Greening Wireless Communications: A Top-Down Overview

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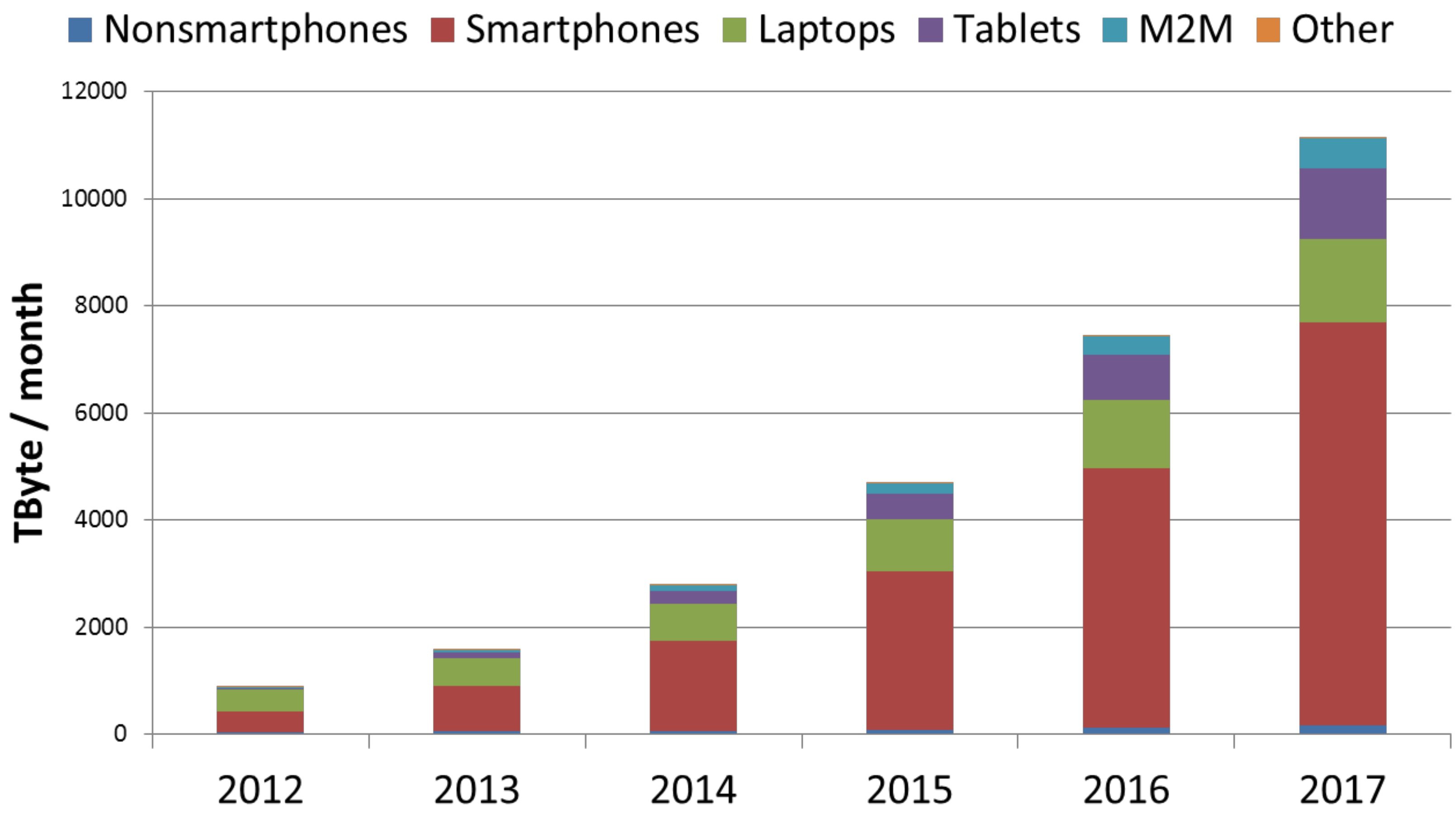
Motivation: Green all the things

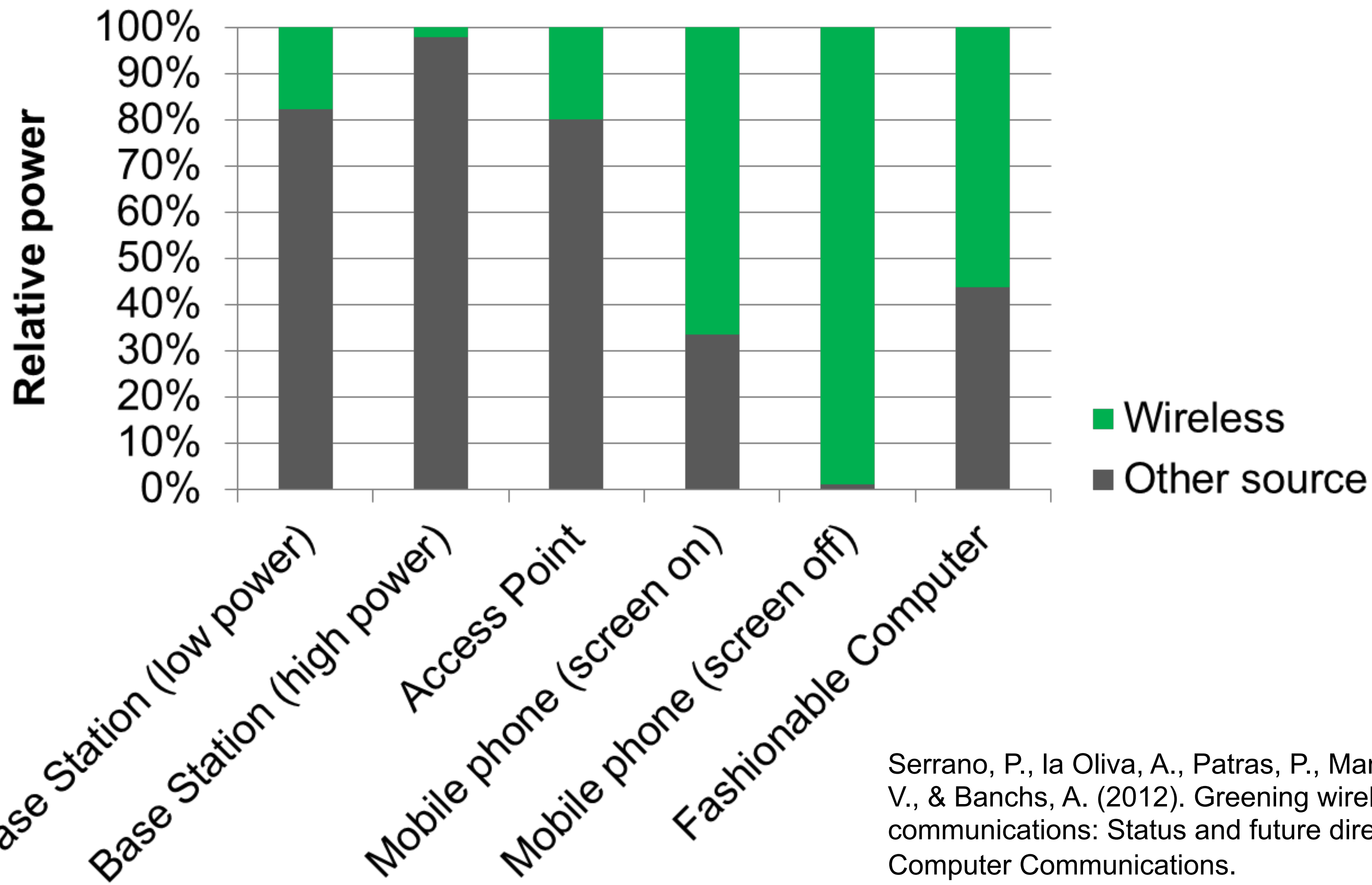
- Global warming
- CO_2 emissions
- Cost reduction
- More efficient operation

Motivation

- Cisco Visual Networking Index: Forecast of mobile data traffic



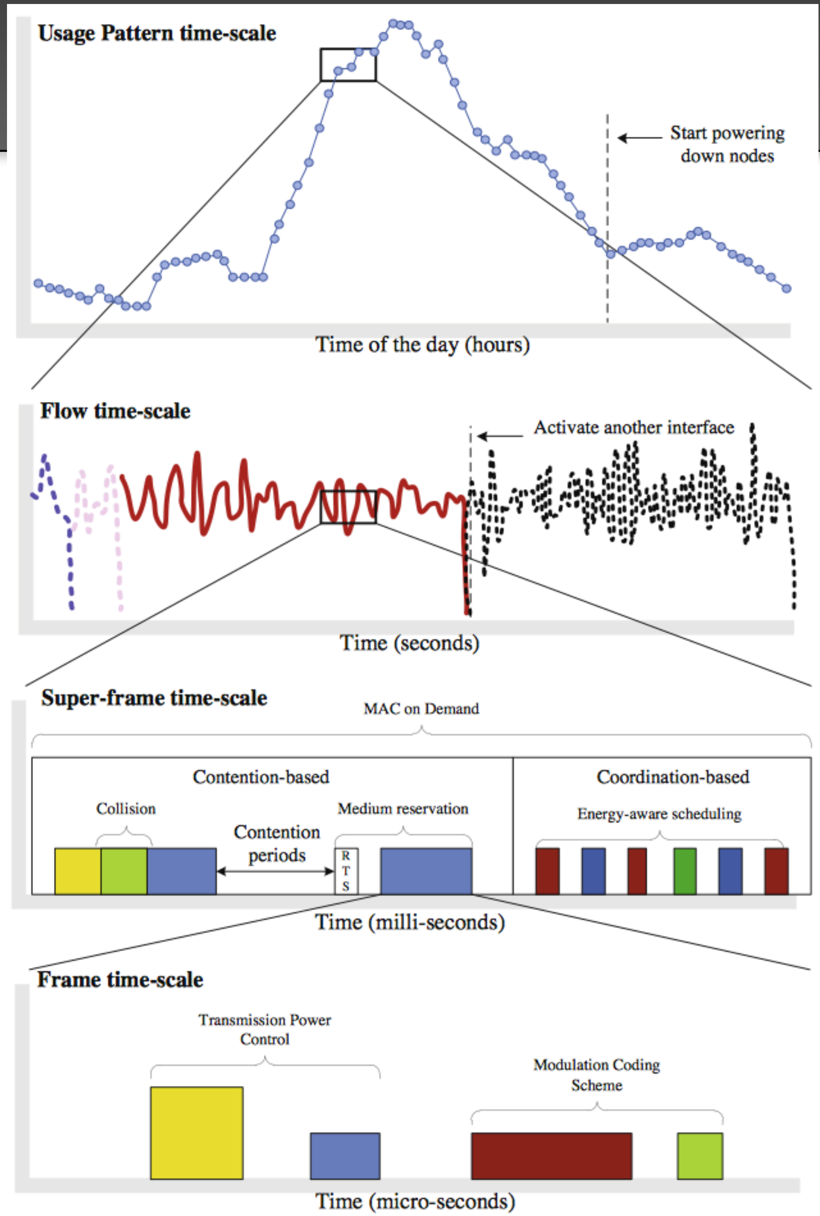
Energy consumption decomposition



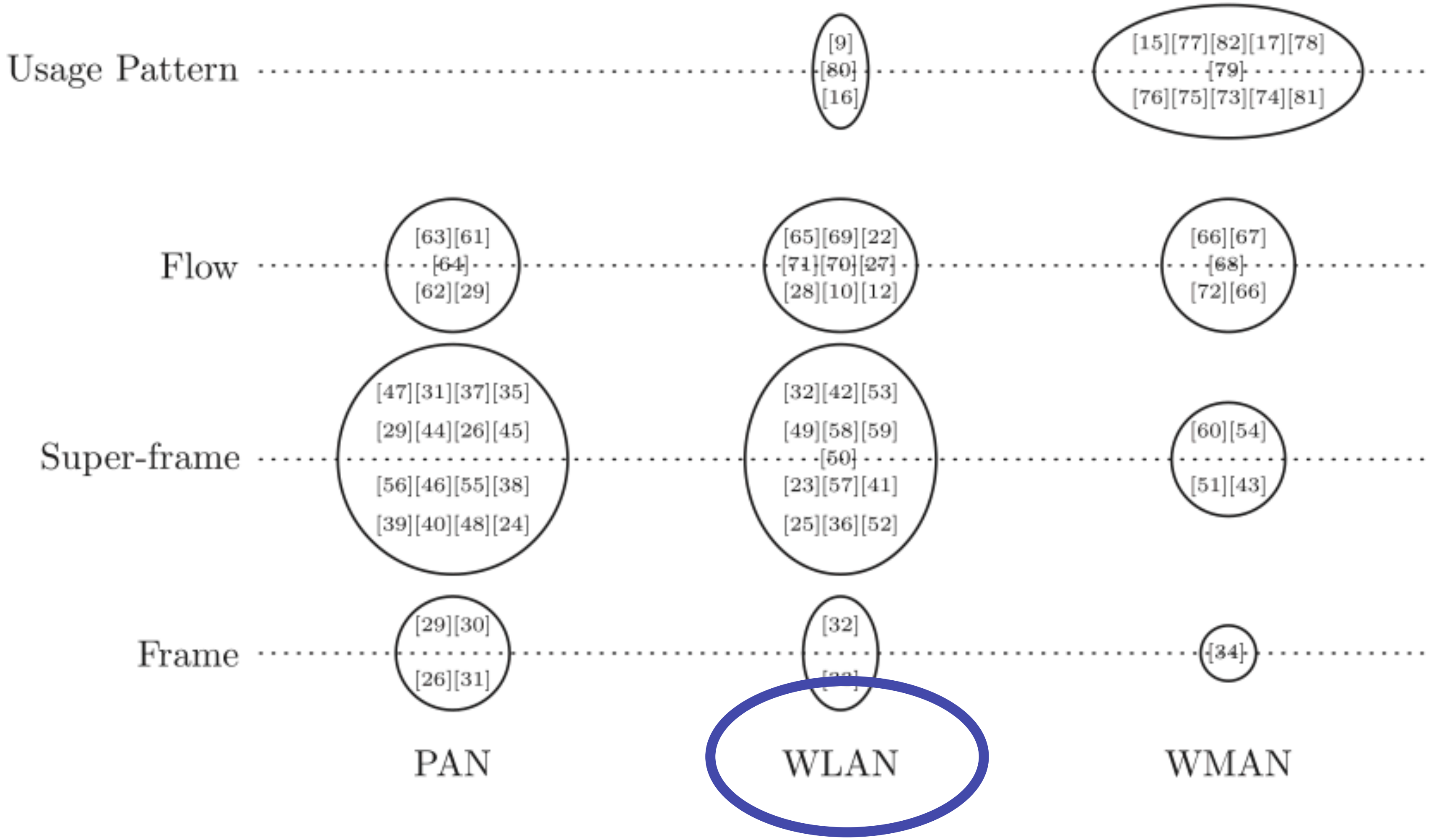
Serrano, P., la Oliva, A., Patras, P., Mancuso, V., & Banchs, A. (2012). Greening wireless communications: Status and future directions. Computer Communications.

Timescales

- Usage pattern
- Flow
- Super-frame
- Frame



Timescale vs. Wireless tech



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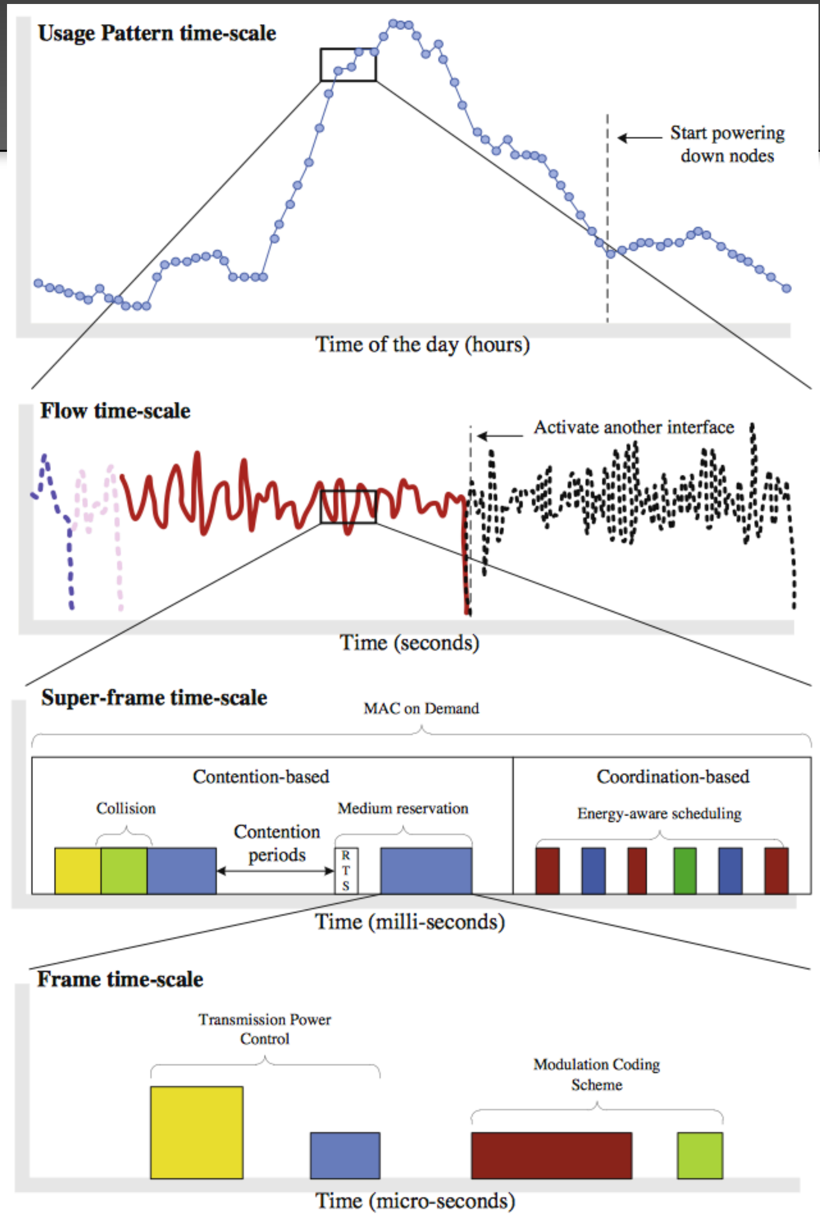
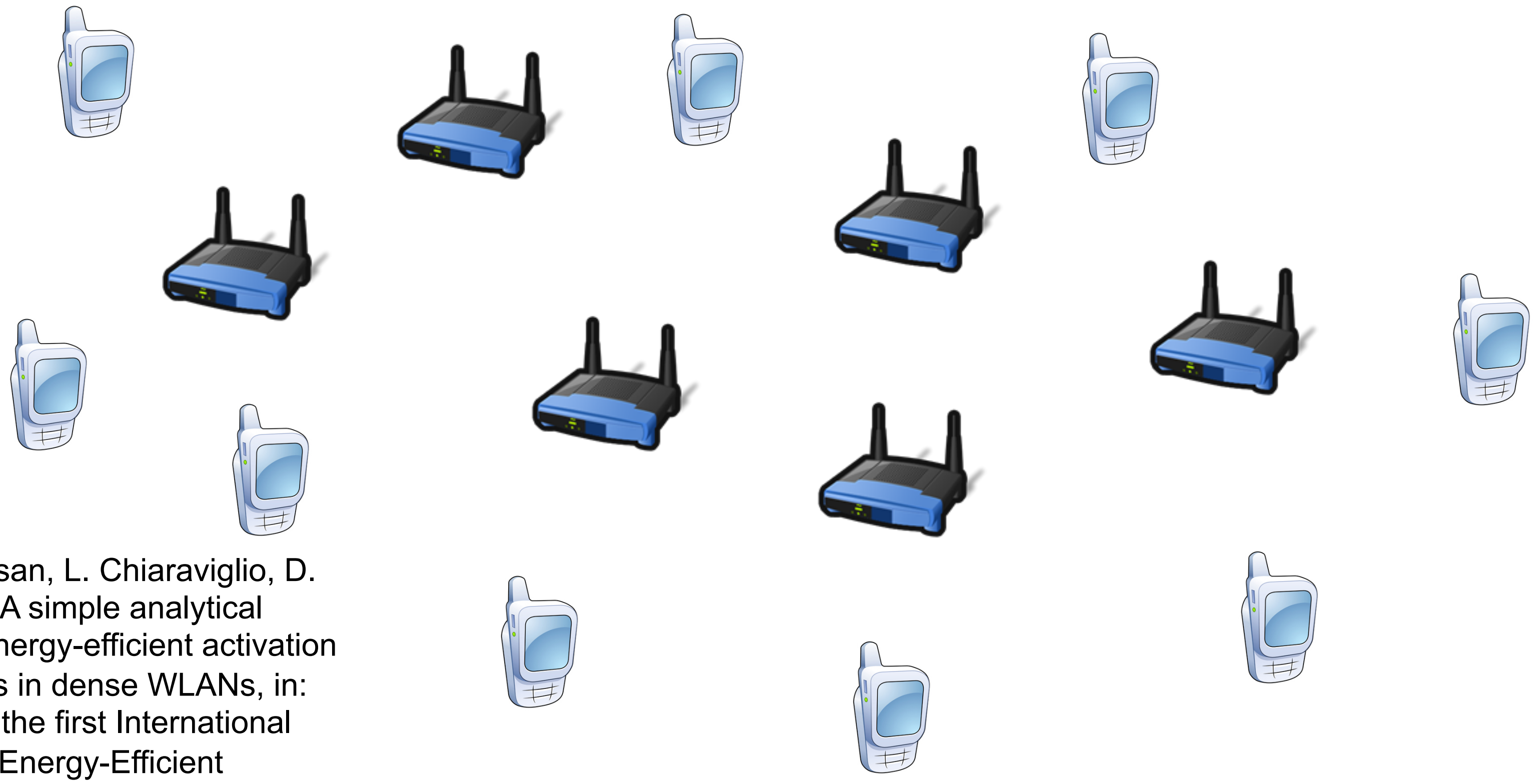


Resource on Demand schemes

- Power on/off the infrastructure as required



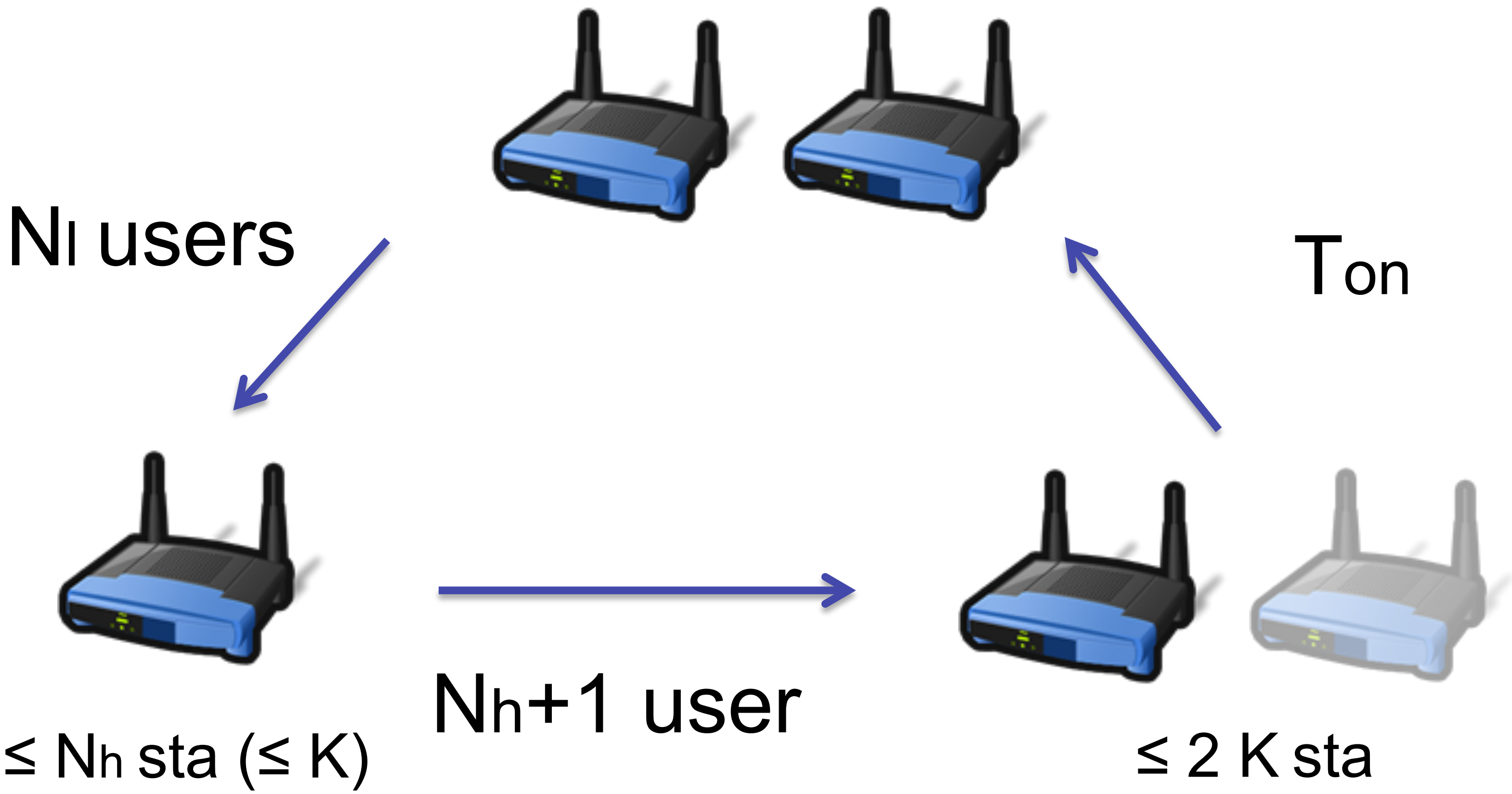
M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo, A simple analytical model for the energy-efficient activation of access points in dense WLANs, in: Proceedings of the first International Conference on Energy-Efficient Computing and Networking, ACM, 2010, pp. 159–168.

Powering on/off a device

- Linksys WRT54GL with OpenWRT 10.03.1

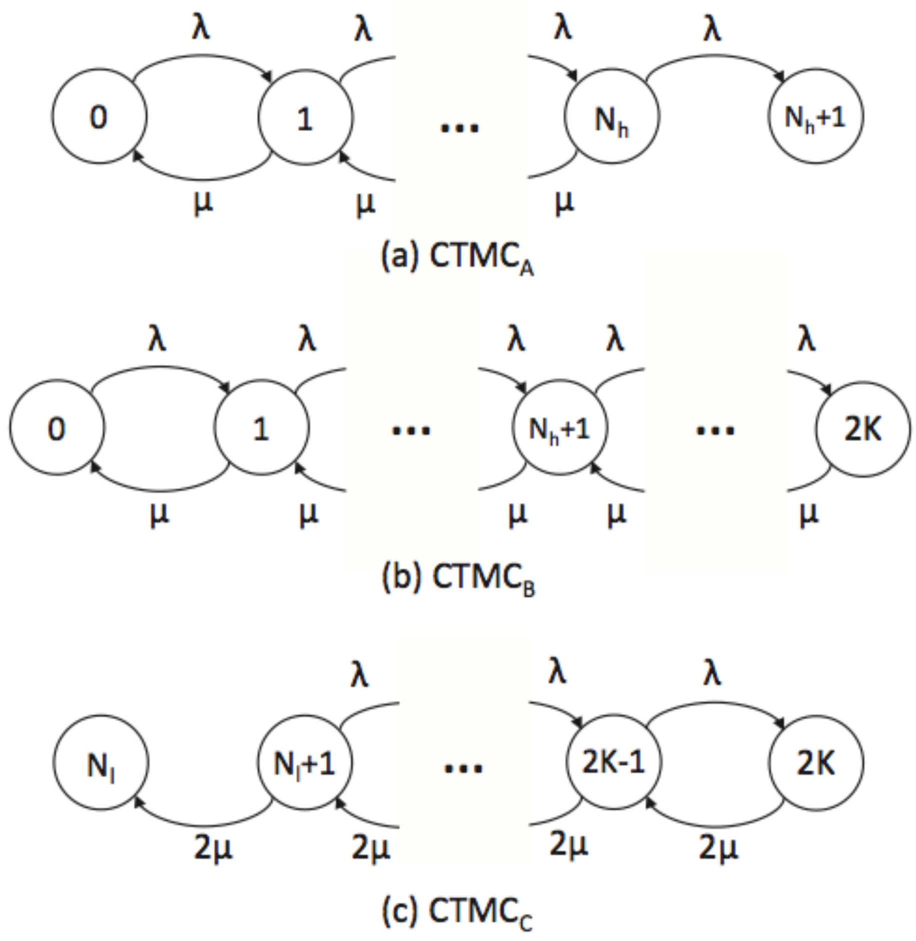
From	To	Time
OFF	ON (3 W)	55 s
ON	OFF (0 W)	5 s
IDLE	ON	< 1 s
ON	IDLE (1 W)	< 1 s

System Model: regenerative process



System Model

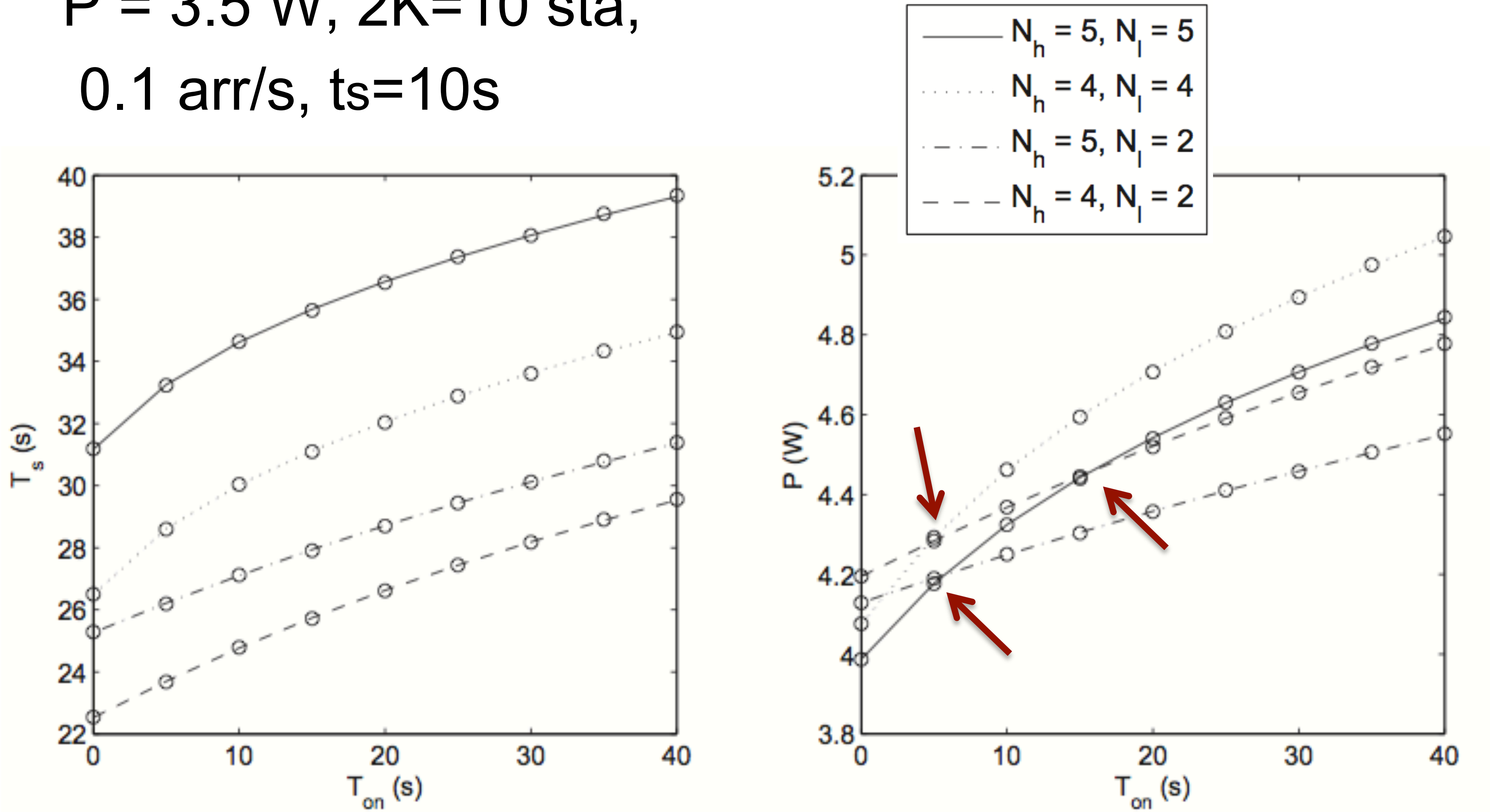
- Three different chains (BW is shared)
- Performance figures
  - Average delay
  - Power consumption



Results

P = 3.5 W, 2K=10 sta,

0.1 arr/s, ts=10s



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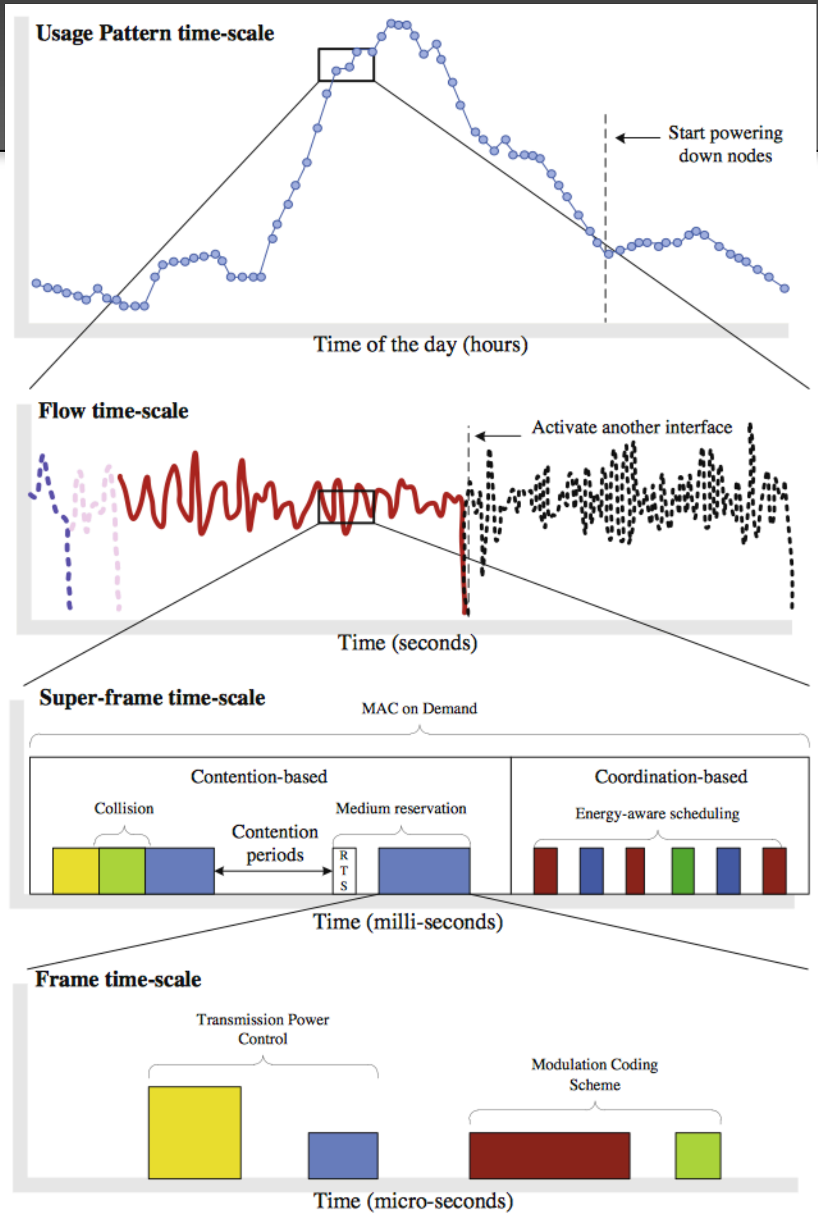
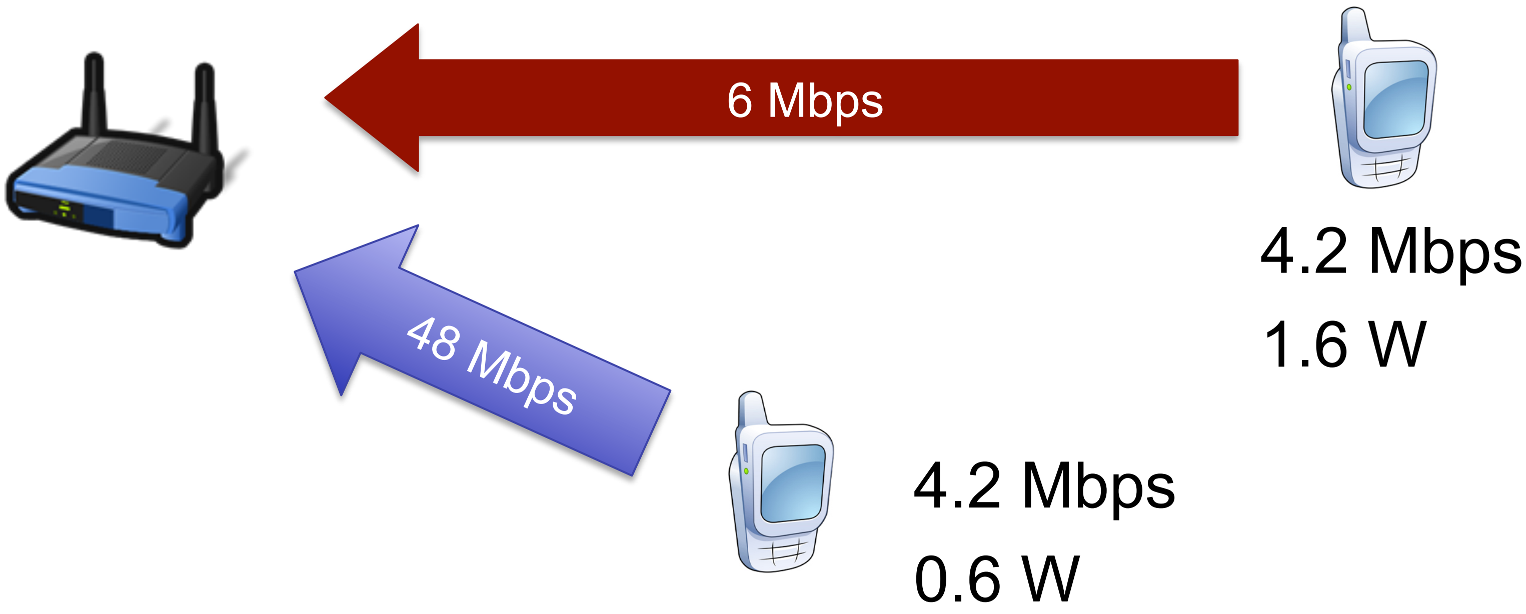


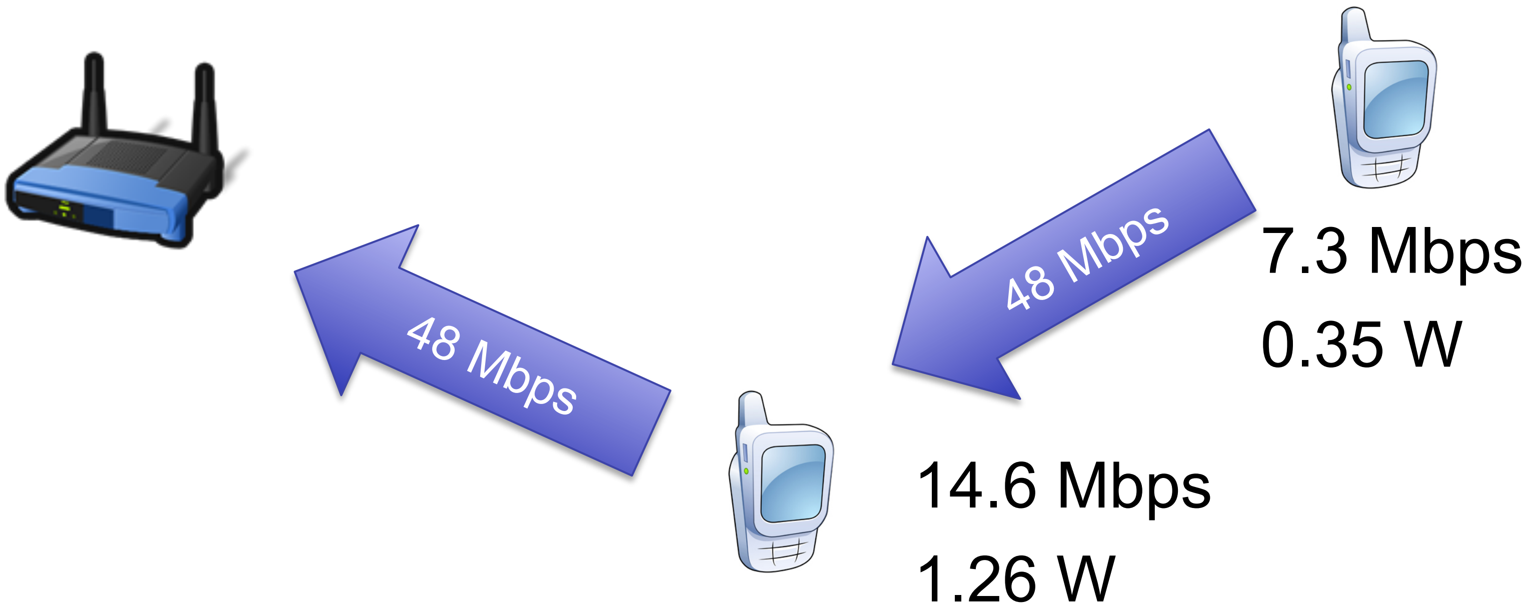
Generalizing the Perf. Anomaly solution

- Performance Anomaly: a node far away reduces the overall performance



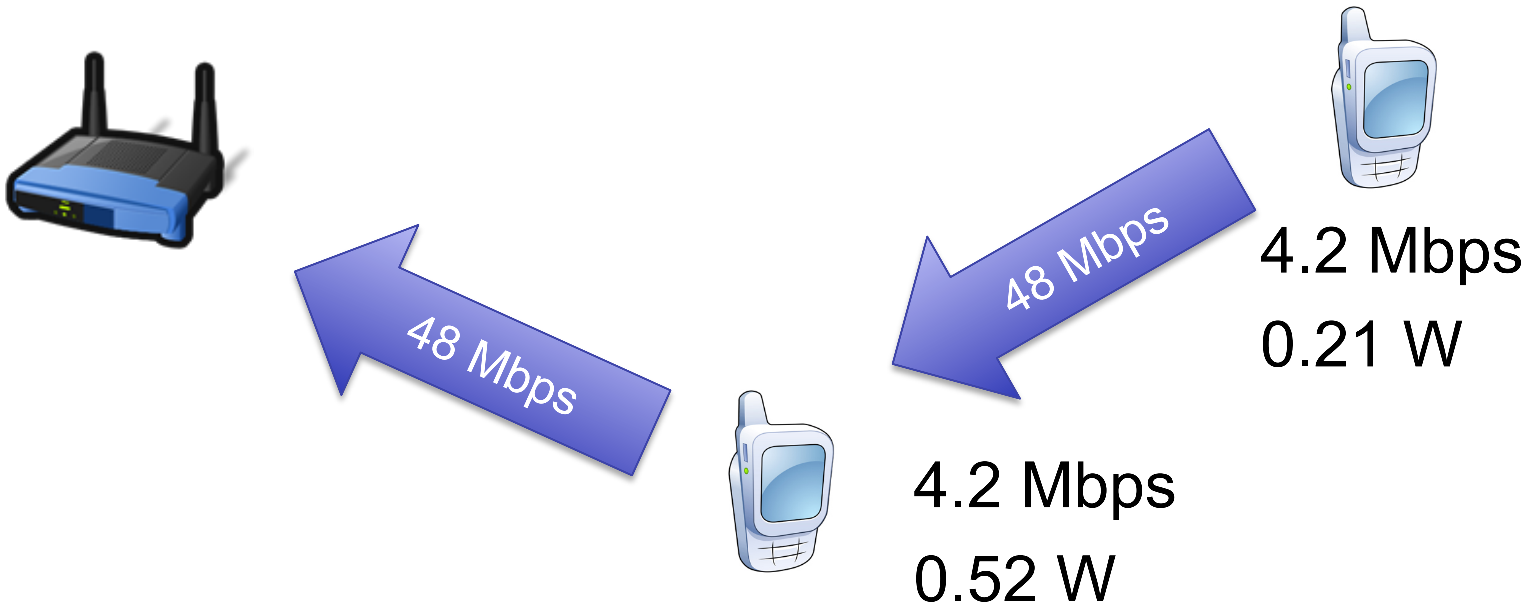
Usual Solution

- Opportunistic relaying can alleviate the issue, depending on the topology
  - Based on e.g. Wi-Fi Direct



Yet Another Solution

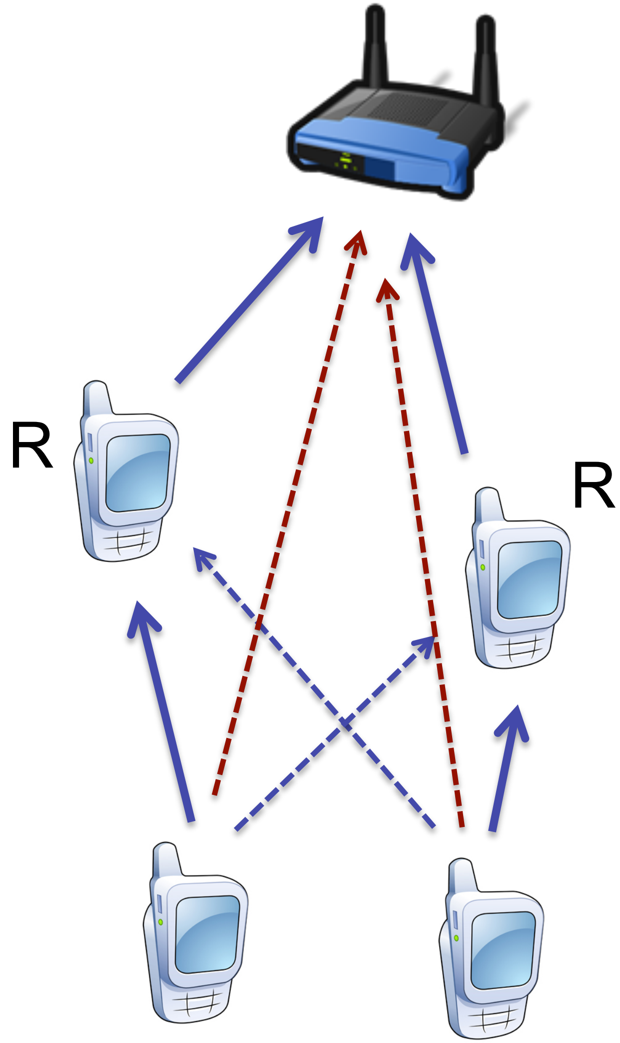
- Degrees of freedom: the relay can decide how to spend its time: tx, relay, sleep



Problem Formulation

- 1 AP, legacy nodes, relay-capable nodes
- Topology: paths used to reach the AP
- Schedule: timing of the relays

- For every topology, find the *best* schedule



Problem Formulation

- Throughput

$$X_n = \sum_{\mathcal{V} \in \mathbb{W}^{A_n}} R_{\mathcal{V}}(n) F_{\mathcal{V}}^{A_n}.$$

$$X_s = \sum_{\substack{\mathcal{V} \in \mathbb{W}^{A_s} \\ s \in \mathcal{V}}} F_{\mathcal{V}}^{A_s} R_{\mathcal{V}}(s) - \sum_{t \in \mathcal{T}_s} X_t.$$

- Power

$$Y_n = \sum_{\mathcal{V} \in \mathbb{W}^{A_n}} F_{\mathcal{V}}^{A_n} P_{\mathcal{V}}^T(n) + (1 - \sum_{\mathcal{V} \in \mathbb{W}^{A_n}} F_{\mathcal{V}}^{A_n}) \rho_s.$$

$$Y_s = \sum_{\substack{\mathcal{V} \in \mathbb{W}^{A_s} \\ s \in \mathcal{V}}} F_{\mathcal{V}}^{A_s} P_{\mathcal{V}}^T(s) + \sum_{\mathcal{V} \in \mathbb{W}^s} F_{\mathcal{V}}^s P_{\mathcal{V}}^R(s)$$
$$+ (1 - \sum_{\substack{\mathcal{V} \in \mathbb{W}^{A_s} \\ s \in \mathcal{V}}} F_{\mathcal{V}}^{A_s} - \sum_{\mathcal{V} \in \mathbb{W}^s} F_{\mathcal{V}}^s) \rho_s.$$

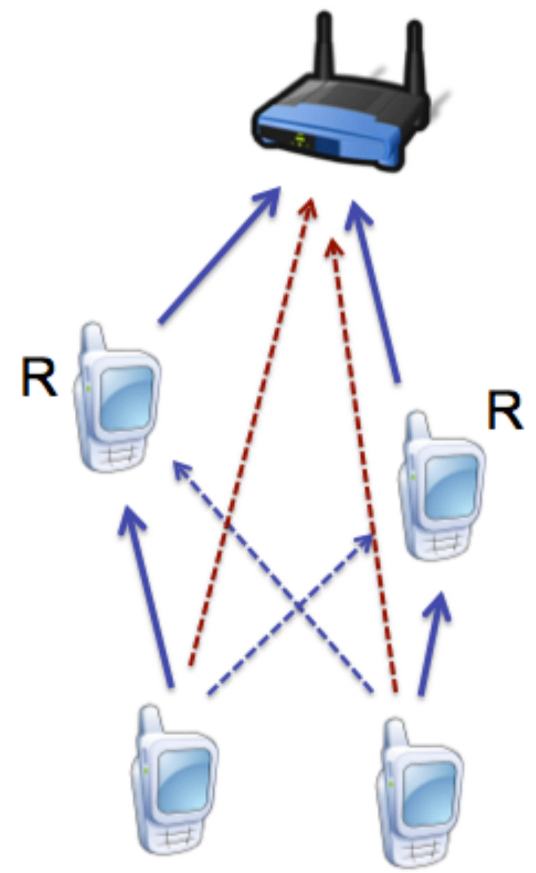
- Maximize

$$V_n = U_n(X_n) - L_n(Y_n)$$

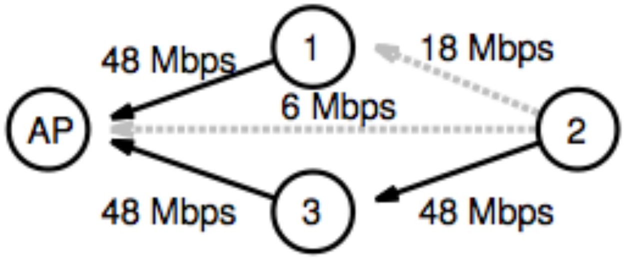
$$U_n(X_n) = \alpha_n log(X_n)$$
$$L_n(Y_n) = (1 - \alpha_n) Y_n,$$

Finding a Solution

- Scheduling: maximize a concave objective function under a convex set of constraints and thus admits a unique optimum.
- Topology: combinatorial problem, and efficiently finding the optimal topology does not appear to be possible
  - Search, closest, heuristic



Results: 1 legacy, 2 relays



$$U_n(X_n) = \alpha_n log(X_n)$$
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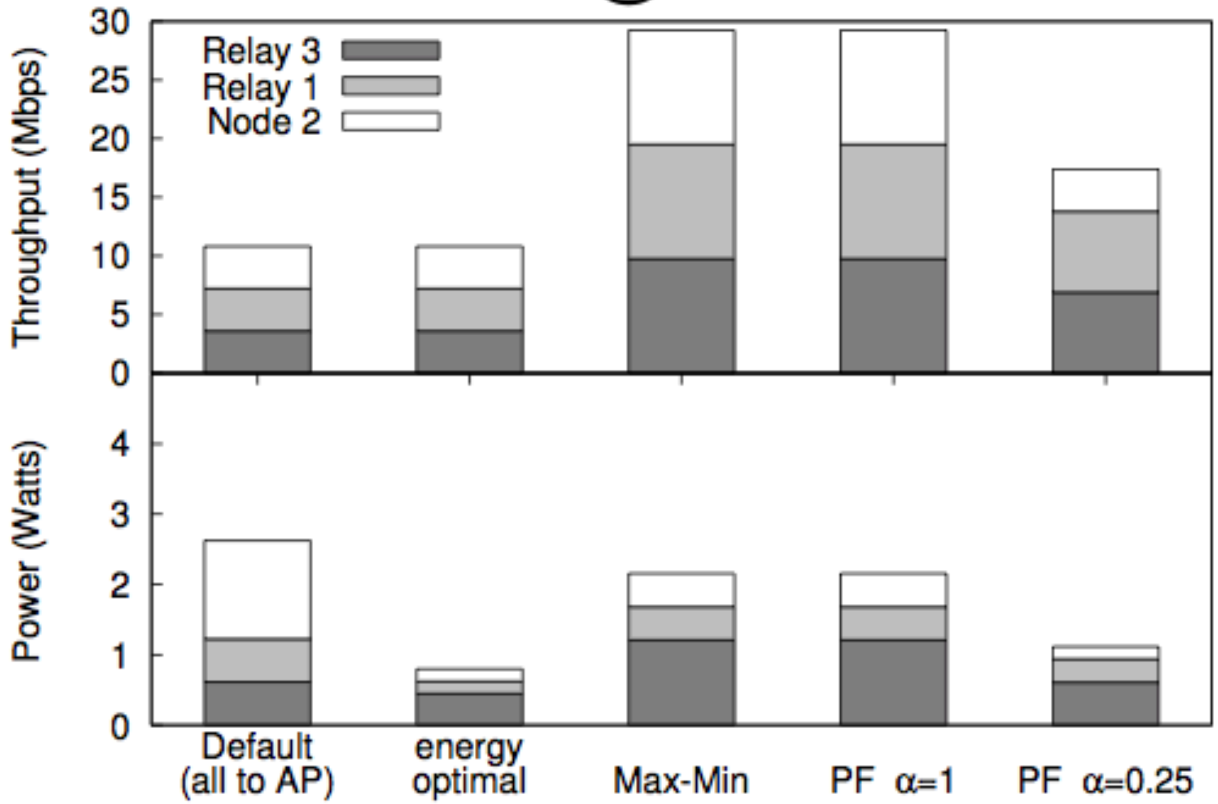
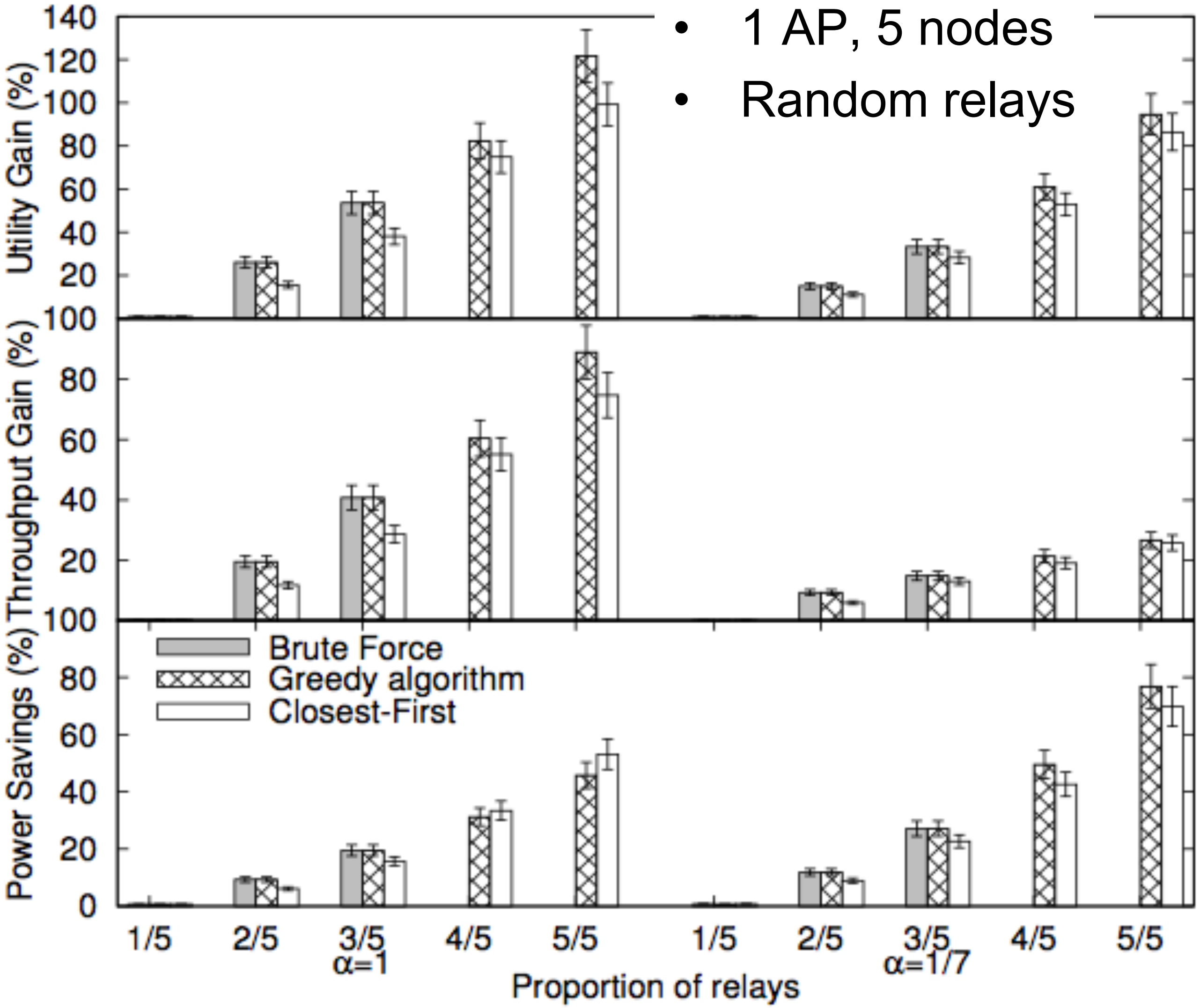


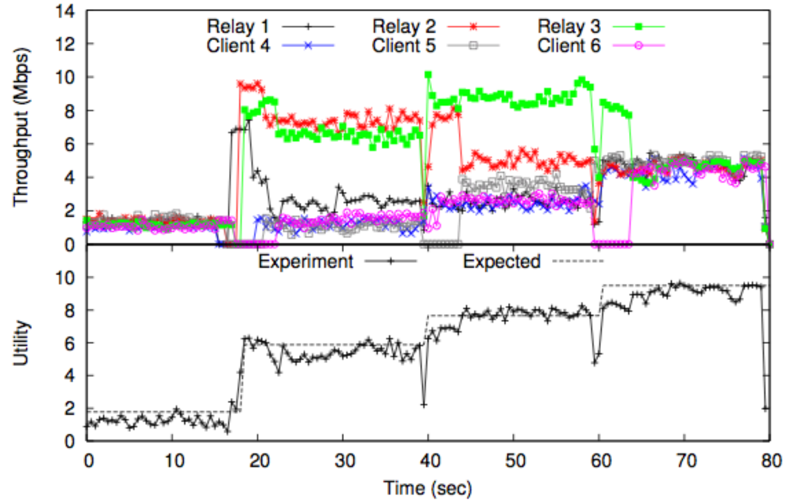
Results: incremental deployment

- 1 AP, 5 nodes
- Random relays



Opportunistic Relaying: Challenges

- Trade-off between throughput (performance) and cost (energy consumption)
  - Not that much explored
  - Heterogeneous settings
- Works in practice, but
  - Estimate network cond.
  - Force re-associations, silence nodes
- Enabler: Wi-Fi Direct?
  - Not immediate (~5 s)



D Camps-Mur, A Garcia-Saavedra, P Serrano, "Device-to-device communications with Wi-Fi Direct: overview and experimentation"

IEEE Wireless Communications, June 2013

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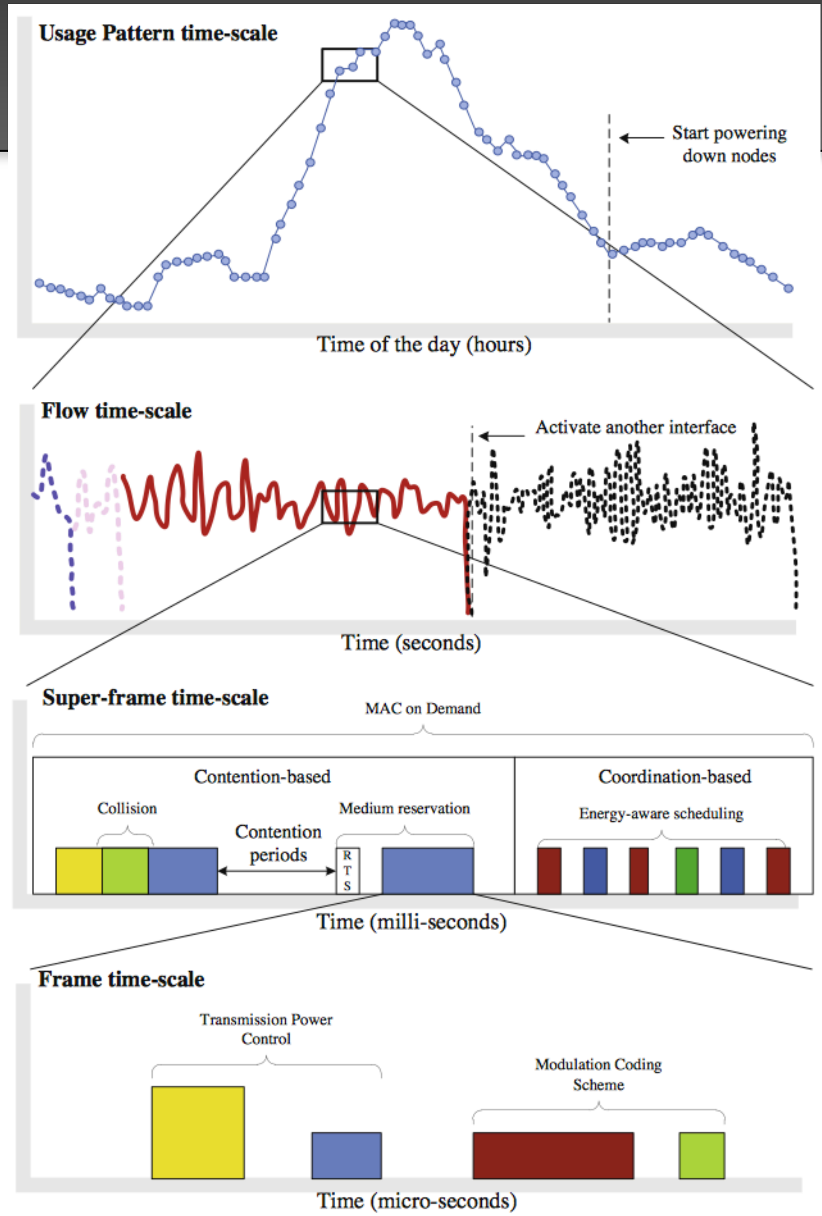


Energy Efficiency of 802.11 MAC

- Usual model
  - Transmission, Reception, Idle

#	Card	ρ^{tx}	ρ^{rx}	ρ^{id}
A	Lucent WaveLan	1.650	1.400	1.150
B	SoketCom CF	0.924	0.594	0.066
C	Intel PRO 2200	1.450	0.850	0.080
D	Agilent Card Test	1.188	1.138	1.108

S. Chiaravalloti, F. Idzikowski, L. Budzisz, Power consumption of WLAN network elements, TKN Technical Report Series TKN-11-002, Telecommunication Networks Group, Technical University Berlin (Aug. 2011).

$$\eta_i = \frac{\text{bits successfully transmitted}}{\text{energy consumed}} = \frac{Throughput_i}{power_i}$$

Revisiting Channel Access

- Bianchi-based:

$$e_i = \sum_{j \in \Theta} E_i(j) p(j)$$

$$p(e) = \prod (1 - \tau_j) \quad p(s,i) = \tau_i \prod_{j \neq i} (1 - \tau_j)$$

$$p(s, \neg i) = \sum_{j \neq i} \tau_j \prod_{k \neq j} (1 - \tau_k) \quad p(c,i) = \tau_i (1 - \prod_{j \neq i} (1 - \tau_j))$$

$$p(c, \neg i) = 1 - \tau_i - p_e - p_{s,\neg i}$$

- With

$$E_i(s,i) = \rho_i^{tx} T_s + \rho_i^{rx} T_{ack} + \rho_i^{id} (SIFS + DIFS)$$

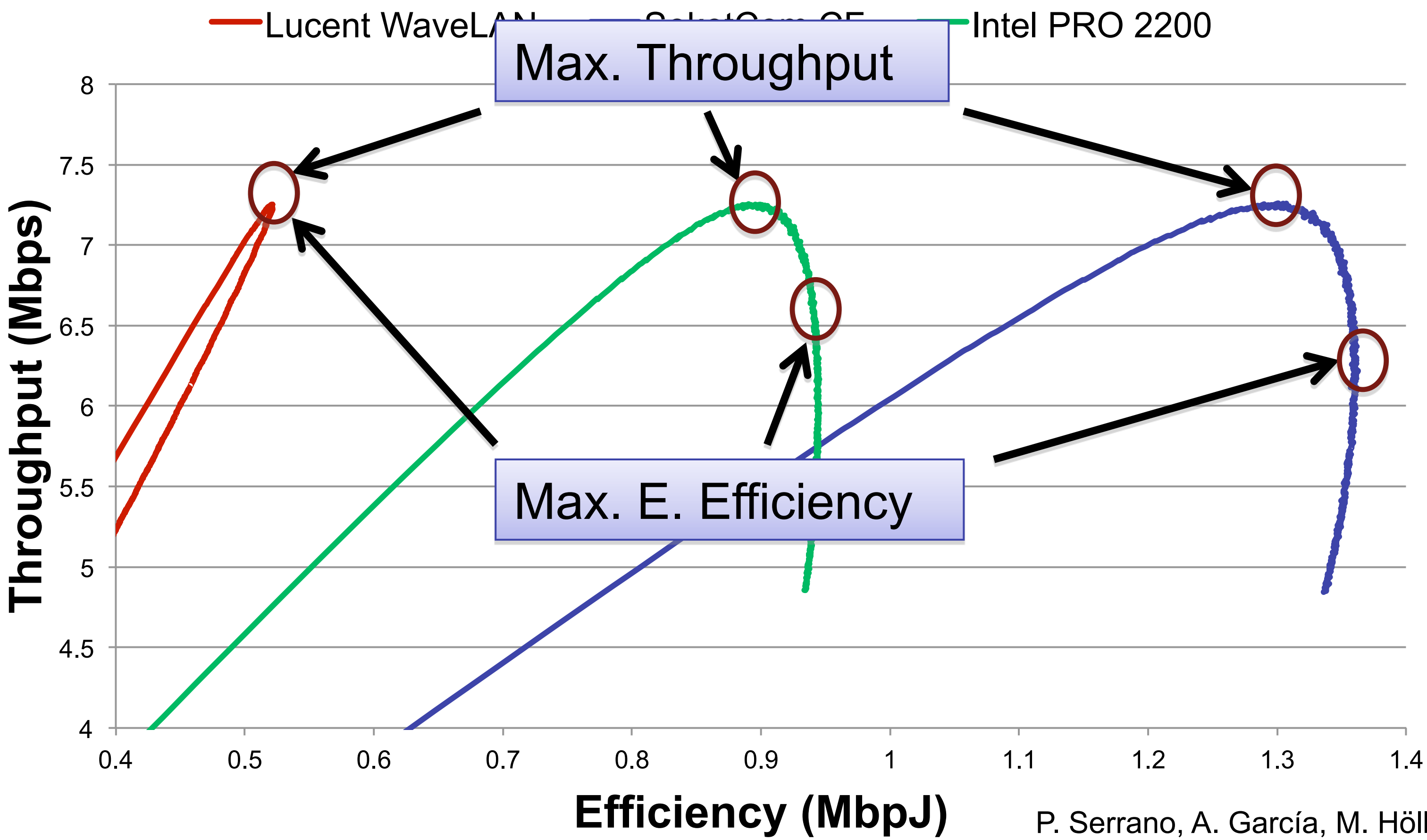
$$E_i(s,\neg i) = \rho_i^{rx} (T_s + T_{ack}) + \rho_i^{id} (SIFS + DIFS)$$

$$E_i(e) = \rho_i^{id} T_e \qquad E_i(c,i) = \rho_i^{tx} T_s + \rho_i^{id} EIFS$$

$$E_i(c,\neg i) = \rho_i^{rx} T_s + \rho_i^{id} EIFS$$

* 10 stations

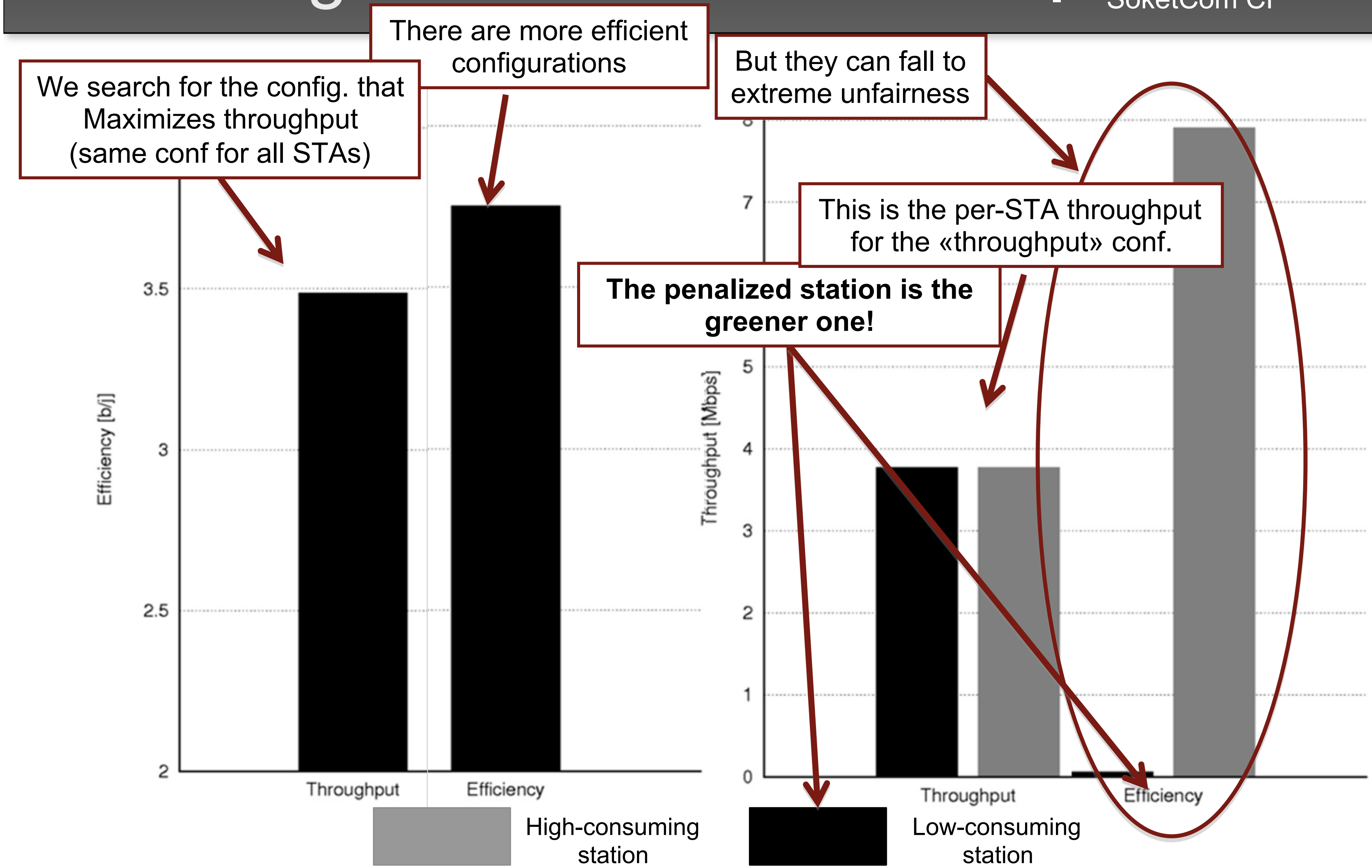
Homogeneous scenario: search



P. Serrano, A. García, M. Höllick, A. Banchs, “On the Energy Efficiency of IEEE 802.11 WLANs”, European Wireless 2010

Heterogeneous scenario

* 2 stations
- Lucent WaveLAN
- SoketCom CF



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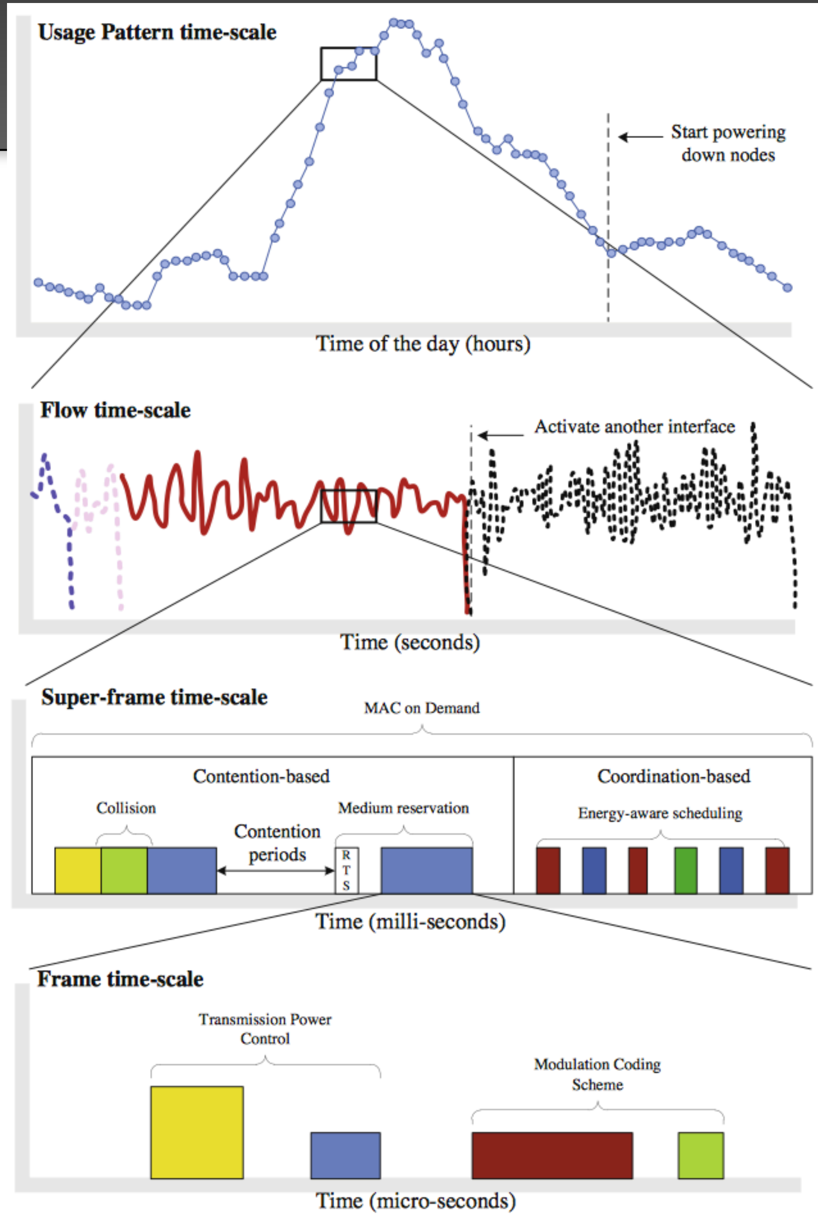
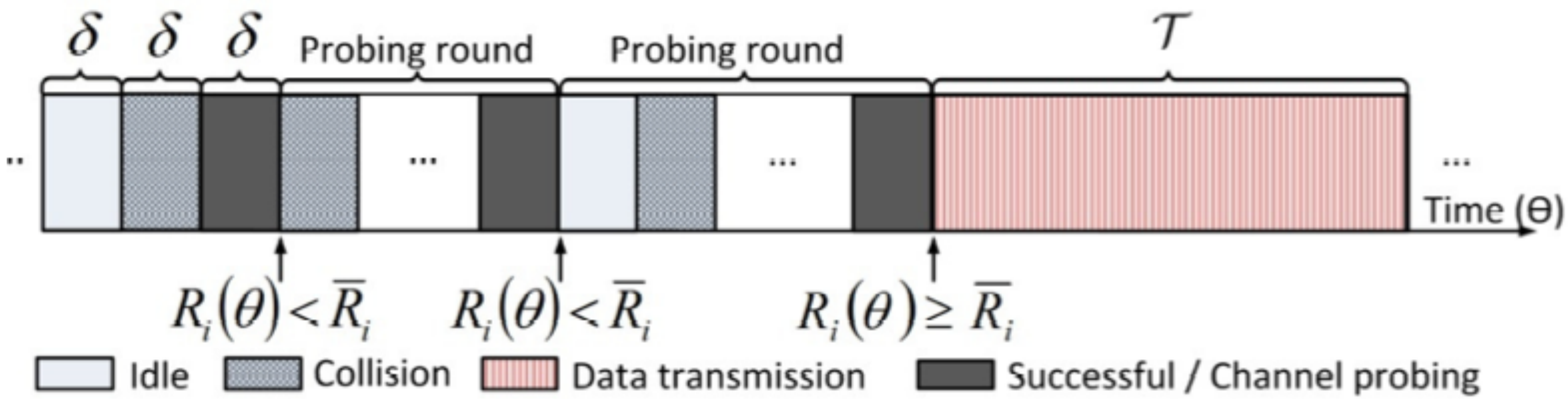
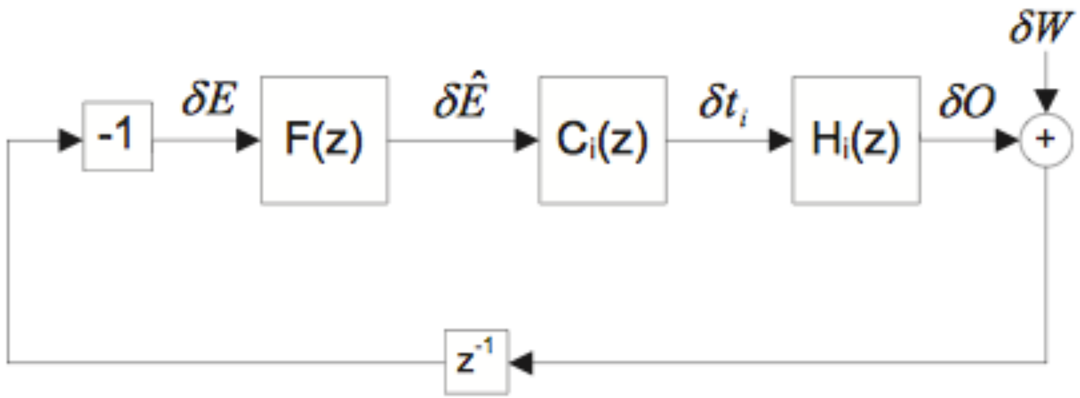


Distributed Opportunistic Scheduling

- Revisiting DOS

$$E\left[R_i(\theta) - \bar{R}_i^*\right]^+ = \frac{\bar{R}_i^* \tau}{\mathcal{T}/e}$$



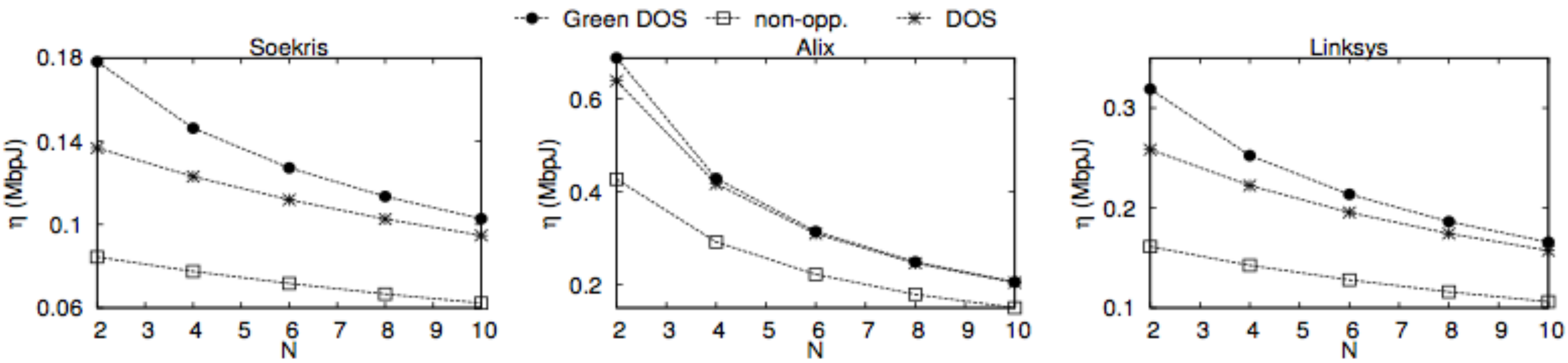


Andres Garcia-Saavedra, Albert Banchs, Pablo Serrano, Joerg Widmer, “Distributed Opportunistic Scheduling: A Control Theoretic Approach” IEEE INFOCOM 2012, Orlando, USA, March 2012

Green DOS

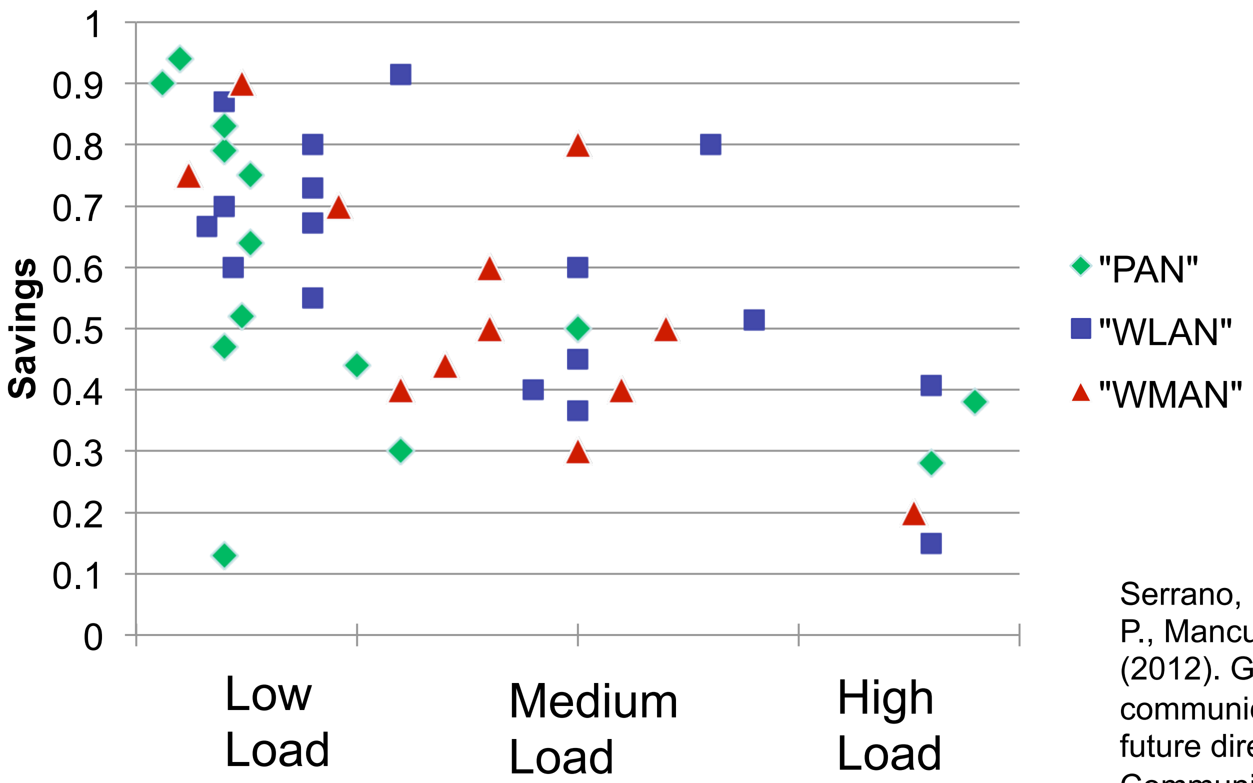
- Like in the previous case, add the power consumption when probing, tx, etc.

$$E\left[R_i(\theta)-\bar{R}_i^*\right]^+=\frac{\bar{R}_i^*\tau}{\mathcal{T}/e} \longrightarrow \bar{R}^*\frac{e_{cp}}{(\gamma_{xg}+\mathcal{T}\pi_{tx})}=E\left[R_N-\bar{R}^*\right]^+$$



Review of existing mechanisms

- Typical savings achieved depending on network load for ~40 different mechanisms evaluated



Serrano, P., la Oliva, A., Patras, P., Mancuso, V., & Banchs, A. (2012). Greening wireless communications: Status and future directions. Computer Communications.

Open Challenges

- Standardizing benchmarks
  - Otherwise, hard to compare
  - Understand trade-offs
  - Criterion? $\max \sum \log(\eta_i)$

A.P. Bianzino, A. K. Raju, D. Rossi, "Apples-to-apples: a framework analysis for energy-efficiency in networks", ACM SIGMETRICS Perf. Ev. Review, Dec. 201

- More experimentation
  - For WMAN
  - But not only! IoD for 802.11?
  - And new findings

A. Garcia-Saavedra, P. Serrano, A. Banchs, M. Hollick, "Balancing Energy Efficiency and Throughput Fairness in IEEE 802.11 WLANs" Elsevier Pervasive and Mobile Computing, vol. 8, no. 5, October 2012.

Time for experimentation

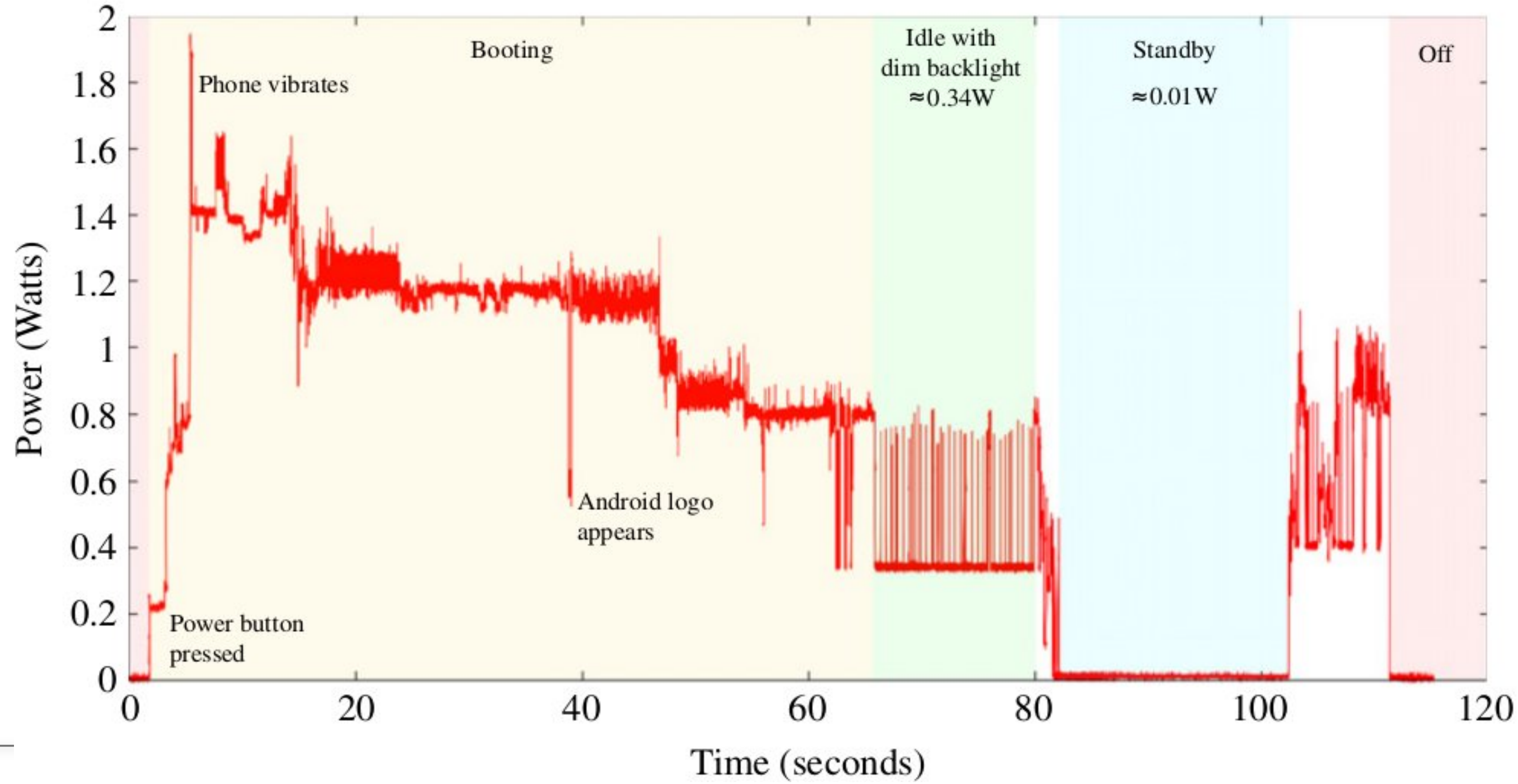
Try to put well in practice what you already know; and in so doing, you will in good time, discover the hidden things which you now inquire about.

Practice what you know, and it will help to make clear what now you do not know.

Rembrandt

What we wanted to do...

- Huge research efforts dedicated to improve energy efficiency
- We need to understand the power behavior of our devices
  - Per-state measurements of power consumption in e.g. laptops, cell phones…



A. Rice, S. Hay "Measuring mobile phone energy consumption for 802.11 wireless networking" Pervasive and Mobile computing. 2010

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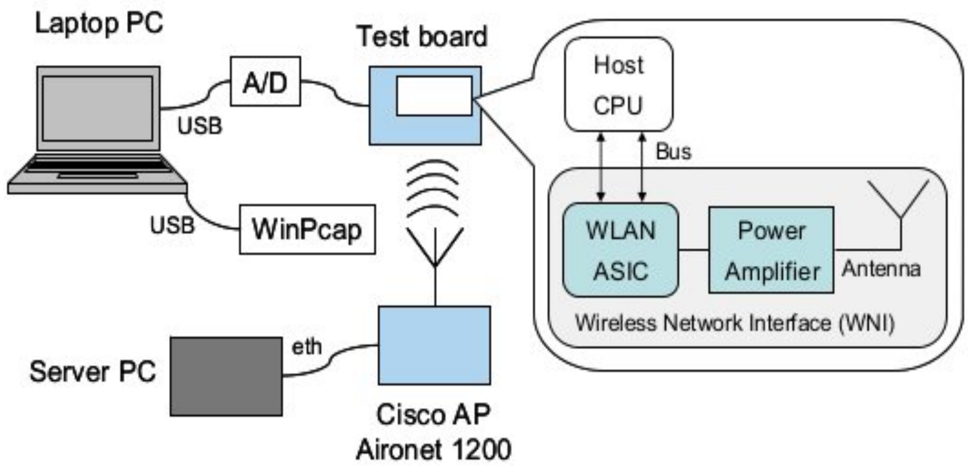
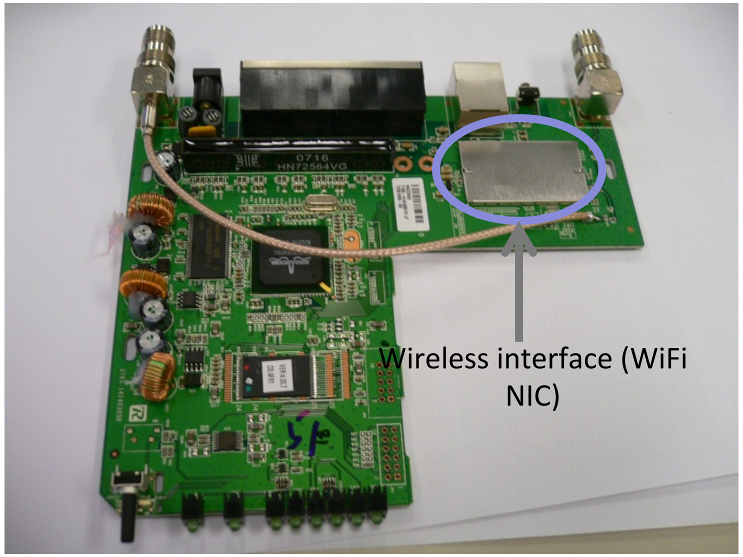


Rantala et al. "Modeling energy efficiency in wireless internet communication" ACM Mobiheld, 2009



Linksys WRT54GL WiFi router HW

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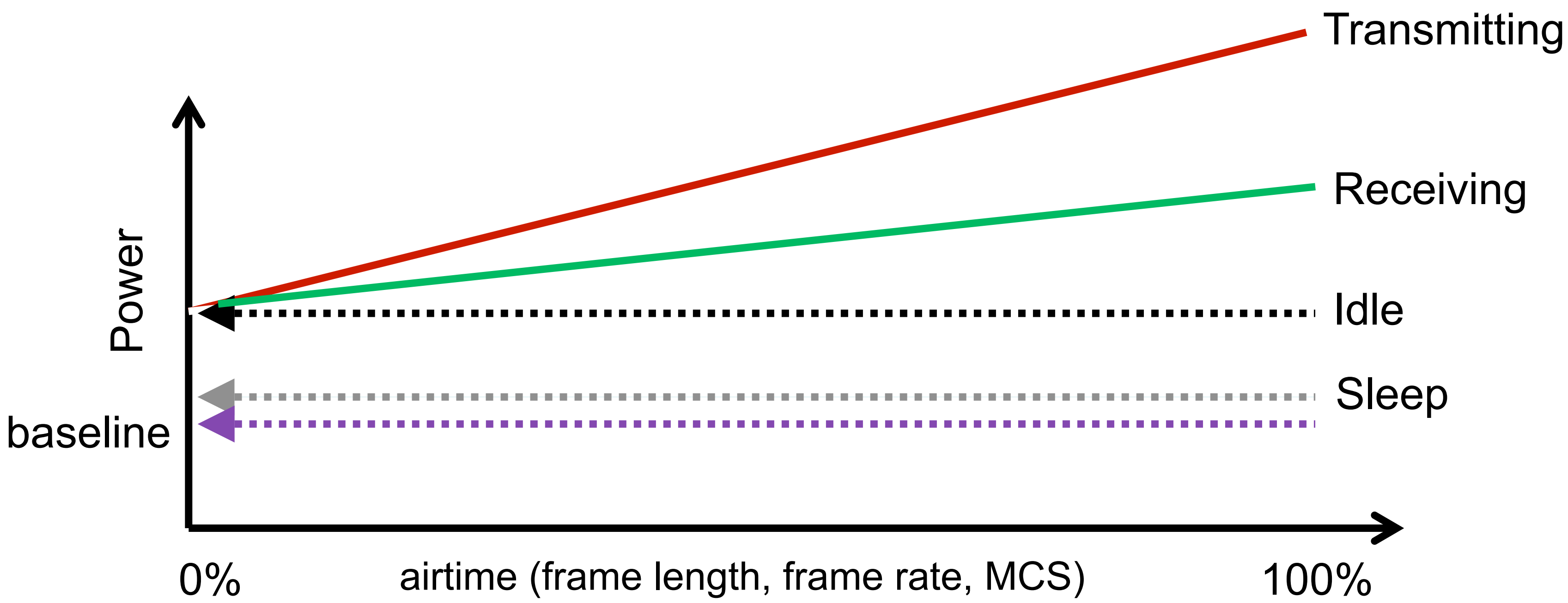
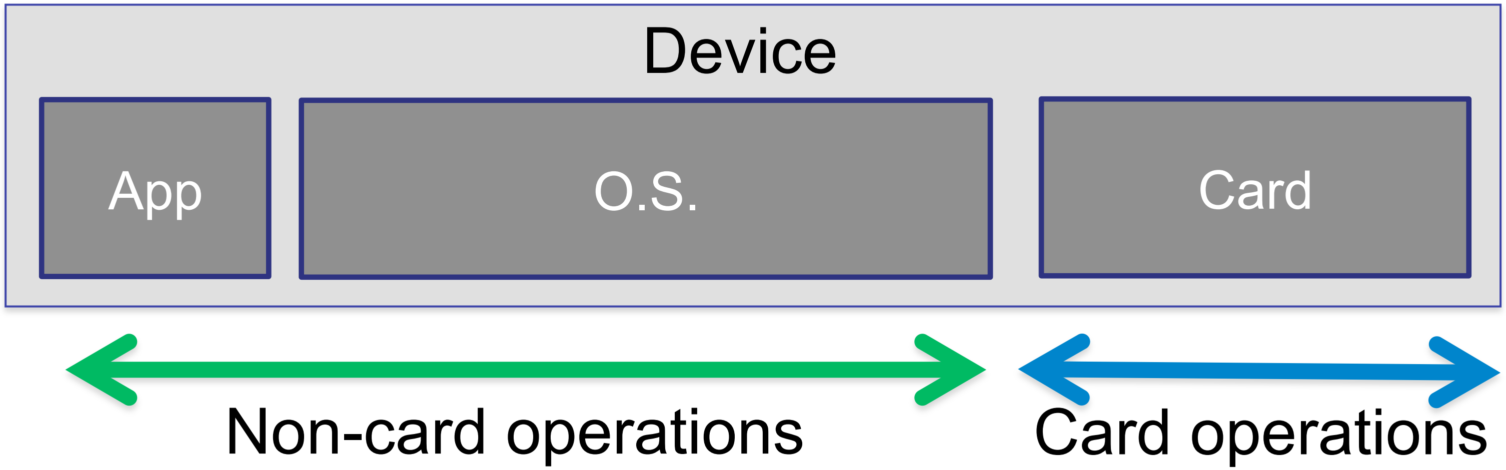


What we found out..



- Non-card operations can dominate
  - This questions previous schema's real performance
  - Opens the door to new designs

Andres Garcia-Saavedra, Pablo Serrano, Albert Banchs, Giuseppe Bianchi, "Energy consumption anatomy of 802.11 devices and its implication on modeling and design" ACM CoNEXT 2012, Nice, France, December 2012

Experimental characterization





- Experimental characterization in several devices
- Power generator/Power meter

TX characterization

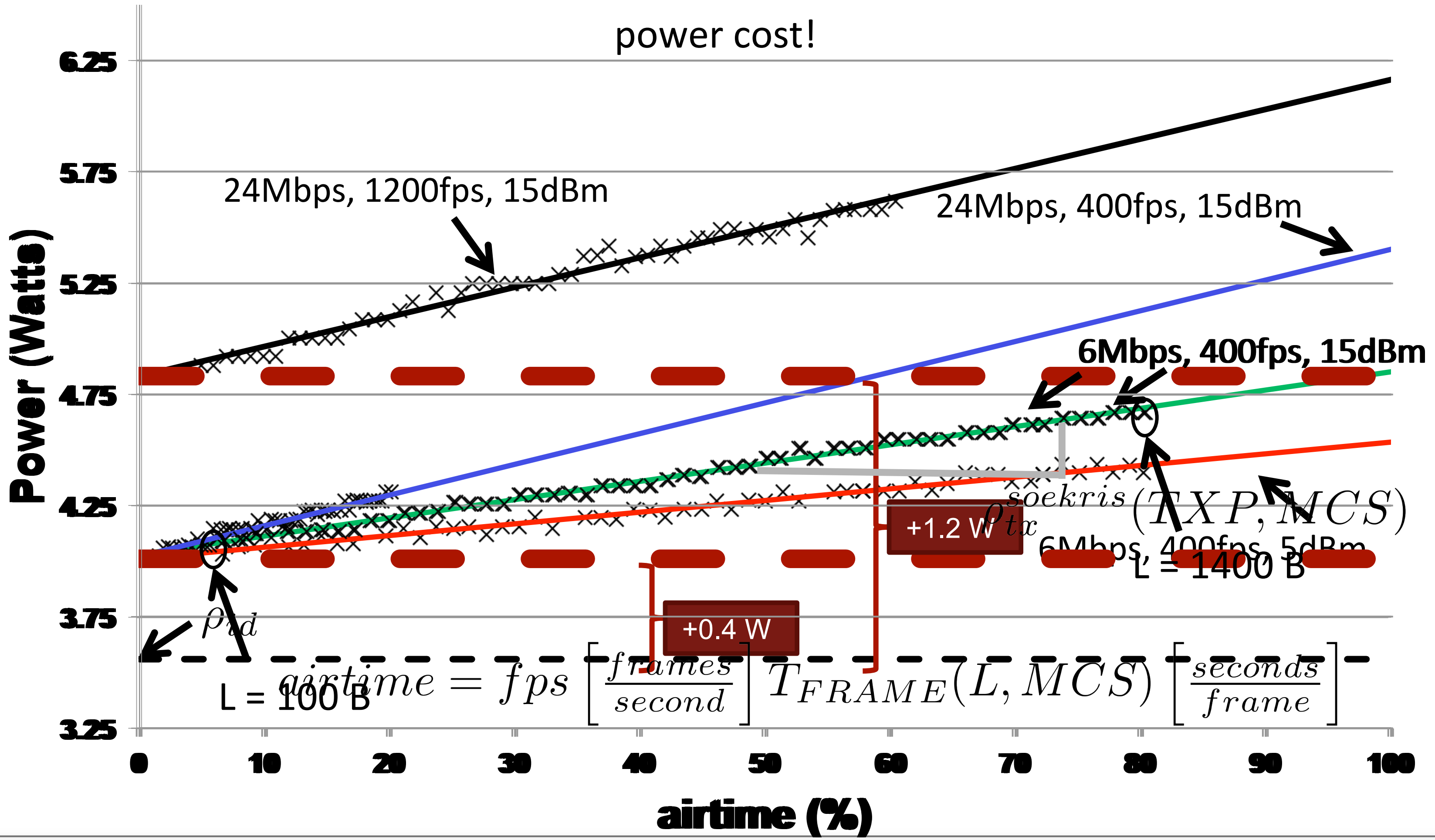
*Soekris, UDP, no acks

$$\mathbf{P} = \rho_{id} + {\color{red}P_{offset}} + \rho_{tx}\tau_{tx}$$

Base (idle) consumption

There is an extra power cost!

«classical» consumption



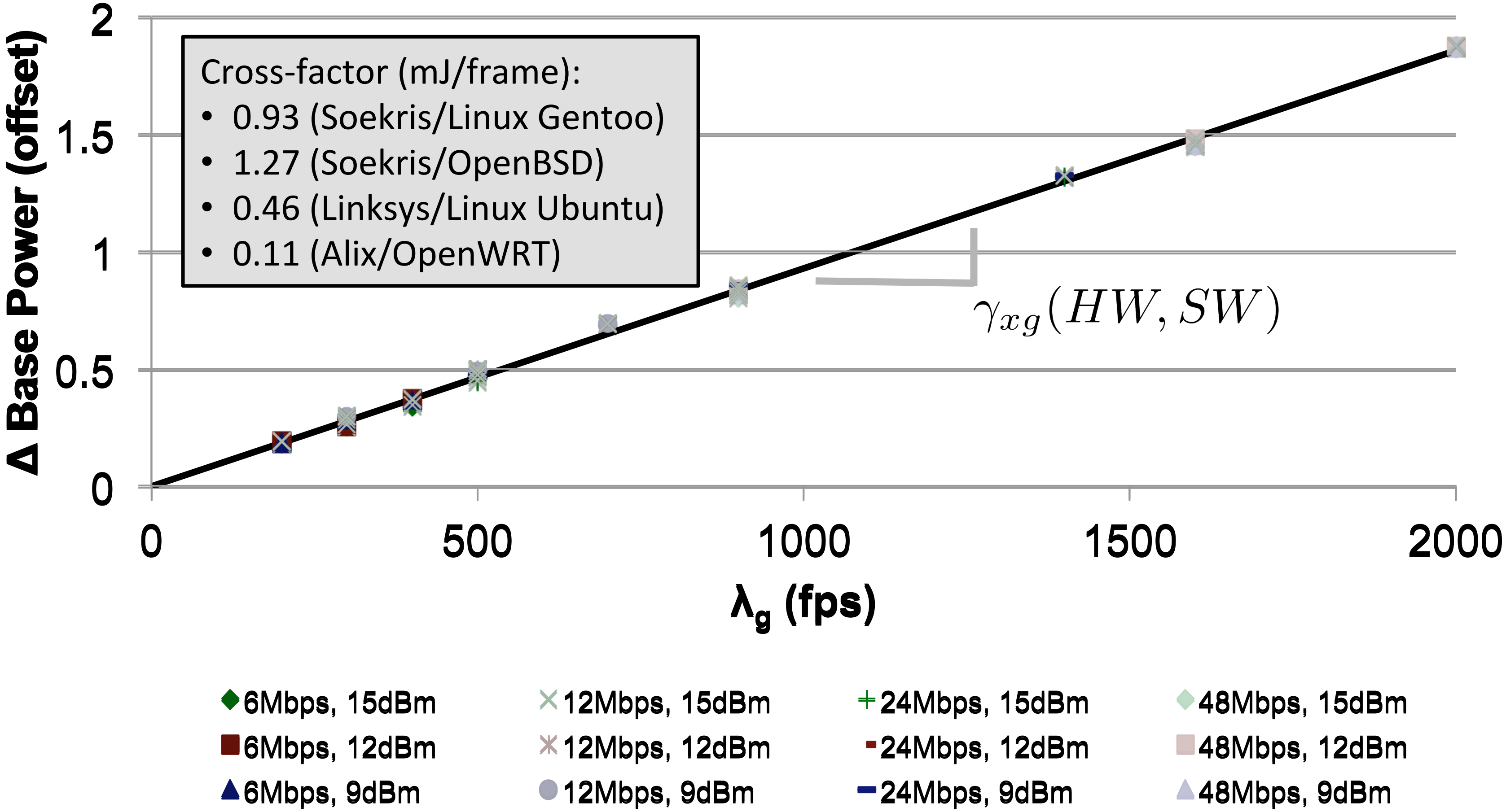
Energy consumption anatomy

$$\mathbf{P} = \rho_{id} + \gamma_{xg}\lambda_g + \rho_{tx}\tau_{tx}$$

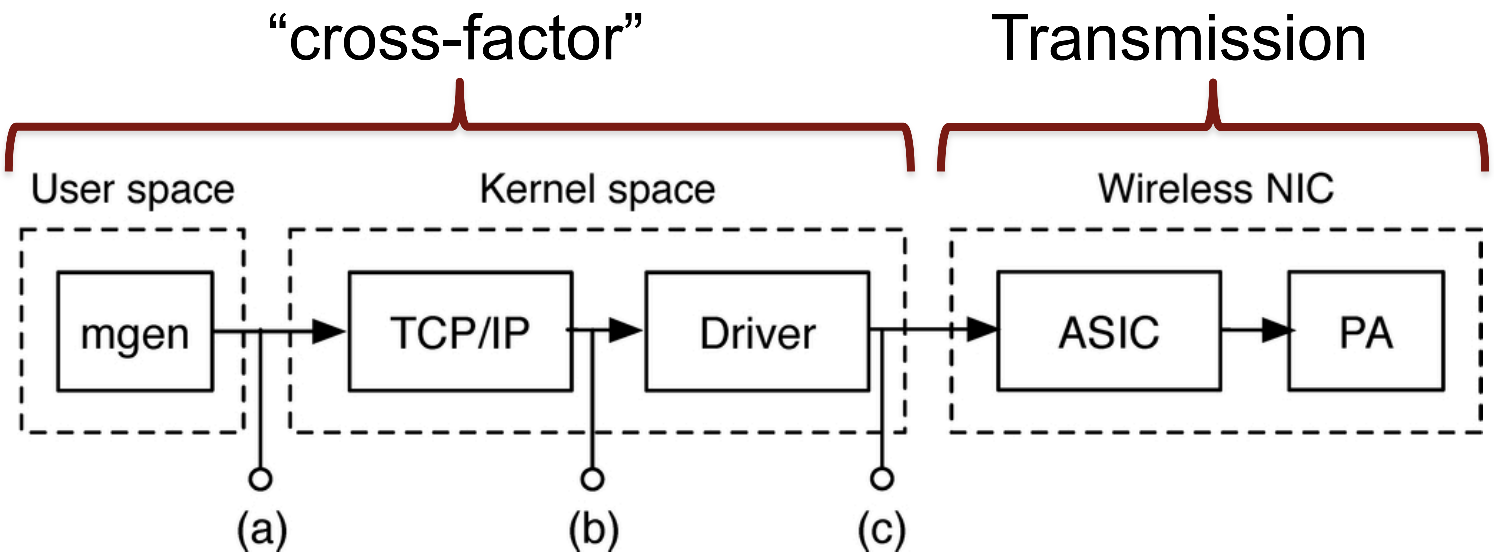
Base (idle) consumption

Cross-factor (mJ/frame)

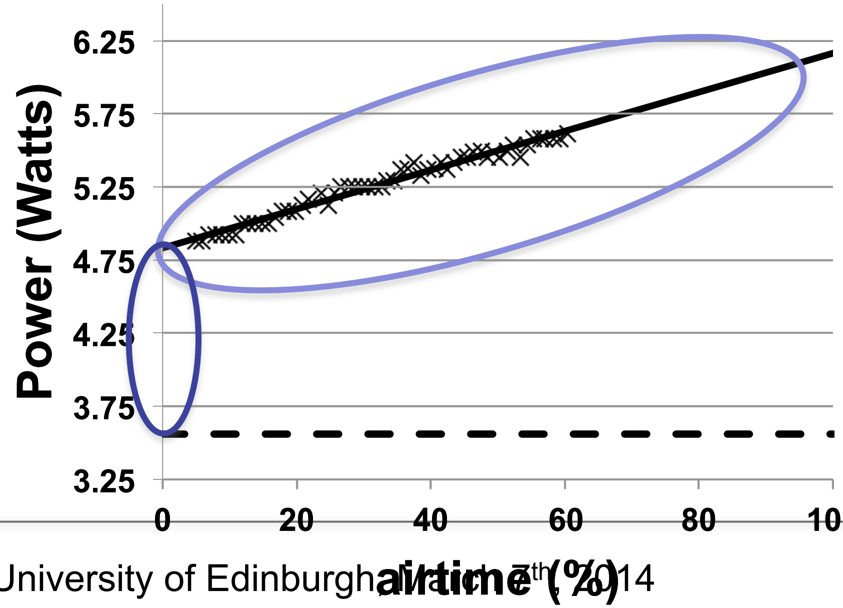
«classical» consumption



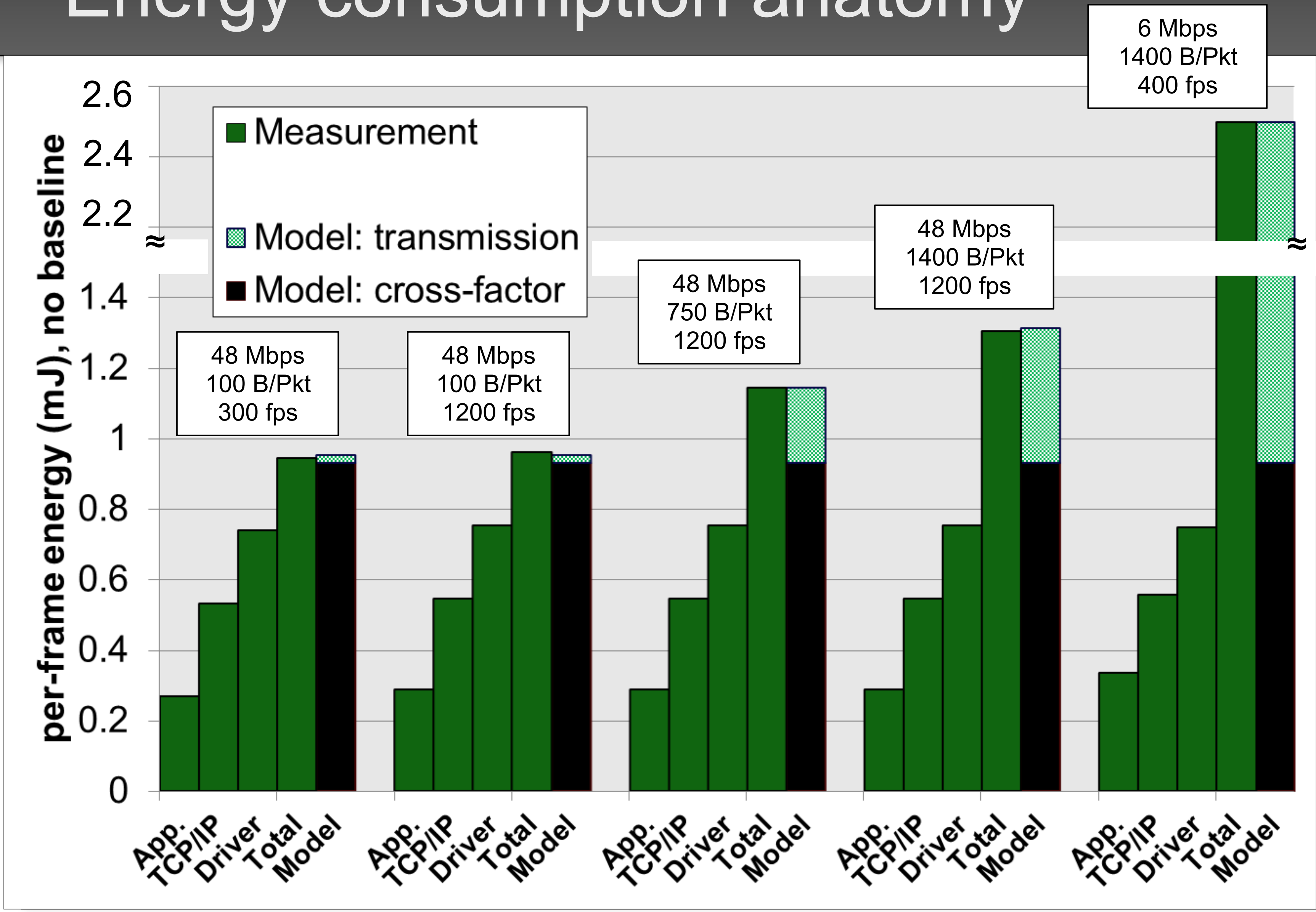
Energy consumption anatomy



(a) App.: discarded before OS
(b) TCP/IP: discarded after TCP/IP
(c) Driver: discarded after driver
Total: Full transmission (w/o ACKs)



Energy consumption anatomy



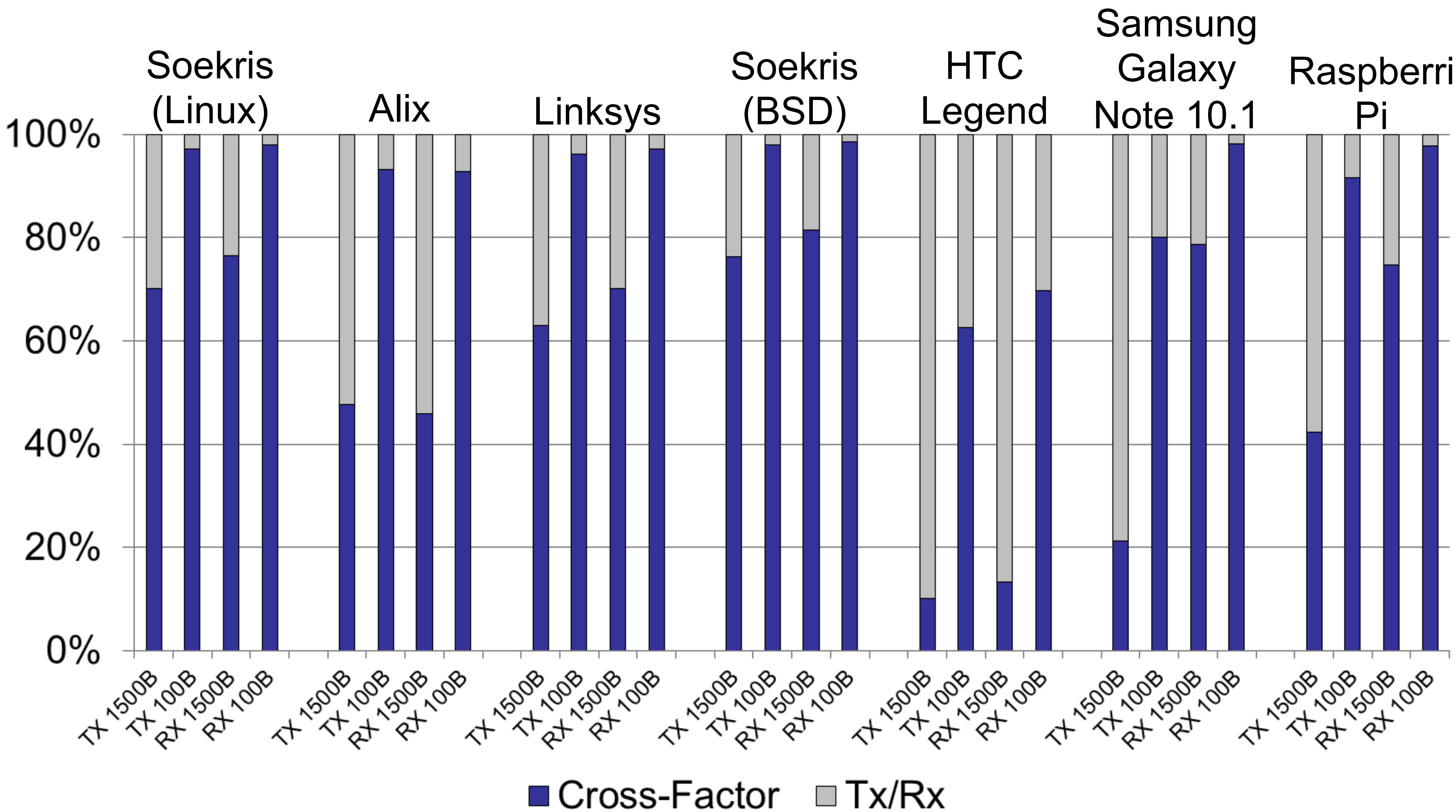
The cross-factor

- Cross-factor: energy «toll» to process a frame
  - ~ independent of frame size
  - Total Power > base power + card power
- Consumption weights (soekris)

App	TCP/IP	Driver	NIC
24%	33%	21%	22%

- This packet processing cost is not negligible
  - Soekris: 37%-97% energy/frame

The cross-factor

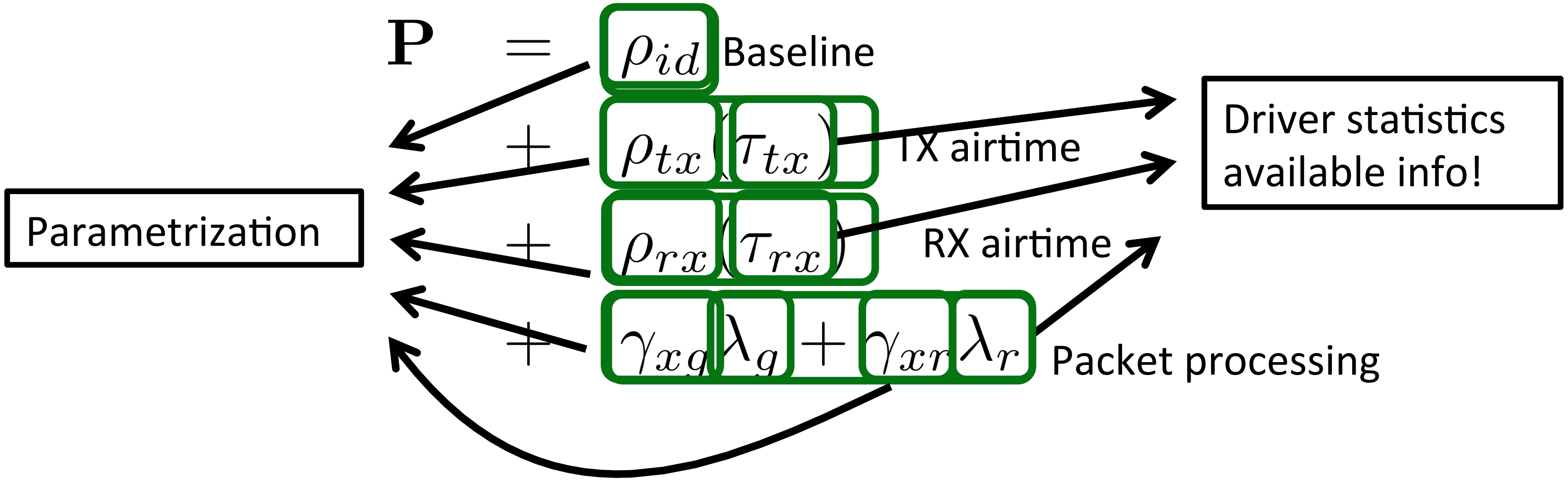


Several other experiments

- Retransmissions
  - No X-Factor
- ACKs
  - No X-Factor
  - Very small impact (as expected)
- Reception
  - There is X-Factor

Model

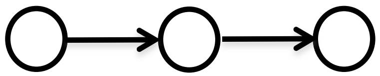
$$\mathbf{P} = \overbrace{\boxed{\rho_{id}}}^{\text{Baseline}} + \overbrace{\boxed{P_{xg} + P_{tx} + P_{retx}}}^{\text{Data transmission}} + \overbrace{\boxed{P_{xr} + P_{rx}}}^{\text{Data reception}} + \overbrace{\boxed{P_{rx,Ack} + P_{tx,Ack}}}^{\text{Ack rx/tx}}$$



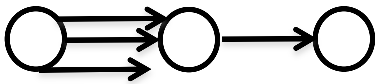
Implications

What about those mechamisms that
do not consider this?

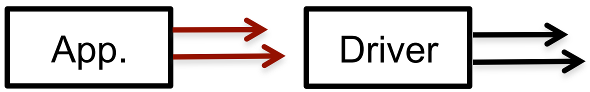
- Packet relaying



- Relay & compress

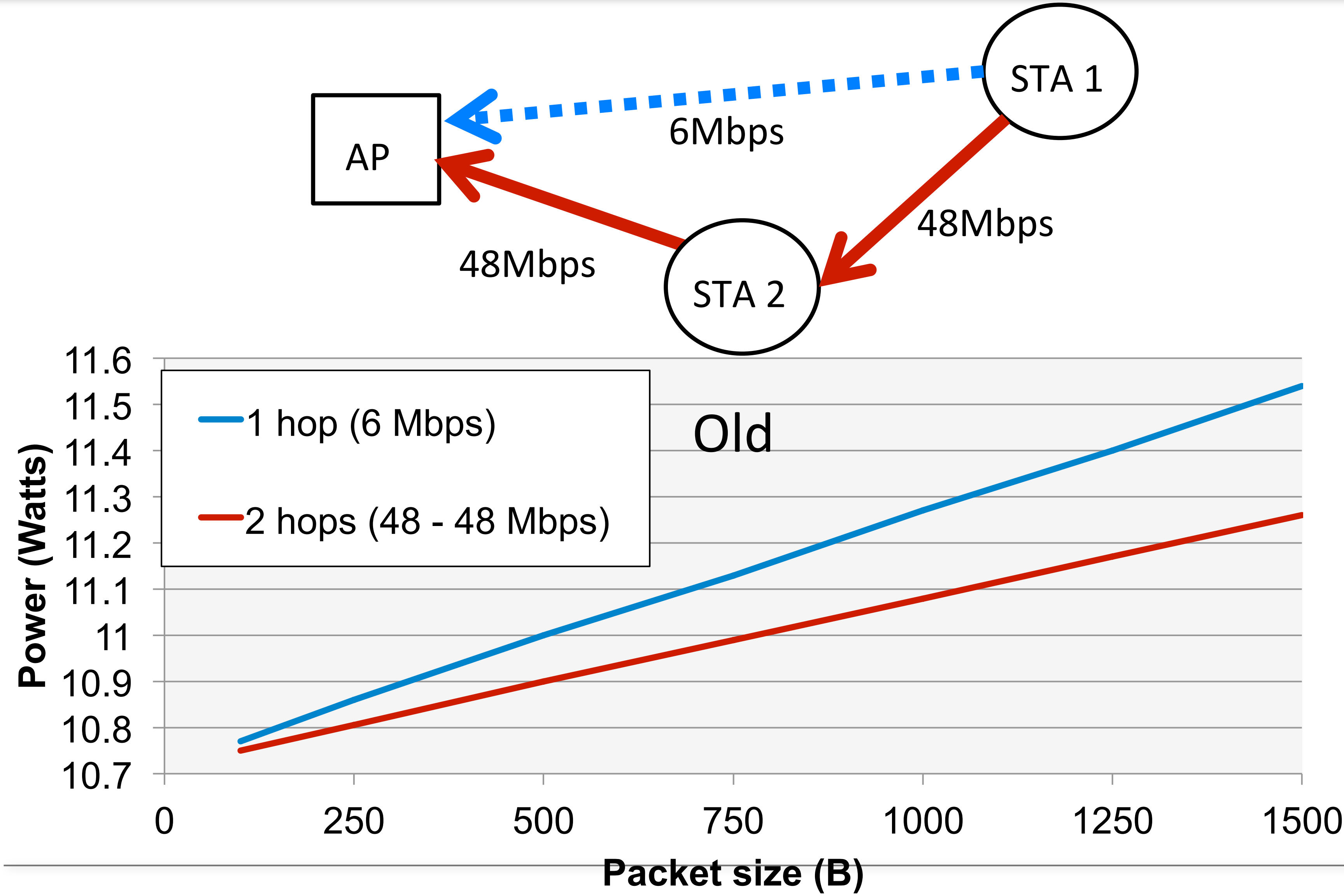


- Multicasting



Implications – e.g. relaying

* Soekris, 15 dBm



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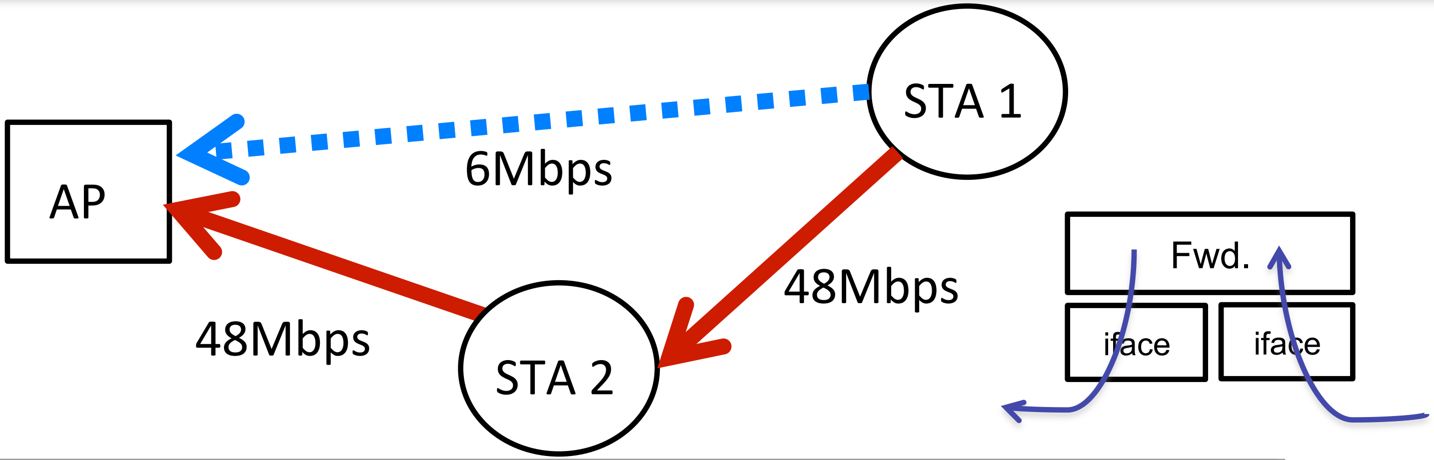
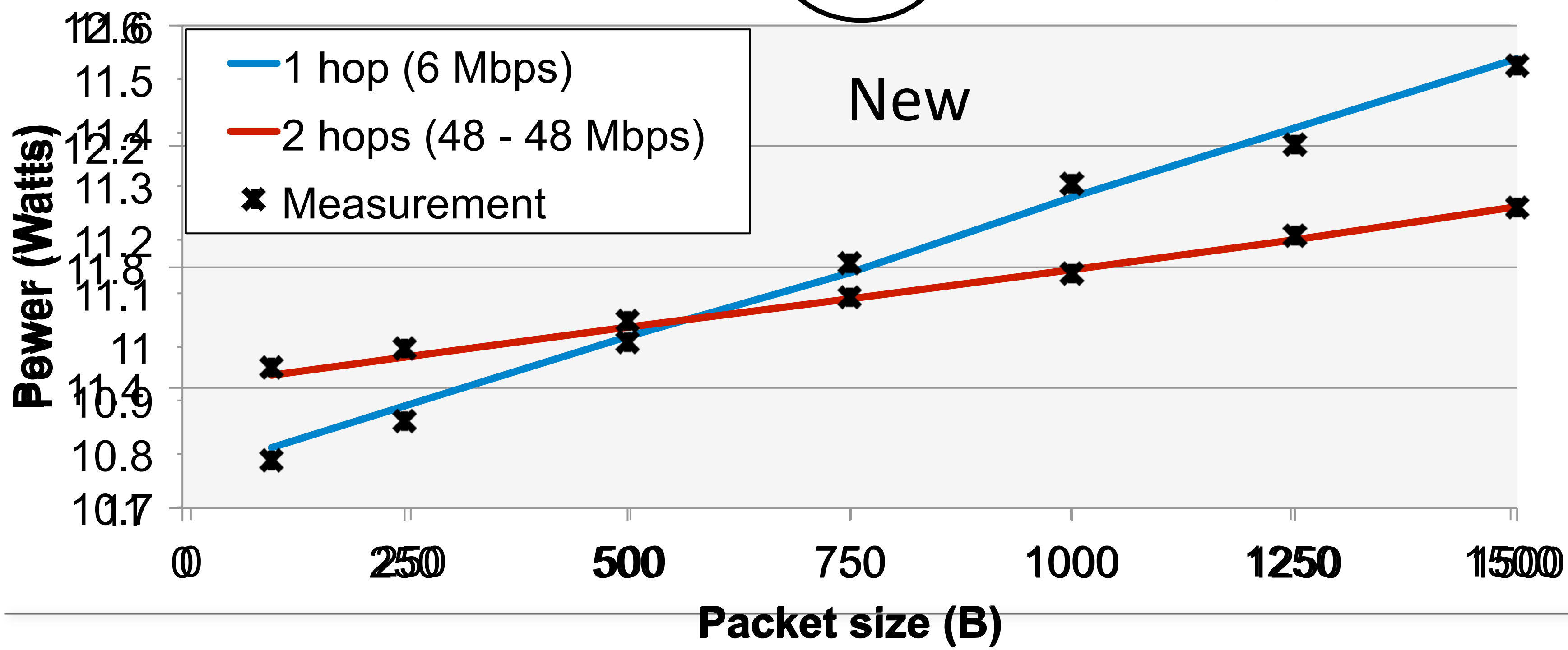
* Soekris, 15 dBm

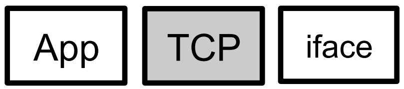




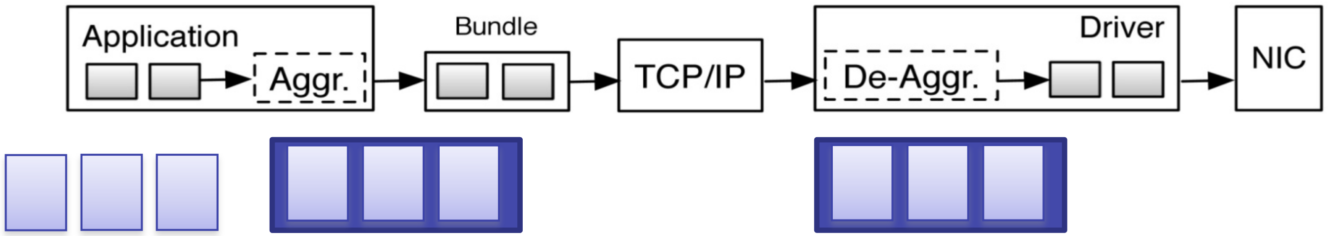
Implications

Can we **exploit** this knowledge?

- «raw» sockets

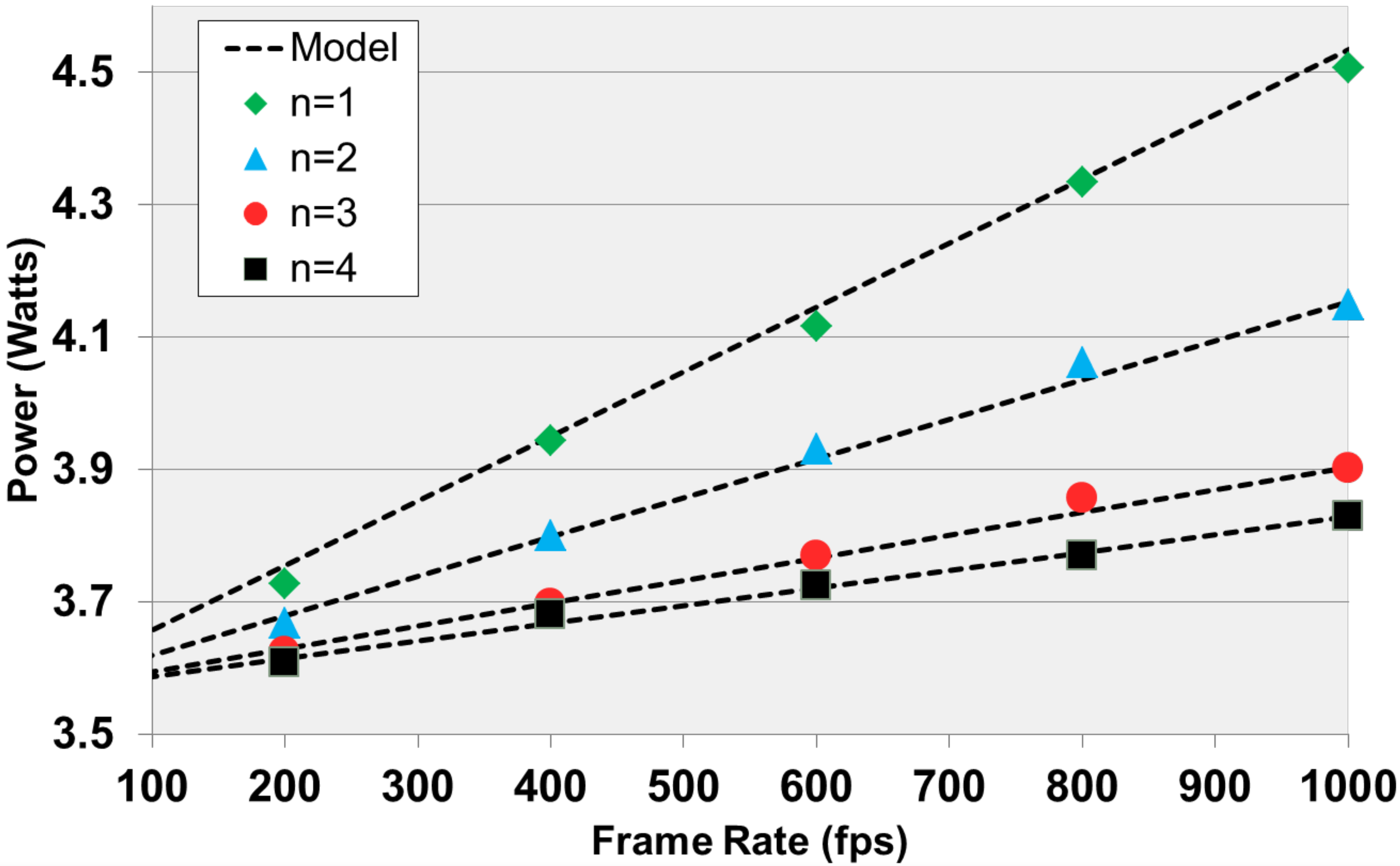


- Packet batching



* Soekris, 100B, 48 Mbps

Implications – e.g. batching



Conclusions and Future Directions, pt. 2

- Much effort has been devoted to reducing the energy consumption of wireless devices
- Most of the efforts conducted so far
  - Switching devices off
  - Reducing the consumption of the wireless card
- But ≥ 50% of the per-frame energy is consumed by the packet processing of the protocol stack
  - Need to revisit previous models
  - Explore new approaches to save energy

Many Thanks!

Greening Wireless Communications:
A Top-Down Overview

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