Green Networks: Reducing the Energy Consumption of Networks

Ken Christensen
Department of Computer Science and Engineering
University of South Florida
Tampa, Florida USA 32620
christen@cse.usf.edu
http://www.csee.usf.edu/~christen

Funding for this work from NSF (CNS-0520081 and CNS-0721858) and Cisco

Keynote talk at ISITCE 2010 – Pohang, Korea
Thank you to James Won-Ki Hong for inviting me to give this talk. I am very honored to be here in Korea for my first time.
Where do I come from?

University of South Florida and Tampa

47,000 students

Yes, we have lots of alligators
Acknowledging my students

Some of the work presented here was done by past and present students including,

• Chamara Gunaratne (PhD in 2008)
  - Early Proxying and Ethernet work

• Miguel Jimeno (PhD in 2010)
  - Proxying (especially for applications)

• Mehrgan Mostowfi (MS in 2010, continuing to PhD)
  - Recent Ethernet work
Why green networks?

One of the most urgent challenges of the 21st century is to investigate new technologies that can enable a transition towards a more sustainable society with a reduced CO$_2$ footprint.

We need to reduce energy consumption
The challenge to ICT

What role will ICT play in this grand challenge?

• Directly reduce energy consumed by ICT

• Enable energy savings in non-ICT
Notion of “comfortable conservation”

Two ways to consume less energy...

1) Have and do less = conservation

2) Improve performance = efficiency

“I mean using less energy for identical performance, measured in whatever way the consumer wishes.”
- Richard Muller (Physics for Future Presidents, 2008)

In network speak, same QoS for less energy
Product lifecycle and green

Focus of this talk

Production
- Cleaner mining
- Cleaner manufacturing
- Use less toxic materials
- Use less materials overall
- Use less energy overall

Use
- Use less energy
- Extend lifetime

End-of-use
- Recycle materials
- Refurbish for reuse

Energy consumed by a PC*
- Production = 2000 KWh
- Life (5 yrs) = 4200 KWh

1 kWh = $0.10

Roadmap of this talk

This talk has four major topics

• Quantifying the energy use of ICT
• Reducing direct energy consumption
• Reducing induced energy consumption (if time permits)
• Future challenges (if time permits)
Key definitions

Direct energy use

• Energy used by network links and equipment, but not hosts

Induced energy use

• Incremental additional energy used for a higher power state of hosts needed to maintain network connectivity
Quantifying the energy use of ICT

How much energy does ICT consume?

... the Internet is part of this
Electricity use in the USA – big picture

All electricity ~3700 TWh

Buildings electricity ~2700 TWh

Electronics ~290 TWh

Networked ~150 TWh

Network equip ~20 TWh

1 kWh = $0.10

$15 Billion

Where (exactly) is this electricity used?

How much of it is wasted?

How much can be saved?

From Bruce Nordman, LBNL, 2010.

Green Networks: Reducing the Energy Consumption of Networks
A view from the Climate Group

The SMART 2020 report

- Focus is on ICT’s role in reducing greenhouse gases
  - Both of and by ICT

- A view of the world in 2020
  - Taking into account “likely” technology developments

- Supporting organizations
  - Include Cisco, Intel, HP, Sun, national telecoms, and telecom operators
Global ICT CO₂ footprint

Today ICT is 2% of global CO₂

From SMART 2020 report

Green Networks: Reducing the Energy Consumption of Networks
Global ICT CO\textsubscript{2} footprint continued

Telecom and PCs not data centers major contributors

Data centers are less than 15%

From SMART 2020 report

Green Networks: Reducing the Energy Consumption of Networks
ICT CO₂ > Aviation CO₂

A very significant statistic…

“The global information and communications technology (ICT) industry accounts for approximately 2 percent of global carbon dioxide (CO₂) emissions, a figure equivalent to aviation.”

- Gartner Group, Inc. (2007)
Most energy use is from the end user

More significant statistics...

“Desktop computing accounts for 45 percent of global carbon emissions from information technology.”
- govtech.com

“Most PC energy use in the US occurs when no one is there, and this is greater than the total energy use of all network equipment.”
- Bruce Nordman (LBNL)
Statistics from Italy – Broadband

17.5 million broadband users, overall population is 60 million


<table>
<thead>
<tr>
<th></th>
<th>power consumption [W]</th>
<th>number of devices [#]</th>
<th>overall consumption [GWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home</td>
<td>10</td>
<td>17,500,000</td>
<td>1,533</td>
</tr>
<tr>
<td>Access</td>
<td>1,280</td>
<td>27,344</td>
<td>307</td>
</tr>
<tr>
<td>Metro/Transport</td>
<td>6,000</td>
<td>1,750</td>
<td>92</td>
</tr>
<tr>
<td>Core</td>
<td>10,000</td>
<td>175</td>
<td>15</td>
</tr>
</tbody>
</table>

Overall network consumption 1,947

How much is wasted?

Most energy used in networks is wasted

- Networks are lightly utilized
  - Over provisioned for peak and redundancy
  - 1% to 5% utilization typical at edges

- Network elements have high base power
  - Not energy proportional
  - 80% base power is typical for PCs, routers, links, etc.

Significant potential for large energy savings
Notion of energy proportional computing

Relationship of power use and utilization

How do we move from the red line to the green line?

Note: Rate scaling is not very useful approach for actual case
Notion of “doing nothing well”

Much of the time our systems are idle but on

• What we seek is the ability to do nothing well…

“… but, the key starting point in conserving energy is: Do nothing well.”
- David Culler (UC Berkeley)

Because most of our systems are doing “nothing” most of the time
ICT consumes and wastes a lot of energy

- ICT contributes about 2% of human emitted CO$_2$
  - About equal to aviation industry
  - Rapidly growing

- Most of this energy consumption comes from the edge
  - From edge networks, edge network equipment, and PCs
  - Not from data centers

- Most of the energy consumed is wasted
  - Due to provisioning for peak resulting in low average utilization
  - High base power
Reducing direct energy consumption

Can we reduce energy used by Ethernet?

... Energy Efficient Ethernet (EEE)
Reducing energy use of Ethernet

Key observations:

- Most Ethernet links are lightly utilized (1% to 5%)
  - Majority of links are desktop to wiring closest
- Ethernet power consumption independent of utilization

Can we adapt power use to utilization?

- First idea: Adaptive Link Rate (ALR)
- Better idea: Low Power Idle (LPI)
Adaptive Link Rate (ALR)

Proposed in 2005 by Nordman and Christensen

- **Goal:** Save energy by matching link data rate to utilization
- **Change (or adapt) data rate in response to utilization**
  - Use 10 or 100 Mb/sec during low utilization periods
  - Use 1 or 10 Gb/sec during high utilization periods
- **Need new mechanism**
  - Current auto-negotiation is not suitable (too slow)
    - Designed for set-up (e.g., boot-up time), not routine use
- **Need policies for use of mechanism**
  - *Reactive policy* possible if can switch link rates “quickly”
  - *Predictive policy* is needed otherwise

Low Power Idle (LPI)

Proposed in 2007 by Intel

Active/Idle Toggling with 0BASE-x Concept

- Principle: Transmit data at fastest rate then return to idle
  - Energy savings come from power cycling between active/idle states

- Active/Idle toggling could be used instead of PHY rate shifting
  - Offers the best energy efficiency on links with lower utilization
  - Integrates well with existing PC power management schemes (e.g., ACPI)
  - Clock & power gating (on/off) is easier than rate shifting

- Asymmetrical operation would provide even better energy efficiency
  - Each direction could enter active & idle states independently
  - Most end-node traffic is heavily weighted toward either send or receive
  - Tx & Rx data paths already operate independently above the PHY

The link sleeps between packets

How LPI works

PHY goes to sleep between packets

- Sleep is idle = about 10% of full power
  - Periodic refreshes to keep synchronized
  - Has wake-up and sleep transitions
    » First packet after an idle incurs a wake-up transition ($T_w$)
    » After last packet in a burst a go to sleep transition ($T_s$)
Effect of LPI overhead

Efficiency for single packet case

\[ \text{Efficiency} = \frac{T_{\text{Frame}}}{T_{\text{Frame}} + T_w + T_s} \]

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Min ( T_w ) (( \mu s ))</th>
<th>Min ( T_s ) (( \mu s ))</th>
<th>( T_{\text{Frame}} ) (1500B) (( \mu s ))</th>
<th>Frame eff.</th>
<th>( T_{\text{Frame}} ) (150B) (( \mu s ))</th>
<th>Frame eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Base-Tx</td>
<td>30</td>
<td>100</td>
<td>120</td>
<td>48%</td>
<td>12</td>
<td>8.5%</td>
</tr>
<tr>
<td>1000Base-T</td>
<td>16</td>
<td>182</td>
<td>12</td>
<td>5.7%</td>
<td>1.2</td>
<td>0.6%</td>
</tr>
<tr>
<td>10GBase-T</td>
<td>4.16</td>
<td>2.88</td>
<td>1.2</td>
<td>14.6%</td>
<td>0.12</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

Effect of LPI overhead continued

Efficiency for 10 Gb/s (Poisson arrivals)

Simulation. Fixed length 1250 byte packets.

There is potential for improvement!

Packet coalescing to improve EEE

Addressed EEE improvements in recent paper

IEEE 802.3az: The Road to Energy Efficient Ethernet

Authors: K. Christensen, P. Reviriego, B. Nordman, M. Bennett, M. Mostowfi, and J.A. Maestro

- Explored coalescing of packets at transmitter
  - Reduce overall wake and sleep overhead
  - Trade-off energy savings for delay

- Paper to appear in special issue on Green Communications in *IEEE Communications* magazine
Reproduced previous 10 Gb/s experiment

Key parameter values for simulation model

- EEE parameter values
  - T_WAKE = 4.16 μs
  - T_SLEEP = 2.88 μs
  - For 1250 byte packet service time = 1.0 μs

- Coalescing parameter values
  - max = 10 packets or $t_{\text{coalesce}} = 12 \, \mu\text{s}$
  - max = 100 packets or $t_{\text{coalesce}} = 120 \, \mu\text{s}$

- Assume that idle power use is 10% of full power use

- Vary offered load from 0% to 95%
  - Poisson arrivals, fixed length packet
EEE with coalescing results

Efficiency of 10 Gb/s with coalescing

Energy use (%)

Offered load (%)

Fixed (no EEE)
EEE
Proportional
Coalesce (10 pkt / 12 μs)
Coalesce (100 pkt / 120 μs)

Note significant improvement
EEE with coalescing results continued

Packet delay for 10 Gb/s with coalescing

Coalesce (100 pkt / 120 µs)

EEE

Coalesce (10 pkt / 12 µs)

no EEE

Factor of 1000x less than end-to-end delay in Internet
Future work for coalescing

Need to consider effects of added delay

• What are effects of coalescing on TCP?
  - ACK compression?

• Are there other system-wide effects?
Expected savings

Energy savings have been estimated for USA

- Assume 2008 stock of Ethernet links as the “future”
  - Assume all interfaces support EEE
  - 250 million 1 Gb/s and 65 million 10 Gb/s
  - Per link savings of 1 W for 1 Gb/s and 5 W for 10 Gb/s
  - Get efficiency values from simulation graphs

EEE savings per year in the USA = $410 million
Additional savings from coalescing = $80 million
History of IEEE 802.3az

• Opportunity for energy savings to IEEE 802.3 in 2005
  - Presented idea of ALR
  - A Study Group was formed
  - Mike Bennett from LBNL became the chair

• Became “Energy Efficient Ethernet”
  - IEEE 802.3az task force

• ALR became RPS, which then became LPI

• Standard based on LPI to be ratified in September 2010

• Vendors are now sampling products (based on LPI)
  - Broadcom and Realtek

Logo by Glen Kramer of Teknovus, Inc. (full permission for use granted via email dated January 27, 2007)
The IEEE 802.3az standard

The IEEEDraft P802.3az/D3.2 standard

- “… adds changes required to enable energy efficient operation of several existing Physical Layers.”
- Mike Bennett (LBNL) is chair
- Expected to be ratified in September 2010
Summary of EEE

IEEE 802.3az improves energy efficiency of Ethernet

- Ethernet links typically have low utilization

- EEE = Energy Efficient Ethernet
  - Based on Low Power Idle (link sleeps between packets)
  - Sleep and wake overhead may be an issue to savings
  - Estimated savings are $100s of million per year in the US

- Packet coalescing can improve EEE savings
  - Trade-off of reduced energy use for added delay
  - Added delay is in 10s of microseconds – probably not an issue for end-to-end delay in an Internet connection
Reducing induced energy consumption

Can we reduce energy used by hosts?

... Proxy to maintain network presence
Reducing energy use of network hosts

Key observation

• “Today, billions of dollars’ worth of electricity are used to keep Ethernet (and other) connected devices fully powered on at all times only for the purpose of maintaining this connectivity.” (Bruce Nordman, 2007)

• The need for network presence is driving PCs to be left fully powered-on at all times

Defining “network presence” is a key challenge
Network Connectivity Proxy

How can we maintain network presence?

• Two possible approaches
  1) Redesigning protocols and applications
  2) Encapsulating intelligence for maintaining network presence in an entity other than the core of the network devices

• Approach (2) best in the near-term

• A proxy is “an entity that maintains full network presence for a sleeping device”
  - Host appears to other devices as fully operational
High level view of a proxy

Operation of a proxy

1) Host awake; becomes idle
2) Host transfers state to proxy on going to sleep
3) Proxy responds to routine traffic for sleeping host
4) Proxy wakes up host as needed

Proxy can be in separate entity, or within host NIC
The first work on proxying

- Described proxying for ARP and TCP keep-alives
- Described a centralized proxy covering for many hosts on a shared Ethernet LAN
Describing proxying to industry

• A whitepaper to bring proxying to industry folks
  - Industry folks do not read academic papers

• High-level view of proxying
  - Why we need it
  - How it might work
  - Next steps
  - FAQ

This was the first step to a standard
Early work: A prototype ARP/SYN proxy

Emulated proxy to allow a web server to sleep

Recent work: A proxy for SIP phones

IP phones are a new energy consumer

- IP phones need to maintain network presence
  - In order to receive a “ring” signal on incoming call

- IP phone draws about 10 to 20 W (so, $10 to $20 per year)

- Can also use a PC to make a “soft phone”
  - PC then needs to remain powered-up at all times
The Magic Jack product

A new product to replace landline telephone service

- USB device to plug an analog phone into a PC
  - Then use a SIP-based IP telephony service
  - Uses your Broadband service “for free”

Requires PC to be fully powered-on to be able to participate in SIP protocol

Power costs can exceed savings from canceling landline service
The “SIP catcher” – system view

Developed a proxy within a Linksys router

- Knows sleep/wake state of a soft phone PC or IP phone
- Handles SIP protocol and wakes IP phone as needed
The “SIP catcher” – packet flow view

Key steps:
1) Wakes up phone when call detected (incoming INVITE)
2) Responds on behalf of phone (TRYING)
3) Forwards INVITE to phone when it is awake

Delay added by SIP Catcher to allow IP phone to wake-up

Wake-up time is small
The “SIP catcher” – a demonstration

Full 8 minute version on YouTube
Future work for proxying

Explore selective connectivity as an architecture

\[ \begin{align*}
\text{on} & \quad \text{Connected} \\
\text{off} & \quad \text{Not connected}
\end{align*} \]

- Traditional Internet
- Delay Tolerant Networks

**A proxy**

- Assistants
- Exposing state
- Evolving state
- Host-based control
- Application primitives
- Security

Expected savings

Energy savings have been estimated for USA

• For desktop PCs most time is spent as on and idle

• Proxying could save more than half of energy used by these products

Savings potential for desktop PCs = $0.8 to $2.7 billion
History of Proxying

• Discussions toward a standard started in 2007 to 2008
  - To address IPv4 and IPv6 “lower layers”
    » Layers below applications

• Starting of Ecma effort in 2008 to 2009
  - Bruce Nordman led the effort

• Standard approved in February 2010

• Standard referenced in EPA Energy Star
  - Will drive adoption of proxying
The Ecma proxying standard

Ecma-393 ProxZzzy for sleeping hosts

- “… maintenance of network connectivity and presence by proxies to extend the sleep duration of hosts”

- Satisfies EPA Energy Star “platform-independent industry standard”

- Approved in February 2010

Does not include proxying for applications (e.g., P2P)
Proxying in EPA Energy Star

EPA Energy Star for Computers, Version 5.0

• "Proxying refers to a computer that maintains Full Network Connectivity as defined in Section 1 of this specification. For a system to qualify under the proxying weightings above, it must meet a non-proprietary proxying standard that has been approved by the EPA and the European Union as meeting the goals of ENERGY STAR."*

The Ecma standard is key to this


Green Networks: Reducing the Energy Consumption of Networks
Proxying in products

Apple Snow Leopard

• “Wake on Demand. This is Apple’s name for a new networking feature that lets a Snow Leopard Mac go to sleep while a networked base station continues to broadcast Bonjour messages about the services the sleeping computer offers.”*

Bonjour Sleep Proxy, supports ARP, file and print serving, and SSH login initiation.

From “Wake on Demand lets Snow Leopard Sleep with One Eye Open,” MacWorld, August 28, 2009
Summary of Proxying

Ecma ProxZzzy reduces induced energy use of hosts

- Hosts usually idle but connected to maintain “presence”

- Idea of a network connectivity proxy
  - Based on low-power hardware covering for high-power hardware
  - Supporting applications is a challenge
  - Estimated savings are on the order of $1 billion per year in the US

- Future work in addressing applications
  - Including P2P in all forms

- Future work in Selective Connectivity architecture
  - A future view of the Internet as not “always on”
Future challenges

Where do we go from here?

… energy savings of and by ICT
Future challenges in green networks

Future challenges in four areas

1) General

2) Network core and edge

3) Network hosts

4) Distributed applications
Future challenges continued

General

• Metrics
  - How do we measure energy-performance trade-offs?

• Models
  - How do we model energy-performance trade-offs?

• Exposing power and usage state
  - Need to be able to remotely determine power/use state
  - How to know when something is idle?

• Architectures for selective connectivity
  - Need mechanisms/protocols for selective connectivity
  - Includes notions of proxying
Future challenges continued

Network core and edge

- Energy efficient routers and switches
  - Support sleep states and rate adaptation

- Energy efficient links
  - Adapt link rates to load

- Traffic shaping
  - Shape traffic for short-term sleep during idle periods

- Traffic engineering
  - Consolidate routes for long-term sleep of idle routes

- Data caching
  - Cache popular data to reduce load on network and servers
Future challenges continued

Network hosts

- Discovery of devices, capabilities, content, and services
  - Need to be able to discover low-power substitutes

Distributed applications

- Move computing work to where power is cheapest
  - “Follow the moon” for data center activity

- P2P, multiplayer games, and virtual worlds
  - When idle should sleep

- Webcams and sensors everywhere (Internet of things)
  - When idle should sleep
Future challenges continued

My thoughts on the “best” challenges

• I think that the biggest challenges are at the edge
  - Most energy use there
  - Most opportunity for making changes

• Need applications and protocols that allow for and enable hosts and network equipment to sleep
  - Notion of selective connectivity

• Be careful to not work on problems already solved
  - Much has now been solved (the “low hanging fruit”)
  - Always be able to quantify expected savings and argue that they are sufficient to be of interest
Conclusions

- ICT has large and growing energy use
  - Estimated to be 2% of human generated CO₂

- EEE will reduce direct energy use
  - Hundreds of millions of dollars per year in US expected

- Packet coalescing can improve efficiency of EEE
  - Tens of millions of dollars per year saving in US possible

- Proxying will reduce induced energy use by hosts
  - Potential for billions of dollars per year savings in the US

- There are future challenges to be addressed
Any questions?

Ken Christensen

http://www.csee.usf.edu/~christen/energy/main.html

Many collaborations with Bruce Nordman at LBNL

The Energy Efficient Internet Project

This project addresses the increasingly critical need to improve the energy efficiency of the Internet by focusing on the primary and often neglected energy consumer, edge devices. Unfortunately, due to limits of existing protocols and architectures, networked desktop computers typically remain powered-up during frequent and often lengthy periods of idleness. As network devices, they are prevented from operating in an energy-efficient manner due to their need to respond to network transactions of various types without warning. In this project, we address network induced energy use for current and future edge devices. We also address reducing the direct energy use of high-speed links connecting these edge devices to the Internet.

Current project partners:

• The Second International Workshop on Green Communications is being organized as part of GLOBECOM 2009. Ken Christensen is one of the four organizers of this workshop.
• The notion of a power state MIB was presented at IETF by Juergen Quittek, see here.