Energy Efficient Cooperative Communications

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20th November 2013
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www.csiro.au
Rural and Remote Broadband Communications

50 Mbps uplink and downlink
14 simultaneous users
28 MHz BW

10 Gbps
Using 3 microwave bands
Reconfigurable in software
STAGE 2: Ngara access demonstrations
Marsfield, Sydney December 2011
Wireless Sensor Networks

- Light, Temp
- Water Quality: pH, Redox, Temp, Conductivity
- Soil Moisture
- Motion: GPS, Accel, Gyro, Magnetometer
- Strain Gauges
- DSP: Audio, Video
In the Field: Example CSIRO Deployments
Wireless Localisation System

System developed with features:

• High accuracy localisation
• Low cost hardware
• Provides high rate data communications
• No cabling required
• Operates in severe multipath
Wireless Localization Trials

[Images of various trials and equipment setup]
Contributors to Energy Footprint

Datacenters

Backbone

Access network

PCs & peripherals
For the operator, 57% of electricity use is in radio access
Energy consumption of Telcos

2.1 TWh
3.7 TWh
4.5 TWh
9.9 TWh

* Goma et al., Insomnia in the Access, SigComm, 2011
ICT Carbon Footprint
A view from Nokia Siemens Networks

Total CO₂ footprint from human activity

40GtCO₂e

CO₂ footprint of ICT

28%

Data centers

2%

PCs, peripherals, and printers

80-90%

Radio networks

(BTS sites: 78-89%)

CO₂ footprint of telecoms

43%

Devices

Fixed infrastructure

CO₂ footprint of radio networks

Sources: SMART2020 Report (The Climate group 2008) and Nokia Siemens Networks
A view from Alcatel-Lucent

2020 ICT CARBON FOOTPRINT

820m tons CO₂

• 2007 Worldwide ICT carbon footprint: 2% = 830 m tons CO₂
• Comparable to the global aviation industry
• Expected to grow to 4% by 2020

Total emissions: 1.43bn tonnes CO₂ equivalent

The Climate Group, GeSI report “Smart 2020”, 2008
More from Alcatel-Lucent

POWER CONSUMPTION OF MOBILE COMMUNICATIONS

- **Users**
  - Total Energy = 2 TWh/yr
  - 0.1W per user for 3 billion Subscriptions

- **Base Station**
  - Total Energy = 60 TWh/yr
  - 1kW per user for 4 million Base Stations

- **Network Control**
  - Total Energy = <1 TWh/yr
  - 1kW per user for 10,000 Controllers

- **Core & Servers**
  - Total Energy = 14 TWh/yr
  - 10kW per user for other elements

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The greatest opportunity to reduce energy consumption is to improve base stations

Based on: ETSI RRS05_024, NSN

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15 | AT THE SPEED OF IDEAS  
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Alcatel-Lucent
Outline

• Energy in WLAN Access
• Basic sleep modes
• Cooperation in Wireless Networks
• Cooperative Sleep Modes in WLAN
• Machine to Machine communications
• Energy Efficient Ethernet
• Software Defined Networking
Motivations for exploring energy efficient WLAN

- Power consumption of BS ($P_{BS}$) and AP ($P_{AP}$):
  
  $$P_{BS} \text{ (typically : 1000W)} \gg P_{AP} \text{ (typically : 10W)}$$

However, WLAN is widely deployed in most homes

- Typically, in a given area, the number of BS($N_{BS}$) and AP($N_{AP}$):

  $$100N_{BS} \ll N_{AP}$$
WiFi Access

- Huge number of devices
  - 2 orders of magnitude more gateways than DSLAMs
  - 3 orders of magnitude more gateways than metro devices
  - 4 orders of magnitude more gateways than backbone devices

- High per bit energy consumption
  - At full load, access devices consume 2-3 orders of magnitude higher energy-per-bit than metro/backbone

- Utilization < 10%

![Graph showing daily utilization of 10K access links in a commercial ADSL provider](attachment:image.png)

* Marco Canini
WLAN Access Point - Carbon Footprint

One household AP (Home AP)
• 10 W, 24x7 active: produces 48 kg of CO₂ annually

Australian NBN proposes to connect 10 million premises
• Combined power consumption: 100 Mega Watts
• Equivalent to 500 Tonne of CO₂ annually

Overall: WLAN power consumption is not to be neglected.

V. Sivaraman, C. Russell, I.B. Collings and A. Radford,
Importance of Implementation

Energy Efficient Hardware Design
• RF frontend: radio transceiver
• FPGA: modulation, MAC, Security
• Microprocessor: device control, Internet access

AP Sleep modes
• Microsleep: turn off RF frontend
  implement 802.11 intra-frame power saving
• Deepsleep: turn off FPGA and RF
  implement cooperative long sleep
Cross Layer Considerations

- Models for circuit energy consumption highly variable
- Transmit energy can be minimized by waiting for good channels
- Circuit energy consumption increases with on-cycle duration
  - Introduces a delay versus energy tradeoff for each bit
- High-level modulation costs transmit energy but saves circuit energy (shorter transmission time)
- High order precoding techniques not necessarily energy-efficient
- Short distance transmissions require TD optimization
- Coding costs circuit energy but saves transmit energy
- Sleep modes save energy but complicate networking
Standard Sleep Modes

• For long sleep duration, network access delay increases
• Long sleep could prevent some applications starting and/or operating
  – some applications (e.g. Skype, Messenger, Sensors) generate low rate keep-alive or report stream (a data packet every 1~100ms), which result in an AP not busy, but also not inactive – cannot go to sleep.

• If sleeping duration is small, boot up time dominates
  – low sleep efficiency
Cooperative Sleeping

- AP deployment density is high
- AP is on low or no traffic most of the time (80~90%)

Idea
- Share AP among neighbouring households
- Low rate and start up applications have network access through a shared “AP "On Duty"
- Most APs can have long sleep – improving sleeping efficiency
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Large Scale Multi-Antenna Networks

Wireless Sharing Spectrum

RoF
Large Scale Multi-Antenna Networks

- Antenna Coordination
- CSI Feedback
- Antenna Selection
- Channel Estimation
- Interference Management
- Transmission Mode
- Resource Allocation
- Synchronization
- User Scheduling
Adaptive Wireless Access Networks

Reconfigurable topology
Adaptive spectrum allocation

Performance of the New Adaptive Architecture

Simulation setup
- A 6-floor 18-antenna indoor wireless network
- The number of BSEs is from 2, 4, 5 and 6
- Network bandwidth: 20 MHz
- Independent and identical distribution (IID) of traffic demands

Conclusion
- New architecture with 4 BSEs outperforms existing approaches with 5 BSEs
- CAPEX saving is 20% on BSEs

indicates how significantly traffic demands (bandwidth requirements) change.
Distributed Wireless Networks
When do relays improve performance?

Cooperation: All the relays transmit and all the antennas at the destination combines the signal with MRC.

Non-cooperation: The relays are switched off. The source transmits directly to the destination which combines using MRC.
Cooperation vs Non-Cooperation

Strong Direct Link Scenario

- Non-cooperation outperforms cooperation

Weak Direct Link Scenario

- Cooperation outperforms non-cooperation

To achieve a desired diversity order it is better to design a multi-antenna receiver than design a relay system.

It is better to design a relay system, assuming you have the extra bandwidth/timeslots.
Selection Diversity vs All-Participate in Cooperative Networks

- Core concept: A wireless mesh network in which only the strongest link amongst the N+1 links is selected for transmission.

- Benefits: Cooperative diversity typically comes at the expense of N+1 orthogonal channels for the source and all the relays to transmit. Relay selection offers a low network complexity without spectral efficiency loss since only two orthogonal channels are required.
Selection Diversity vs All-Participate in Cooperative Networks

SD outperforms MRC when a total power constraint is applied at the relays.

For the comparison with MRC, we divide the transmit power by the number of relays, N.

SD can outperform All-participate without added complexity and bandwidth requirements.
Exploit both multi-antenna diversity and multiuser diversity with low complexity and low feedback overhead in multiuser relay networks.

Viable option for emerging standards, e.g., IEEE 802.16j multihop relay networks and IEEE 802.11s mesh networks.

Finding: Diversity Order: \[ G_d = N_R \times \min\{N_S, N_D K\} \]
Application in MIMO Multiuser Relay Networks

SER versus power allocation $\eta$ between the source and the relay for different antenna configurations.

The optimal power allocation varies according to the number of destinations and the number of antennas at the source, the relay, and the destinations.

Application in Two-Way MIMO Relaying

Motivation: Transmit/Receive antenna selection exploits the multi-antenna diversity in two-way MIMO relaying in a low complexity manner.

One possible Algorithm: A single transmit/receive antenna is selected at each node.

Benefits: The full diversity order of $\min\{N_A, N_B\}$ is achieved, as if all the transmit antennas were used, e.g., beamforming.
Eigen Direction Alignment PNC for MIMO TWRC

This figure shows a 2 by 2 MIMO two-way relay channel case. The gap between our scheme and the capacity upper bound is almost unnoticeable at a medium-to-high SNR.

The gap between our scheme and the capacity upper bound is almost unnoticeable at a medium-to-high SNR.

Our proposed scheme outperforms existing amplify-and-forward and decode-and-forward scheme by up to 40% in spectral efficiency at practical SNR levels.

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Greening via Aggregation

Aggregation: Assign clients to small number of access points, put rest to sleep

On average 5-6 WiFi networks overlap in typical urban settings
Distributed Implementation (Canini, Sigcomm’11): Broadband Hitch-Hiking (BH^2)

Load on home gateway is low
- direct light traffic to a neighbor gateway and let home gateway sleep

Load on neighbor gateway is low
- look for another neighbor or go back to home gateway

Load on neighbor gateway is high
- go back to home gateway
Issues with Distributed implementation of Cooperative Sleeping

• Client-side machinery:
  – Complex to install and maintain:
    – interface virtualisation
    – reverse network address translation (NAT)
    – traffic snooping
  – Requires updating clients:
    – Many household devices, heterogeneous OS
    – Non-compliant / malicious clients can cheat system

• Sub-optimal: no bounds on performance

• Fairness:
  – Unfair sharing of bandwidth and energy costs
Our approach: Centralised Implementation

- Central entity computes optimal assignments
- Minimise: Power $P = \sum_j W_j X_j$
  - $X_j$: binary variable 1 if AP-$j$ selected, 0 otherwise
  - $W_j$: weight of AP-$j$ (used to control fairness)
- Constraints:
  - $\forall i, j$: $x_{ij} \leq e_{ij}$, i.e. client-$i$ can connect to AP-$j$ only if link is feasible
  - $\sum_j x_{ij} = 1$, i.e. client-$i$ can connect to only one AP
  - $\sum_i b_t x_{ij} \leq C_j$, i.e. total bandwidth needed by clients connected to AP-$j$ does not exceed capacity of AP-$j$
  - $\sum_i x_{ij} \leq X_j \sum_i e_{ij}$, i.e. AP-$j$ is turned on if any client connects to it.
Heuristic Solution

- **Greedy algorithm:**
  - Pick (previously unpicked) AP that covers largest number of uncovered clients, normalised to weight
  - Repeat until all clients covered

- **Solution within log(n) of optimal (n = # clients)**

- **Assignment of clients to APs:**
  - Clients with (rate > threshold θ) stay with home AP
  - Other clients moved to “least cost” AP
  - AP-cost = energy-cost + guest-data-cost
    - Exponentially averaged
    - Tracking of cost helps maintain long-term fairness
Evaluations: Trace Data

Campus building with 30 APs
4 x 24-hour traces with ~26K client sessions
Client on average sees 5.8 APs
90% of sessions have avg. data rate < 20Kbps
Simulation Results

- 50-70% energy savings possible (85% on weekends)
- Increasing migration threshold increases energy savings, but also increases migration disruptions
- Increasing fairness (marginally) decreases energy savings
Prototype: 6 Households

- Commodity AP: TP-LINK DD-WRT
- Home and guest SSID
- WiFi device discovery, NetFlow
- Controller runs algorithm
- Clients unmodified:
  - PowerShell scripts
  - Video, Skype, Browsing
Experimental Results

<table>
<thead>
<tr>
<th>Time</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 AM</td>
<td>15</td>
</tr>
<tr>
<td>9 AM</td>
<td>20</td>
</tr>
<tr>
<td>12 PM</td>
<td>25</td>
</tr>
<tr>
<td>3 PM</td>
<td>30</td>
</tr>
<tr>
<td>6 PM</td>
<td>15</td>
</tr>
<tr>
<td>9 PM</td>
<td>20</td>
</tr>
<tr>
<td>12 AM</td>
<td>25</td>
</tr>
<tr>
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<td>30</td>
</tr>
<tr>
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<td>15</td>
</tr>
</tbody>
</table>

Data rate (Mbps)

Aggregate Data Rate for WAPs

Power with Algorithm

Power without Algorithm

57-77% energy savings
Fairness in power usage and guest costs
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IEEE 802.11 for M2M Networks

IEEE 802.11 Task Group AH

- Started July 2010, targeting standard release IEEE 802.11ah in 2014
- Sub 1 GHz spectrum
- Longer reach – 1 km
- More devices – 6000 STAs per AP
- Traffic: periodic, light
  - Uplink: meter reading
  - Downlink: control message

Potential issues

- Physical layer
- MAC
- **Power Saving** *

Issues on M2M Communication Networks

When multiple STAs have aligned wakeup periods

- High collision: $p=30\%$ when as few as 15 STAs aligned (out of the 1000’s) ➔ higher delay,
- STAs have to wake up longer (consume more energy) than STA w/o collision.
- Bad for a M2M Communication Network:
  - Designed network lifetime = 5 years
  - Some 5% (aligned) nodes die earlier (after 6 months) due to aligned periods
  - Whole system collapse!

(a) Collision between PS-Polls results in longer active periods
Collision probability

Find the relationship between

- Transmit probability matrix $T$ and collision probability matrix $C$

$$T_{i+1,k} = \begin{cases} 
\frac{1}{W_0}, & \text{for } i = 0, j = 1, \ldots, W_0, \\
\sum_{j \in B(i,k)} \frac{1}{W_i} C_{i,j}, & \text{for } i = 1, \ldots, s, B(i,k) \neq \emptyset, \\
0, & \text{else,}
\end{cases}$$

$$C_{i,k} = T_{i,k} (1 - [1 - \sum_{j=0}^{s} T_{j+1,k}]^{N-1}),$$

Collision probability solved

- Match simulation results

$$p(N) = \frac{\sum_{i=0}^{s} \sum_{k=1}^{W_{tot}} C_{i+1,k}}{\sum_{i=0}^{s} \sum_{k=1}^{W_{tot}} T_{i+1,k}}.$$
Our Proposal: Power Save with Offset ListenInterval (PL-OLi)

AP maintains a beacon occupancy table (BOT)
- Records the number of PS STAs at each beacon interval

AP find the lowest Beacon interval for the STA\textsubscript{m}
- Search BOT for lowest entry
- Calculates an offset to be applied to the Listen Interval

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|c|c|c|c|}
\hline
Beacon \# & 0 & 1 & 2 & 3 & 4 & 5 & \ldots & N_{B} - 1 \\
\hline
Occupyancy & 1 & 1 & 1 & 0 & 1 & 0 & \ldots & 1 \\
\hline
\end{tabular}
\end{table}

(b) Collision is avoided by adding an offset to the ListenInterval in OLi
Performance Analysis – Energy

Energy consumption to retrieve a packet

\[ E(N) = P_s(1)E_s + \sum_{k=2}^{W_{tot}} P_s(k)(E_s + \sum_{j=1}^{k-1} e(j)). \]

where

\[ e(k) = \frac{P_n(k)E_n + P_{xs}(k)E_{xs} + P_c(k)E_c + P_{xc}(k)E_{xc}}{1-P_s(k)}. \]

PS-OLi improve lifetime

– by up to 30% (10 months)

Implements scalability

– By up to 40%
  (scale up to 5800 nodes)
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Greening Enterprise Ethernets

Ethernet switches dominate enterprise networks
(7.9 TWh per-year in the US)


IEEE 802.3az: Energy Efficient Ethernet (EEE)

• Introduces “low power idle” (LPI) mode
  – Interface put to “sleep” during idle periods
  – Periodic wake-up to maintain sync and check for packets
• Energy savings very dependent on traffic profiles
EEE Savings vs. Traffic Load and Packet Size

- New profile (via measurement) of the actual performance of EEE switches available on the market.
- A new (and simple) model that is able to predict the energy savings with EEE based on simple parameters such as traffic load, packet size, and traffic burstiness.

Savings roughly linear in traffic load
Savings larger for larger packets (for same load)
EEE Savings vs. Traffic Burstiness

- Burstier traffic better for energy savings
  - Longer sleep periods
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Current Internet
Closed to Innovations in the Infrastructure
“Software Defined Networking” approach to open it
The "Software-defined Network"

North-bound interface API

OpenFlow API

Network Operating System

- LB service
- FW service
- IP routing service
- Unchanged mgmt API

Simple Packet Forwarding Hardware
AusSDN – an SDN Infrastructure Platform

SDN test network in Australia based around an SDX (SDN Internet Exchange)

- Partners can prototype research
- Leverage collective capability to seek resources from government and other sources (e.g. LIEF)
- Involve other organizations (Google, NICTA, ISPs, vendors?)
- Develop student skills in SDN (mentoring, projects, internships)
- Have an impact on the Australian NBN and networks of the future
AusSDN

Australian Open Network Experimental Test-bed

An OpenFlow-based test network to prototype inter-domain SDN use cases

OF switch (Pica8 3290)
Summary

- Energy is a major factor for wireless access networks
- Cooperation between nodes can have significant benefits
- Cooperative Sleep Modes in WLAN have great potential
- Sleep modes in M2M communications are more challenging
- SDN offers hope for an Energy Efficient Ethernet
Thank you

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