Energy-aware networks

A tutorial on Green Networking

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Before starting...

Focus of this tutorial

- *What is this tutorial about...* vs. what is out of scope
  - *Interconnected devices and protocols...* vs. standalone devices
  - *Interconnected routers...* vs. data center servers and end-user PCs
  - *Wired networking...* vs. wireless

Aim of this tutorial

- Give you a two levels vision
  - Broad overview
  - In-depth focus
  - hence, difficult other than pointless to cover all in details
- Give you interesting pointers
  - Rich 70+ items bibliography
  - Seminal work, follow ups, related work in close areas
- Reasonably up to date
  - Many, but not all, recent work
  - Latest updates are not included (eg 2010 conferences upcoming november SI of IEEE CommMag)

Agenda (1/2)

- Motivations
- Definition of Green networking
  - Environmental, economical, regulator, engineering
- Key paradigms
  - Proportional Computing
  - Resource Consolidation
  - Selected Connectedness
  - Virtualization
- Taxonomical criteria
  - Timescale, scope, OSI layer, approach, branch, etc.

Agenda (2/2)

- Taxonomy of Green Networking research:
  - Adaptive Link Rate
  - Interface Proxying
  - Energy Aware Infrastructure
  - Energy Aware Applications

  with focus on selected work
- A few words on:
  - Power measurement and modeling
  - Data centers and user devices
  - Parallels with wireless world
- Conclusion and future research directions
- Bibliography

Motivations and definitions

What? use less watts!

Motivations

- Information Communication Technology (ICT) sector is among the Big power consumers:
  - Power consumption of the same order of the airline and train industries
  - Moving *bits* is as costly as moving *people:* can't we do better ?
- How big, exactly ?
  - Estimations place ICT between 2% [3] and 10 % [4]
  - Precise estimations are still a challenge (see power model & measurement later on)

Definition: Environmental viewpoint

- Green networking objective = minimizing the Green House Gas (GHG) emission
  - GHG reduction: benefits higher than investment [2]
  - Use renewable sources of energy
  - Dislocate facilities close to the energy source
  - Use alternative cooling sources [9,10]
    - Google uses the Columbia river water [9]
    - Microsoft leaves servers to the open air [10]
- Note
  - Interesting techniques but oblivious to networking
  - Potential side effects even from environmental viewpoint (e.g., water temperature rise)

Definition: Economical viewpoint

- Green networking objective = minimizing the total $$ cost due to power consumption
  - Energy cost is volatile
  - Buy and use energy where is cheeper [11]
  - Already used by Amazon
- Note
  - "Green" related in this case to the cashflow color!
  - Optimum in terms of expenditure may be sub-optimal in terms of energy consumption

Definition: Regulator viewpoint

- Green networking objective = adopting the best practices given by current technology
  - Governmental duties, enforcement by:
    - Deterrence (e.g., tax on GHG emissions)
    - Incentives (e.g., provide funding for innovative technos)
    - Ban technology (e.g., 100W light bulb, old cars engines)

    - Divert/steer research funds
      - FP7 STREP Towards Real Energy-efficient Network Design (TREND)
      - FP7 IP Energy Aware Radio and neTwork tecHnologies (EARTH)
      - FP7 IP Low Energy Consumption Networks (ECONET)

Definition: Engineering viewpoint

- Green networking objective =
  - minimizing the energy required to achieve a task,
  - while maintaining the same performance level
- Note:
  - This is the viewpoint we adopt in this tutorial
  - Has implication on previous viewpoints
  - Outlines an interesting tradeoff

Key paradigms

How to use less watts?

Key paradigms

- Consider traditional networking paradigms
  - Over-provisioning
  - Redundancy

  Replication of effort & resources is not green !

- Green networking challenge
  - Introduce/exploit paradigms *inherently opposed* with respect to traditional networking paradigms
    - Proportional computing
    - Resource consolidation
    - Selective connectedness
    - Virtualization

  Radical paradigms (Proportional computing, Resource consolidation, Selective connectedness)

  Enabler (Virtualization)

Key paradigm: Proportional computing

Idea: power consumption should be proportional to the usage level

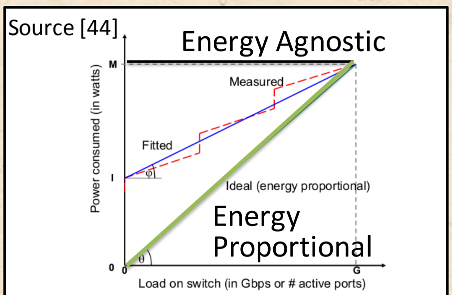


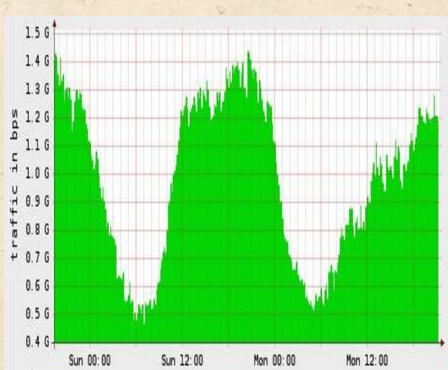
Fig. 2. Ideal (energy proportional) and measured power characteristics of network devices

Observation

- *Introduced by [17]*
- *Applies to both networked and standalone devices*

Key paradigm: Resource consolidation

Idea: use the least possible amount of resources for any given task

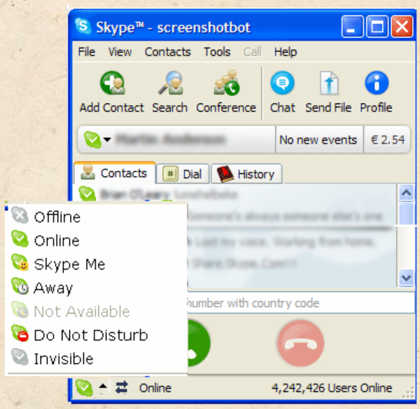


Observation

- *Popular in server and datacenters fields*
- *Applied to networks, it translates into selecting the subset of devices/ links/routers, adapted to the current conditions*

Key paradigm: Selective connectedness

Idea: allow single pieces of equipment to go idle, as transparently as possible for the others

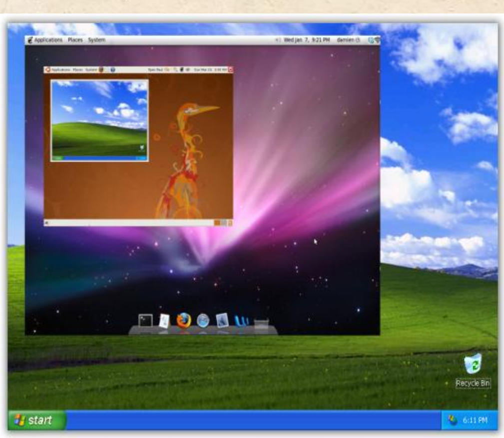


Observation

- *Introduced in [12,13]*
- *Selective connectdness tied to user activities*
- *Resource consolidation* ***within*** *the network,*
- *Selective connectedness at the* ***network edge***

Key paradigm: Virtualization

Idea: allow more than one service to operate on the same piece of hardware



Observation

- *General paradigm*
- *See [15] for a survey on virtualization focused on computer architectures*
- *See [16] for a networking viewpoint on virtualization*
- *Production stable: UPS virtualized 85% server [14]*

Green networking taxonomy

Strategies
in practice

Toward a Green networking taxonomy

- To better organize this tutorial on the state of the art on Green networking, let us:
  - Define taxonomical criteria
    - General enough to apply to all overviewed work
  - Identify a few branches of research
    - So to group similar work altogether in the explanation

Taxonomical criteria (1/2)

- Timescale
  - **Online vs. Offline**
  - Note: finer timescale discrimination are possible
    - *ns* – *μs* : CPU and instruction level
    - *μs*- *ms* : system layer, intra-packets, intra-flow
    - *ms-s* : networked devices, intra and inter-flow
    - *>s :* network, higher degree of interaction possible

online

offline

- Scope
  - **Local vs. Global**
    - Depending on where the information required to take a decision is available
  - Note: as Offline=Global, scope applies to Online work

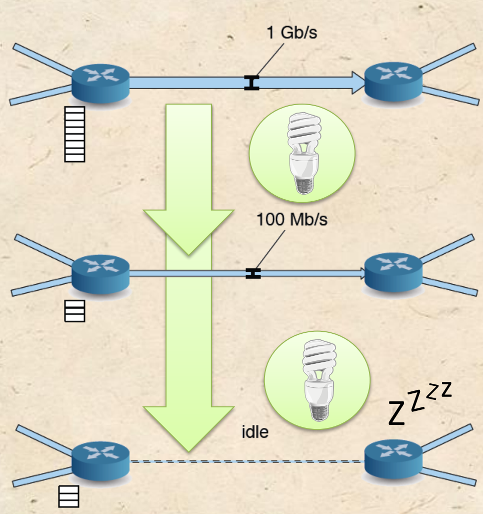
Taxonomical criteria (2/2)

- OSI Layer
  - **Link, Network, Transport, Application, Cross-layer**
  - Identify which entities shall collaborate
- Approach
  - **Traffic analysis, Model, Simulation, Sw/Hw prototype**
  - Flavor of the study, all with relative pros/cons
  - Note: correlates with the level of maturity of the branch
- Other criteria (relevant but left out)
  - Input process (learning and adaptation capabilities)
  - Network segment (access, edge, core)

Research branches

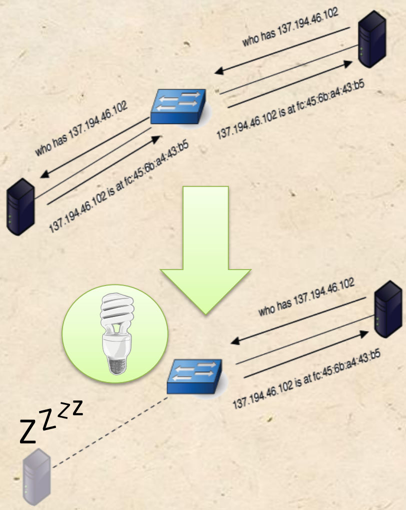
- Branches
  - Define the main context of application:
    - **Adaptive link rate (ALR)**
    - **Interface proxying (Proxy)**
    - **Energy aware infrastructure (EAI)**
    - **Energy aware applications (EAA)**
  - Note
    - Branches do not map 1-to-1 with Key paradigms, hence we briefly introduce them
    - Branches relates to pioneer work defining new directions, then followed by a number of studies

Adaptive Link Rate (ALR)



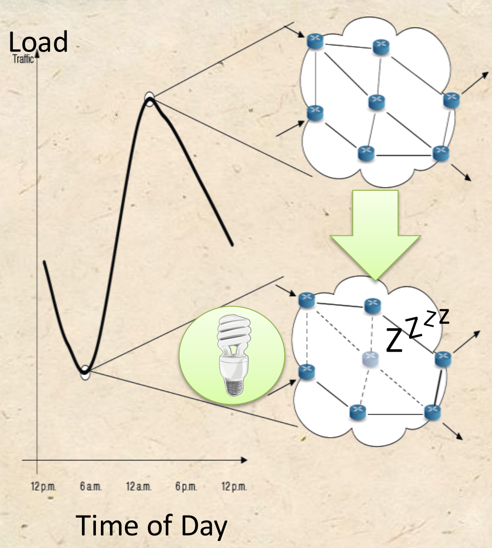
- Main idea
  - Slow down when no traffic to serve
- Key paradigm
  - Proportional computing
- Status
  - Most studied, products expected soon
  - Standardized by IEEE 802.3az [41]
  - EnergyStar program

Interface Proxying (Proxy)



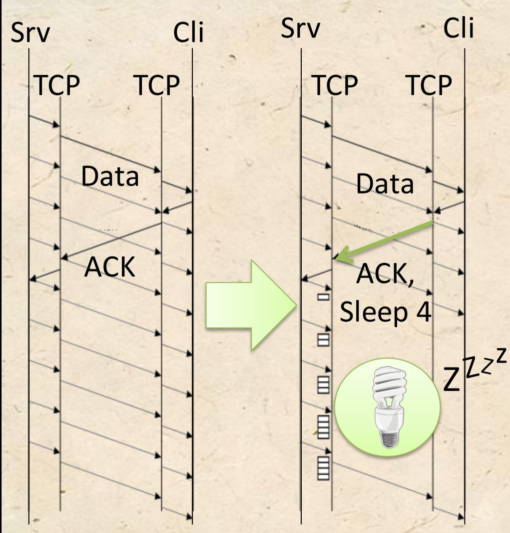
- Main idea
  - Delegate tasks that forbid you to sleep
- Key paradigm
  - Selective connectedness
- Status
  - Well studied, several hardware prototypes
  - Standardized at ECMA [42]

Energy-Aware Infrastructure (EAI)



- Main idea
  - Orchestrate less network resources to provide the very same service
- Key paradigm
  - Resource consolidation, virtualization
- Status
  - More recent, but work is rapidly coming up

Energy-Aware Applications (EAA)



- Main idea
  - Embed energy-awareness deep in protocol design
- Key paradigms
  - Resource consolidation, selective connectedness, proportional computing
- Status
  - Long studied, more heterogeneous, but fewer studies,

Taxonomy at a glance

Branch	Ref	Timescale on	Timescale off	OSI Layer	Approach (comment)
Adaptive Link Rate (ALR)	[20,23,25] [22,26] [24,46,47]	L		L2 L2 L2/L3	Trace driven simulation (Sleep mode SM) TD sim. + Markov chain (Rate switch RS) Sim/Sw proto/analysis (cfr SM vs. RS)
Interface Proxying (Proxy)	[27,28] [29] [30,31]	L		L7 L3 Cross	TD sim, HW prototype (NIC/Ext Gnutella) TD sim + analysis (NIC proxying, DPI) Hw/Sw prototype (NIC/Ext many apps.)
Energy Aware Infrastructure (EAI)	[32] [34,35] [33] [36]	 L G	Di De 	L3 L3 L3 L7	Architecture design Operational research (EA routing) TD sim (Resource control) TD sim (Grid5000 management system)
Energy Aware Applications (EAA)	[37] [38] [39] [40] [77]	L L L L	 De 	L4 L4 L7 L7 L7	Sw proto (TCP protocol modification) Sw proto (TCP optimization) Sw proto (Telent protocol modification) Sim (BitTorrent protocol modification) Experimental (Web browser modification)

Legend: On=Online (L=Local, G=Global) , Off=offline (De=Design, Di=Dimensioning)

Adaptive Link Rate (ALR)

Branch (1/4)

ALR Agenda

- Energy saving opportunities
  - Evidence from network measurements
- Two main families of ALR approaches
  - Rate switching vs. Sleeping mode
    - Overview of seminal work of both families
  - Comparison of switching vs. sleeping
    - Networking, scheduling and datacenter perspective
- Summary
  - Bottom line
  - Advancement status

ALR: Energy saving opportunity (1/5)

- Application of Proportional computing paradigm

Source [19]

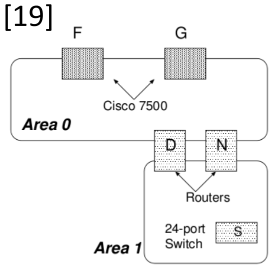


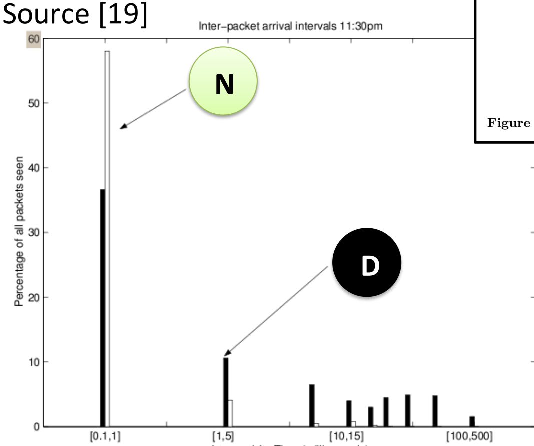
Figure 1: Data collection network.

Methodology

- *Network measurement performed in [19,20]*
- *Collect traffic at several points in the network*
    - *Routers (area 0 & 1)*
    - *Switches (single port, all ports)*

ALR: Energy saving opportunity (2/5)

Source [19]



Histogram of inter-arrival times at an interface for area routers D and N.

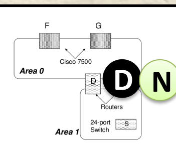


Figure 1: Data collection network.

Observation [19]

- *Large fraction of pkts arrive with large inter-arrivals*
- *Opportunity: switch off or reduce the rate*

ALR: Energy saving opportunity (3/5)

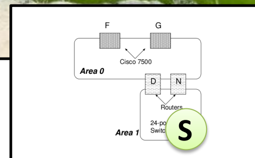


Figure 1: Data collection network.

Source [19]

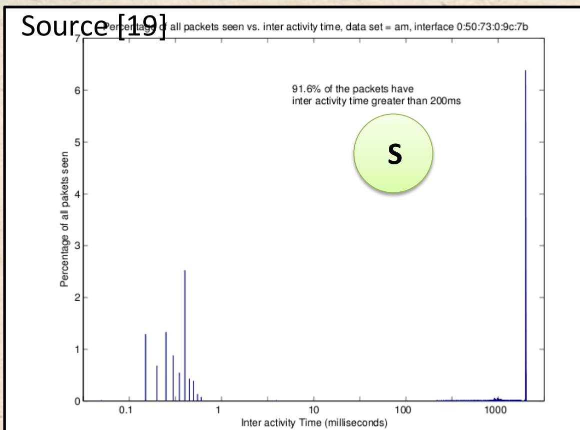


Figure 3: Inter-packet (inter-activity) times at interface of switch S (based on 2 hour traces in the morning on a weekday).

Observation [19]

- *This is especially true toward the network edge*
- *>90% of pkts are spaced of more than 200ms*

ALR: Energy saving opportunity (4/5)

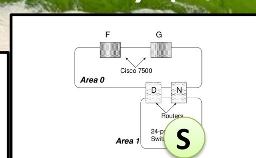


Figure 1: Data collection network.

Source [20]

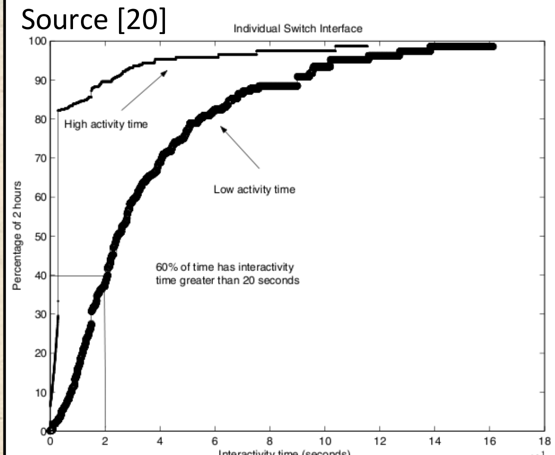


Fig. 1. Interactivity times during high and low activity times.

Observation [20]

- *During low activity, a single Switch port interactivity time is > 20 seconds for 60% of time*
- *During high activity, is still >1 second for 80% of time*

ALR: Energy saving opportunity (5/5)

Source [20]

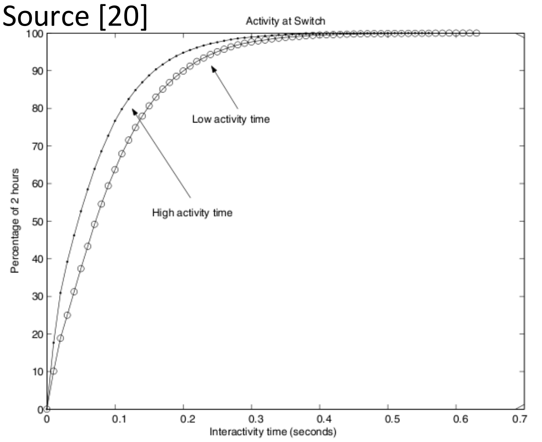


Fig. 1. Interactivity times during high and low activity times.

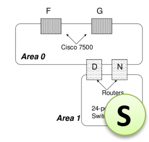


Figure 1: Data collection network.

Observation [20]

- *Aggregating all switch ports: inter-activity time <0.1s for 80% of time*
- *Easy to turn off single links, difficult for the whole switch*

ALR: Two main families (1/3)

- Adaptive Link Rate
  – Sleep mode: Turn off links during idle times [20,23,25]
  – Rate switch: Reduce rate when load is low [22,26]
  – Note: Sleep mode can be considered as Rate switch with two (maximum & null) rates
- Interest of Sleep Mode
  – Ethernet power consumption largely independent from the load [34,43,44]
- Interest of Rate switch
  – High transmission rates requires higher power [21,24]
    - 1Gbps Ethernet requires 4W more than100Mbps [21]
    - Dynamic consumption scales quadratically with line rate [24]

ALR: Two main families (2/3)

- Common challenges
  - Decide when & for how long to sleep/rate-switch
  - Avoid oscillations and unstable behavior
  - Avoid loosing packets, guarantee QoS
- Common approaches
  - TX notifies RX of sleep/rate-switch (with some differences)
    - Define specific MAC exchange, avoid Eth auto-negotiation (requiring > 256ms –but typical several seconds [20,26])
  - Buffer packets at sleeping/reduced rate interface
  - Simulative performance evaluation (generally)

ALR: Two main families (3/3)

- Different aim
  - Sleep mode: reduce fixed idle power consumption
  - Rate switch: reduce variable dynamic power component
- Power model and assumptions

$$P = P_{sleep} + P_{active} = P_{sleep} (1 + \alpha)$$
$$E = P_{sleep} T_{sleep} + P_{active} (T - T_{sleep})$$

Note:
$P_{active} = f(\rho)$, ρ *utilization*
$\alpha = P_{sleep}/P_{active}(\rho_{max})$

  - Note: assumption, simplification and values may differ
    - Transition times: 0.5ms [20], 0.1ms [26] and 0.1-10ms [24]
    - [24] uses $\alpha=P_{sleep}/P_{active}(\rho_{max})$ in [0.01,0.5], while [20,25] sets it to α=0.3 (from Wireless domain) and [20star] only report T_{sleep}
    - only [25] takes into account a power spike due to state transition
  - Hence, we avoid making direct performance comparison

Sleep mode: generic approach (1/3)

- Sleep mode challenges [20,23,25]
  - Decide *when* and *how long* to sleep
  - Avoid loosing packets when in sleep mode

Source [20]

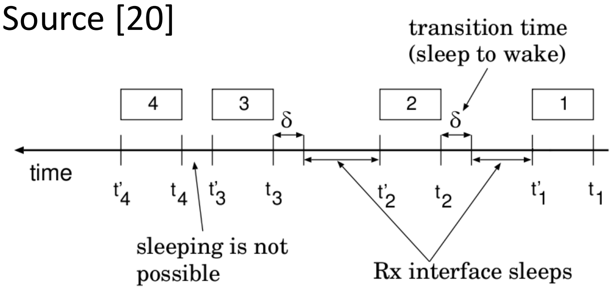


Fig. 2. Explanation of the fundamental problem.

Sleep mode: generic approach (2/3)

- *When* and *How long*: three possibilities
  - Sender decides, then notifies receiver
    - Con: notification overhead
    - Pro: as TX is aware that RX is off, no packets are lost
  - Receiver decides autonomously
    - Pro: decision based on arrival forecast, same as sender
    - Con: loss can happen when estimate fails
  - Receiver puts itself in indefinite sleep and WoP
    - as with Wake on Packet (WoP), due to transition time, packets may get lost, there is need of a dummy packet
    - Pro: longest possible sleep
    - Con: dummy packet overhead

Sleep mode: generic approach (3/3)

- Approaches explored
  - Sender-based notification [20,25]
  - Wake on packet [24,25]

Source [20]

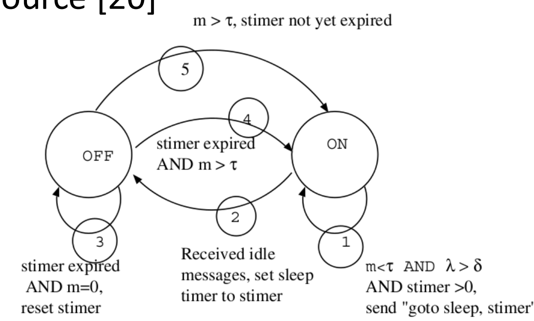
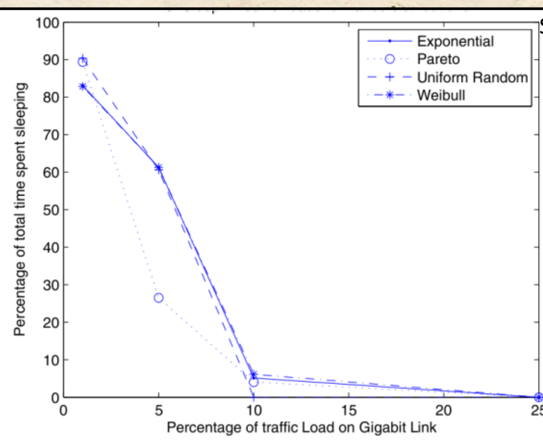


Fig. 2. State machine for the upstream link

Sleep mode: performance (1/3)



Source [20]

Fig. 4. DELS:Variation of sleep times with load and distributions

Observation

- *Very high gain for very low load*
- *No loss observed*
- *Sleep time set according to a Gamma approx. (goal: ensure that buffer size during sleep is <αB)*

Sleep mode: performance (2/3)

- Shadow port + Wake on Packet [25]
  - Shadow port buffers traffic of sleep ingress ports

Source [25]

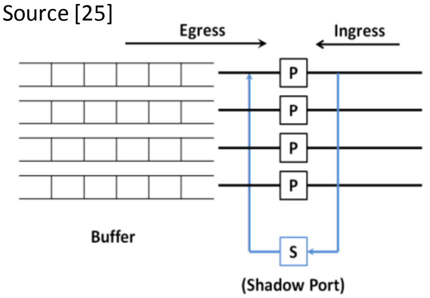


Figure 1: **Shadow Port for a cluster of size 4**

Observation

- *Ports transition in sleep mode based on estimated traffic*
- *On consecutive sleeps, ports enter Wake on Packet (WoP)*
- *WoP ports packets not buffered by shadow port*
- *Time window prediction (TPW) based on EWMA of arrival*

Sleep mode: performance (3/3)

- Shadow port + Wake on Packet [25]

Source [25]

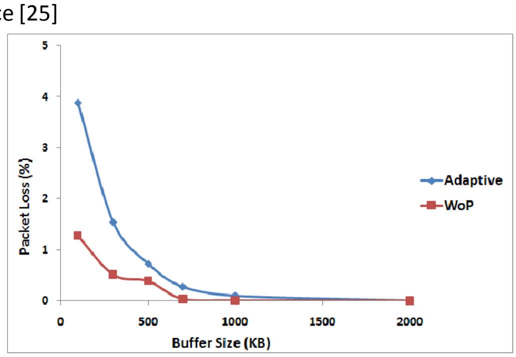


Figure 3: **Packet Loss with TWP**

Observation

- *1 Shadow port every 12 normal ones (else larger losses xor fewer gain)*
- *WoP achieves 80% of optimal saving, reduces losses*
- *Bounded but non-0 pkt loss*

Rate switch: generic approach (1/3)

- Rate switch challenges [21,22,26]
  - Decide when to switch, avoid oscillation & buffer drops

Source [26]

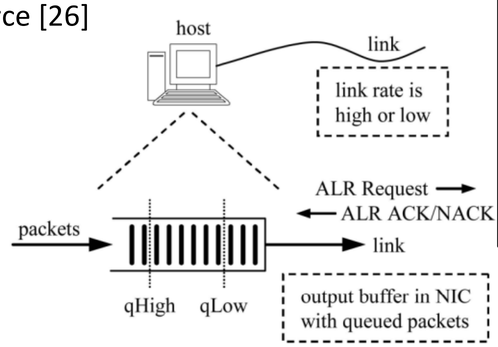


Fig. 2. Example NIC output buffer with high and low thresholds.

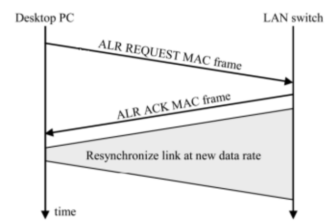


Fig. 1. Timing diagram for an ALR MAC frame handshake mechanism.

Policy [21,22,26]

- *Switch based on dual threshold queue occupancy*

Rate switch: generic approach (2/3)

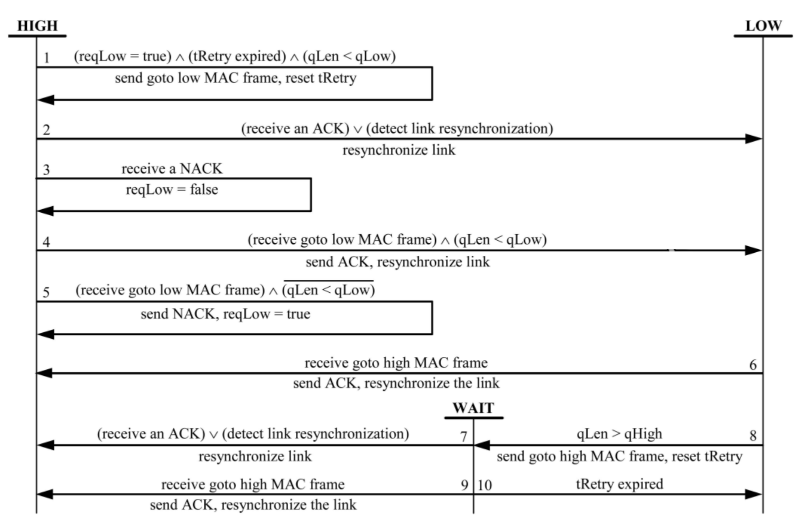


Fig. 3. FSM for the ALR dual-threshold policy.

Source [26]

Rate switch: generic approach (3/3)

- Problem: Oscillations due to dual-threshold policy arise with smooth traffic or long bursts

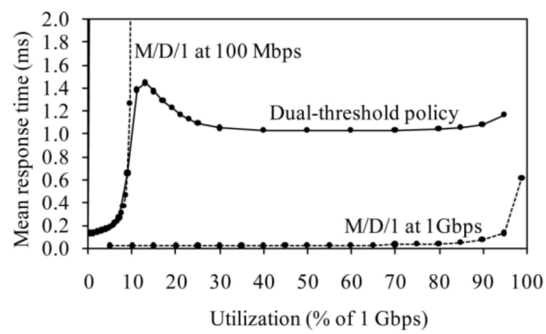


Fig. 5. ALR dual-threshold policy and M/D/1. Source [26]

Solutions [26]

- *Utilization-criterion Transition HI->LO only when load is below a given level*
- *Or, impose min persistence time in each state*

Rate switch: performance (1/3)

- Oscillations effectively limited by both strategies
  - Markov-chain based analysis [26]

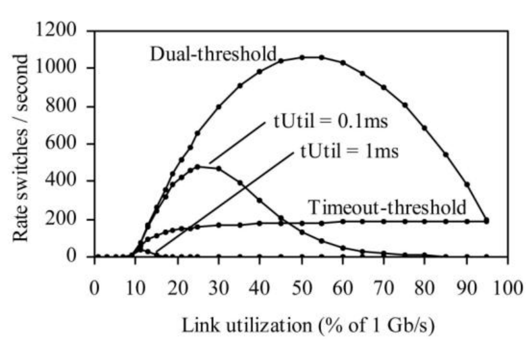


Fig. 12. Rate oscillations for ALR policies. Source [26]

Observation

- *Utilization-criterion largely affected by measurement lapse*
- *Utilization-criterion preferable though it requires further processing (w.r.t. persistence timer)*

Rate switch: performance (2/3)

- Bottom line [26]
  - Energy/QoS tradeoff
  - Practically applicable (<1ms response time)
- Utilization threshold
  - Short= high energy gain
  - Long= faster response (longer post-burst lag)

Energy gain

QoS cost

Source [26]

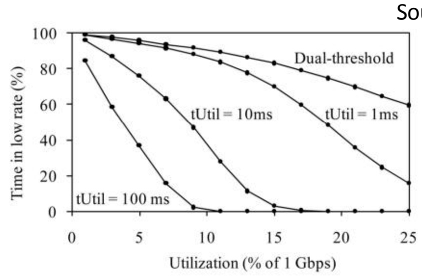


Fig. 18. Time in low rate from bursty traffic experiment #1 for the utilization-threshold policy.

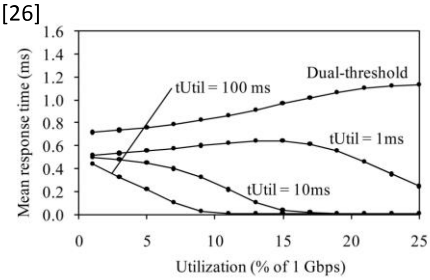


Fig. 17. Response time from bursty traffic experiment #1 for the utilization-threshold policy.

Rate switch: performance (3/3)

- Scenario [21]: replay trace of big downloader (1GByte in 30min), 10/100Mbps rate switch

Source [21]

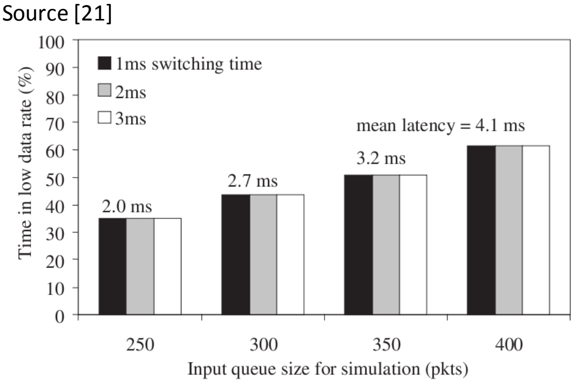


Figure 5. Time spent in low data rate (mean latency is shown)

Observation

- *Big downloader bottleneck is the aggregate rate of cable and DSL uploaders*
- *No noticeable performance loss, but large saving*

Comparison: Rate switch vs. Sleep mode

- Comparison from several viewpoints
  - Networking [24]
  - Datacenters and servers [46,47]
- Networking [24]
  - Addressed from a global standpoint (considering Abilene topologies)
  - Realistic scenarios, different traffic models (CBR, bursty), ns2 simulation
  - Slightly different Rate switch (RS) and Sleep mode (SM) briefly introduced in the following
    - Both optimal and practical algorithms are evaluated

Networking comparison: RS

- Rate switch
  - Rates r_i uniformly distributed in $[r_{Max}/\lambda, r_{Max}]$
  - Queue ***q***, predicted arrival ***rf*** (ewma), Delay constraint ***d***, Switch delay δ
  - Optimal solution by iterative application of shortest Euclidean curve separating Arrival and Service curves
- Policy
  - Rate increase from r_i iff: $q/r_i > \delta$ OR $(\delta\, rf + q)/r_{i+1} > d - \delta$
  - Rate decrease from r_i iff: $q=0$ AND $rf < r_{i-1}$

delay constraint would otherwise be violated

2nd condition avoids oscillations (cfr. [26])

Networking comparison: SM (1/2)

- Sleep mode (uncoordinated)
  - "Buffer and Burst" (BB) buffer during T_B, send rearranged packets in bursts w.r.t destination
  - Optimal solution by brute-force exploration of set of start times that optimize burst at network level

Source [24]

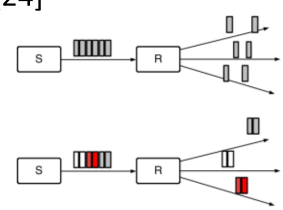


Figure 1: Packets within a burst are organized by destination.

Note

- *Radical approach as, traditionally, research in networking avoids bursts (token bucket, packet pacing, etc.)*

Networking comparison: SM (2/2)

- Sleep mode (coordinated)
  - Interesting but hard to achieve in practice

Source [24]

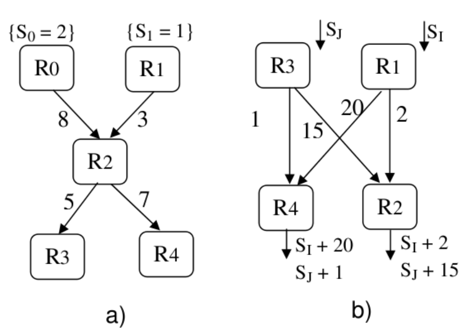


Figure 9: Examples of burst synchronization.

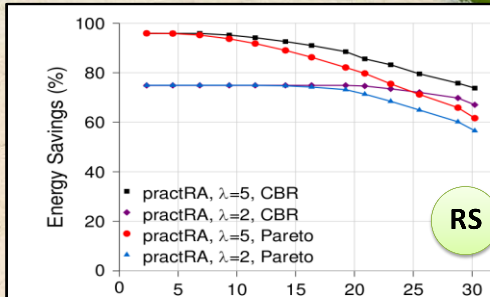
Observation

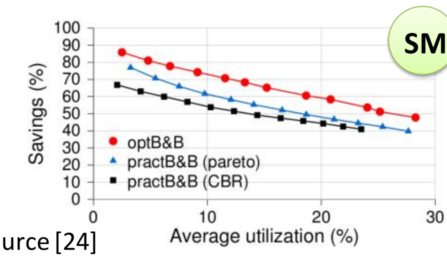
- *Routers may try to coordinate burst start times*
- *a) if R1 transmits at S_1=7 instead of S_1=1 R2 would receives all bursts at time 10*
- *b) no simultaneous burst tx possible*

Networking comparison: SM vs RS (1/3)

- Performance tradeoff
  - Rate switch: benefits of smooth CBR traffic
  - Sleep mode: benefits of bursty pareto traffic
- Intuitive explanation
  - Rate switch: process as slowly as possible (use lowest power states)
  - Sleep mode: longer sleeps with bursty traffic (maximize idle time)

Note: λ = extent of rate scaling capabilities

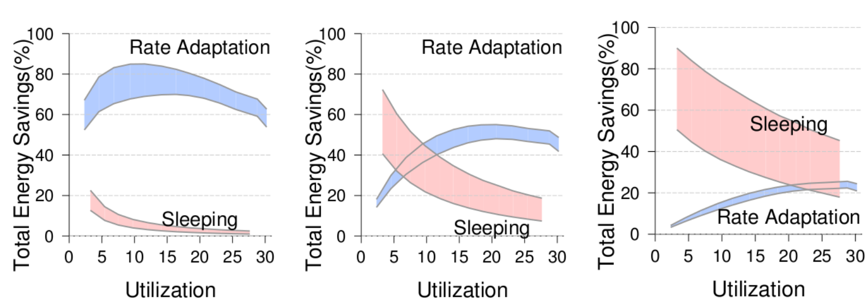




Source [24]

Networking comparison: SM vs RS (2/3)

- Boundary utilization
  - Below which SM is best
  - Above which RS is best
  - Precise boundary evaluation hard
  - Largest impact of Utilization and α=$P_{sleep}/P_{active}(\rho_{max})$ params.
  - Other par. -> max & min envelope



(a) $\alpha = 0.01$ (b) $\alpha = 0.1$ (c) $\alpha = 0.5$

Source [24]

Figure 15: Total Energy Saving of Sleeping vs. Rate Adaptation

Networking comparison: SM vs RS (2/3)

Source [24]

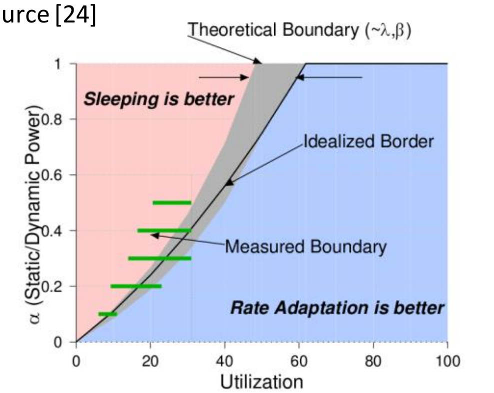


Figure 16: When is it better to sleep/rate adapt

Observation

- *Preferred strategy for static-to-dynamic power ratio α and utilization levels*
- *Mesured boundary = varying parameters*
- *Idealized border for SM = longest sleep, RS = average rate*

Scheduling comparison: SM vs RS (1/4)

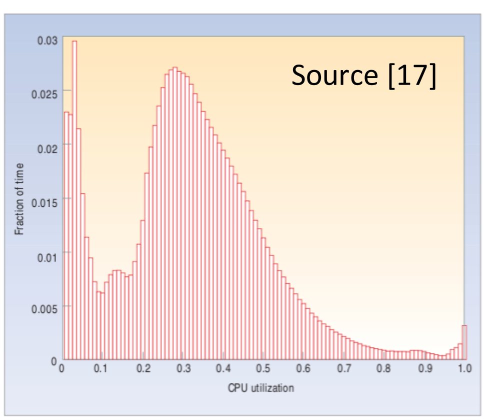


Figure 1. Average CPU utilization of more than 5,000 servers during a six-month period. Servers are rarely completely idle and seldom operate near their maximum utilization, instead operating most of the time at between 10 and 50 percent of their maximum utilization levels.

Motivations

- *Data center, servers, PCs are typically* [17] *largely under-utilized*
- *Job scheduling can adopt SM and RS strategies:*
  - *SM: run at full rate, then stop*
  - *RS: run at lowest possible rate*

Scheduling comparison: SM vs RS (2/4)

PowerNap [46]

- Sw prototype compared to voltage scaling techniques

Source [46]

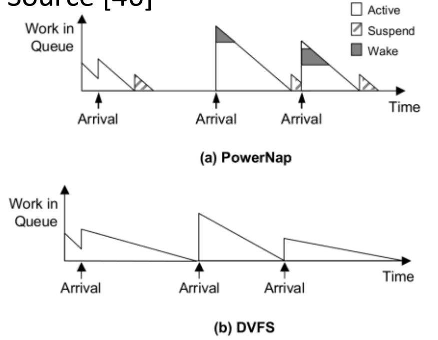


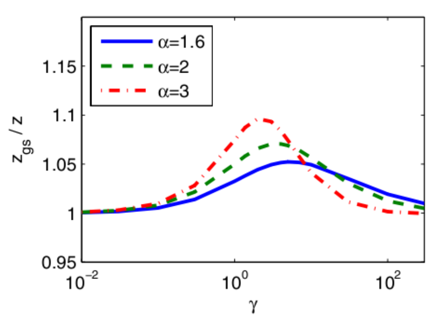
Figure 5: PowerNap and DVFS Analytic Models.

Analytical study [47]

- Compares three techniques
  - Static provisioning (constant “optimal” speed)
  - Gated static provisioning (sleep mode, speed=0 when idle)
  - Dynamic speed scaling (rate switching, speed is continous)
- Cost model
  - z=E[T] +E[E]/β weighted average of energy E and delay T
  - E[E] = f(s) = s^{α}
s=speed, α=system parameter
  - $\gamma = \rho / \beta^{1/\alpha}$
lumping parameter, ρ = utilization

Scheduling comparison: SM vs RS (3/4)

Source [47]



(b) Ratio of cost for gated static to optimal, z_{gs}/z.

Fig. 3. Cost z vs energy-aware-load γ.

Observation [47]

- *Simpler SM strategy achieves near optimal results (within 10%)*
- *Recall $\gamma = \rho / \beta^{1/\alpha}$ with ρ utilization and β control the relative energy/ delay weight*
- *Similar results from [46]*

Scheduling comparison: SM vs RS (4/4)

- RS is more robust than SM, though
  - SM: speed overprovisioning lead to energy waste,
  - SM: speed underprovisioning to unstability

Source [47]

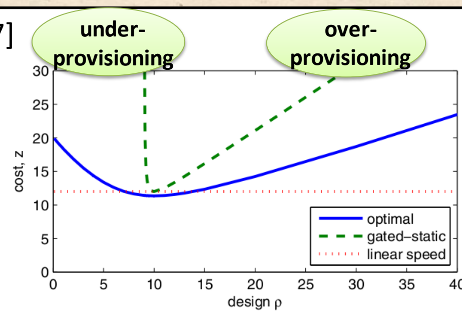


Fig. 5. Cost at load $\rho = 10$, when speeds are designed for "design ρ" $\beta = 1$, $\alpha = 2$.

ALR: Summary (1/2)

- Motivation
  - Most of the time, network devices are either idle [19] or under utilized [46]
- Two techniques
  - Rate switch: reduce dynamic power consumption [20, 23,25]
  - Sleep mode: reduce fixed idle power consumption [22,26]
- Comparison in networking [24]
  - Rate switch: benefit of smooth traffic (lower rate)
  - Sleep mode: benefit of bursty traffic (longer sleep)

ALR: Summary (2/2)

- Bottom line
  - Application of the Proportional computing paradigm
  - Sleep mode at low load, rate switch at higher load [24]
  - Sleep mode simpler & preferable (other context) [46,47]
  - Rate switch robust to wrong parameter settings [47]
  - Survey on energy efficient scheduling [45]
- Advancement status
  - IEEE standard 802.3az under way [41]
  - Support for low-power transitions likely follow (EnergyStar program)

Interface Proxying (Proxy)

Branch (2/4)

Interface Proxying Agenda

- Energy saving opportunities
  - Evidence from network measurements
- Two main families of Proxying approaches
  - External proxying
  - Network Interface Card or NIC Proxying
- Summary
  - Bottom line
  - Advancement status

Proxy: Energy saving opportunity (1/4)

- Not only datacenters, but also end-user devices, are often lightly loaded

Source [31]

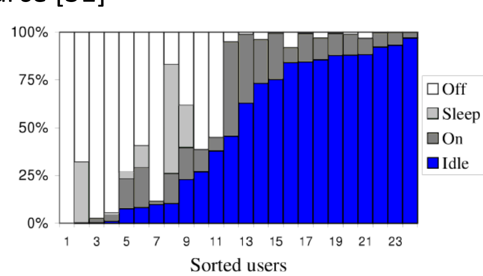


Figure 1: Distribution of the split among off, idle and active periods across users.

Observation

- *Measurement on 24 home and office PCs*
- *PCs are most of the time idle* [31]
- *So, can't we use Sleep Mode at the edge as well ?*

Proxy: Energy saving opportunity (2/4)

- To assess sleep-mode gain, [31] investigate the distribution of idle-periods durations

Source [31]

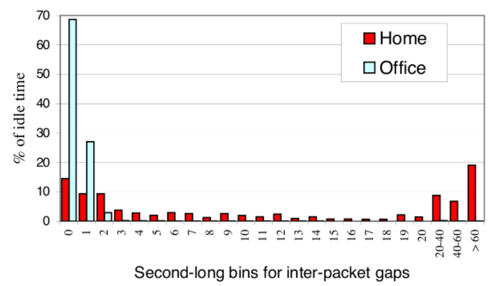


Figure 3: Histogram of the fraction of the idle time made up of inter-packet gaps of different size.

Observation

- *Office: 90% of the idle periods <2s*
- *Home: 70% <20s*
- *Sleep mode not efficient solution for transition time on the order of a few seconds*

Proxy: Energy saving opportunity (3/4)

Source [21]

Protocol	% in trace	Discard	Proxy	Wake-up	Comments
ARP Request and Reply	52.50 %	Most	Yes	No	Requests for IP address answered by proxy
Universal Plug by & Play	16.50	Most	Yes	No	Discovery messages answered proxy
BRIDGE "Hello"	7.80	All	No	No	Can be discarded by proxy
Cisco Discovery	6.90	All	No	No	Can be discarded by proxy
NetBIOS Datagram	4.40	Some	No	Possible	Directed packets need a PC wake-up
NetBIOS Name Service	3.60	Some	Yes	Possible	Directed packets need a PC wake-up
Banyan System	1.80	All	No	No	Can be discarded by proxy
OSPF	1.60	All	No	No	Can be discarded by proxy
DHCP	1.20	All	No	No	Can be discarded by proxy
IP Multicasts	1.00	All	No	No	Can be discarded by proxy
RIP	0.50	All	No	No	Can be discarded by proxy
SMB	0.40	Some	No	Possible	Directed packets needs a PC wake-up
NetBEUI	0.31	All	No	No	Can be discarded (deprecated protocol)
Unknown port scans	0.30	All	No	No	Contains TCP SYNs (unneeded wakeups)
BOOTP	0.25	All	No	No	Can be discarded by proxy
NTP	0.20	All	No	No	Can be discarded by proxy
NetBIOS Session service	0.12	Some	No	Possible	Directed packets need a PC wake-up
ICMP (including ping)	0.08	Some	Yes	No	Echo requests answered by the proxy
DEC Remote Console	0.08	All	No	No	Can be discarded by proxy
SNMP	0.06	Some	No	Possible	Can be discarded unless SNMP agent
ISAKMP	0.04	All	No	No	Can be discarded by proxy
X Display Manager	0.02	All	No	No	Can be discarded by proxy

Table 1. Breakdown of received packets on an idle PC connected to the USF network

Observation

- *Edge devices are continuously receiving traffic: ICMP, DHCP, UPnP, SMB, NTP, NetBIOS..*
- *[21] calls this traffic "chatter"*
- *Most chatter need simple operations*
- *Delegate this to proxies!*

Proxy: Energy saving opportunity (4/4)

- Saving comes from Selective connectedness

Source [27]

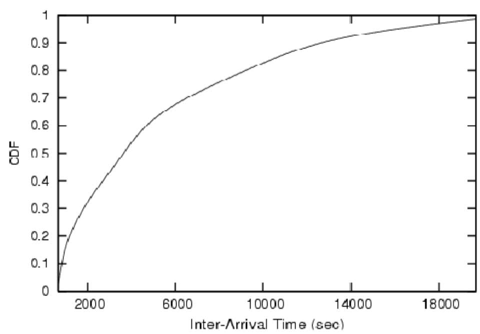


Figure 2: File Upload Request

Observation

- *Delegate also P2P maintenance traffic (query forwarding, peer exchange, etc.)*
- *Only requests for content need to be handled by peers*
- *>60% of requests for Gnutella file upload are >1hr apart [27]*

Proxy: Delegation strategies

- Two possibilities
  - Delegate to an external proxy [28,31]
    - A single proxy for several end-devices
    - More suited for environments such as LAN, offices
    - Application-specific (Gnutella) [28] , General purpose [31]
  - Delegate to an onboard low-power NIC [27,29,30]
    - One proxy for each end-device
    - More suited for home environment
    - Application specific (Gnutella) [27], General purpose [29,30]

Proxy: External proxying (1/4)

- Application specific proxy for Gnutella [28]

Source [28]

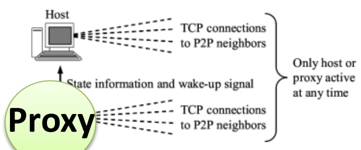


Figure 1. P2P host with a proxy sub-system

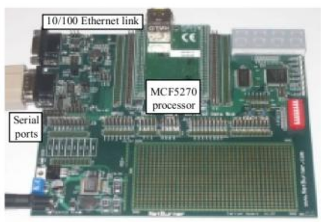


Figure 6. Netburner development kit

Observation

- *Software prototype, based on HTTP redirection*
- *Developed for low-cost (non "low-power") Netburner*

```
Process getServer() – Standard HTTP server

Process redirector()
  while (true)
    wait for a connection on port 80
      if (receive an HTTP GET)
        wake-up the proxied host
        send an HTTP 302 to redirect request to host
```

Figure 5. Processes specific to host or proxy

Proxy: External proxying (2/4)

- Generic-proxy architecture for all chatter [31]

Source [31]

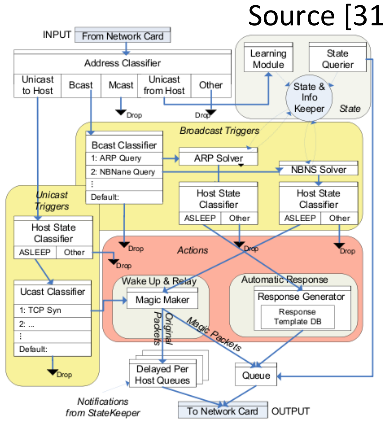


Figure 17: Example Click implementation.

Methodology

- *Consider 4 increasingly complex proxy settings:*
  - *A) Ignore simple traffic, wake on other traffic*
  - *B) =A + handle mechanical response, wake on other*
  - *C) =B + wake on user-selected application, drop others*
  - *D) =C + wake on scheduled activities (backup, antivirus)*

Proxy: External proxying (3/4)

Ignorable	HSRP, PIM, ARP (for others), IPX, LLC, EIGRP, DHCP	
Mechanical Response	**Protocol**	**State**
	ARP	IP address
	NBNS	NB names of machine and local services
	SSDP	Names of local plug-n-play services
	IGMP	Multicast groups the interface belongs to
	ICMP	IP address
	NBDGM	NB names of machine and local services. Ignores pkts. not destined to host, wakes host for rest

Table 2: Protocols that can be handled by ignoring or by mechanical response. We classify DHCP as ignorable because we choose to schedule the machine to wake up and issue DHCP requests to renew the IP lease – an infrequent event.

Source [31]

Proxy A

Ignore simple traffic, wake on other traffic

Proxy B

Ignore simple traffic, handle mechanical reply, wake on other traffic

Proxy: External proxying (4/4)

- Performance evaluation

Source [31]

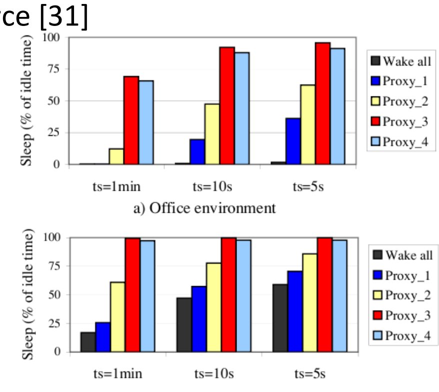


Figure 16: Savings achieved by different proxies in home and office environments.

Observation

- *Broadcast & multicast traffic easy to handle*
- *Unicast more tricky (need state and infer the chatter intent)*
- *Home: fewer gain for more complex proxies*
- *Office: complexity needed for energy saving*

Proxy: NIC proxying (1/4)

- General-purpose proxying also on NICs [30]

Source [30]

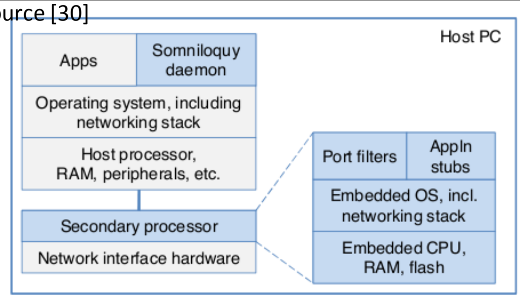


Figure 1: *Somniloquy augments the PC network interface with a low power secondary processor that runs an embedded OS and networking stack, network port filters and lightweight versions of certain applications (stubs). Shading indicates elements introduced by Somniloquy.*

Observation

- *Low power HW with storage* ***S***
- *Handles chatter + application stubs (Web, BitTorrent)*

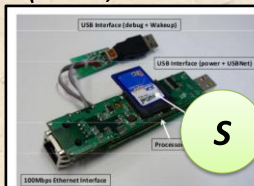


Figure 4: *Photograph of the gumstix-based Somniloquy prototype - Wired-1NIC version.*

Proxy: NIC proxying (2/4)

- Performance evaluation[30] (dataset [31]):
  - Limited latency increase, large battery life increase

Source [30]

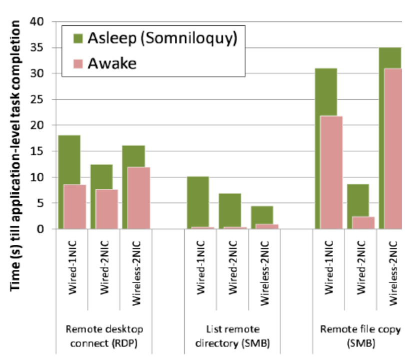


Figure 6: *Application-layer latency*

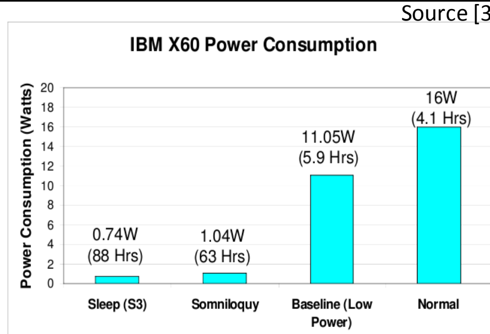


Figure 7: *Power consumption and the resulting estimated battery lifetime of a Lenovo X60 using Somniloquy.*

Proxy: NIC proxying (3/4)

- Design of TCAM-based architectures for power efficient-pattern matching [29]
  - Chatter filter, application-stubs need pattern matching to trigger appropriate actions
  - Define a partitioned architecture with a Prefix TCAM, a Suffix TCAM and a Suffix Cache
  - In lack of known patterns for chatter traffic, authors employ Intrustion Detection (Snort) and anti-virus (ClamAV) pattern

Sample Signature: A B C D E F G H A B C D J K L M E F G	
Prefix Pattern: A B C D	**Suffix Patterns:** E F G H A B C D J K L M E F G *

Fig 1: Prefix and suffix patterns for a sample signature for a TCAM width $w = 4$. (* = don't care) Each character represents an arbitrary byte

Source [29]

Proxy: NIC proxying (4/4)

- Performance evaluation [29]
  - Energy saving exploits redundancy and traffic locality (suffix cache)
  - Optimal partitioning depending on signature length

Source [29]

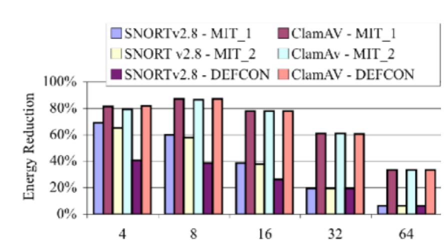


Fig 7: Energy reduction for a partitioned system compared to a non-partitioned system verses TCAM width for real-time traffic traces.

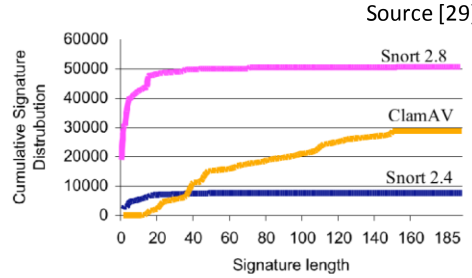


Fig 3: Cumulative number of rules (distribution) for increasing signature lengths for Snort and ClamAV signature sets.

Interface Proxying: Summary (1/2)

- Motivation
  - Chatter traffic continuously received by idle PCs
  - Many non-interactive operations can be delegated too
- Two flavors
  - External: one well-defined entity for a set of machines
    - Application specific [28]
    - General purpose [31]
  - NIC: a dedicated low-power device for each machine
    - Application specific [27]
    - General purpose [29,30]

Interface Proxying: Summary (1/2)

- Bottom line
  - Application of the Selective connectedness paradigm
  - Increasing complexity
    - Broadcast and multicast traffic easily filtered
    - Unicast traffic need more sophisticated interaction
    - Full-blown user-specific applications can be delegated to proxy (e.g., BitTorrent download)
  - Needed level of proxying depends on environment:
    - Home generally requires simpler treatment w.r.t. Office
- Advancement status
  - Under standardization at ECMA [42]
  - Well advanced prototypes

Energy Aware Infrastructures (EAI)

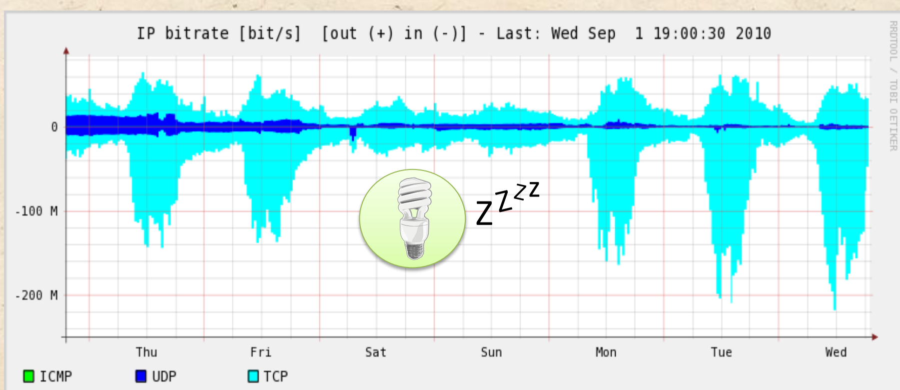
Branch (3/4)

EAI Agenda

- Energy saving opportunities
  - Evidence from network measurements
- Two main families of EAI approaches
  - Energy aware architectures
    - Clean-slate design [32]
    - Incremental deployment [36]
  - Energy-aware traffic engineering
    - Routing and operational research [34,35]
    - Control and traffic engineering [33]
- Summary
  - Bottom line
  - Advancement status

EAI: Energy saving opportunity (1/2)

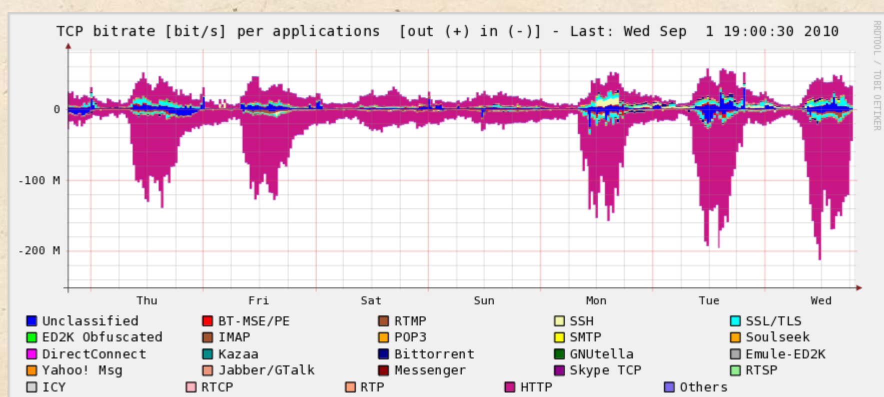
- Saving comes from resource consolidation
  - Traffic has known day/night/weekend trends



Source: http://tstat.tlc.polito.it

EAI: Energy saving opportunity (2/2)

- Saving comes from resource consolidation
  - Advertisement: now Tstat does traffic classification



Source: http://tstat.tlc.polito.it

EAI: Energy aware architectures (1/3)

- Clean slate design [32]
  - Rooted on Cisco forecast that video >90% traffic
  - Infrastructure virtualization, two layer hierarchy
    - Asynchronous IP for data traffic
    - Scheduling for deterministic traffic

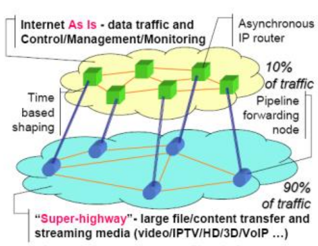


Figure 3: Parallel networks on the same fiber infrastructure with WDM.

Source [32]

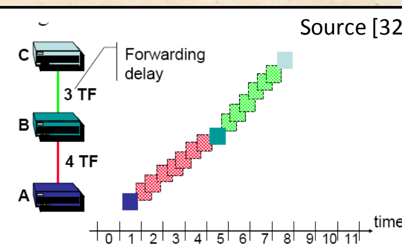
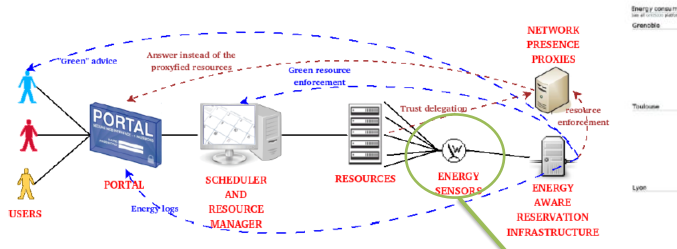


Figure 2: Pipeline forwarding operation.

EAI: Energy aware architectures (2/3)

- Incremental deployment[36]
  - Applied to Grid5000 management (French grid infrastructure for research)
  - Dynamically adapt infrastructure to the measured load (Resource consolidation)



Source [36]

Figure 1. The GREEN-NET framework

Figure 3. Monitoring of 18 nodes sensors

EAI: Energy aware architectures (3/3)

Algorithm 1 Prediction based Scheduling

N - Total nodes in the Grid
N_{down} - Nodes currently switched off
N_{up} - Nodes currently in active mode
N_{hib} - Nodes in hibernate mode
W - Lookahead time window(e.g say 1 hr)
Q - Queue of the Grid
$PastJob_{nodes}$ - Past history of peak node utilization of job arriving in Grid based on (hour,day) over W.
$\triangle$ - Buffer machines kept in case of sudden load

```
if (Q full for W) then
    if (maxnodesusage(Q_jobs)=N) then
        LookHibernate(Q)
    end if
end if
N_1 ← N − maxnodesusage(Q_jobs)
N_2 ← N_1 − PastJob_nodes − △ /* Look for nodes that can be shut down */
if (N_2 > 0) then
    SwitchDown(N_2 − N_down) /* if N_2 < N_down indicates nodes are already down */
end if
```

Methodology

- *Replay 2-years logs applying energy aware job scheduling on the grid*

Source [36]

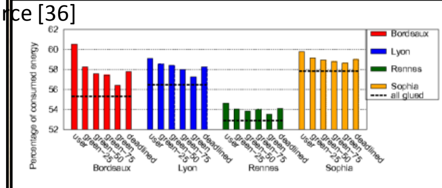


Figure 5. Results of EARI for 4 sites

EAI: Energy aware traffic engineering (1/4)

- Energy aware routing [34,35]

$$\min : (1-\alpha)\sum_{j\in N} P(X^j) + \alpha\frac{1}{\gamma}\sum_{u\in M}\left(\frac{X_u}{C_u - X_u}\right)$$

$$\text{where } X^j = \sum_{(o,d)}\sum_{u\in\Gamma^-(j)} X_u^{od} + \sum_{(o,d)}\sum_{u\in\Gamma^+(j)} X_u^{od} \quad \forall j \in N$$

s.t.:

$$\sum_{u\in\Gamma^+(i)} X_u^{od} - \sum_{u\in\Gamma^-(i)} X_u^{od} = \begin{cases} f^{od}, & \text{if } i = o, \\ -f^{od}, & \text{if } i = d, \\ 0, \text{otherwise...} \end{cases}$$

$\forall i \in N, o \in O, d \in D;$

$$\sum_{od} X_u^{od} \leq C_u, \quad \forall u \in M;$$

$$X_u^{od} \geq 0, \quad \forall\, u \in M,\ o \in O,\ d \in D.$$

Source [35]

Methodology

- *First introduced by [34]*
- *Operation research*
- *Fixed time frame, known traffic matrix*
- *Green delay/energy tradeoff parameter (α in [0,1]) by [35]*
  - *High α, lower delay*
  - *Low α, higher saving*

EAI: Energy aware traffic engineering (2/4)

- Energy aware routing [35]
  - Extreme cases, the network is either a tree ($\alpha=0$) or original topology with all links & nodes ($\alpha=1$)

Network delay

Source [35]

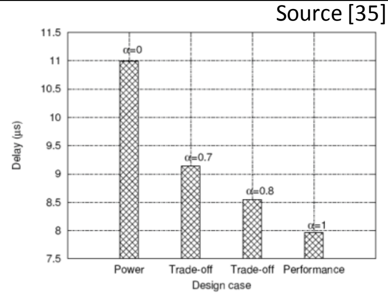


Figure 8. System performance for the four different designs

Power expenditure

Source [35]

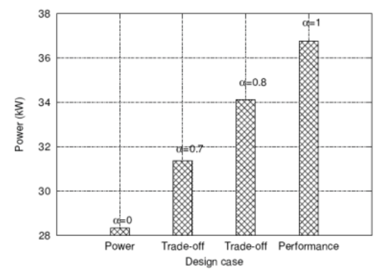


Figure 7. Power consumption for the four different designs

EAI: Energy aware traffic engineering (3/4)

- Energy aware control [33]

Source [33]

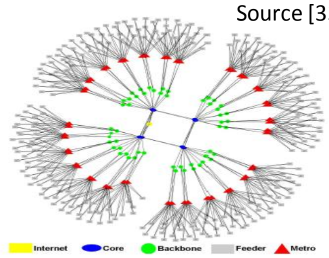


Fig. 1. Topology representation (3D-view)

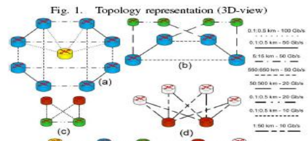


Fig. 2. Link description

Methodology

- *Temporal evolving system*
- *Large topology of real ISP*
- *Periodically run (5min) an heuristic control algorithm*
  - *Sort nodes according to energy footprint*
  - *Loop over nodes, try to switch off most consuming nodes first*
  - *At the end of the nodes loop, iterate over the powered links*

EAI: Energy aware traffic engineering (4/4)

Source [33]

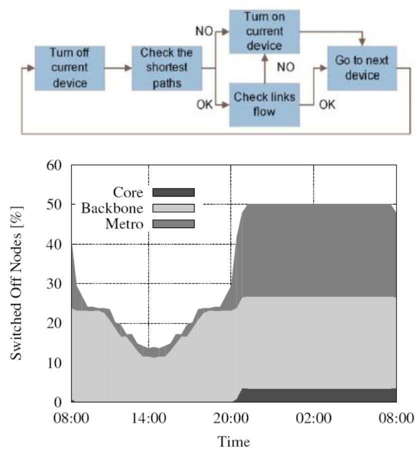


Fig. 7. Energy Saving for each class of node

Observation

- *Largest gain during night time, as expected*
- *Still, it is possible to power of 1/10 of the backbone node even during busy daytime*
- *Practical interest for continuous adaptation*
- *Need to cope with routing algorithms (i.e., avoid considering sleeping as faulty)*

Energy aware infrastructure: Summary (1/2)

- Motivation
  - Load on network elements naturally fluctuates, adapt to achieve energy-load proportionality
- Two main families
  - Energy aware architectures
    - Clean-slate design [32]
    - Incremental deployment [36]
  - Energy-aware traffic engineering
    - Routing and operational research [34,35]
    - Control and traffic engineering [32]

Energy aware infrastructure: Summary (2/2)

- Bottom line
  - Large gain possible in practical scenarios due to good'ol network over-provisioning & redundancy
  - Current work investigate efficiency/QoS tradeoff
  - Need to investigate efficiency/resilience tradeoff
  - Need to take into account inter-dependence with current routing protocols (ie. sleep vs fault)
- Advancement status
  - Fewer work so far, but interest is growing and more work is rapidly coming up (esp. in 2010), recently IETF drafts (MIB, power benchmark) started to appear

Energy Aware Applications (EAA)

Branch (4/4)

EAA Agenda

- Energy saving opportunities
  - Evidence from network measurements
- Two main families of EAA approaches
  - Protocol and application design
  - Protocol and application optimization
- Summary
  - Bottom line
  - Advancement status

EAA: Energy saving opportunities (1/3)

- Consider the following example application [53]
  - Question is, which alternative is more energy efficient?

Source [53]

Alternative 1: Without Compression

```
f = new FileStream("/var/records.mds");
f.Open("rw");
/* Workload: read/edit data items */
f.Close();
```

Alternative 2: With Compression

```
f = new GZipStream("/var/records.zds");
f.Open("rw");
/* Workload: read/edit data items */
f.Close();
```

EAA: Energy saving opportunities (2/3)

- Consider the following example application [53]
  - Question is, which alternative is more energy efficient?

Table 1: Total and Breakdown of Energy Usage.

Cost	Uncompressed IO	Compressed IO
Total Time, T (s)	22.358	14.935
CPU: f_{Active} (%)	4.37	44.25
E_{CPU} (J)	409.12	377.56
Disk Active (s)	19.218	0.965
Disk Energy (J)	92.96	25.29
Total Energy (J)	502.08	402.85

Source [53]

EAA: Energy saving opportunities (3/3)

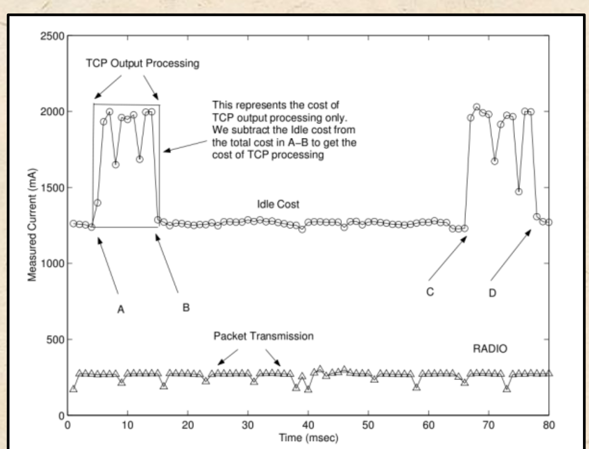
- Higher variability at application layer
  - Saving opportunities may vary depending on the application design, coding style, etc.
- Larger design space, hence several key paradigms may be exploited
  - Selective connectedness
  - Resource consolidation
  - Proportional computing

EAA: Two main families

- Application and protocol optimization
  - Transport-layer (L4)
    - Energy-efficient optimization of TCP stack [38]
  - Application-Layer (L7)
    - Improving Web browsers energy efficiency [77]
- Application and protocol design
  - Transport-layer (L4)
    - Green TCP [37]
  - Application-layer (L7)
    - Green Telnet [39]
    - Green BitTorrent [40]

EAA: Protocol optimization (1/4)

- Optimization of TCP networking stack [38]



Source [38]

Methodology

- *Experimental measurement*
- *BSD (v4.2 and v5) and Linux (v2.4)*
- *TCP consumption = whole system – idle – WiFi consumption*
- *Breakdown of TCP consumption*
- *Proportional comp.*

EAA: Protocol optimization (2/4)

- TCP Energy cost (y-axis):
  - Per-packet, increases with MTU size (x-axis)
  - Over multiple transfers, decreases with MTU size

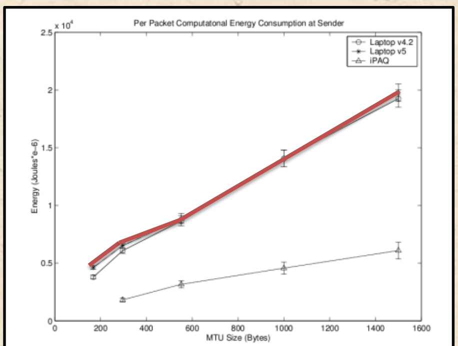
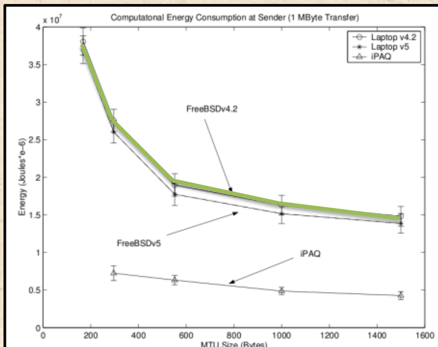


Fig. 3. Per packet cost at the sender.



Src [38] Fig. 2. Total computational energy costs.

EAA: Protocol optimization (3/4)

Source [38]

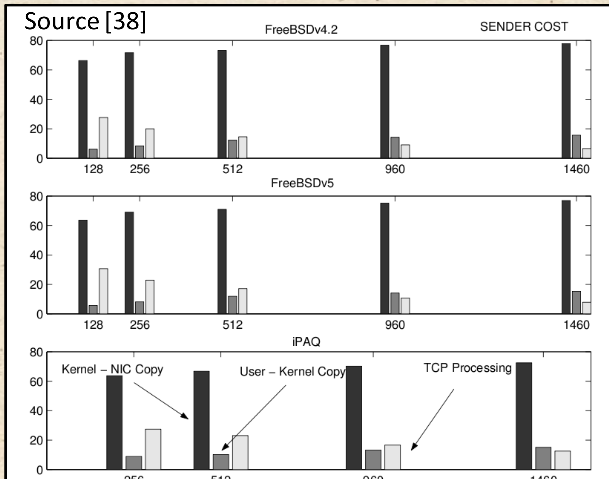


Fig. 5. Relative costs at sender/receiver for sending/receiving 1 MByte

Observation

- *TX breakdown*
  - *Kernel->NIC*
  - *User->Kernel*
  - *TCP processing*
- *Largest fraction is copy from Kernel to NIC (60-70%)*
- *TCP processing in Kernel account for 15-20%*

EAA: Protocol optimization (4/4)

- Finer breakdown:
  - Copy cost (especially Kernel-NIC) is overkill : use 0-copy Kernels
  - Timeout (TO) and Triple Duplicate (TD) extra burden: maintain buffer in the NIC, would benefit in lossy environment (e.g., WiFi)
  - ACK cost very high (almost as a full packet): use batch copy Kernel-NIC (however, drivers must be redesigned to detect end of pkts)

	FreeBSDv4.2		FreeBSDv5	
μJ	MTU 1500	MTU 552	MTU 1500	MTU 552
Normal TCP Proc.	1,589	1,583	1,546	1,520
TD Cost	2,406	2,402	2,380	2,379
TO Cost	2,710	2,592	2,660	2,529
ACK Cost	1,209	1,171	1,188	1,164
Kernel – NIC Copy	16,251	6,744	15,207	6,293
user-to-kernel Copy	1,417	344	3,015	1,058

Source [38]

EAA: Application optimization (1/2)

- Energy efficiency of Web browsers [77]
  - Investigation of factors having more impact
  - 3 HW PCs, 3 OS, 4 SW Browsers, 15 Websites

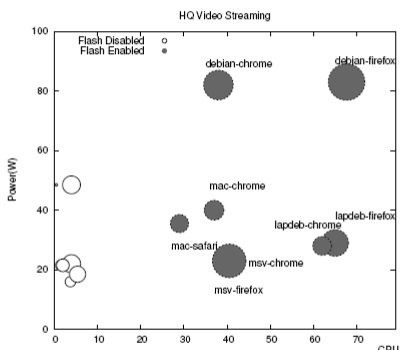
Source [77]

EAA: Application optimization (1/2)

Source [77]

TABLE II
RELATIVE IMPORTANCE OF FACTORS UNDER STUDY.

	I_L	I_P
OS	1.10	1.11
HW	1.45	1.95
SW	1.72	1.08
Web	4.63	1.44



CPU

Observation [77]

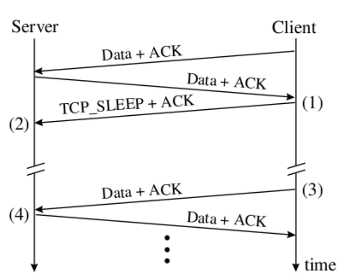
- *HW first factor for Power, followed by Website*
- *Tabbed browsing source for energy waste*
  - *Users interact with a single tab at any time, but CPU-hungry plugins always active on all tabs*
- *Run plugins of active tab of active window only*

Turn off the light while you are in another room!

EAA: Protocol design (1/4)

- Explicitly consider *idle* states in the protocol
  - Application layer [39,40] or transport layer [37]
  - Software prototypes [37,39] or simulation [40]
  - Selective connectedness paradigm

Source [37]



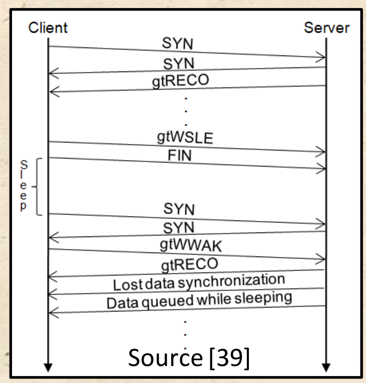
(1) = Client begins shutdown by sending TCP_SLEEP
(2) = Server blocks socket and connection enters "sleep"
(3) = Client wakes-up and sends data to server
(4) = Server receives data and resumes connection

Between (2) and (3) the client can be fully powered-off and the connection is "sleeping"

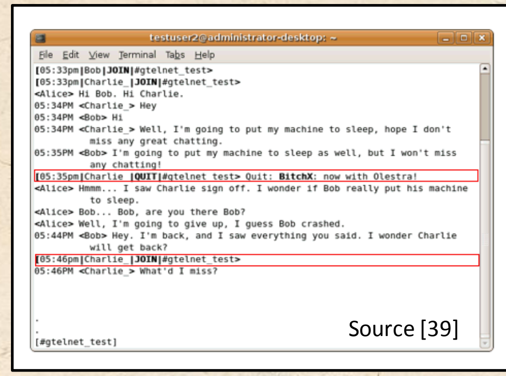
Figure 2 - Connection state diagram showing new sleep state for Green TCP/IP

EAA: Protocol design (2/4)

- Telnet case study [37,39]
  - implemented both as green Telnet L7 application and as an application over a green TCP at L4 [37]
  - bottom line: packets are buffered during idle times



Source [39]



Source [39]

EAA: Protocol design (3/4)

- BitTorrent case study [40]
  - Seeders go idle after not receiving any request from leechers during an *inactivity timer*

Event 1: Time out of connection timer

```
Event 1: Detection of TCP disconnect of a peer
1.  on (detection of TCP disconnect of peer p)
2.      p.state = sleeping

Event 2: Time out of connection timer
1.  on (timeout of connection timer)
2.      check with tracker for new peers as needed
3.      for (all new peers in peer list)
4.          p.state = unknown
5.      while (count of connected peers < max_connect)
6.          p = randomly selected peer in my peer list
8.          if (have tested all peers) exit this loop
9.          if (wake-up condition == true)
10.             send wake-up message to peer p
11.             try to connect to peer p
12.             if (TCP connection established)
13.                 p.state = connected
14.             else
15.                 remove peer p from my peer list
16.     restart connection timer
```

Observation

- *Seeders take care of not waking up other seeders*
- *Leechers may wake up sleeping seeds if they cannot find content elsewhere*
- *Selective connectedness* (seed) *Resource consolidation* (chunk)

wake-up condition in line 9 is:
peer is a seed,
(p.state == unknown)
peer is a leech.
((p.state == unknown) OR (p.state == sleeping))

Source [40]

EAA: Protocol design (4/4)

Source [39]

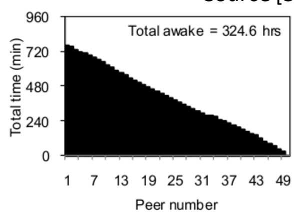


Figure 5. Sleep for standard BitTorrent

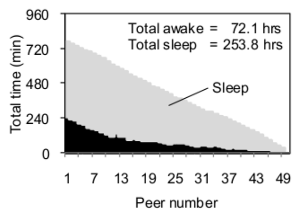


Figure 8. Sleep for green BitTorrent

Observation

- *System parameters*
  - *Transition time = 300 ms (notice that [30] estimates 4-8 sec)*
  - *Inactivity timer = 15 sec*
- *Performance*
  - *Large sleep time (or energy saving)*
  - *Larger download time … but what about LEDBAT (IETF WG on low priority transfer chaired by BitTorrent)*
- *BitTorrent peer selection policies can be tweaked / optimized for:*
  - *Peer locality (i.e., find content from nearby peers)*
  - *Energy-awareness (awake peers)*
  - *… what about both ?*

Energy-aware application: Summary (1/2)

- Motivation
  - – Large potential gain, as less systematically investigated
- Two main families of EAA approaches
  - – Protocol design
    - Explicitly introducing power state in the protocol finite state machine + notification of such states
  - – Protocol optimization
    - Optimize existing protocols and applications by explicitly power-profiling the code

Energy-aware application: Summary (2/2)

- Bottom line
  - Application of several paradigms
  - Large potential benefit (large user population)
  - Application-level modification easy to spread (i.e., download and install)
  - Radical new approaches, solution to old problems
    - Green Telnet does not suffer disconnection, which instead affect SSH (that solves the issue using non-Green keep alive)
- Advancement status
  - Long studied: Green TCP dates back to …. 1998 !
  - More heterogeneous field, fewer studies so far (so start coding!)

A few more words on...

Power modeling, measurement and the network edge

A few more words on…

- Power modeling and measurement
  - Measurement of a device / of the Internet
  - Need for common metrics and benchmarks
  - Metrics overview
    - ECR, ECRW, EER, EPI, PPU, TEER, TEEER, CCR, ….
- At the network edge
  - Server side: Datacenters
  - Client side: PCs
  - Access technology: Wireless

Measurement of a device

- Non-networked devices
  - Traditionally, power profiling and modeling of single, non-networked, devices
  - System-wise [71,72].
  - Component-wise [56,58,70]
    - CPU [56]
    - memory [58]
    - hard-drives [70]
- Networked devices
  - Routers [34,11], switches [43], links [21]

Measurement of the Internet (1/2)

- Measurement issue
  - Device profiling agrees, but data is scattered
  - Internet profiling more complex, hence a large gap
    - [74] microscopic model, [19] black box model

Context	Energy Cost Minimum	Energy Cost Maximum
Router (experimental) [34]	0.31 μJ/bit	
Router (experimental) [11]	0.43 μJ/bit	
Internet (lower bound) [74]	2 μJ/bit	75 μJ/bit
Internet (black box) [19]	16.0 mJ/bit	28.1 mJ/bit

Measurement of the Internet (2/2)

- Internet profiling
  - [73,74] develop a microscopic model (considering individual elements) to power profile the Internet

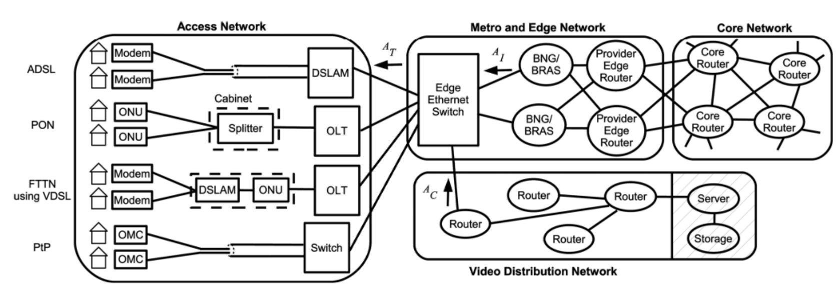


Fig. 1. Schematic of a network structure with access network options including an asymmetric digital subscriber line (ADSL), a passive optical network (PON), fiber to the node (FTTN) and point-to-point optical (PtP). The public Internet includes all equipment in the metro edge and core networks except the edge Ethernet switch. A_T is the total per customer capacity, A_I the per customer capacity in the public Internet, and A_C the per customer capacity in the VDN.

Source [74]

Metrics and benchmark

- Observation
  - Different work on similar subject use arbitrary inputs and outputs, hindering their comparison
- Factual example: ALR [23,24,25]
  - Output : performance index and metrics
    - [23,24] percentage of time in low-power state, [25] total gain
  - Input : traces, power models, assumptions
    - Each uses own traffic traces, different power model (only [25] considers power cost due to state transition)
- Consequence
  - Need for *common datasets* (topologies, traces, models,…)
  - Need for *common practices* (compare with previous assumptions, use common metrics,…)

Metrics overview (1/3): the Big picture

- [76] overviews energy-related metrics in use today

Country-Level	Uses	Description
EPI	Rankings	Environmental Performance Index, benchmarks the country's environmental performance.
ESI	Rankings	Environmental Sustainability Index, indexes the country's environmental sustainability.
EVI	Indicators	Environmental Vulnerability Index, characterizes various environmental issues.
HPI	Rankings	Happy Planet Index, reveals the ecological efficiency of human well-being.

Corporate-Level	Established as	Description
ISO/TC207	Workgroups	Standardization in the field of environmental management tools and systems.
GHG Protocol	Standards	GHG Protocol Corporate Standard provides standards and guidance for companies and other organizations preparing a GHG emissions inventory.

Facility-Level	Range	Description
PUE	1 to ∞	Power Usage Effectiveness, is defined as the ratio of data center power to IT power draw.
DCiE	0 to 100%	Data-center infrastructure Efficiency, is a reciprocal of PUE times 100.
W/ft^2	0 to ∞	Over-estimates the area actually devoted to the servers.
DCP	1 to ∞	Data-center Productivity, accounts only for the "useful work done" by the data-center.

Equipment-Level	Units	Description
ECR	Watt/Gbps	$ECR = E_f/T_f$. Aggregated energy consumption normalized to capacity.
EER	Gbps/Watt	$EER = 1/ECR$. For convenience, defined under the name of EER.
ECRW	Watt/Gbps	$ECRW = (\alpha E_f + \beta E_h + \gamma E_i)/T_f$, with (α,β,γ)=(0.35,0.4,0.25). A weighted metric considering energy consumption at different loads.
EPI	Percentage	$EPI = 100(M - I)/M$. Based on consumption at idle (I) and maximum (M) workload.
Power Per User	Watt/user	Power consumed by each subscriber in the public Internet.
TEER	Gbps/Watt	Telecommunications Energy Efficiency Ratio. Ratio of "useful work" to power consumption.
TEEER	$-\log \frac{watt}{Gbps}$	Telecommunications Equipment Energy Efficiency Rating. Log of the power/throughput ratio.
CCR	rad (Dimensionless)	Consumer level energy metrics, $CCR = E/\Sigma A(j)$, where E is the power rating of a consumer network device, A is the energy allowance per function (DSL, Wi-Fi, etc).
Watts per circuit	Watt	Used for point-to-point (Virtual Leased Line) Ethernet-Line services.
Watts per MAC	Watt	Used for multipoint (MAC Address) Ethernet-LAN services.

Metrics overview (2/3): Facility level

Subject to strong assumptions

Redundancy

Arbitrary parameters

Equipment-Level Metric	Units	Description
ECR	Watt/Gbps	$ECR = E_f/T_f$. Aggregated energy consumption normalized to capacity.
EER	Gbps/Watt	$EER = 1/ECR$. For convenience, defined under the name of EER.
ECRW	Watt/Gbps	$ECRW = (\alpha E_f + \beta E_h + \gamma E_i)/T_f$, with (α,β,γ)=(0.35,0.4,0.25). A weighted metric considering energy consumption at different loads.
EPI	Percentage	$EPI = 100(M - I)/M$. Based on consumption at idle (I) and maximum (M) workload.
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Watts per circuit	Watt	Used for point-to-point (Virtual Leased Line) Ethernet-Line services.
Watts per MAC	Watt	Used for multipoint (MAC Address) Ethernet-LAN services.

Source [76]

And others possible, service dependent

Arbitrary

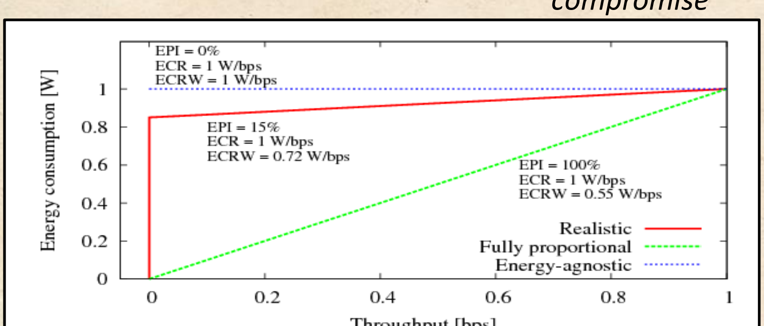
Different possible definitions

Metrics overview (3/3): Example

	TEER	TEEER	ECR	EER
TEER	–	e^{TEEER}	$\frac{Th}{C \cdot ECR}$	$\frac{Th \cdot EER}{C}$
TEEER	$\log TEER$	–	$\log \frac{Th}{C \cdot ECR}$	$\log \frac{Th \cdot EER}{C}$
ECR	$\frac{Th}{C \cdot TEER}$	$\frac{Th}{C} e^{-TEEER}$	–	$\frac{1}{EER}$
EER	$\frac{C \cdot TEER}{Th}$	$\frac{C}{Th} e^{TEEER}$	$\frac{1}{ECR}$	–

Observation

- *TEER, TEEER, ECR, EER: miles/hour or hours/mile ?*
- *EPI: proportionality*
- *ECR: absolute value*
- *ECRW: (arbitrarily) weighted compromise*



Source [76]

At the network edge: Server-side

- With respect to networking, efficiency in datacenters is a more confined and mature field,
  - Dates back to early 2000 [63].
  - Resource consolidation paradigm from datacenters
  - Permeation with Green networking [64]
    - jointly applies ALR with Network Traffic and Server Load Consolidation techniques.
  - For further references and state-of-art see [65]
  - Recent techniques is to break monolithic datacenters into distributed nano-datacenters [66,67].

At the network edge: Client-side

- Systematic exploration of opportunities for energy saving:
  - Starting from conservation in wireless networks [55]
  - Dynamic voltage scaling [18,56]
  - Group instructions to increase scheduling logic efficiency [57]
  - Energy-aware memory allocation [58]
  - Thread migration in multi-core architectures [59]
  - Energy management policies in multi-core systems [60]
  - Tickless kernels [62] available as a patch since Linux 2.6.17

At the network edge: Wireless-side

- Energy = primary concern in wireless
  - Especially due to limited peak voltage batteries
  - Many work, see for instance survey [68]
  - Wireless requirement orthogonal w.r.t. wired
    - Cannot import wireless approaches "as is"
  - Some similarities exist, though
    - Dynamic Voltage Scaling [18] originally proposed in Wireless, then largely diffused in computer systems
    - Low-power low-rates in ALR similar to 802.11
    - Cellular infrastructure dimensioned for peak use, at night it may benefit from resource consolidation [69]

Conclusions & Future research directions

ALR, Proxy, EAI, EAA, and cross-branches

Adaptive Link Rate

- Summary
  - Application of Proportional computing paradigm
  - Sleep mode: simple and preferable at low load
  - Rate switch: preferable at higher load, more robust in case of parameter misestimation
  - IEEE standard 802.3az [41], most studied, products expected soon
- Future work
  - Comparison of the slightly different (though very similar) strategies missing so far

Interface Proxying

- Summary
  - Application of Selective connectedness paradigm
  - External or onboard of NIC, needed degree of complexity depends on environment
  - Under standardization at ECMA [42], well advanced prototypes
- Future work
  - Set-top-box proxying neglected (ideal for home)
  - Coordination of different subsystem (eg NIC of multi-homed devices) not treated yet

Energy Aware Infrastructures

- Summary
  - Application of Resource consolidation paradigm
  - From clean-slate architectures, to optimization of existing protocols
  - IETF drafts started to appear, fewer work but research rapidly increasing
- Future work
  - Need to investigate efficiency/resilience tradeoff
  - Much effort directed into *optimal* solutions: need for *practical* solutions as well
    - If similar performance, choose the one minimize reconfiguration
  - Precisely define required changes in routing protocols to allow differentiate between *sleep* vs *faults*

Energy Aware Applications

- Summary
  - Application of several paradigms
  - Protocol design and optimization, huge saving potential due to large user population
  - Fewer work, but heterogeneous and thus good coverage
    - kernel vs user, protocol tweak vs design, client-server vs P2P, etc.
- Future work
  - Need for tools to automate energy profiling
  - Need for improving energy-efficiency of *popular* libraries and applications
  - Translate green paradigms in good programming practices
    - Eg. Packet pacing non-green while TCP-bursts are green

Measurement and models

- Summary
  - Core tool in finding new green opportunities
    - ALR motivated by traffic arrival patterns [19,21]
    - Proxying motivated by chatter analysis [21,31]
  - Core tool in benchmarking new green strategies
    - A number of metrics proposed [44] and compared [76]
- Future work
  - Improve use of common metrics, assumptions, benchmark, dataset, practices
  - Reduce the gap in Internet power consumptions estimates
  - Find new green branches!

Cross-branch

- Future work
  - Investigation of *combined* techniques
  - Desirable joint benefits
    - Proxying handles *incoming traffic,* but application design may handle *outgoing traffic* (e.g., send out message bursts instead of spreading them out)
  - Undesirable inter-dependencies
    - Performance of *Energy-Aware Applications,* connected through a set-top-box implementing *Interface Proxying* with an ISP using *Energy-Aware Routing* on routers interconnected by *Adaptive Link Rate* lines to access a *Green datacenter* ?

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ALR, Proxy, EAI, EAA,
+ relevant work

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