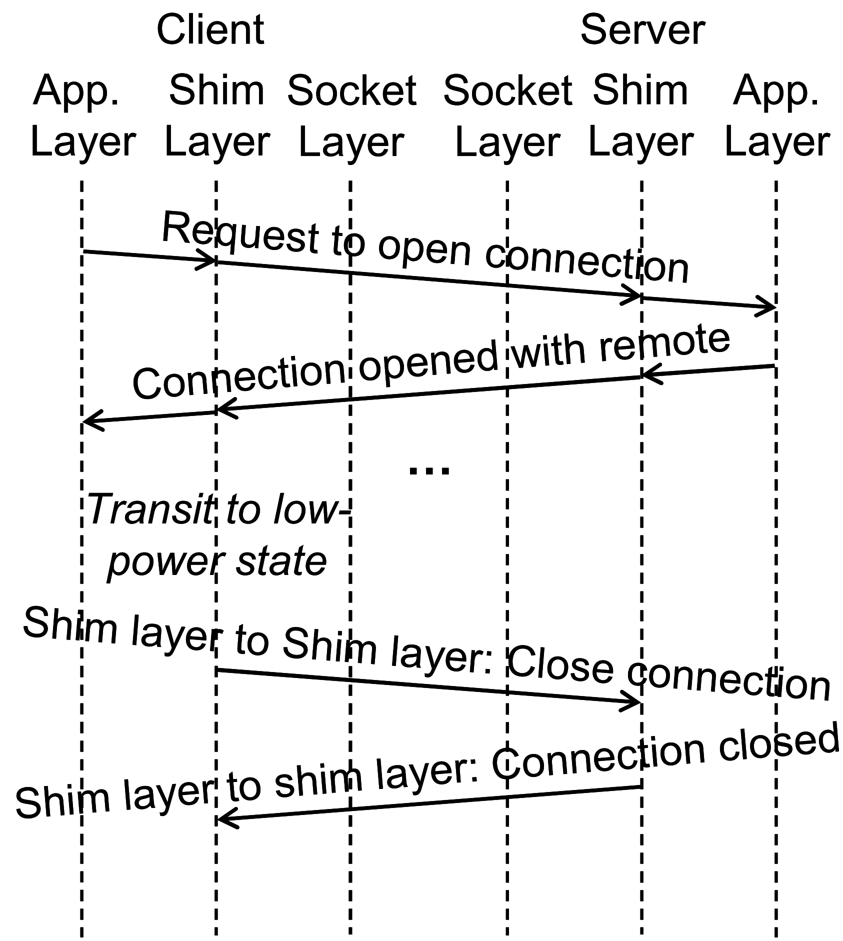
- **Long-lived TCP connections prevent power-off**
  - Need to respond to “keep-alive” messages
  - Lack of response leads to dropped connections

- **A prototype “shim” layer is developed**
  - Drops/resumes connections without application awareness
  - Permits the network host to power off



A first look at TCP connections continued

- **Built prototype "shim" using Telnet client and server**
  - Feasibility demonstrated



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Contributions

1. **The first method for reducing power consumption of Ethernet links**
   - ALR is expected to be an IEEE 802.3 standard!
2. **The first model and solution for a dual-threshold state-dependent service rate queue with rate change at service completion**
3. **A better synthetic Ethernet traffic generator**
4. **An improved idle period detection method using quantile estimation**
5. **Demonstrated feasibility of protocol proxying and splitting a TCP connection**

Publications from this work

1. **C. Gunaratne**, K. Christensen, S. Suen, and B. Nordman, "Reducing the Power Consumption of Ethernet with Adaptive Link Rate (ALR)," *IEEE Transactions on Computers*, to be submitted in December 2006.

2. **C. Gunaratne**, K. Christensen, and S. Suen, "Ethernet Adaptive Link Rate (ALR): Analysis of a Buffer Threshold Policy," *Proceedings of IEEE GLOBECOM 2006*, November 2006. (Acceptance rate = 40%)

3. **C. Gunaratne** and K. Christensen, "Ethernet Adaptive Link Rate: System Design and Performance Evaluation," *Proceedings of the 31st IEEE Conference on Local Computer Networks*, pp. 28-35, November 2006. (Acceptance rate = 35%)

4. **C. Gunaratne**, K. Christensen, and B. Nordman, "Managing Energy Consumption Costs in Desktop PCs and LAN Switches with Proxying, Split TCP Connections, and Scaling of Link Speed," *International Journal of Network Management*, Vol. 15, No. 5, pp. 297-310, September/October 2005. (Acceptance rate = 29%)

5. **C. Gunaratne** and K. Christensen, "A New Predictive Power Management Method for Network Devices," *IEE Electronics Letters*, Vol. 41, No. 13, pp. 775-777, June 2005. (Acceptance rate = low)

6. K. Christensen, **C. Gunaratne**, B. Nordman, and A. George, "The Next Frontier for Communications Networks: Power Management," *Computer Communications*, Vol. 27, No. 18, pp. 1758-1770, December 2004. (Acceptance rate = 26%)