Energy Efficient Multi-radio Platforms for Mobile Applications

Yuvraj Agrawal, Curt Schurgers
Trevor Pering, Roy Want, Intel Research

Rajesh Gupta
University of California, San Diego
MESL.UCSD.EDU

Multiple Radios Are Common

802.11x, BT, GSM

HP h6300: GSM/GPRS, BT, 802.11

Moto CN620: BT, 802.11, GSM

- These radios typically function as isolated air interfaces to isolated networks.

Collaborating Radios Can

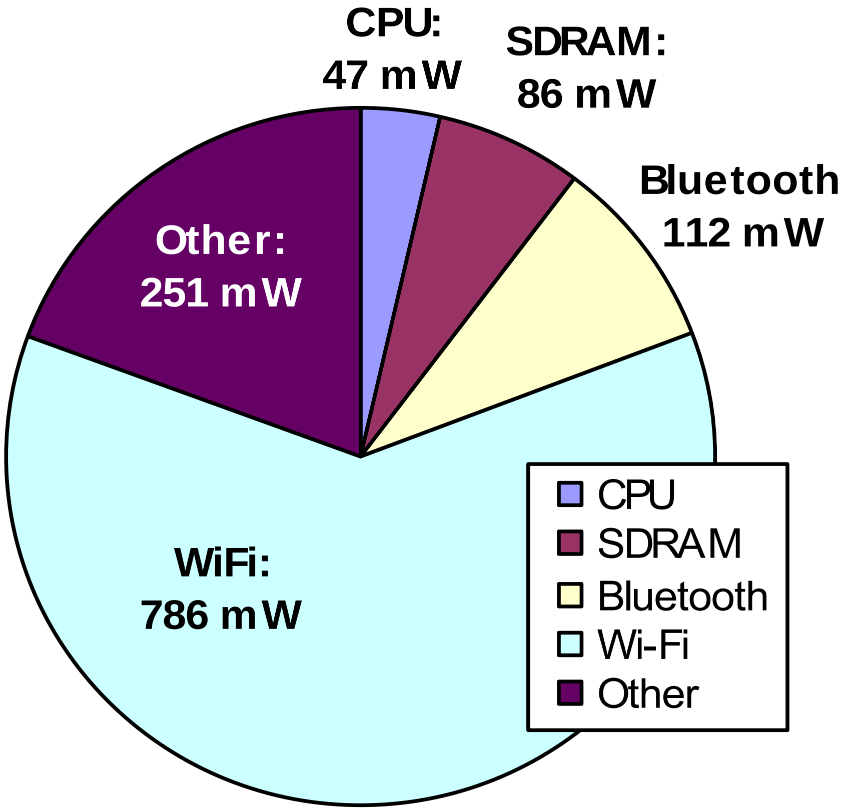
- Improve Performance
  – Aggregate connectivity
- Improve Reliability
  – Radios as backup interfaces
- Improve Security
  – Multiple/Side-Channel Authentication
- Improve Efficiency (Spectral, Energy)
  – Dynamically match radios to traffic, range
  – Use radios to page another, duty cycle other radios

► Collaborating radios have a great potential for system-wide improvement

- Energy, mobility management, capacity enhancement, channel failure recovery, networking, security, ….
- We focus on energy.

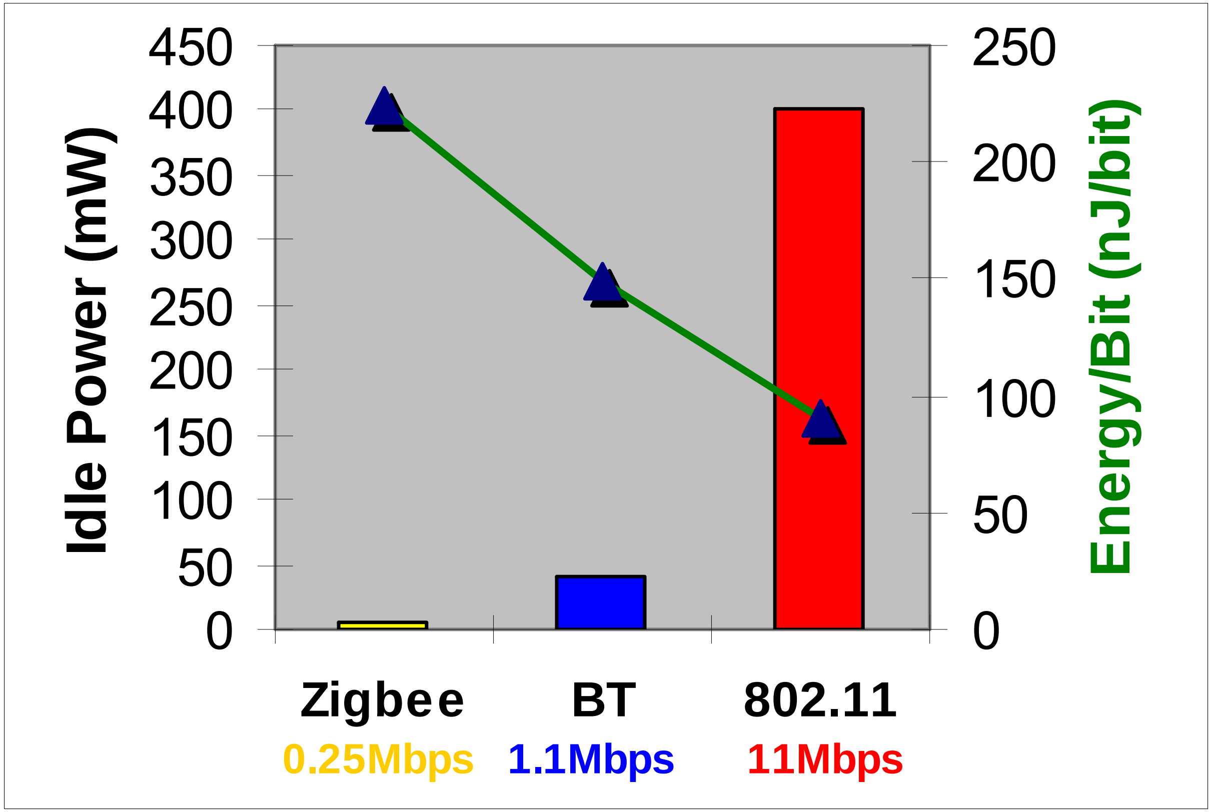
Typical power distribution

Depending on the usage model, the power consumption of emerging mobile devices can be easily dominated by the wireless interfaces!



Power breakdown for a *fully connected* mobile device in *idle* mode, with LCD screen and backlight turned off.

Common Radio Standards



Higher throughput radios have a **lower** energy/bit value

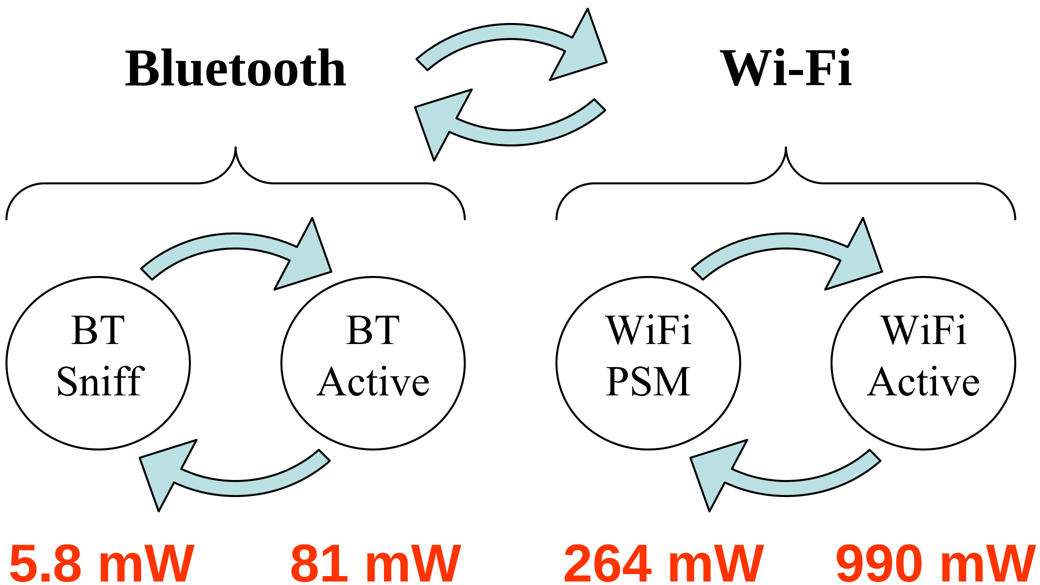
… have a **higher** idle power consumption

And they have different ranges.

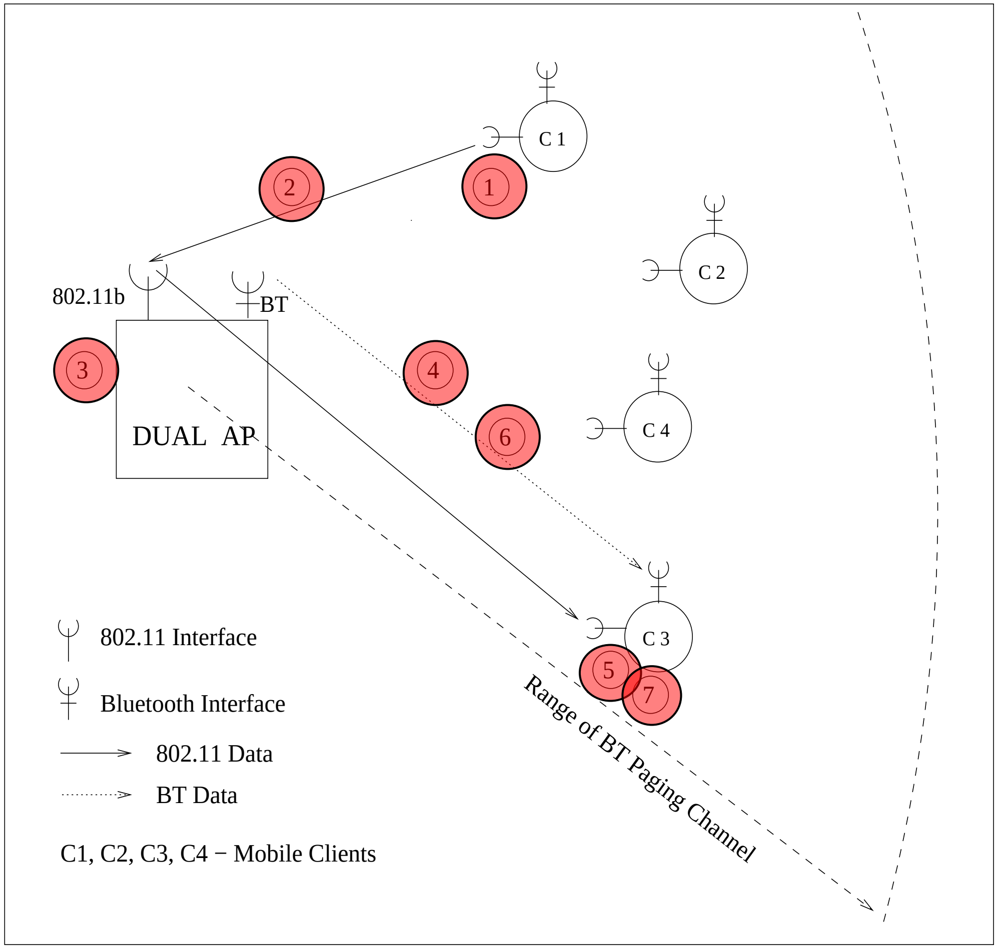
Consider: BT and WiFi

Objective: Always-on low-power operation with high peak bandwidth and overall energy efficiency

- Two possibilities:
  1. Use BT to page WiFi as needed
  2. Build a switching hierarchy for energy efficient operation
     - Effectively expand the power states available at the system level
     - Switching policies are key to a good implementation.



1. BT as a paging radio

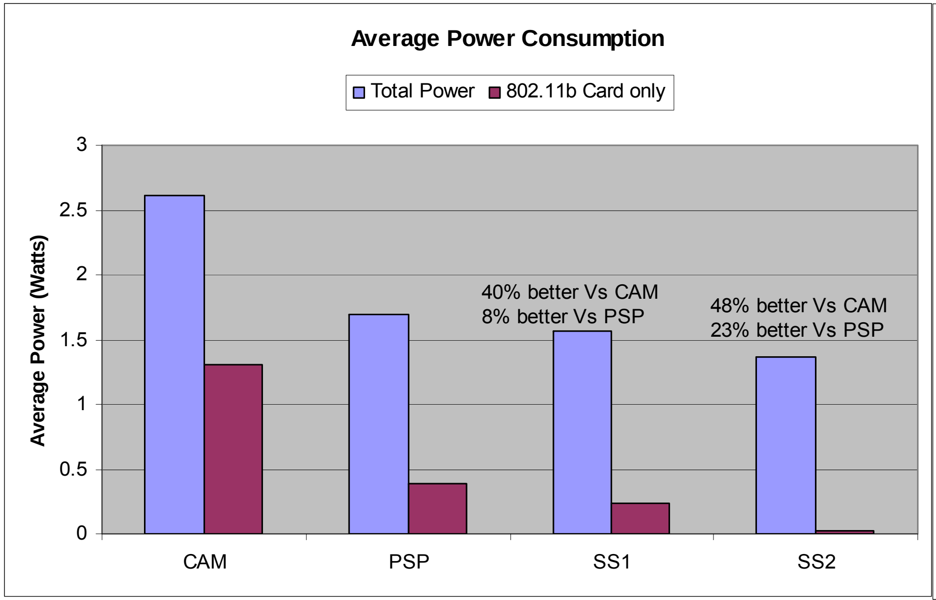


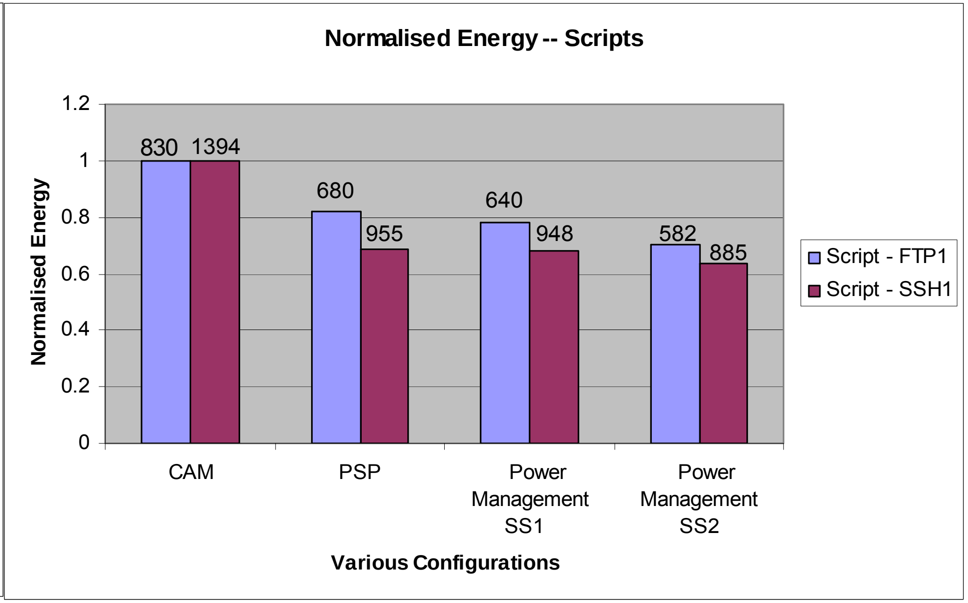
Scenario : An application on C1 wants to communicate with C3

1. C1 turns its 802.11 radio ON
2. C1 starts communication, sends data to AP through 802.11
3. AP matches C3's destination IP with its BT address
4. AP sends WAKE-UP page to C3 via it's BT interface, C3 turns on it's 802.11 radio on receiving the WAKE-UP page
5. When C1 finishes sending data it switches OFF its 802.11 radio
6. If all connections to and from C3 are closed, AP sends SLEEP page
7. On receiving SLEEP page C3 turns OFF its 802.11 radio

Simple paging (with range compensation)

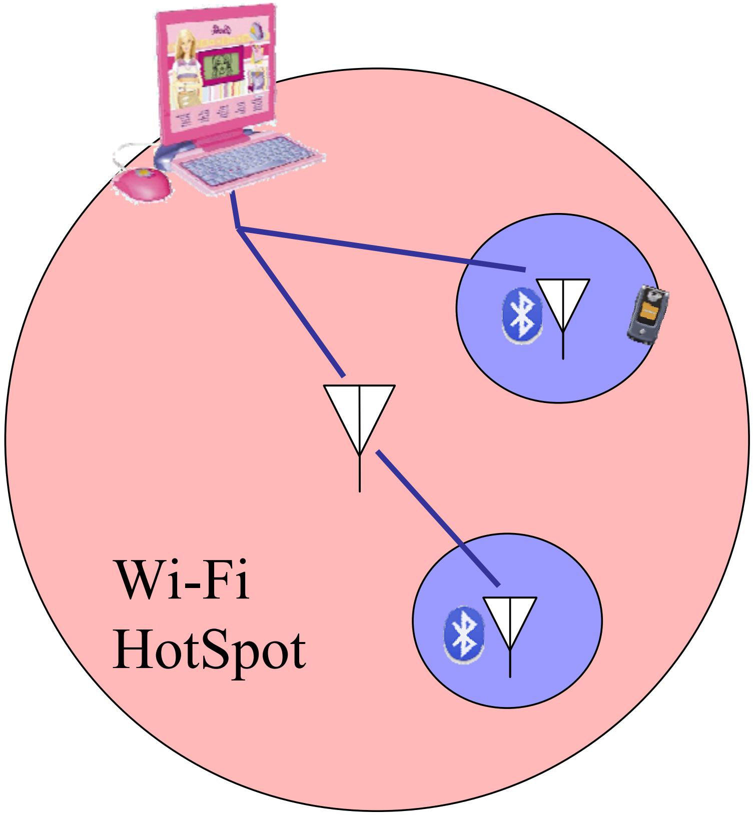
- Implemented iPAQs (3870), familiar linux and CISCO PCM-350, built-in BT
- Measured power and latency on FTP and SSH sessions



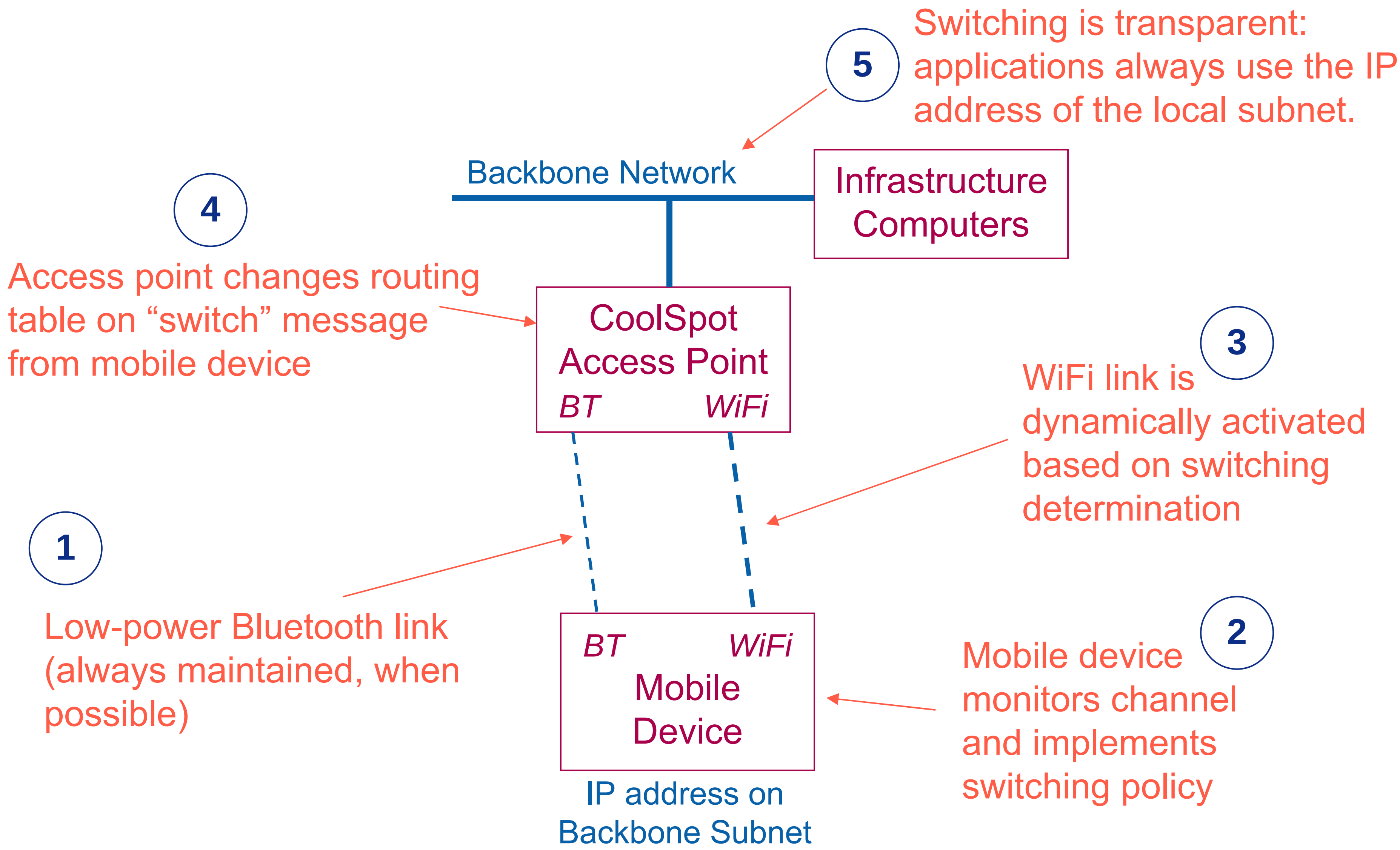


Power Savings for 802.11 card only vs PSP : 41% (SS1) to 95% (SS2)
Throughput - Same as Awake Mode (CAM) , maximum throughput
Latency - Setup latency, amortized across session

2. CoolSpots: Radio Hierarchy



CoolSpots Network Architecture



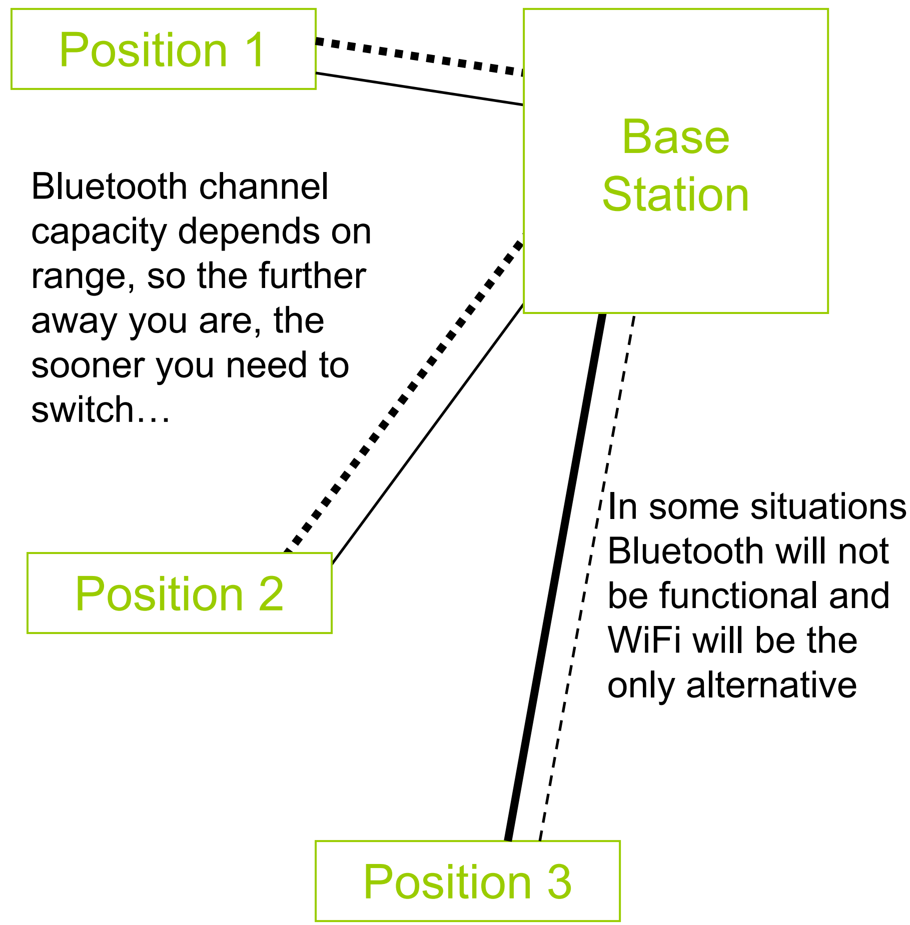
Switching Policies

- Three main components contribute to the behavior of a multi-radio system

- Position: Where you are
  - Need to address the difference in range between Bluetooth and WiFi
- Benchmarks: What you are doing
  - Application traffic patterns greatly affect underlying policies
- Policies: When to switch interfaces
  - A non-intrusive way to tell which interface to use

Where: Position

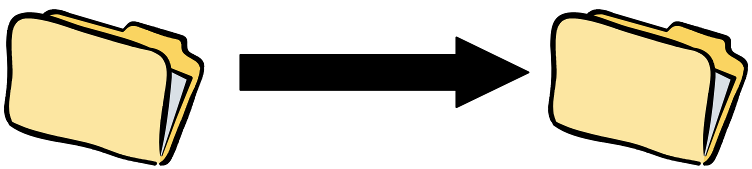
- Different radio ranges affect the switching decision
- However, optimal switching point will depend on exact operating conditions, not just range
- Experiments and (effective) policies will measure and take into account a variety of operating conditions



What: Benchmarks

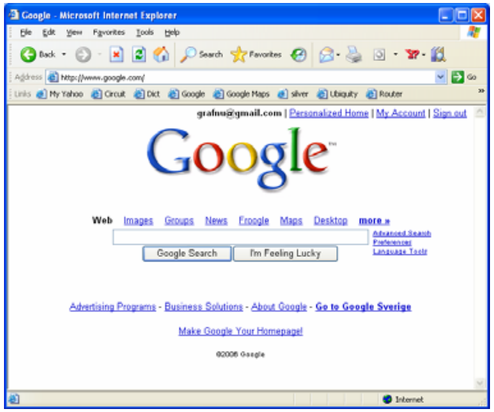
Baseline: target underlying strengths of wireless technologies

- Idle: connected, but no data transfer
- Transfer: bulk TCP data transfer



Video: range of streaming bit-rates varying video quality

- 128k, 250k, 384k datarates
- Streaming data, instant start



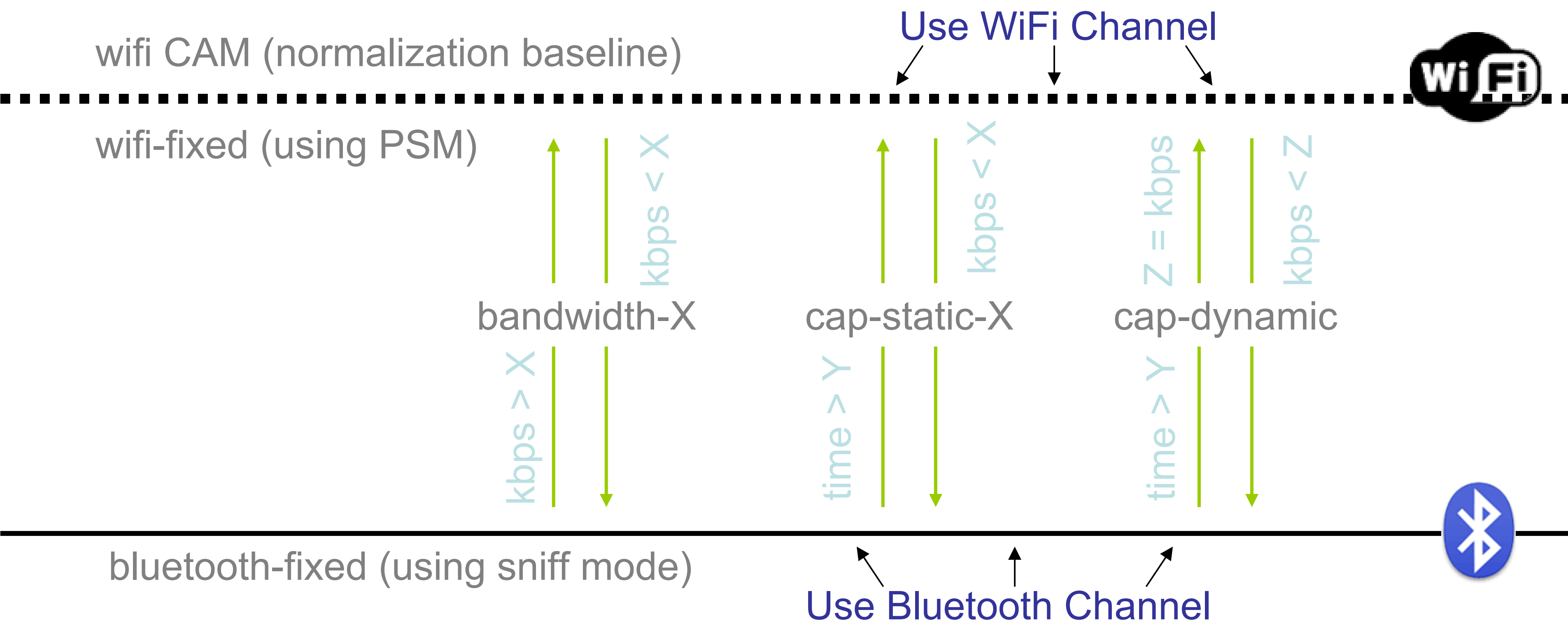
WWW: realistic combination of idle and data transfer conditions

- Idle: “think time”
- Small transfer: basic web-pages
- Bulk transfer: documents or media

What: Benchmarks

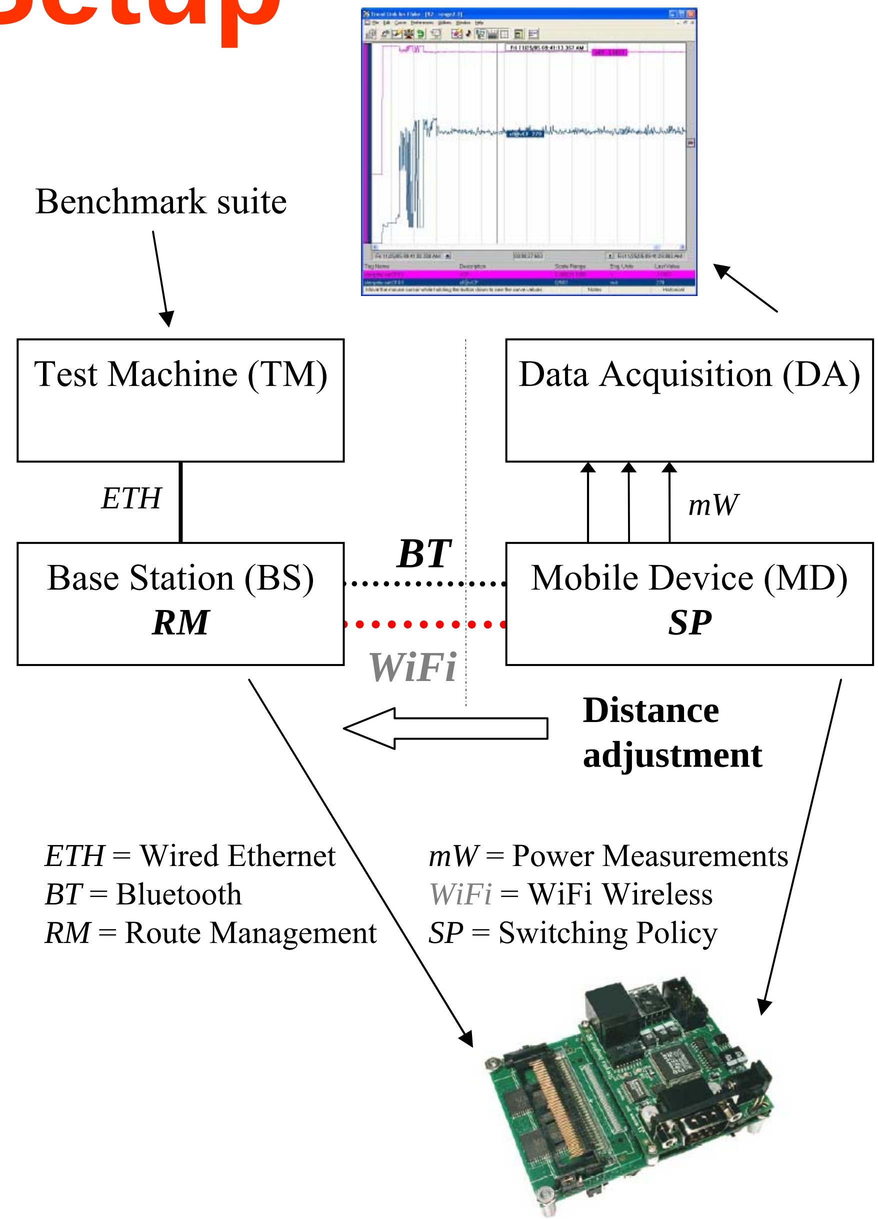
Benchmark	Time over WiFI	Data Transmitted	Average Bandwidth (Data Size / Time)	Data Pattern
idle	60s	0.0 MB	0 kbps	None
transfer-1	13s	6.6 MB	4482 kbps	Bulk transfer
transfer-2	27s	13.3 MB	4519 kbps	Bulk transfer
www-intel	176s	21.6 MB	1022 kbps	Intermittent data
www-gallery	150s	2.9 MB	158 kbps	Intermittent data
video150k	150s	3.1 MB	172 kbps	Real time streaming video
video250k	150s	7.3 MB	402 kbps	Real time streaming video
video384k	150s	8.5 MB	464 kbps	Real time streaming video

When: Policies



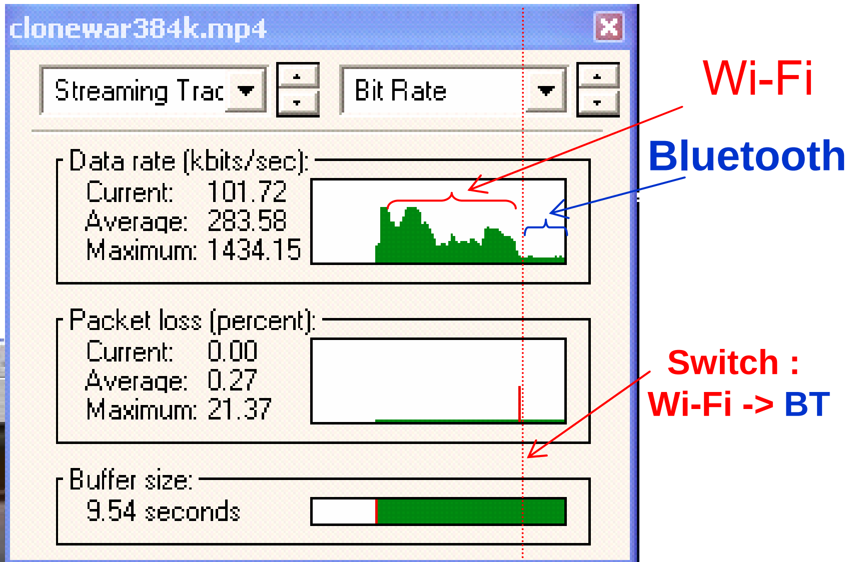
Experimental Setup

- Characterize power for WiFi & BT
  - Multiple Policies
  - Different locations
  - Suite of benchmark applications
- Stargate research platform
  - 400Mhz processor, 64MB RAM, Linux
  - Allows detailed power measurement
- Tested using “today’s” wireless:
  - WiFi is NetGear MA701 CF card
  - Bluetooth is a CSR BlueCore3 module
- Use the geometric mean to combine benchmarks into an aggregate result
- Moved devices around on a cart to vary channel characteristics



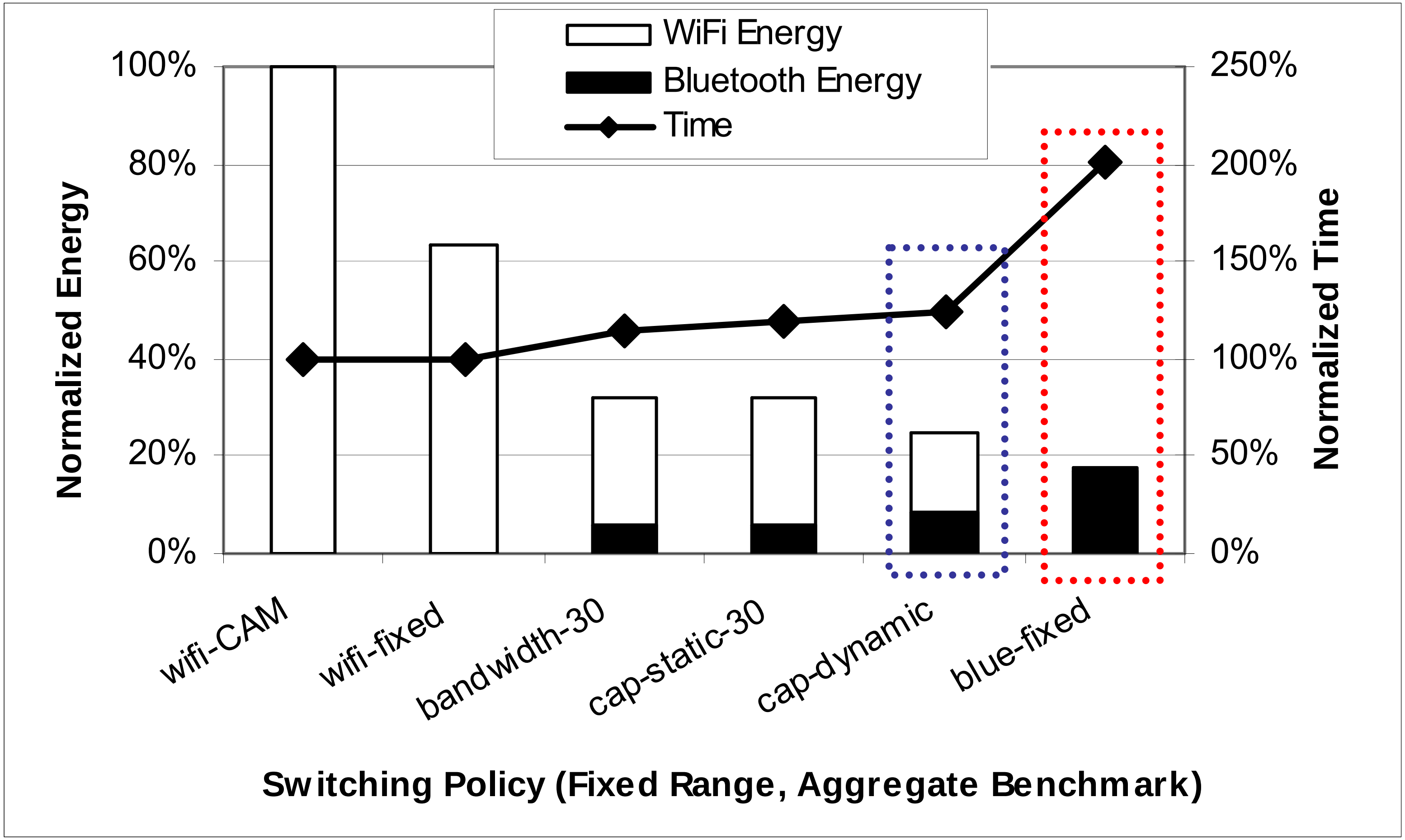
Switching Example: MPEG4 streaming

- Simple bandwidth policy
- Switch from WiFi to BT when application has buffered enough data



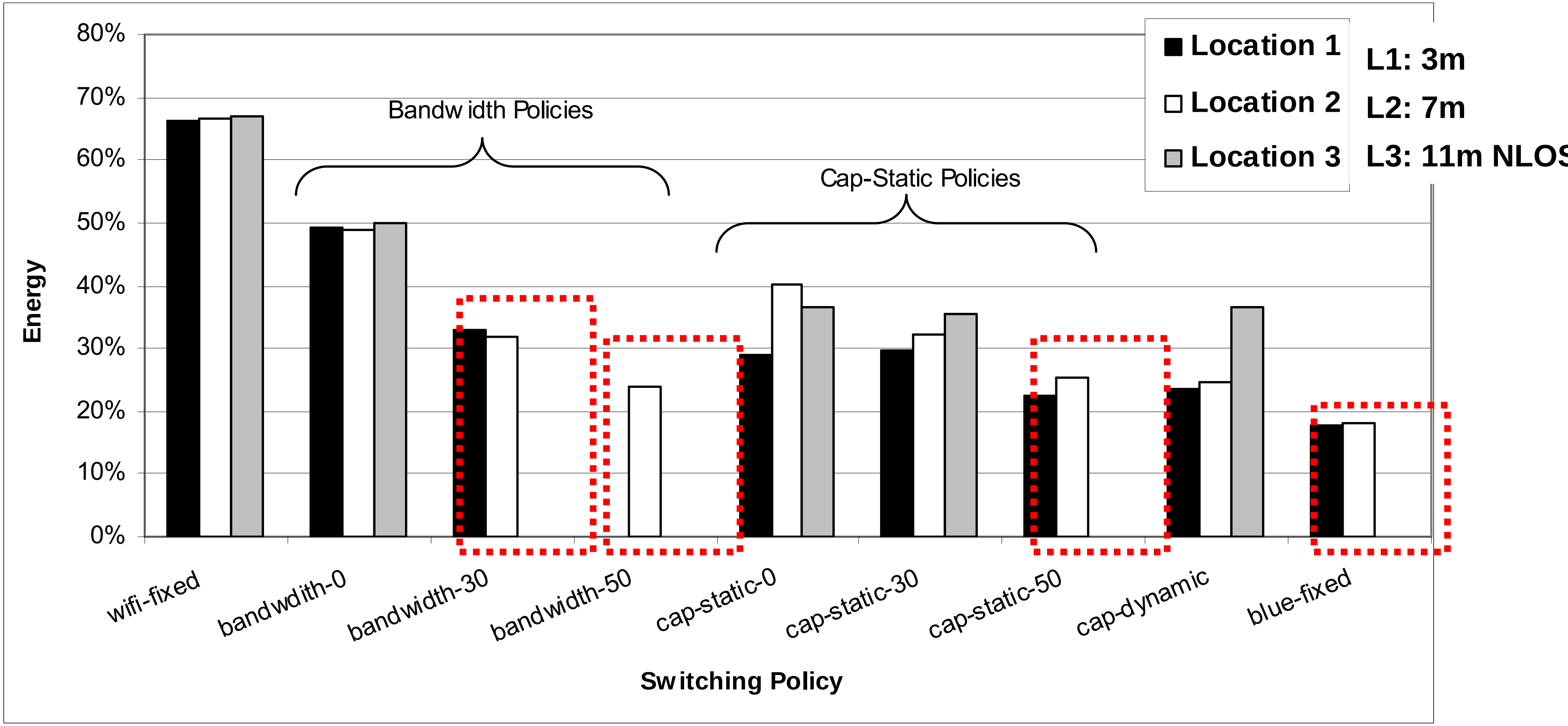
Switching is transparent to unmodified applications!

Results (Intermediate Location)



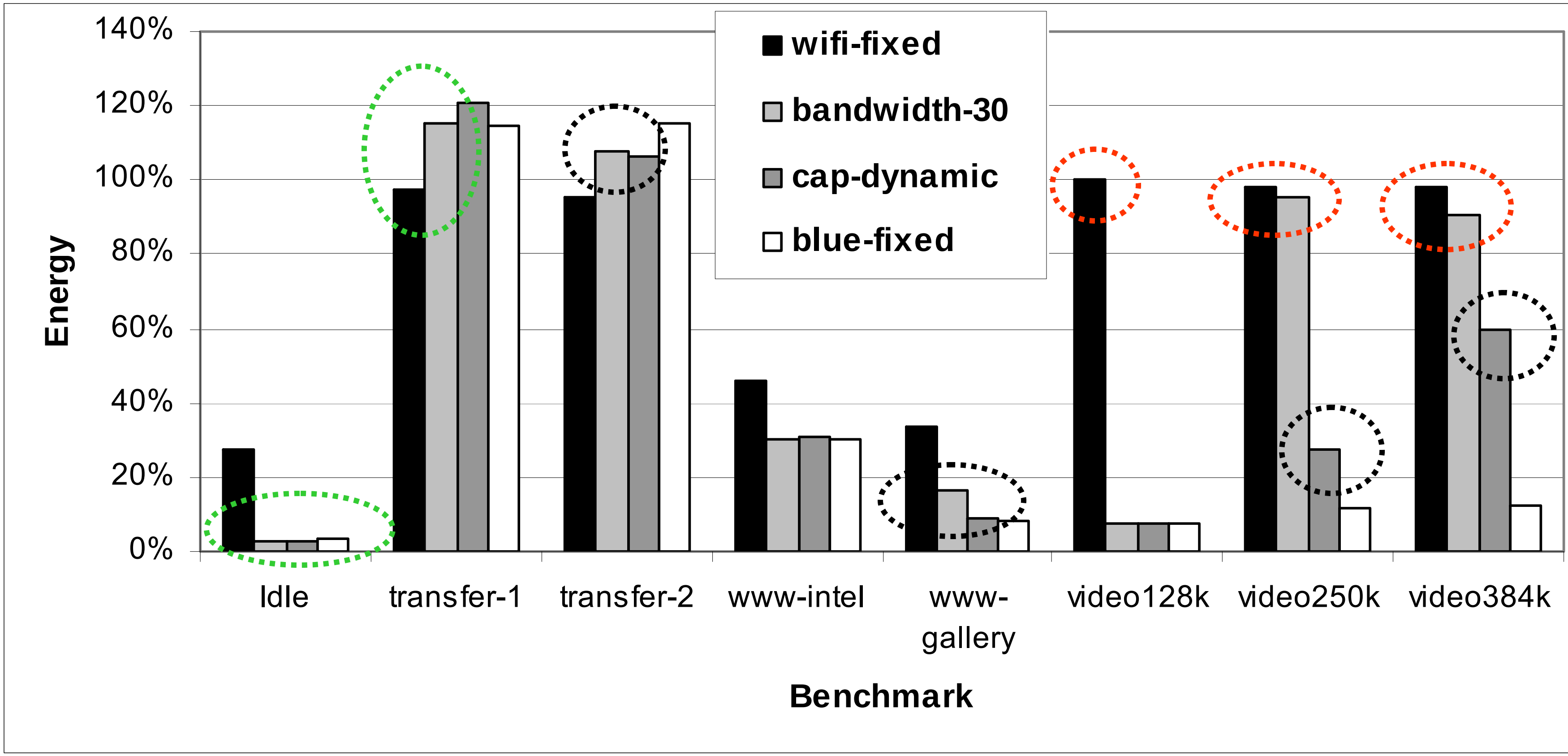
- ***blue-fixed*** **does well in terms of energy but at the cost of increased latency**
- ***cap-dynamic*** **does well in terms of both energy and increased latency**

Impact of Range/Distance



Missing data indicates failure of at least one application, and therefore an ineffective policy!

Results across various benchmarks



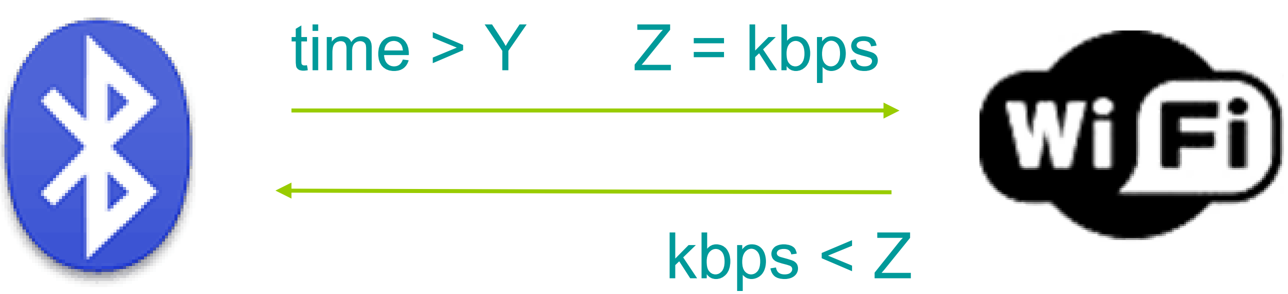
wifi-fixed consumes lowest energy for data transfer, *any bluetooth policy* for idle

Overall, *cap-dynamic* does well taking into account energy and latency

Video benchmarks really highlight problems with *wifi-fixed* and *bandwidth-x*

Cap-Dynamic Switching Policy

- Switch up based on measured channel capacity
  - (ping time > Y): 40ms-800ms, estimates channel conditions
- Remember last seen Bluetooth bandwidth
  - (Z=kbps)
- Switch down based on remembered bandwidth
  - (kbps < Z): limited mobility



Switching Policies – Summary

- "Wifi-Fixed" Policy (WiFi in Power Save Mode)
  - Works best for as-fast-as-you-can data transfer
  - Higher power consumption, especially idle power
- "Blue-Fixed" Policy
  - Very low idle power consumption
  - Increases total application latency, fails at longer ranges
- "Bandwidth" Policy
  - Static coded bandwidth thresholds, fails to adapt at longer ranges
  - Switches too soon (bandwidth-0) or switches too late (bandwidth-50)
- "Capacity-Static" Policy
  - Estimates channel capacity and uses that to switch up
  - Fails at longer ranges due to incorrect switch-down point
- "Capacity-Dynamic" Policy
  - Dynamic policy, remembers the last seem switch-up bandwidth
  - Performs well across all benchmarks and location configurations!

Conclusions

- Multiple radios open up many possibilities for system-level performance and reliability increases
- CoolSpots shows ~50% reduction in energy consumption over current power management in WiFi across applications, ranges
  - No changes to the application themselves.
- Many improvements possible that take into account
  - Application behavior, Radio link quality, Network queues instead of ping latency, other scenarios (multi-user environments, p2p configurations)
  - Network infrastructure instead of standalone CoolSpots APs
- In collaboration with MSR on integration with cellular networks.