Intelligent Offload to Improve Battery Lifetime of Mobile Devices

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Microsoft Research

Phones are Energy Constrained

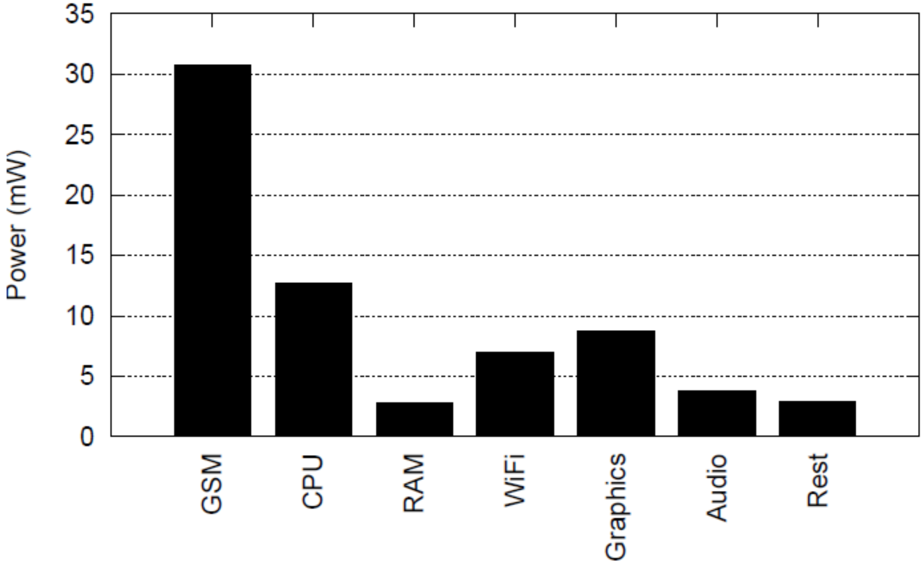
- Energy: A critical issue in smartphones
  - Limited battery lifetime

- Battery energy density only doubled in last 15 years

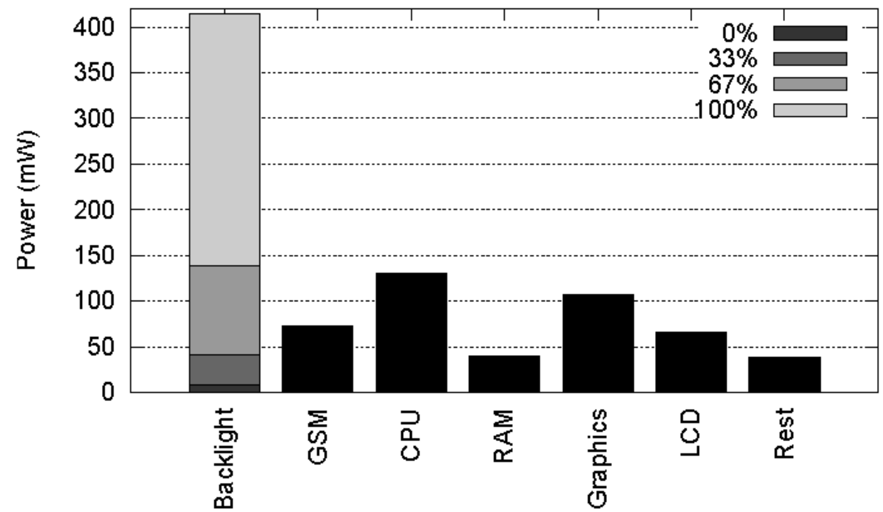
- Smartphone capability has increased drastically
  - Multiple Components: GPS, 3G, retina display, ….

Where Does the Energy Go?

Android G1 energy consumption
"An Analysis of Power Consumption in a Smartphone", USENIX 2010



Suspended State
(68 mW)



Video Playback
(450 mW + backlight)

Network, Display & CPU are the main energy hogs!

Efforts to Improve Battery Life

- **Battery**: bigger, more energy density
  - Challenge: Lighter phones
- **CPU**: low power cores, parking individual cores
  - Challenge: multi-core, faster processors
- **Network**: low power cellular & Wi-Fi states
  - Challenge: LTE, 802.11ac
- **Display**: energy-efficient display, e.g. AMOLED
  - Challenge: larger & brighter displays, video, animation

Mission & Big Bets

"Lasting a week without charge under normal usage"

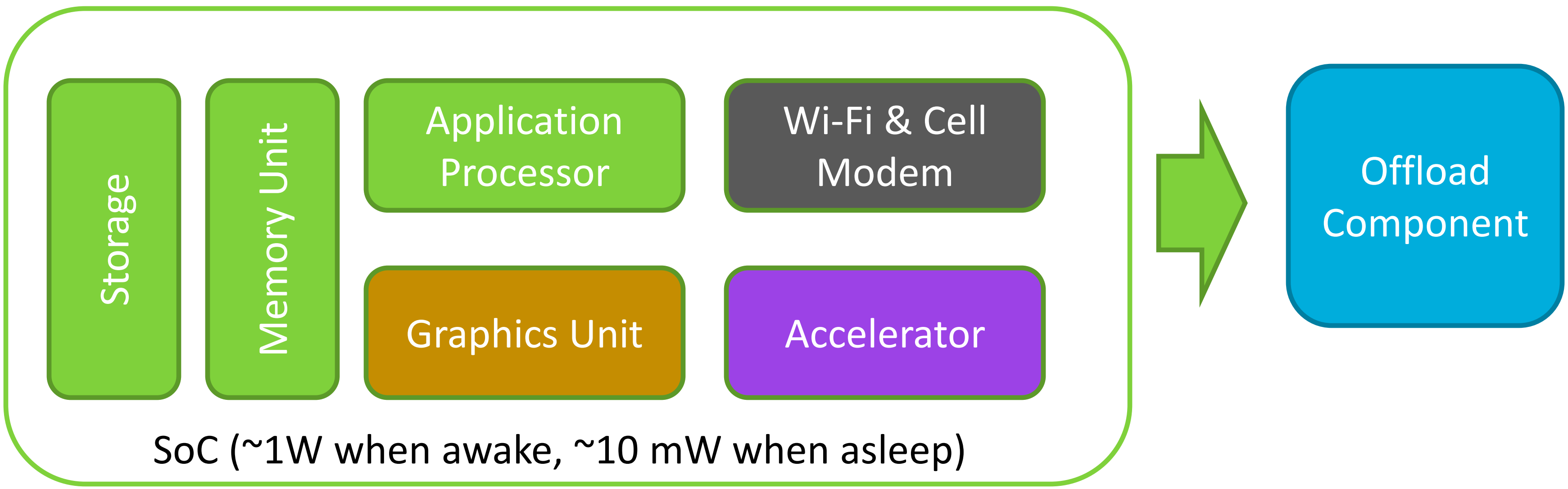
- Profile energy use of each component
  - Application energy profiler
  - Energy debugging

- Big Bets:
  - **Offload:** Intelligently utilize available resources
  - **Energy-aware UI:** based on OLED energy models
  - **Adaptive battery usage:** OS controlled multi-battery systems

OFFLOAD

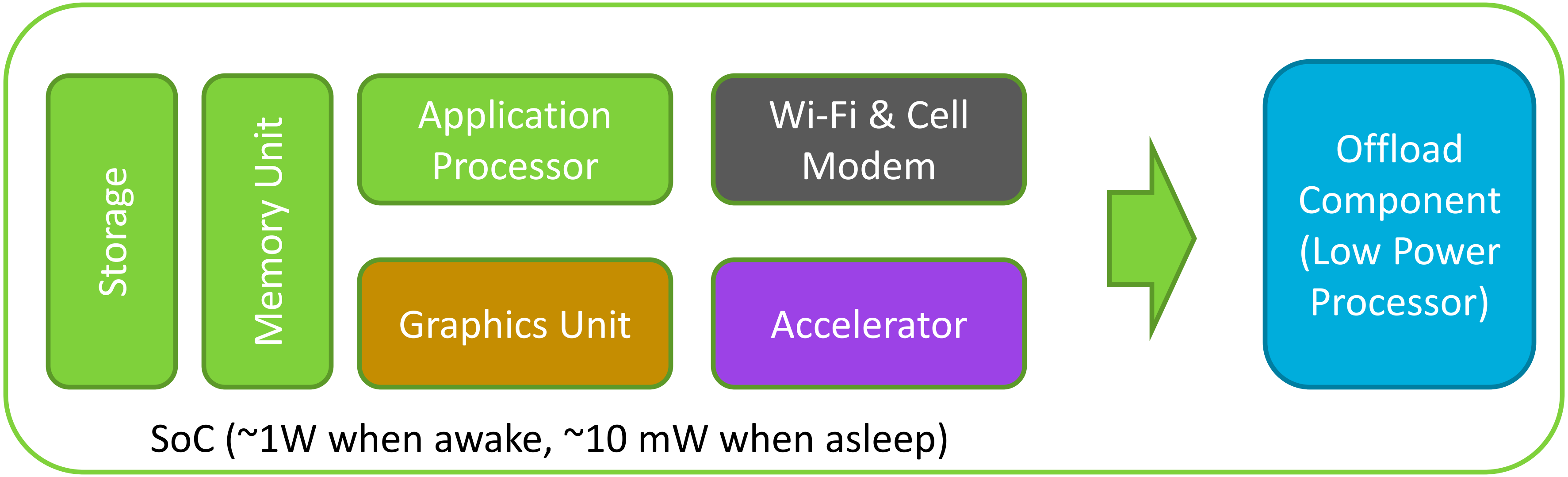
Computational Offload

- Move computation away from main processor without degrading user experience
  - Such that SoC is in low power states for longer



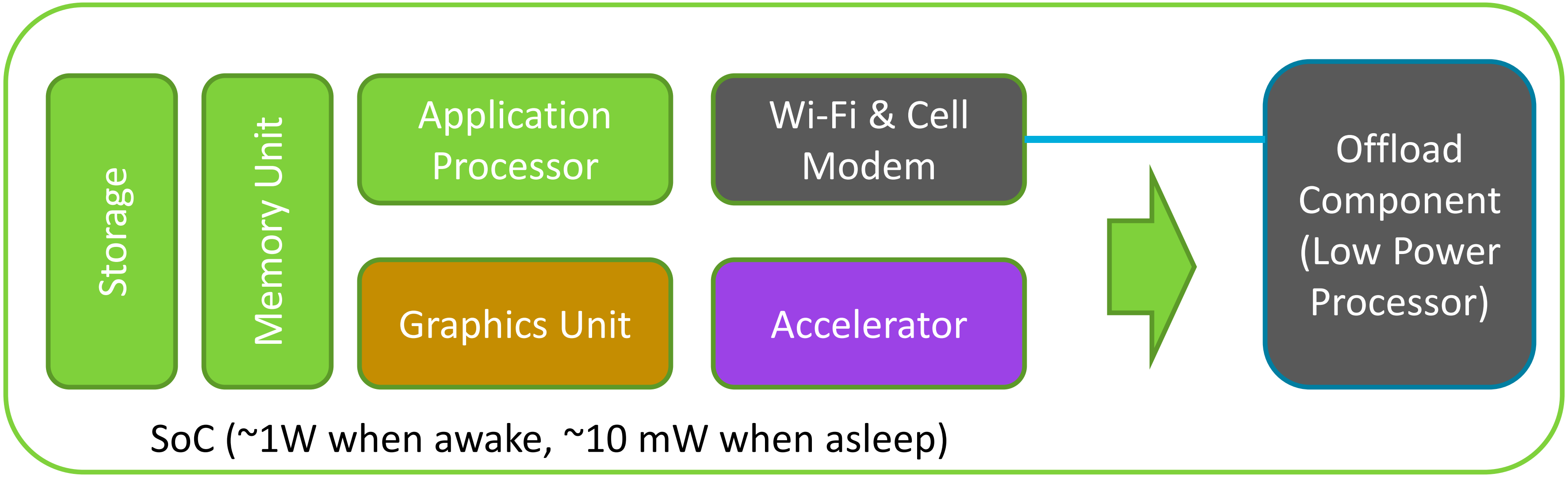
Where to Offload?

- Low power subsystem on SoC
  - Already shipping with TI and other SoC vendors



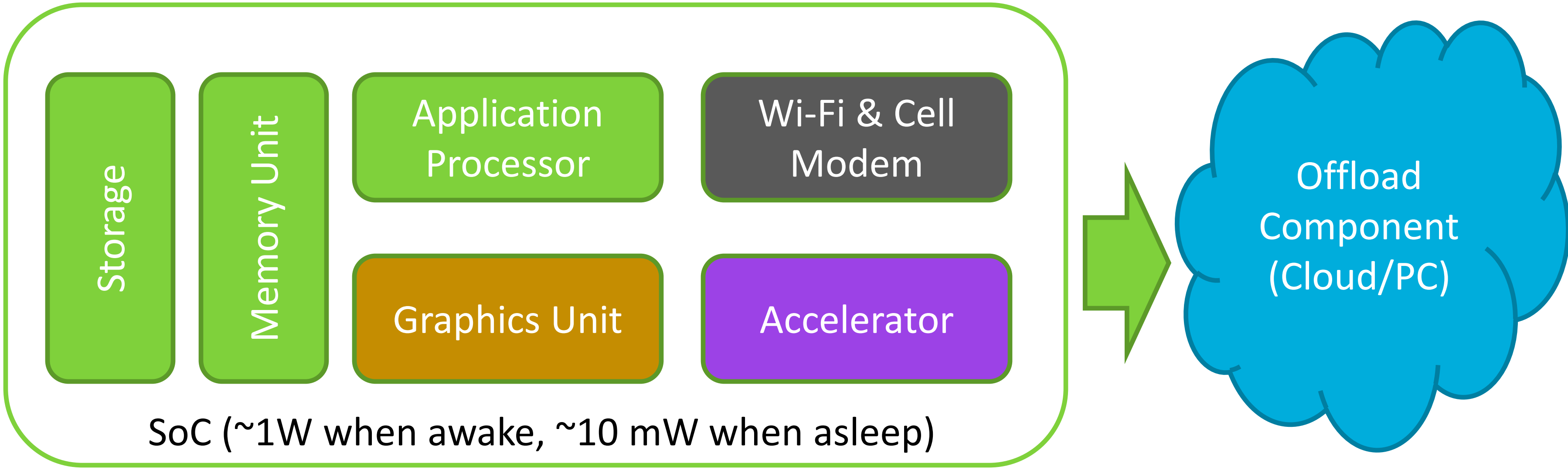
Where to Offload?

- Low power subsystem on SoC
- Low power processor connected to NIC



Where to Offload?

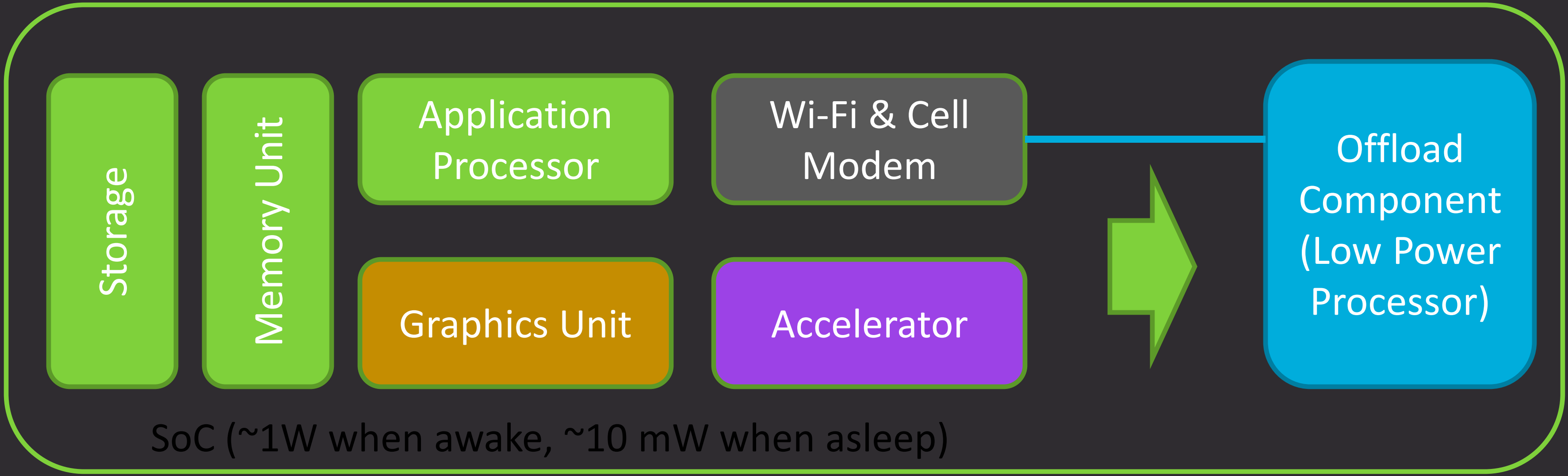
- Low power subsystem on SoC
- Low power processor connected to NIC
- Cloud or another machine

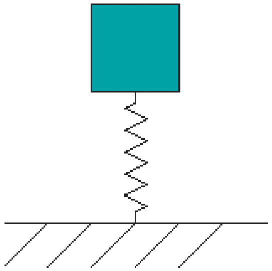


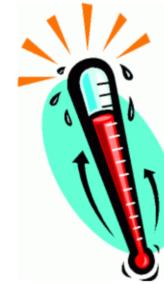
Use Cases

- When display is off
  - Push e-mail
  - Continuous sensing
  - Large downloads
  - Instant Messaging
  - P2P file sharing
- When display is on
  - Gaming
  - Speech translation
  - …

OFFLOAD TO LOW-POWER PROCESSOR





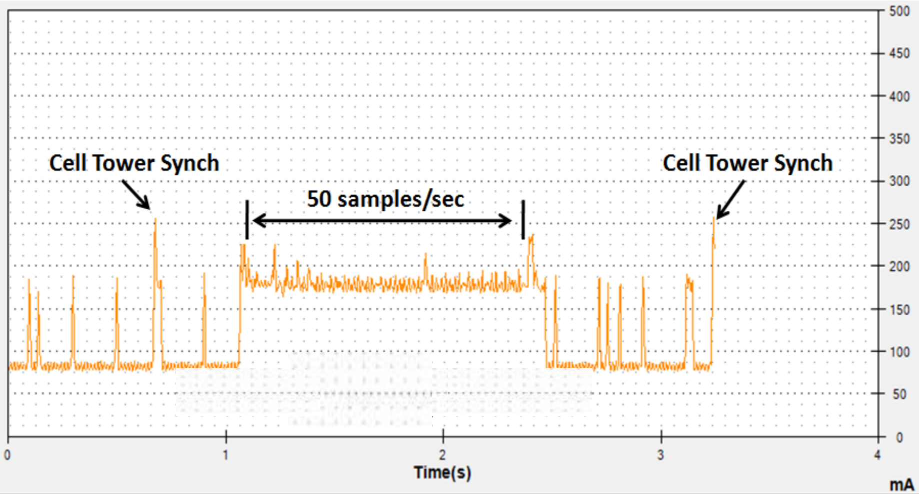


100’s of apps using the accelerometer

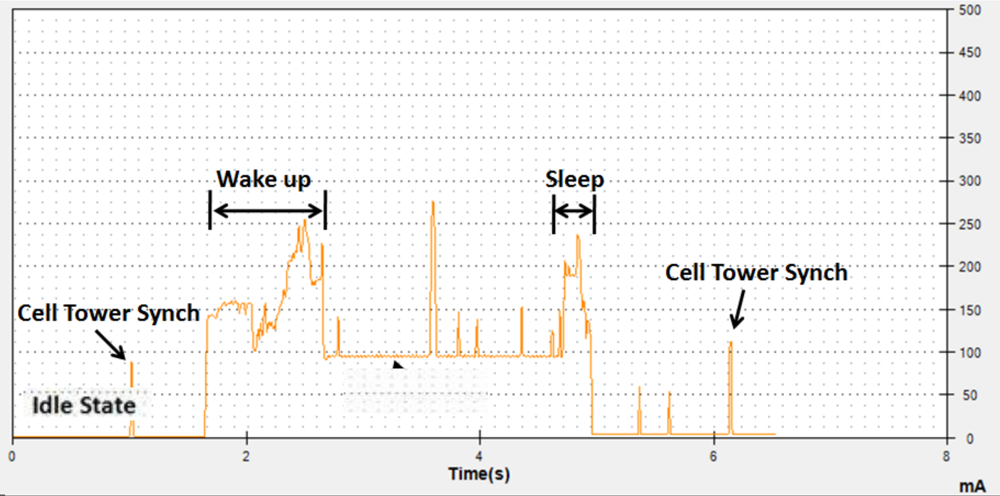
Not using the full potential of sensors

Responsive Sleeping Challenge

Sampling overhead



High wakeup/sleep overhead



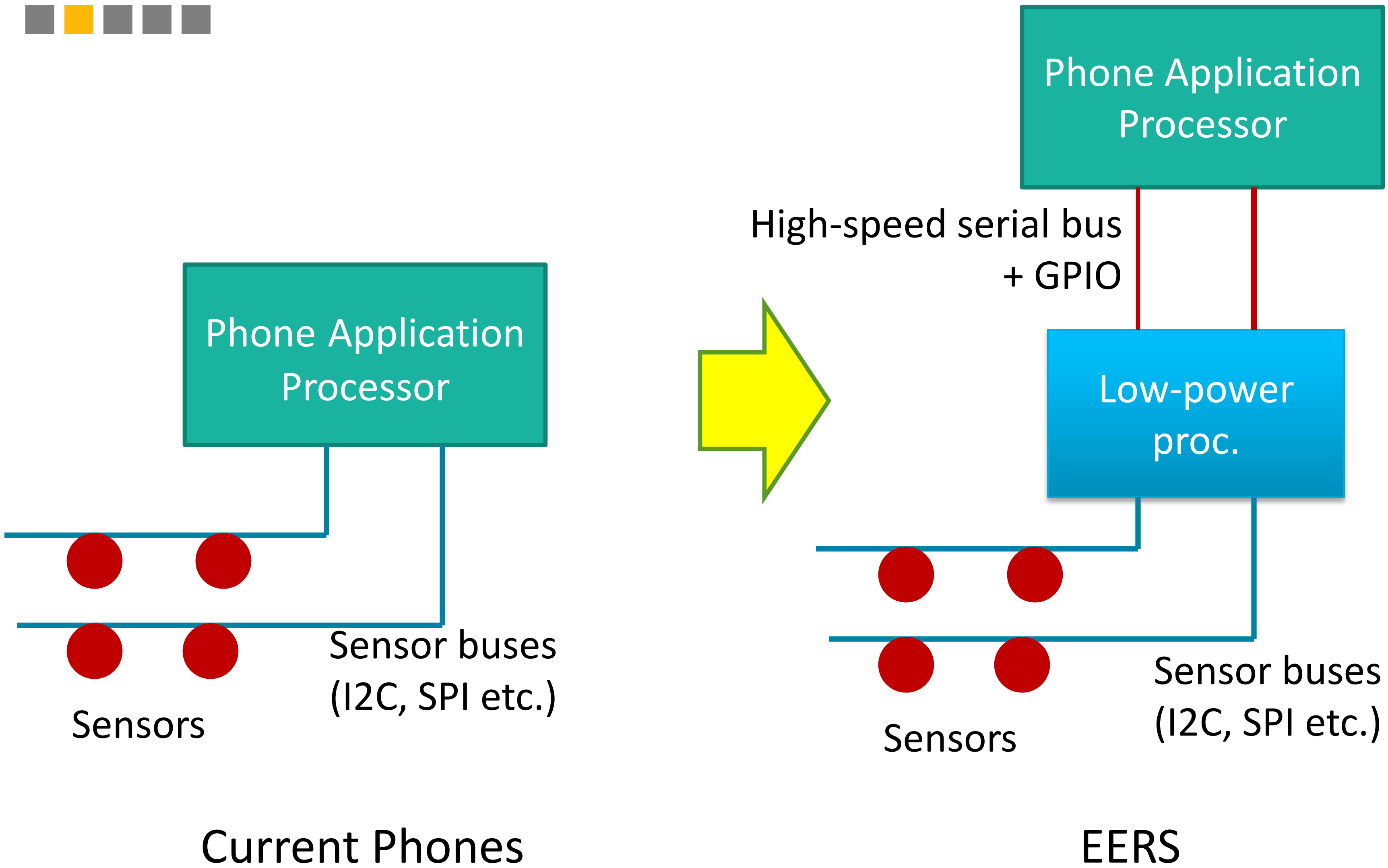
- Sensor (accelerometer): 0.56mW
- Phone (mainly processor): ~600mW

- Wakeup + sleep time: 1200ms
- @ 1Hz sampling, processor can't sleep

Solution: Offload sampling/processing sensor data to a low-power processor

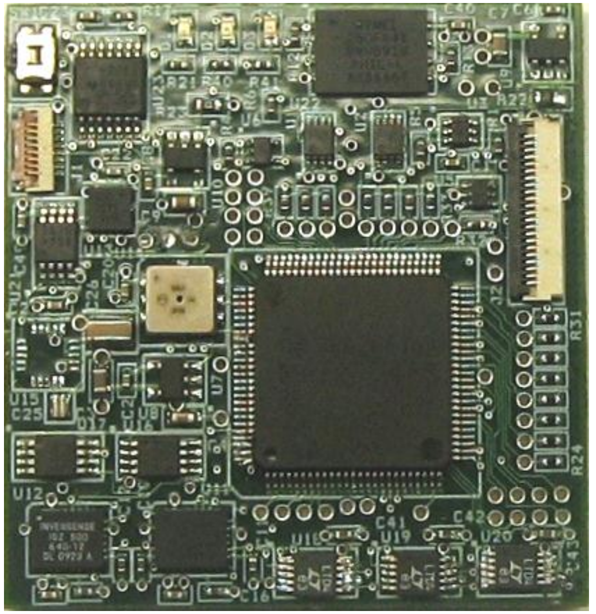
Bodhi, Jie, Dimitrios (2010)

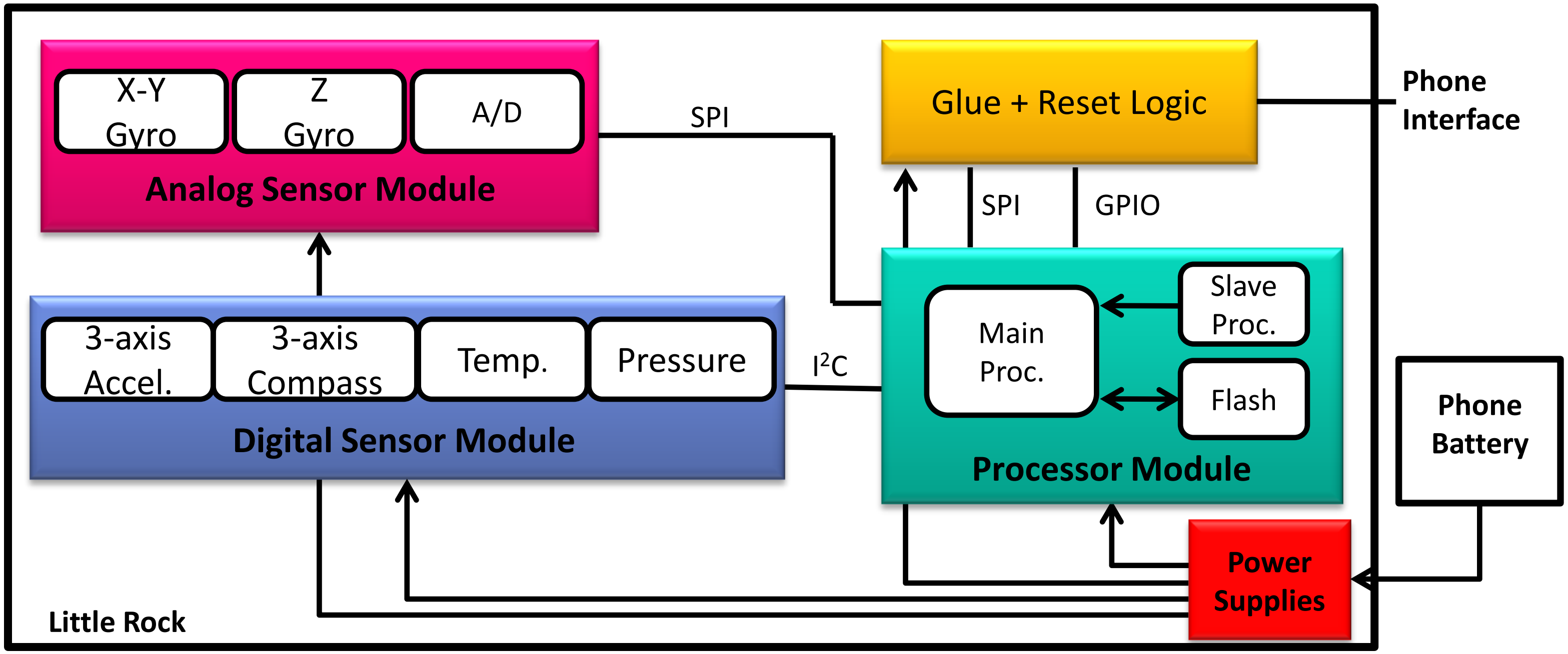
Energy Efficient Responsive Sleeping



Hardware Prototype

- Interfaced directly to phone's AP
- Processor: MSP430F5438
  - 16KB RAM, 256KB Flash
  - Active: 6.6mW @16MHz; sleep: 10μW
  - Wakeup time: 4μs
- Sensors:
  - Temperature
  - Pressure
  - 3D compass
  - 3D accelerometer
  - 3D gyro
  - Capacitive touch sensing (x16)





- Reprogrammable over the phone
- Leakage (sleep) power: 270mW
- Extensible: can accommodate more sensors, radios etc.
- Can interrupt and turn on/off the phone
- Interfaced directly to phone processor (SPI bus + GPIOs)
- Directly powered from the phone's battery

Summary

- Low Power processor on SoC can drive sensors
  - Key application: Continuous sensing

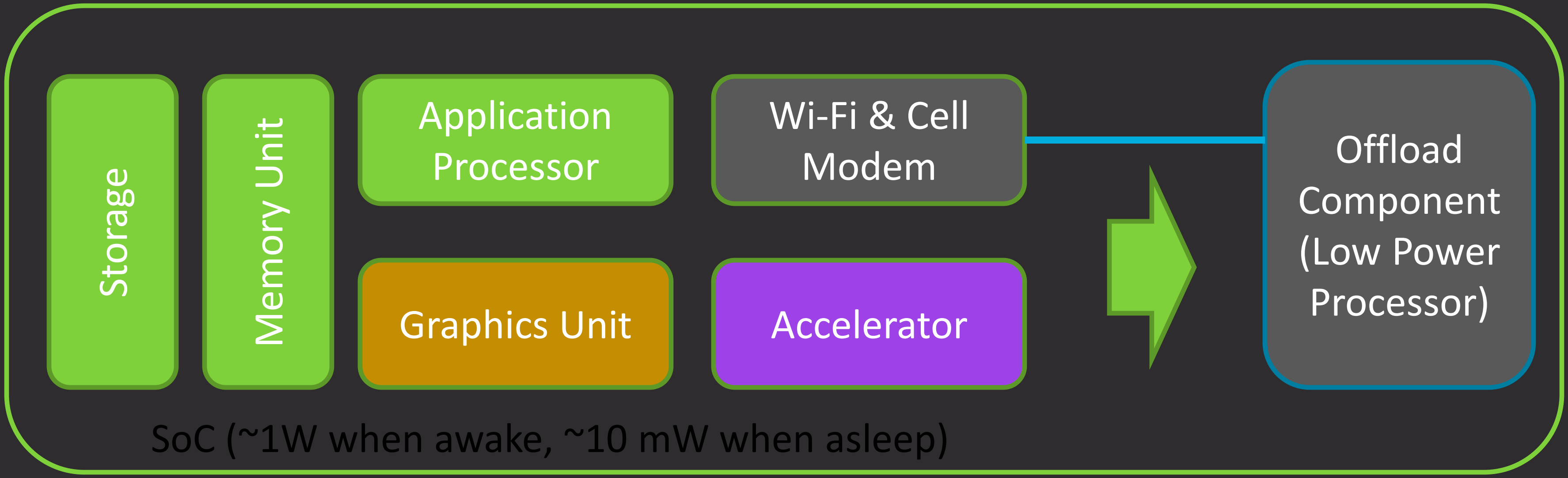
TI announces OMAP 5: two high-performance and two low-power cores, devices next year

By Chris Ziegler posted Feb 7th 2011 12:24PM

BREAKING PR

Windows 8: Microsoft shows off "sensor fusion" support

OFFLOAD TO NETWORK-CONNECTED LOW-POWER PROCESSOR



Collaborators: Yuvraj Agarwal, Steve Hodges, James Scott, Victor Bahl

Power/Energy Efficiency are Key Drivers Today

Battery Powered Computers

Lenovo X61 laptop
- Power: 0.74W (sleep) to 16W (active)
- Goal: improve battery lifetime

"Wall Powered" Computers

Dell Optiplex 745 desktop
- Power: 1.2W (sleep) to >140W (active)
- Goal: reduce energy costs and impact to the environment

Energy efficiency: do more work for less power or energy

IT Equipment Consumes Significant Power

- Yet, shutdown opportunities are rarely used
- Studies show that:
  - 67% of office PCs are left on after work hours
    - "Sleep" modes used in less than 4% of these PCs! [1]
  - Home PCs are left on for 34% of the time
    - 50% of the time they are not being used
- Confirmed by our measurements: CSE@UCSD
  - 600+ desktops left always on (total=700+)
    - @150W each → 100kW (25% of total energy bill)
- Propriety solutions at WaMu, Dell and GE have reported savings of millions dollars per year
  - Thousands of tons of CO_2 emission avoided!!!

[1] J. Roberson et al. "After-hours Power Status of Office Equipment and Energy use of Miscellaneous Plug-load Equipment. *Lawrence Berkeley National Laboratory, Berkeley, California. Report# LBNL-53729-Revised, 2004*

Saving Power Runs into Usability

- Reasons why users do not switch off their PCs
  - Maintain state: desktop and applications preferences
  - ✖ Occasional access
    - Remote desktop/SSH, accessing files
    - Administrative: updates, patches, backups
  - Active applications running
    - ✖ Maintaining presence: e.g. incoming Skype call, IM
    - Long running applications: Web downloads, BitTorrent

Cannot be handled by low-power modes (e.g. Sleep, Hibernate)

Power Management vs. Use Models

- Current design trends in power management:
  - Hosts (PCs): either *Awake* (Active) or *Sleep* (Inactive)
    - Power consumed when Awake = 100X power in Sleep!
  - Network: Assumes hosts are always "Connected" (Awake)

- What users really want:
  - Provide functionality of an *Awake* (active) host…

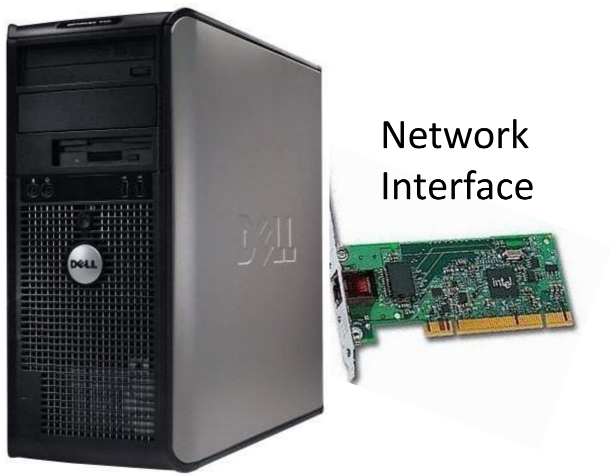
    ….While consuming power as if in *Sleep* mode
  - Resume host to Awake mode only if needed

Change the fundamental distinction between Sleep and Active states…

Augment PC's Network Interface

- Objective: Make PCs responsive even when asleep
  - Maintain availability across the entire protocol stack
    - E.g. ARP(layer 2), ICMP(layer 3), SSH (Application layer)
  - Without making changes to the infrastructure or user behavior

Active State : >140 W
Idle State : 100 W
Sleep State : 1.2 W



Network Interface

Requirements:

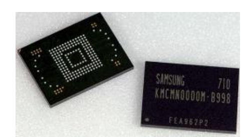
- Functionally similar - masquerade as the host
- Much lower power

Secondary Processor
(Power in active state ~1W)

+ 

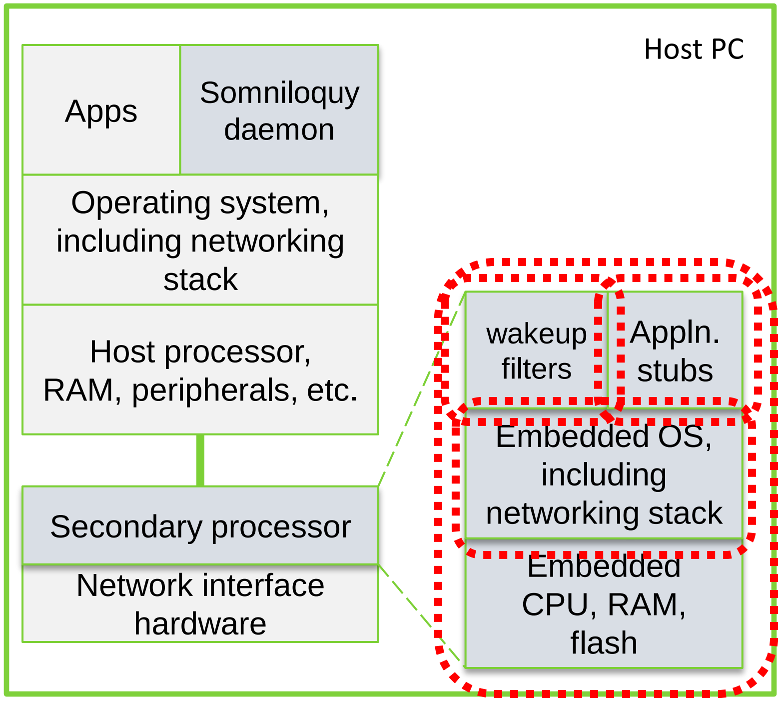
Low Power CPU

+ 
DRAM

+ 
Flash Memory Storage

*Somniloquy**: PCs Talk in their Sleep

- Augment network interfaces:
  - Add a separate power domain
    - Powered on when host is asleep
    - Processor + Memory + Flash Storage + Network stack
  - Same MAC/IP Address
- Wake up Host when needed
  - E.g. incoming connection
- Handle some applications while PC remains asleep
  - Using “application stubs”



Supporting Stateless Apps: Filters

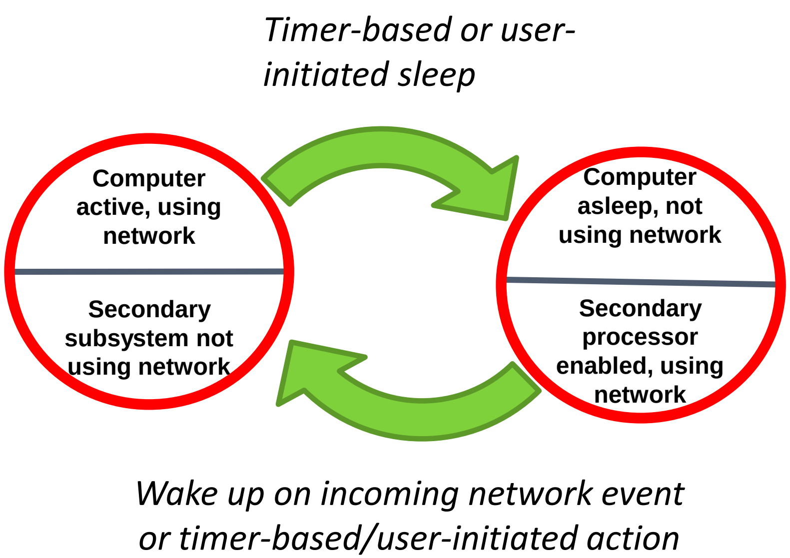
- Wake up host on any user defined "filter"
  - E.g. incoming Skype call, Remote Desktop request
  - Wake-on-LAN either impractical or affects usability
- Specified at any layer of the network stack
  - E.g. from a particular IP (layer 3) or MAC (layer 2)
  - E.g. wake up on finding "MSFTWLAN" Wi-Fi network

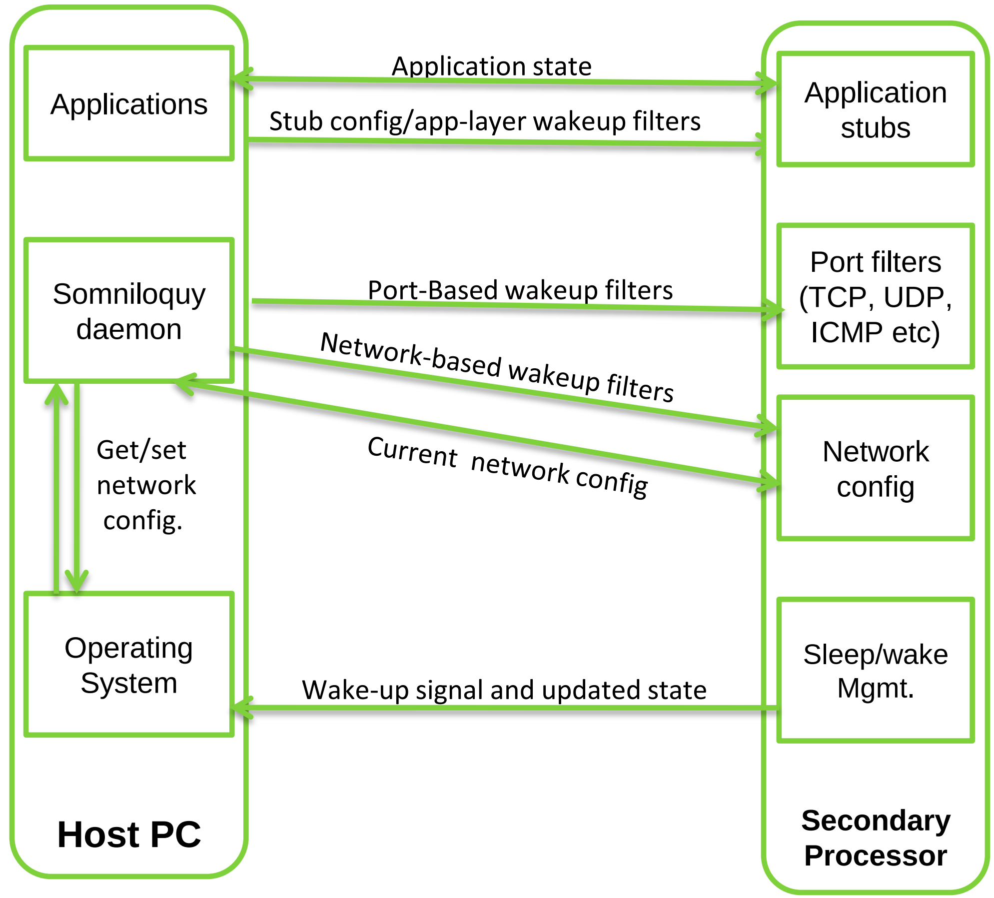
Supporting Stateful Apps: Stubs

- Applications actively maintain state
  - E.g. background web downloads, P2P file sharing (BitTorrent)
  - Need application specific code on the secondary processor
- Challenge: secondary processor limited in resources
  - CPU, memory, flash storage
  - Cannot run the full application
- Offload part of the applications: i.e. “stub” code
  - Generate “stub” code manually
  - Stubs for BitTorrent, Web downloads, IM

Software Components

Somniloquy States





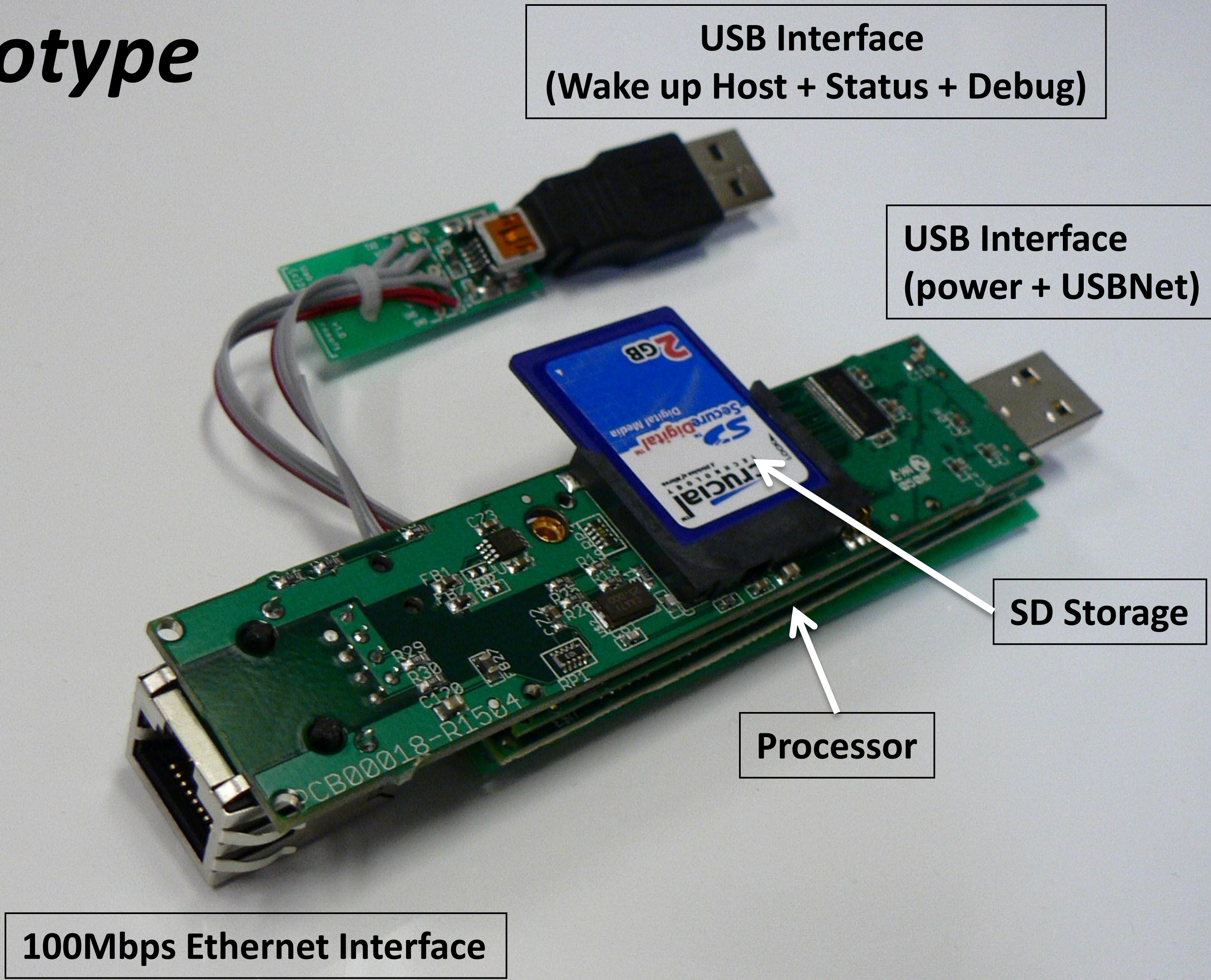
Somniloquy Prototype

- Prototype uses "gumstix" platform
  - PXA270 processor with full TCP/IP stack
  - USB connection to PC for sleep detection/wakeup trigger, power while asleep, and IP networking for data
- Wired and wireless prototypes
- ***-1NIC** version follows initial vision of augmented NIC, where all data goes via gumstix even when PC is awake
- ***-2NIC** version uses PC's internal interface while it is awake, and allows for simpler legacy-friendly support

Wired-1NIC prototype

Wireless-2NIC prototype

Prototype


USB Interface
(Wake up Host + Status + Debug)
USB Interface
(power + USBNet)
SD Storage
Processor
100Mbps Ethernet Interface

Evaluation Methodology

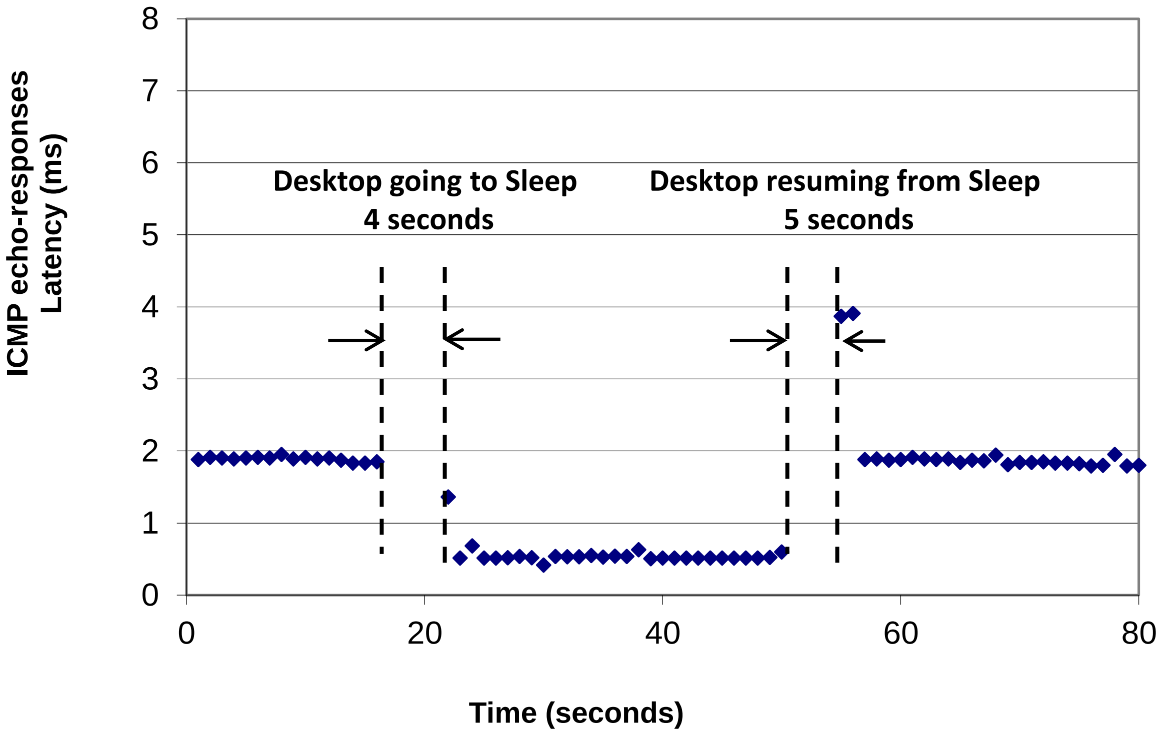
- Maintain network reachability

- Stateless applications (filter based):
  - Measure increase in “application layer” latency
  - Detailed power profile: Gumstix, Host PCs
  - Extend battery lifetime (Laptops), Energy Savings (Desktop)

- Stateful applications (stub based):
  - Measure energy savings

Maintaining Reachability

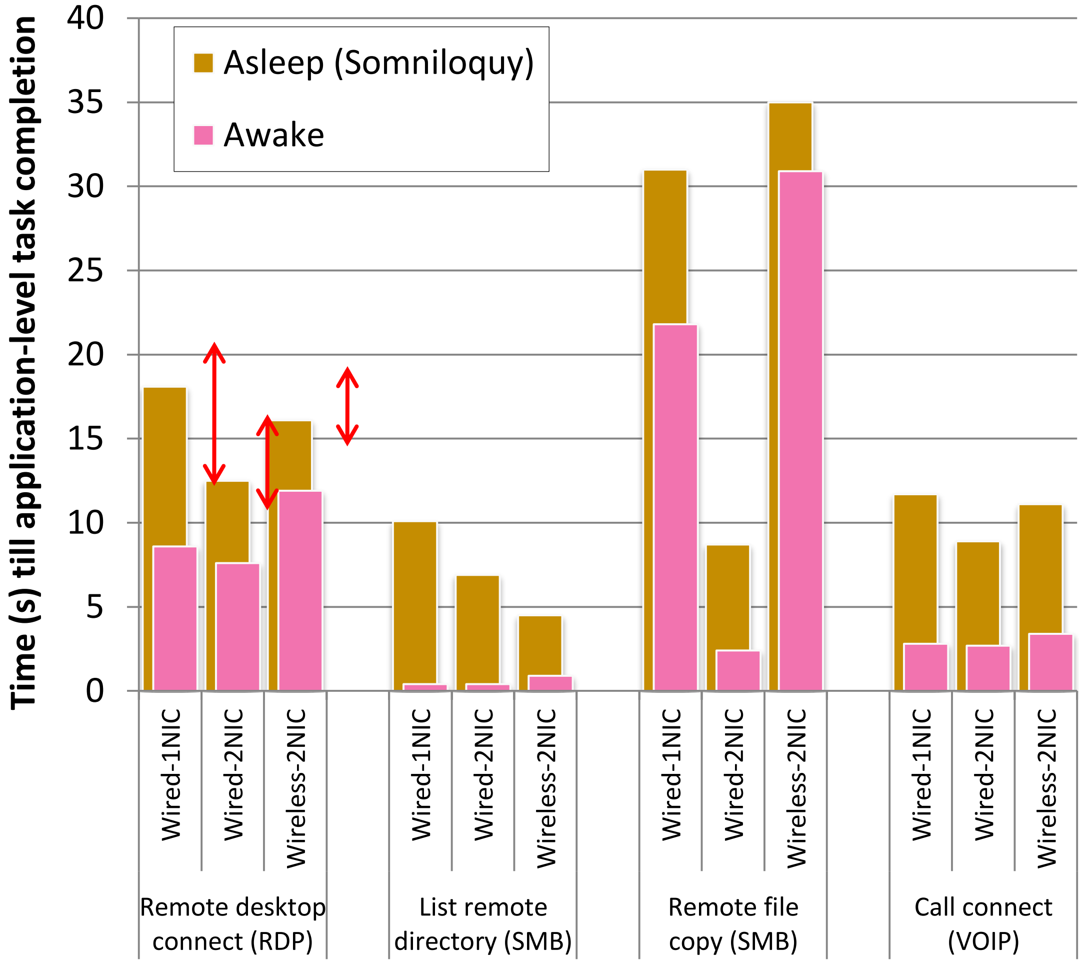
- Respond to “ping”, ARPs, maintain DHCP lease



Break in ICMP responses are due to state transitions: Sleep ⟷ Active

Stateless Apps: “Setup” Latency

- Measured time till *user-perceived* response
- For each, incoming TCP SYN caused wakeup
- Additional latency: 3-10s for all prototypes
- As a proportion of the resulting session, this is OK



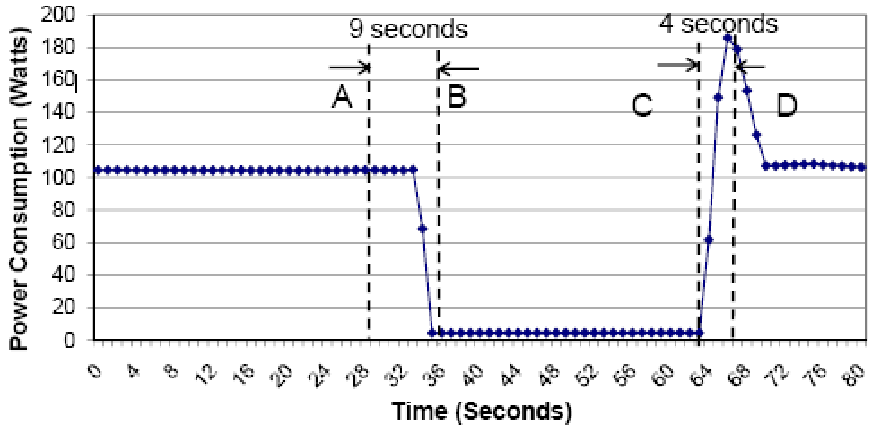
Gumstix: Power Consumption

	Gumstix State	Power
	WIRED VERSION	
1.	Gumstix only – No Ethernet	210mW
2.	Gumstix + Ethernet Idle	1073mW
3.	Gumstix + Ethernet + Write to flash	1675mW
	WIRELESS VERSION	
4.	Gumstix only - no Wi-Fi	210mW
5.	Gumstix + Wi-Fi associated (PSM)	290mW
6.	Gumstix + Wi-Fi Associated (CAM)	1300mW

- Our prototypes consume 290mW (Wi-Fi) to 1W (Ethernet)
  - Similar to power consumed by our test laptop (740mW) in the "sleep" state. ...and our test desktop (1.2W) in the "sleep" state.

Desktops: Power Savings

State	Power
Normal Idle State	102.1W
Lowest CPU frequency	97.4W
Disable Multiple cores	93.1W
"Base Power"	93.1W
Suspend state (S3)	**1.2W**

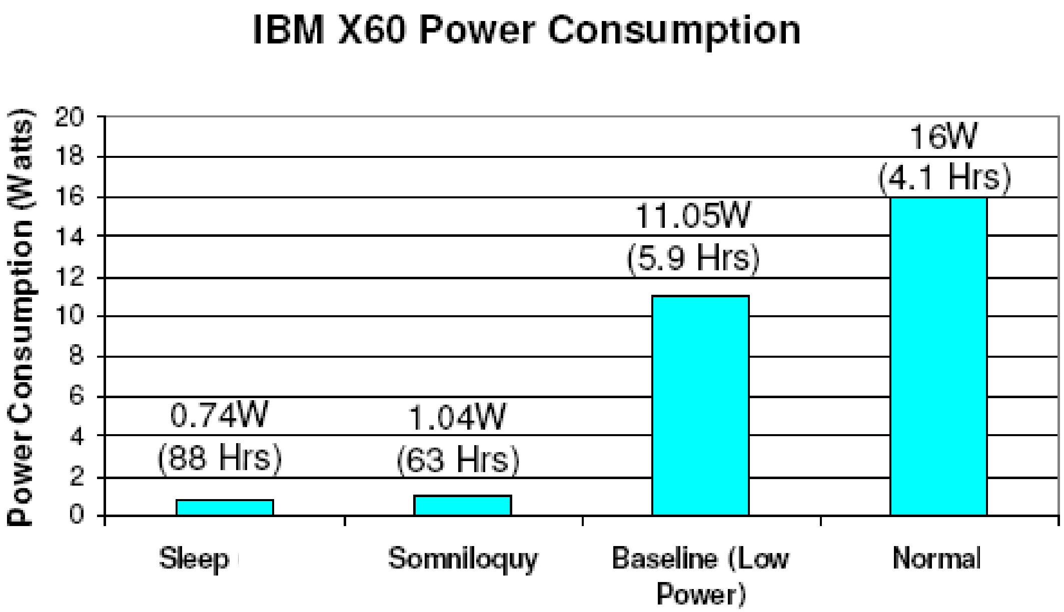


Dell Optiplex 745 Power Consumption and transitions between states

Using Somniloquy:

- Power drops from >100W to <5W
- Assuming a 45 hour work week
  - 620kWh saved per year
  - US $56 savings, 378 kg CO_2

Laptops: Extends Battery Lifetime



Using Somniloquy:

– Power drops from >11W to 1W,
  – Battery life increases from <6 hours to >60 hours
– Provides functionality of the “Baseline” state
  – Power consumption similar to “Sleep” state

Energy Savings for Sample Workloads

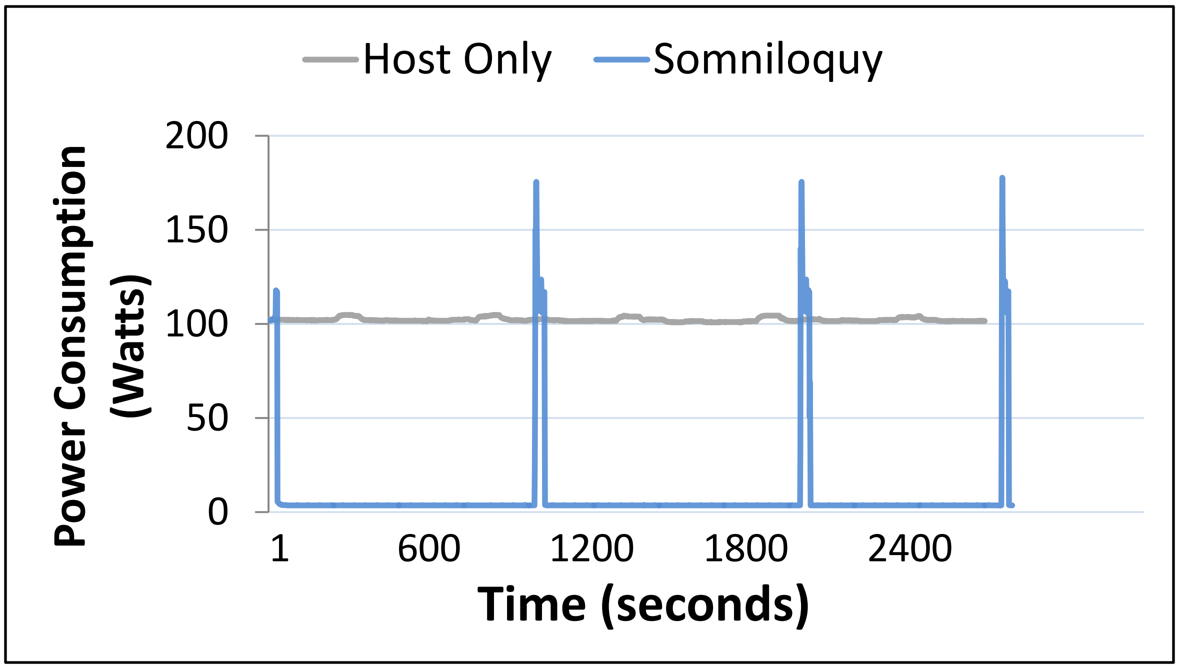
- Use trace data from [*Nedevschi-NSDI2009*]
  - 24 desktop PCs: ON, sleep, idle and OFF durations

- Bin data into 3 categories based on % idle time

% Idle Time	% Energy Saving using Somniloquy
<25% of the time (7 PCs)	38%
25% - 75% of the time (6PCs)	68%
>75% of the time (9 PCs)	85%

Stateful Application: Energy Savings

- Web download “stub” on the gumstix
  - 200MB flash, download when Desktop PC is asleep
  - Wake up PC to upload data whenever needed



  - 92% less energy than using the host PC for download

Summary:

- Somniloquy: augment network interfaces of PCs
  - Maintain reachability and availability transparently
  - Power consumption similar to a *"sleep"* state

- Incrementally deployable prototype
  - No changes to infrastructure, application servers

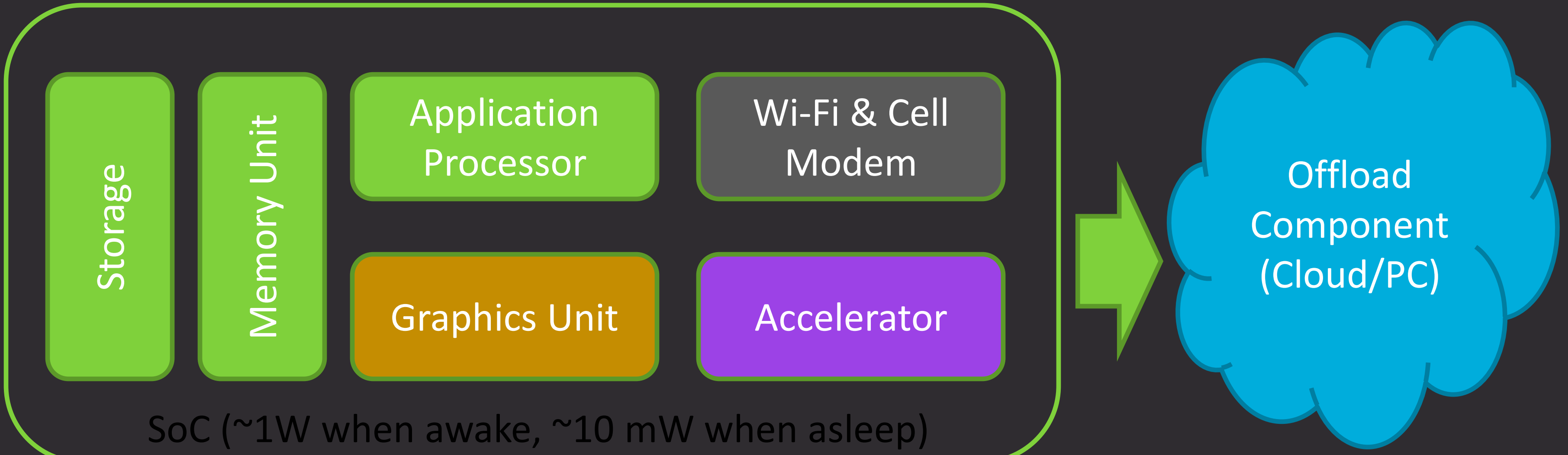
- Demonstrable savings
  - Desktops: reduced energy cost, carbon footprint
  - Laptops: extend battery lifetime

In the context of mobile devices

- Network-connected low power processor can:
  - Sync with e-mail
  - Perform IM tasks
  - Run Skype in the background
  - Download music

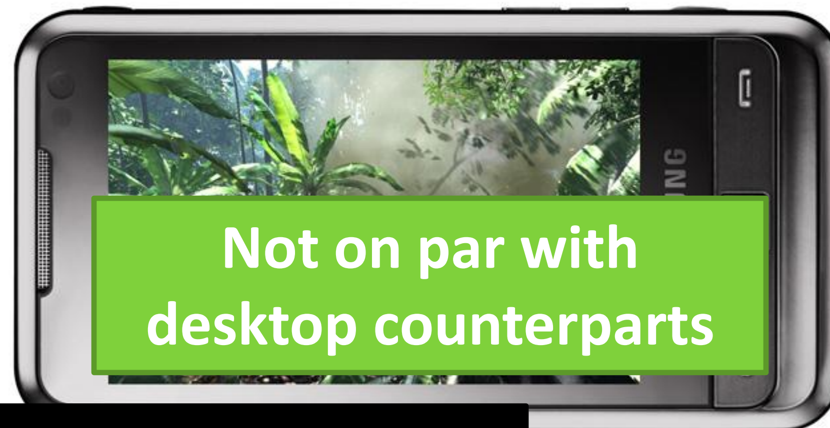
… all without waking up the main processor

CLOUD OFFLOAD



Collaborators: Eduardo Cuervo, Aruna Balasubramanian, Alec Wolman, Stefan Saroiu, Victor Bahl

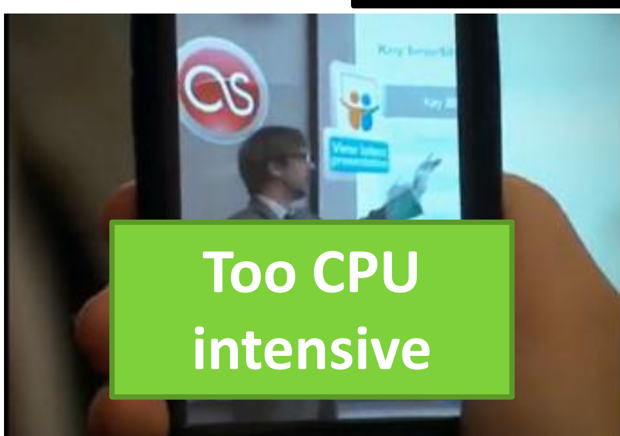
Mobile apps can't reach their full potential



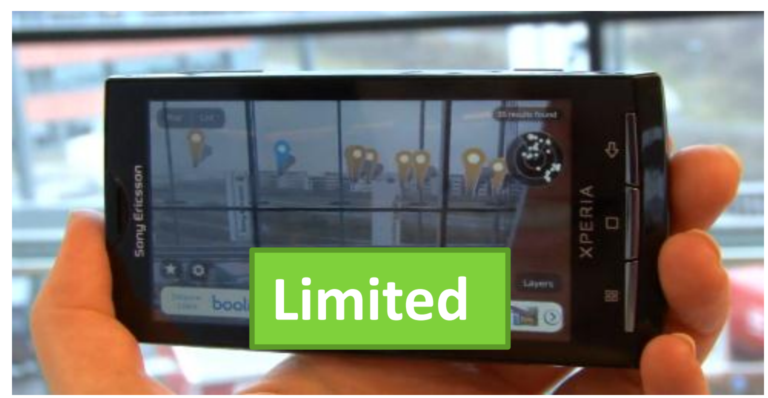
Speech Recogniti

Power Intensive

ames



Augmented Reality



One Solution: Remote Execution

- **Remote execution can reduce energy consumption**

- Challenges:
  - What should be offloaded?
  - How to dynamically decide when to offload?
  - How to minimize the required programmer effort?

MAUI: Mobile Assistance Using Infrastructure

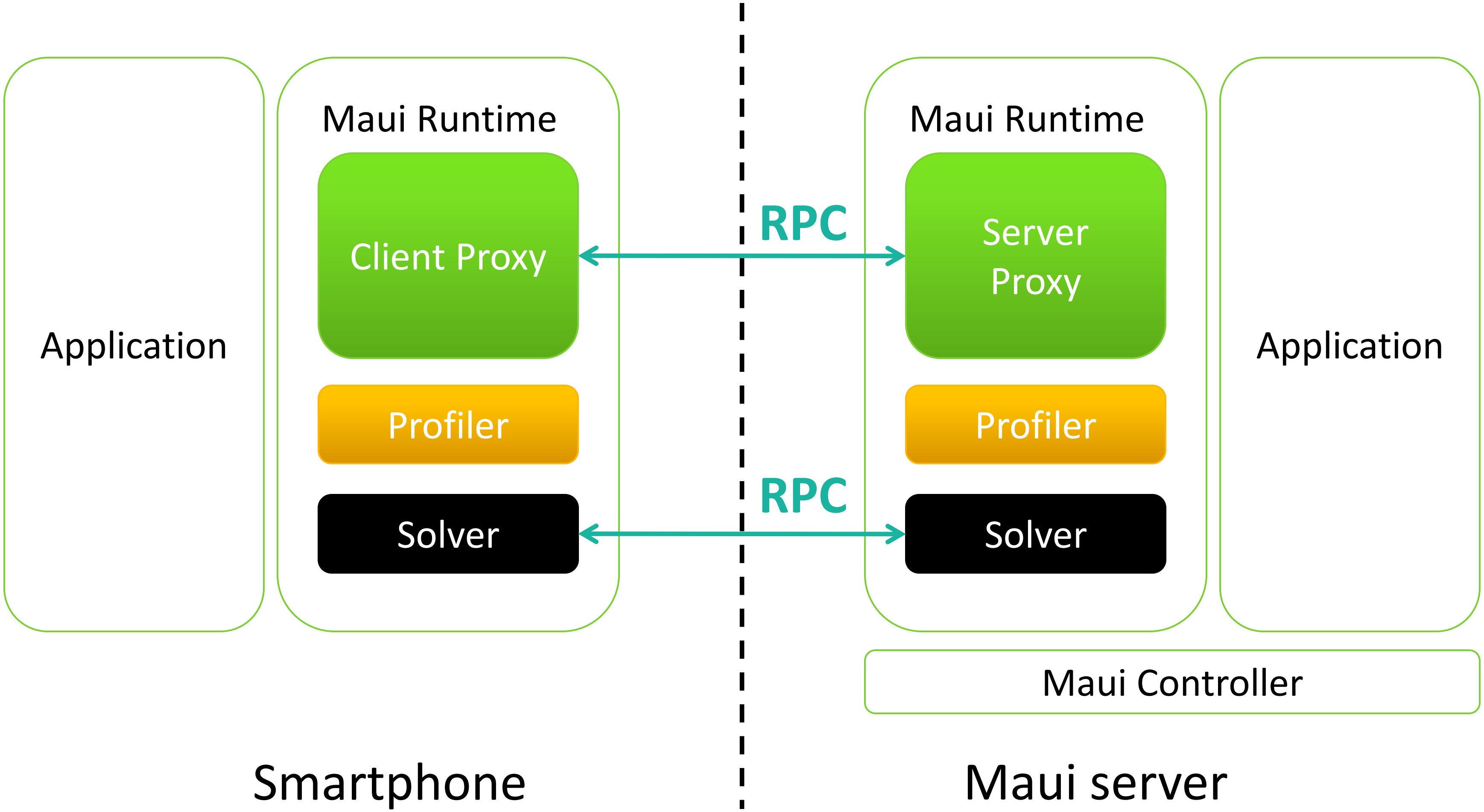
MAUI Contributions:

- Combine extensive profiling with an ILP solver
  - Makes dynamic offload decisions
  - Optimize for energy reduction
  - Profile: device, network, application
- Leverage modern language runtime (.NET CLR)
  - To simplify program partitioning
  - Reflection, serialization, strong typing

Roadmap

- Motivation
- MAUI system design
  - MAUI proxy
  - MAUI profiler
  - MAUI solver
- Evaluation

MAUI Architecture



How Does a Programmer Use MAUI?

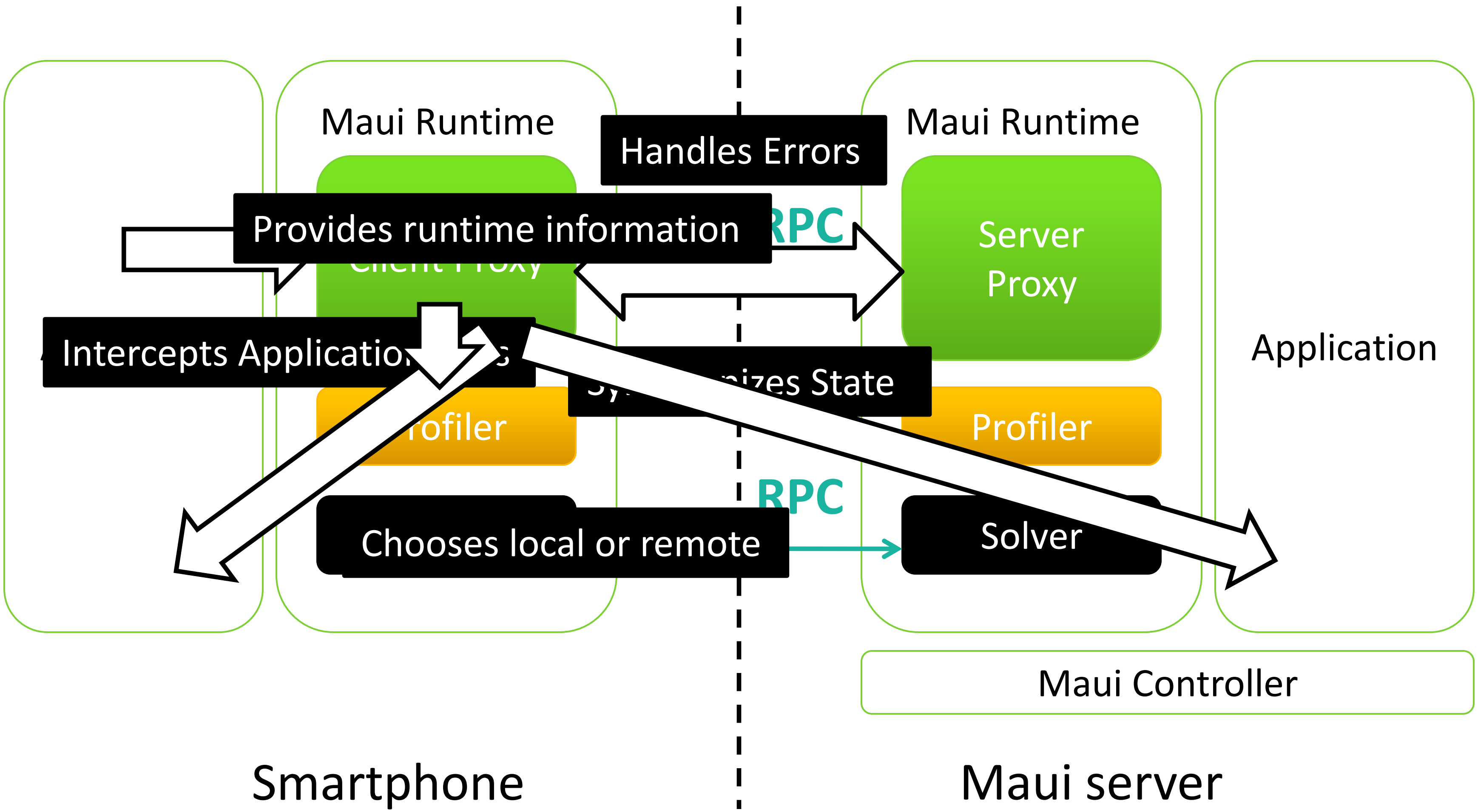
- Goal: make it dead-simple to MAUI-ify apps
  - Build app as a standalone phone app
  - Add .NET attributes to indicate “remoteable”
  - Follow a simple set of rules

```
[Remoteable]
ArrayList GetValidMoves(Square s)
{
    if (s.IsEmpty())
    {
        return new ArrayList();
    }
    if (s.Piece.IsEnemyOf(active))
    {
        //this piece does not belong to the active side, no moves possible
        return new ArrayList();
    }
    //forward the call to the Rule-class
    return rules.getMoves(s);
}
```

Run-Time Support For Partitioning

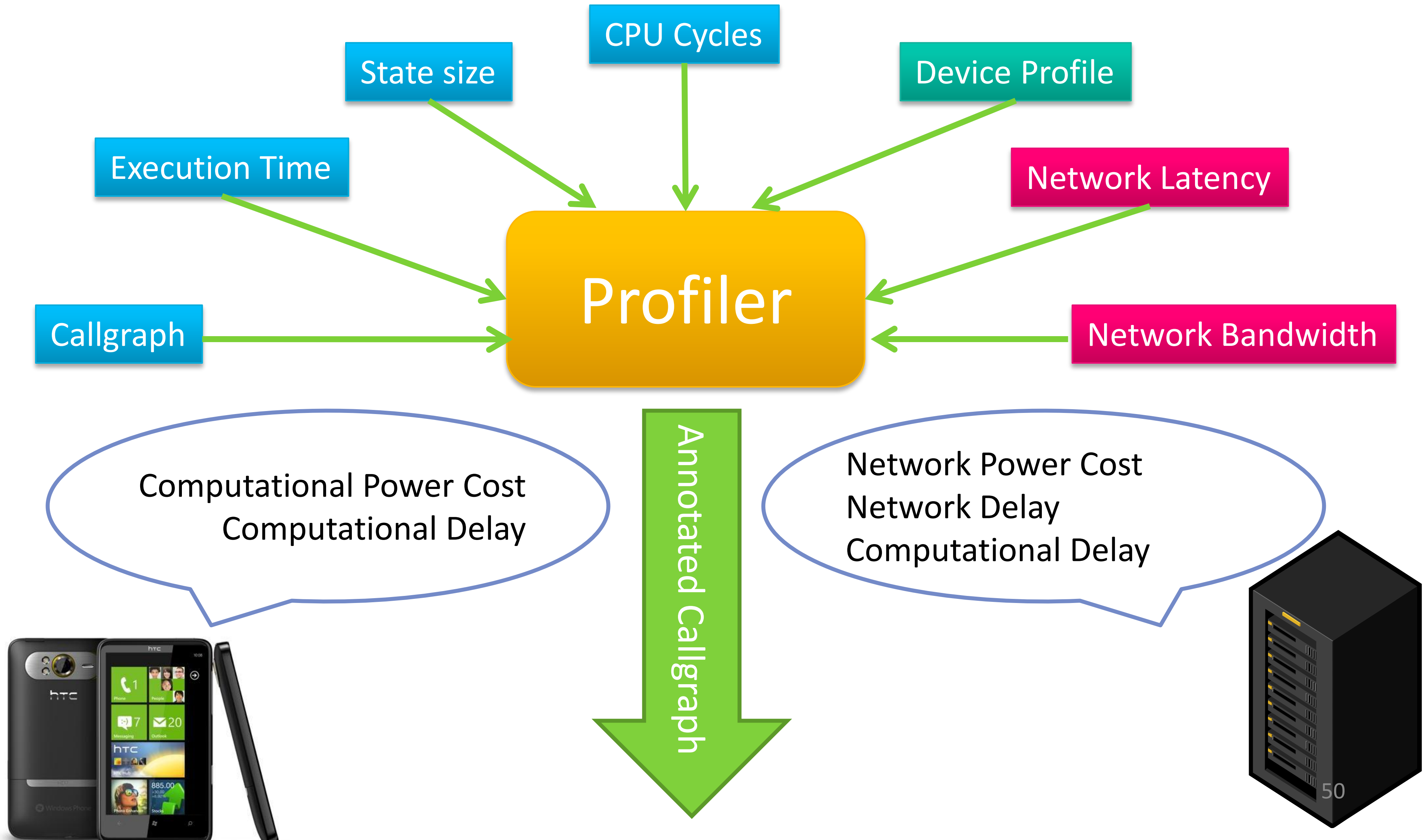
- Portability:
  - Mobile (ARM) vs Server (x86)
  - .NET Framework Common Intermediate Language
- Type-Safety and Serialization:
  - Automate state extraction
- Reflection:
  - Identifies methods with [Remoteable] tag
  - Automates generation of RPC stubs

MAUI Proxy



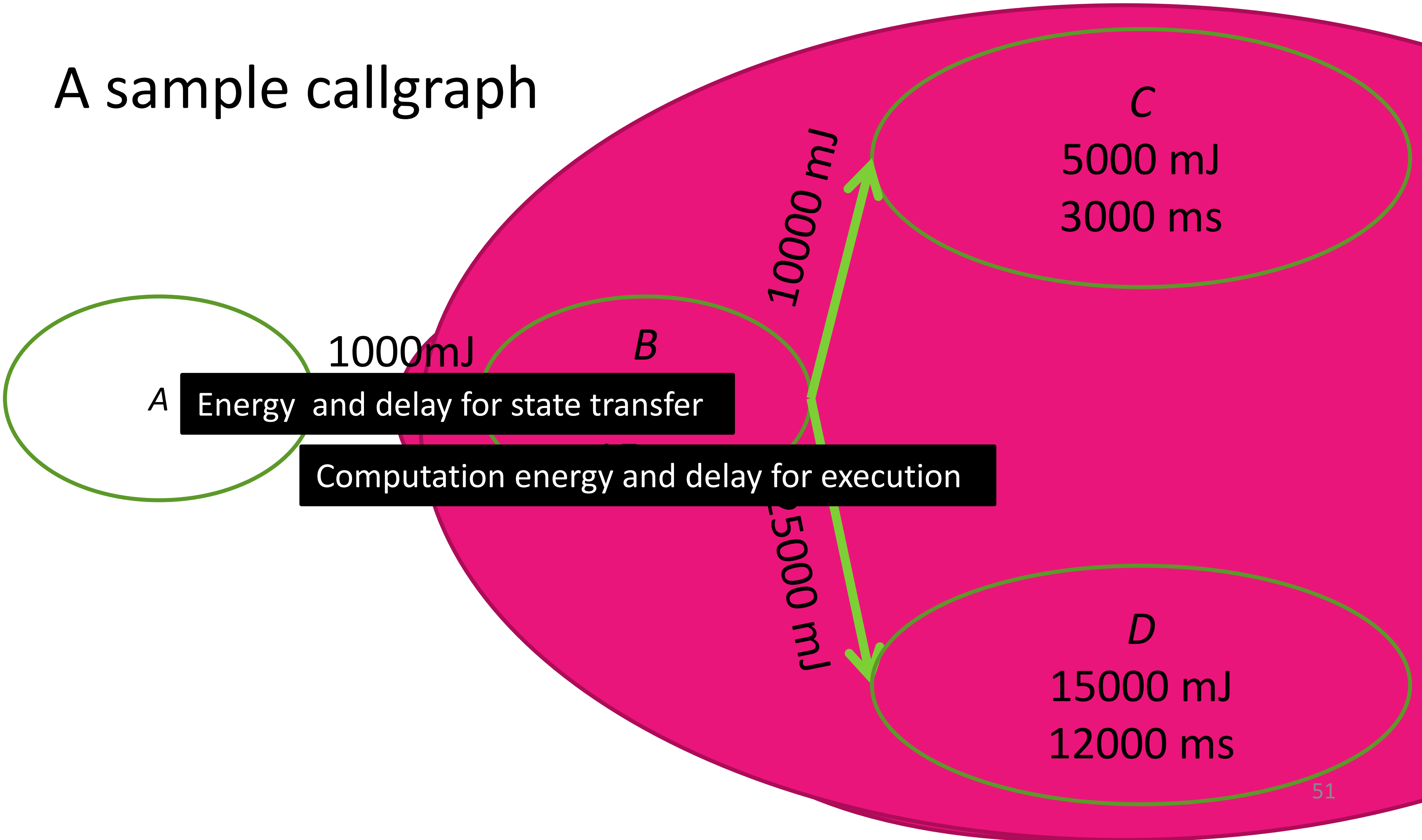
Maui Runtime
Handles Errors
Maui Runtime
Provides runtime information
RPC
Server Proxy
Intercepts
Application
Profiler
RPC
Chooses local or remote
Solver
Maui Controller
Smartphone
Maui server

MAUI Profiler



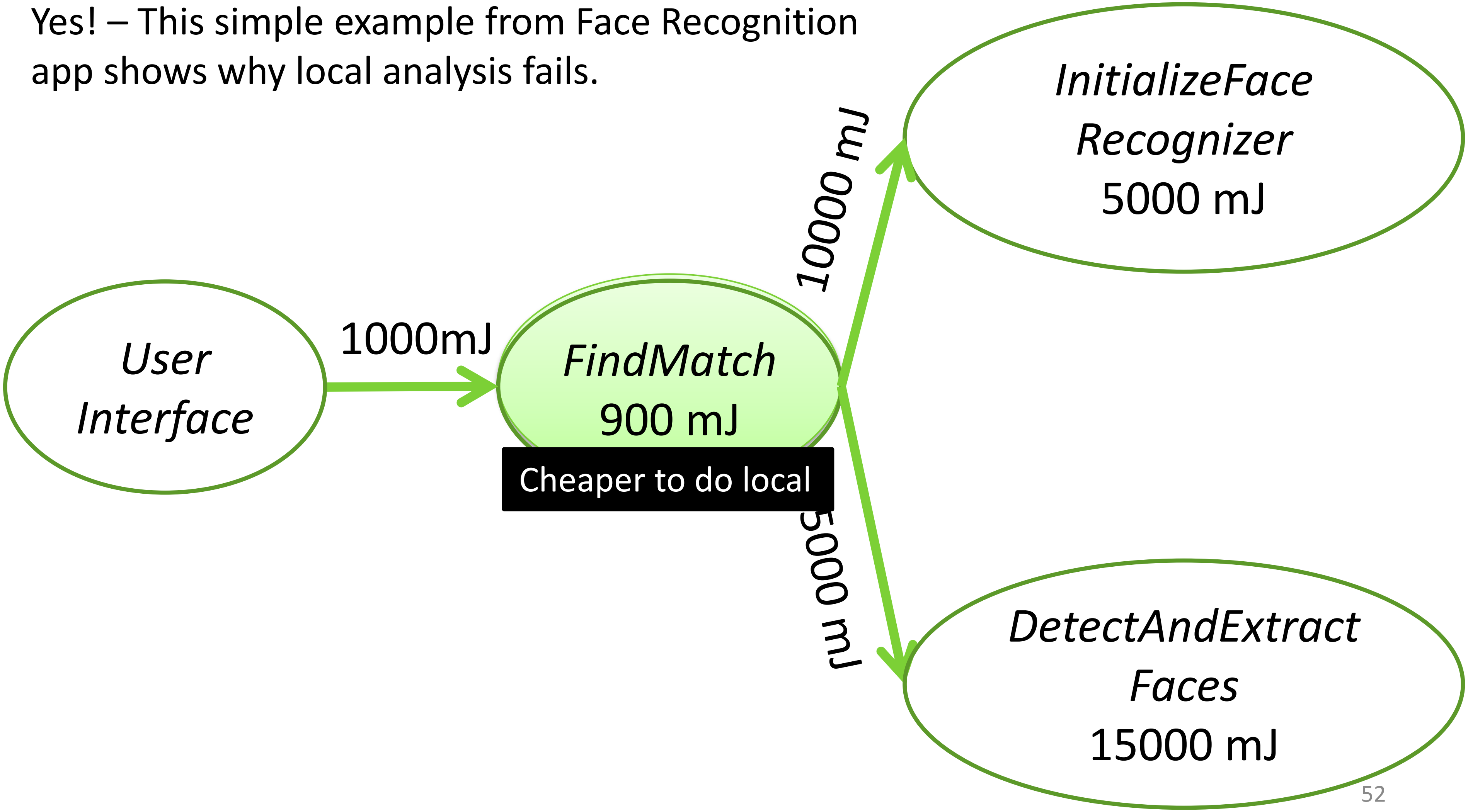
MAUI Solver

A sample callgraph



Is Global Program Analysis Needed?

Yes! – This simple example from Face Recognition app shows why local analysis fails.



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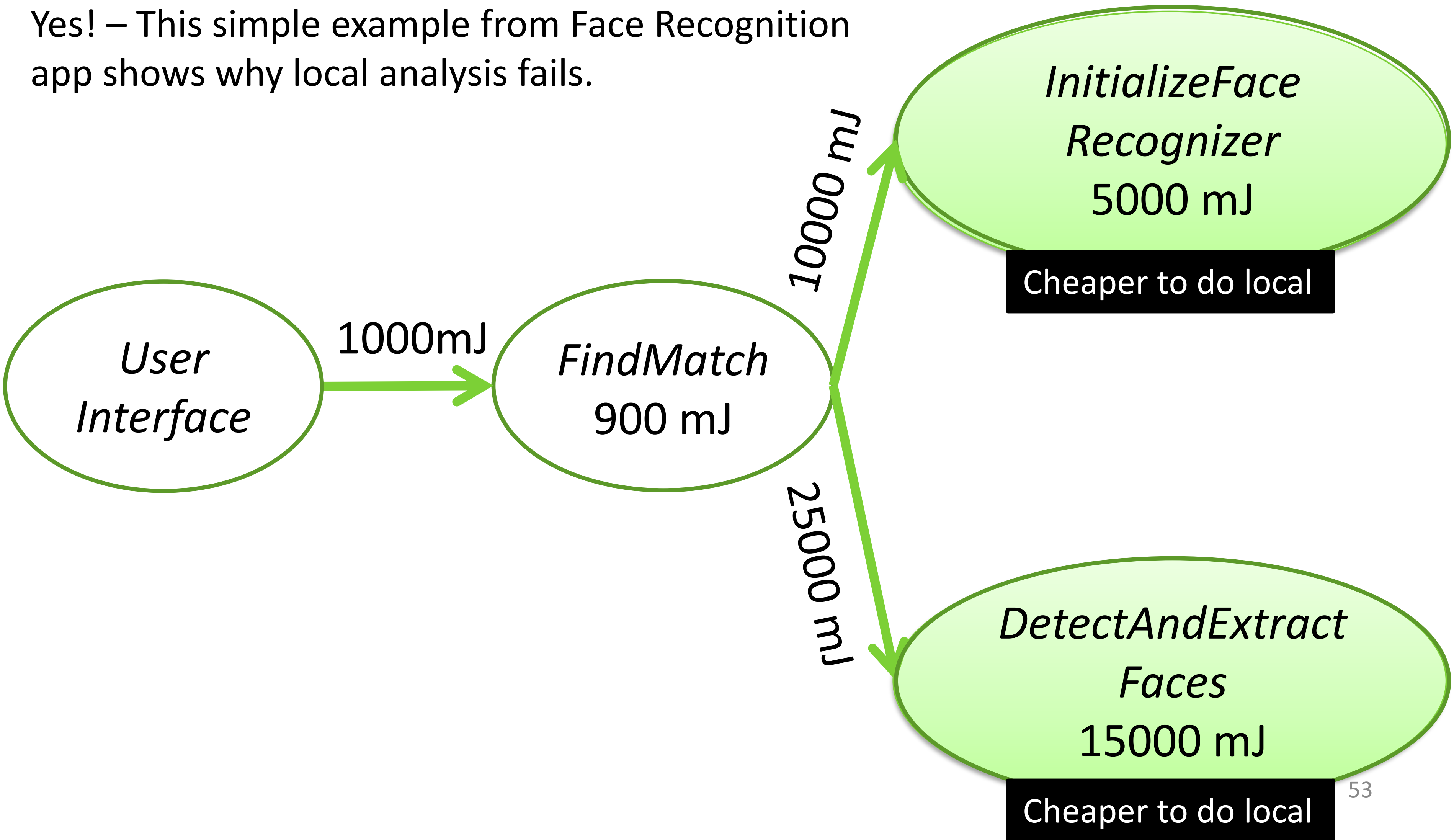

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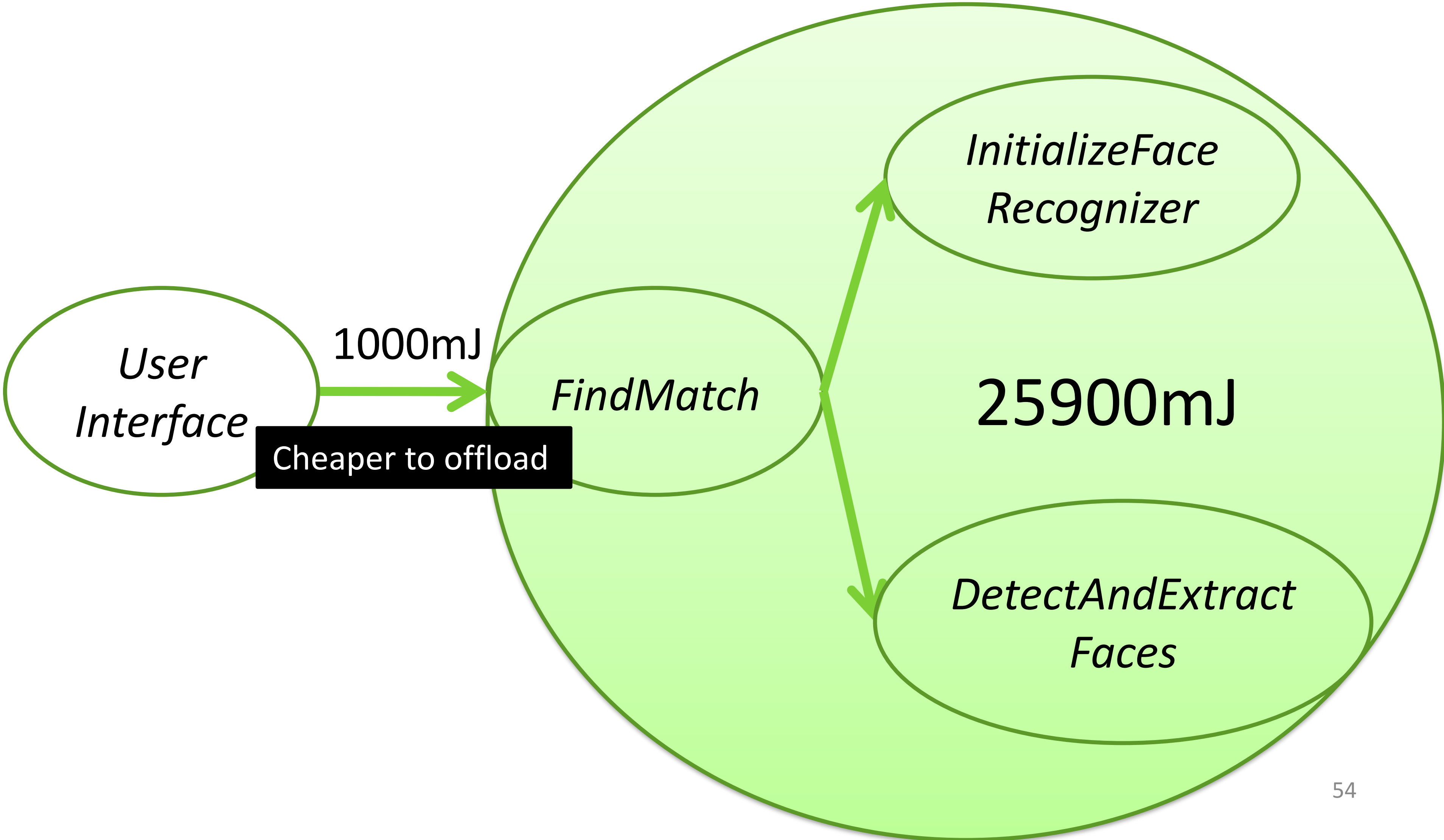
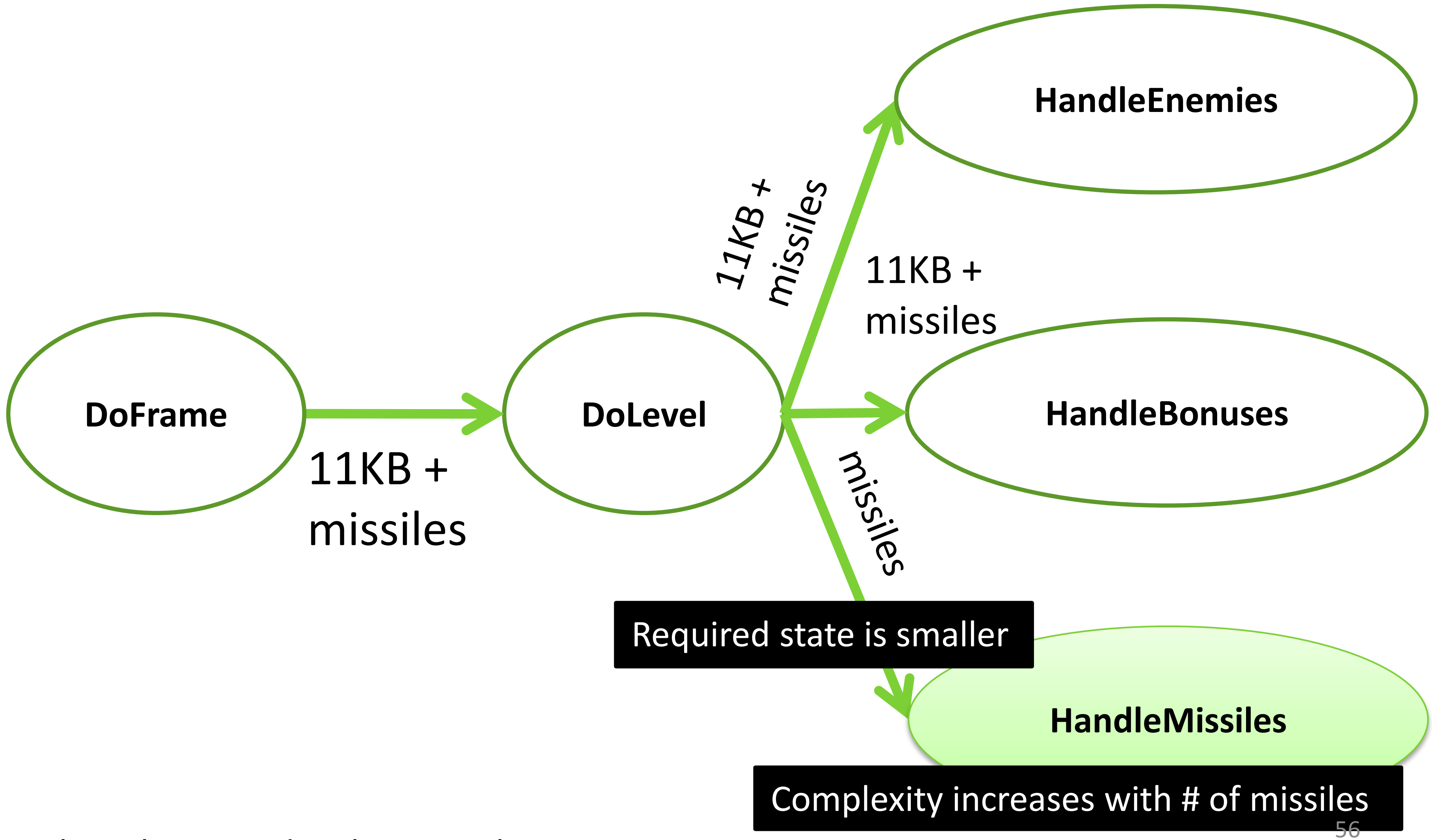


Adapting to Changing Conditions

- Adapt to:
  - Network Bandwidth/Latency Changes
  - Variability on method’s computational requirements
- Experiment:
  - Modified off the shelf arcade game application
  - Physics Modeling (homing missiles)
  - Evaluated under different latency settings

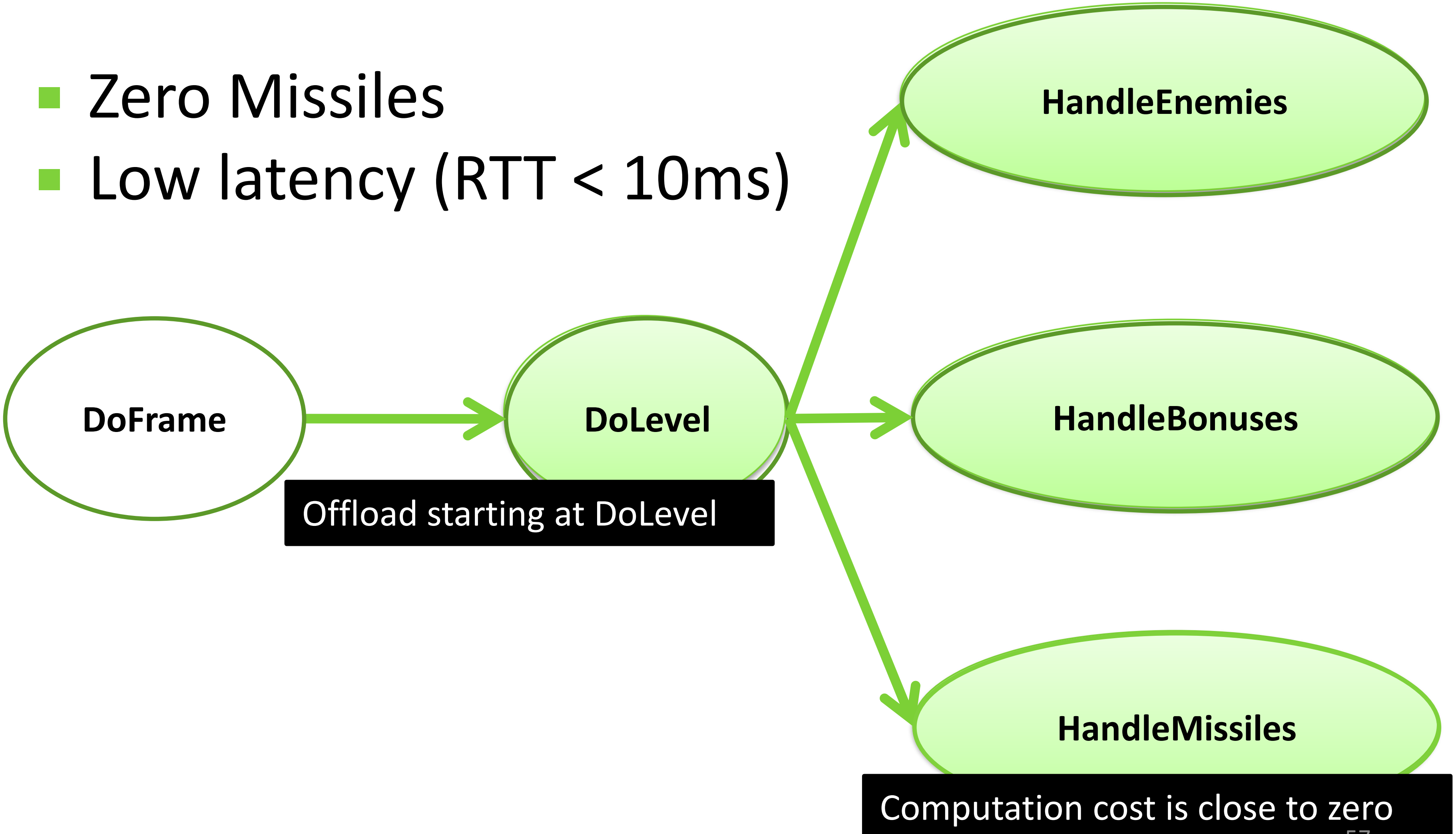
Adapting to Changing Conditions?



*Missiles take around 60 bytes each

Case 1

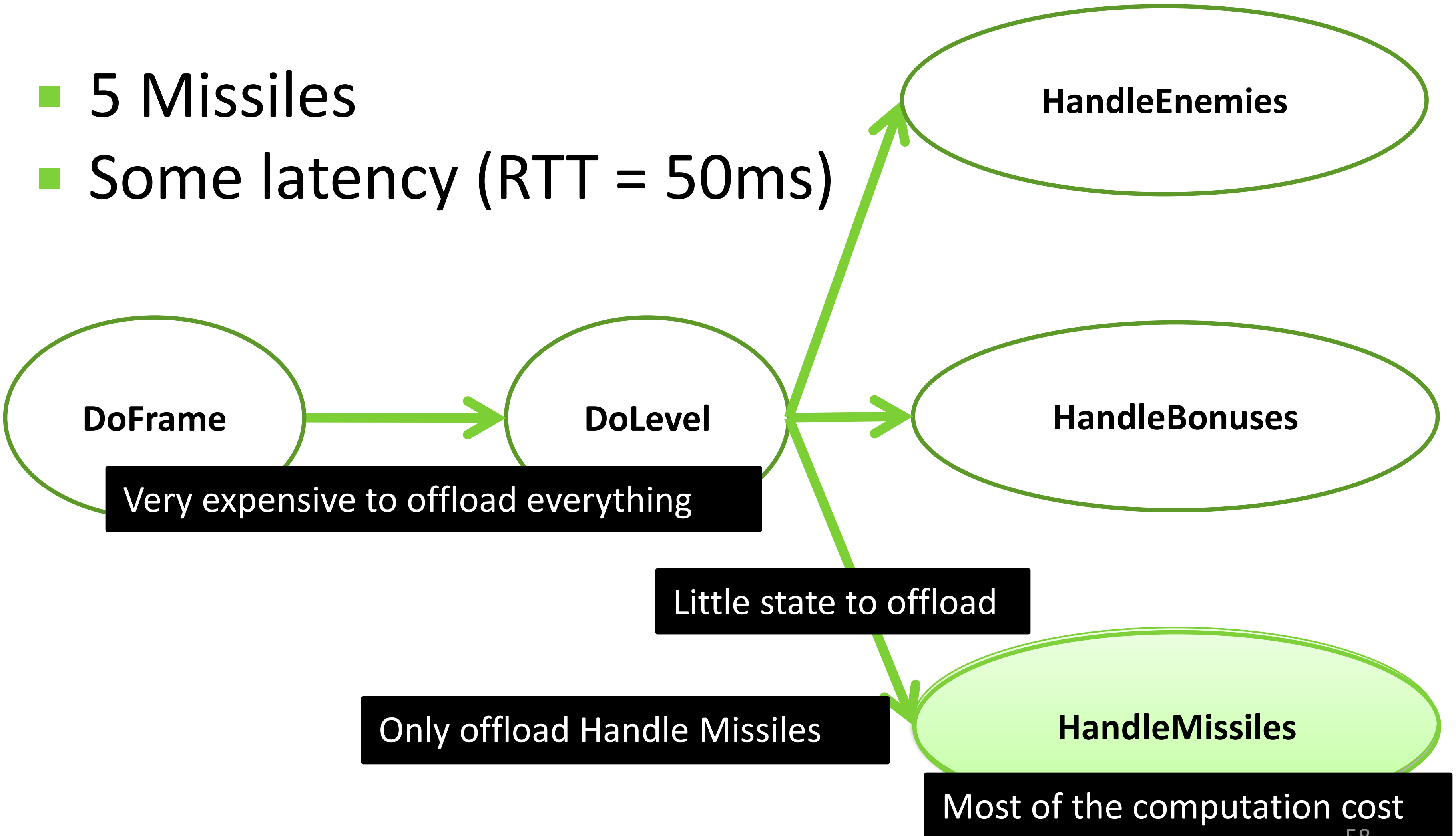
- Zero Missiles
- Low latency (RTT < 10ms)



*Missiles take around 60 bytes each

Case 2

- 5 Missiles
- Some latency (RTT = 50ms)



*Missiles take around 60 bytes each

Roadmap

- Motivation
- MAUI system design
  - MAUI proxy
  - MAUI profiler
  - MAUI solver
- Evaluation

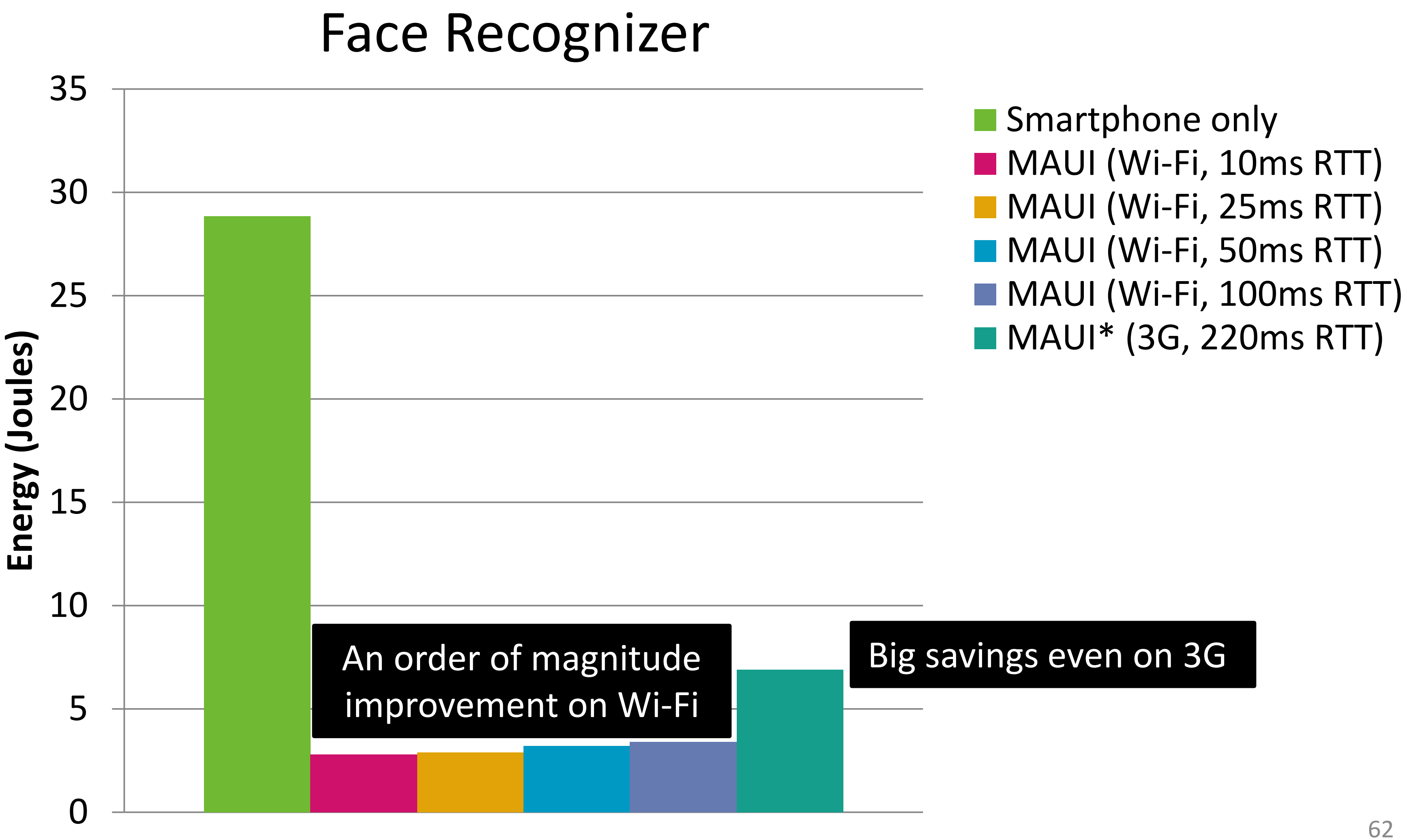
MAUI Implementation

- Platform
  - Windows Mobile 6.5
  - .NET Framework 3.5
  - HTC Fuze Smartphone
  - Monsoon power monitor
- Applications
  - Chess
  - Face Recognition
  - Arcade Game
  - Voice-based translator

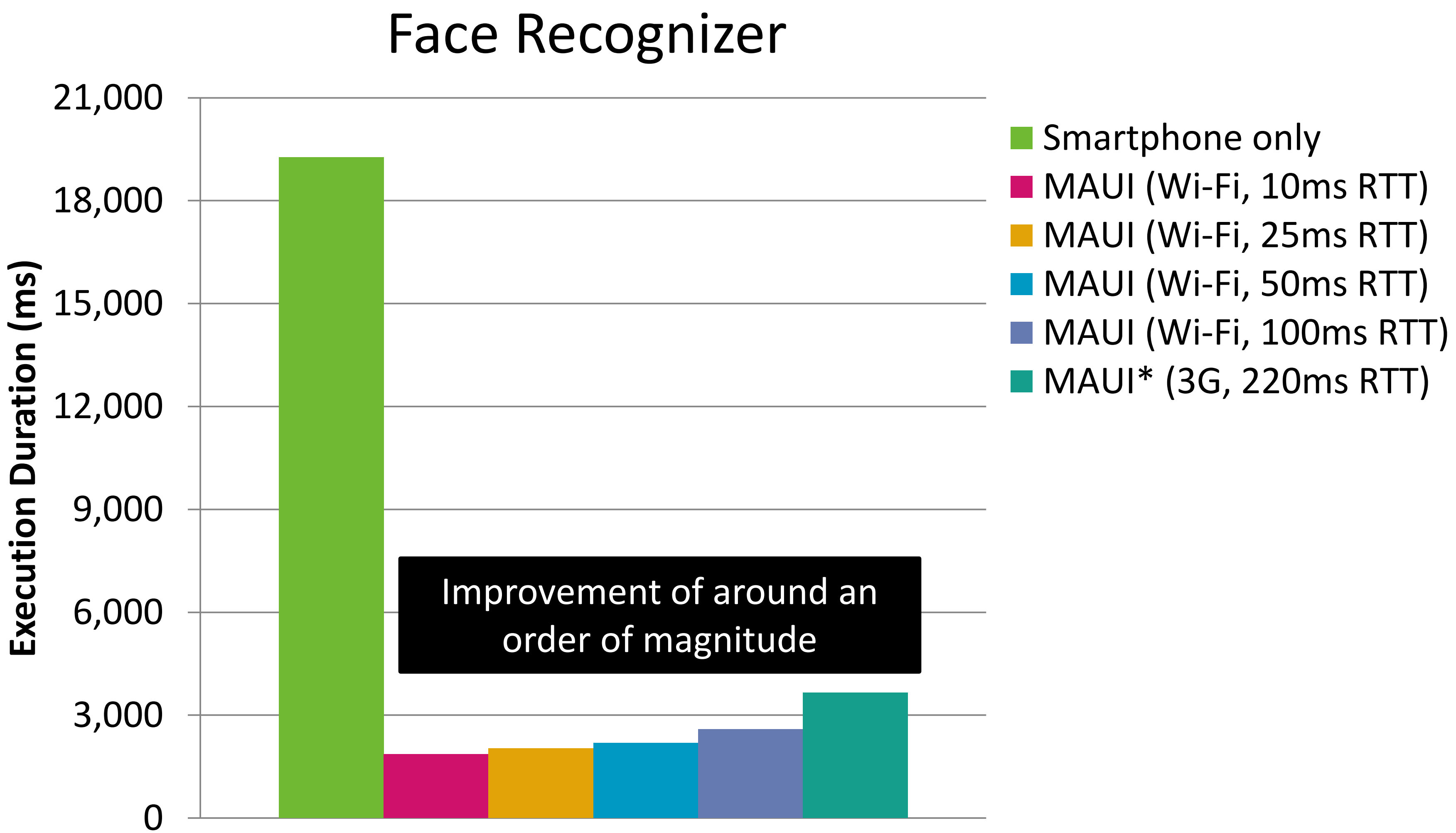
Questions

- How much can MAUI reduce energy consumption?
- How much can MAUI improve performance?
- Can MAUI Run Resource-Intensive Applications?

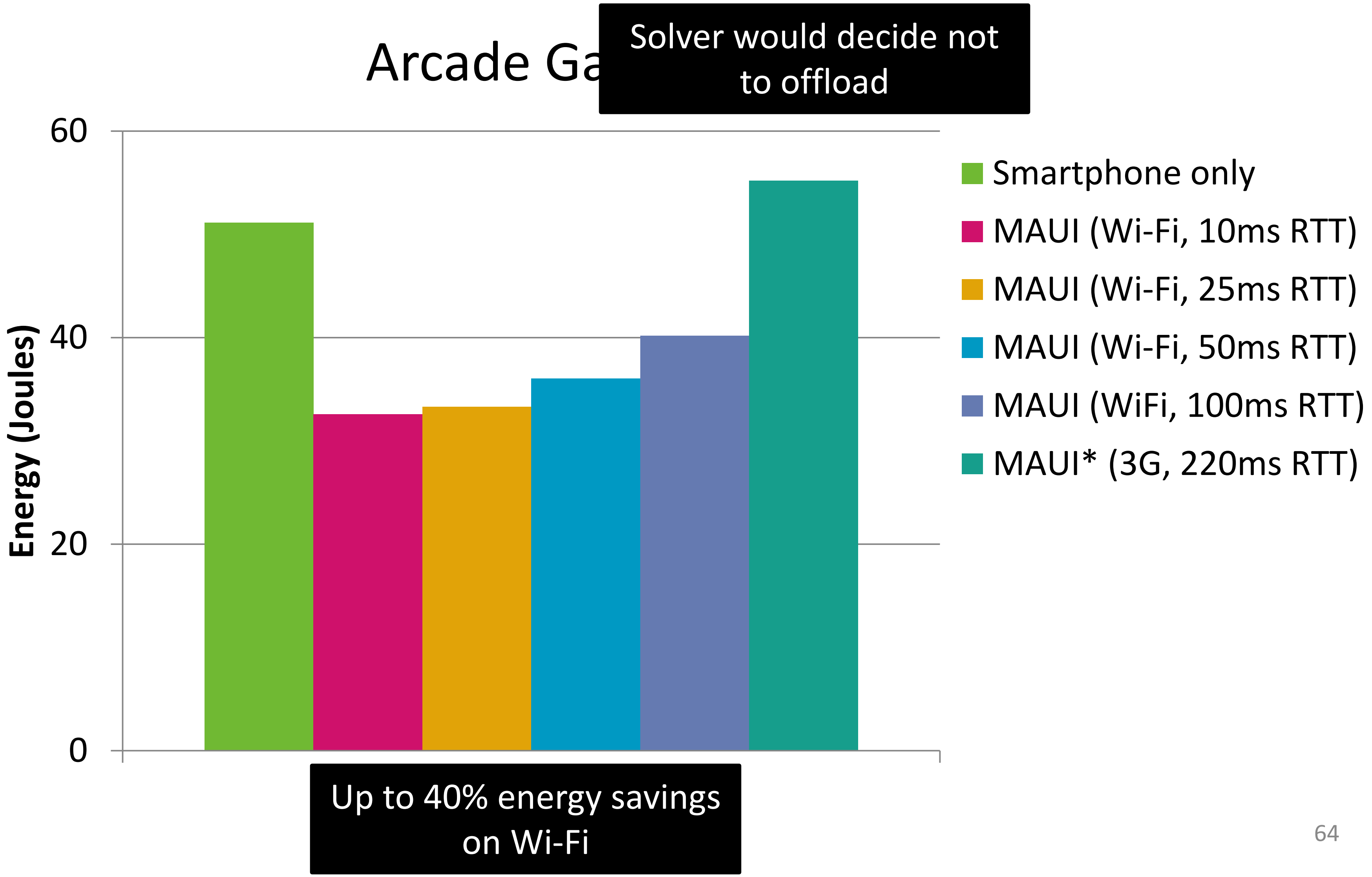
How much can MAUI reduce energy consumption?



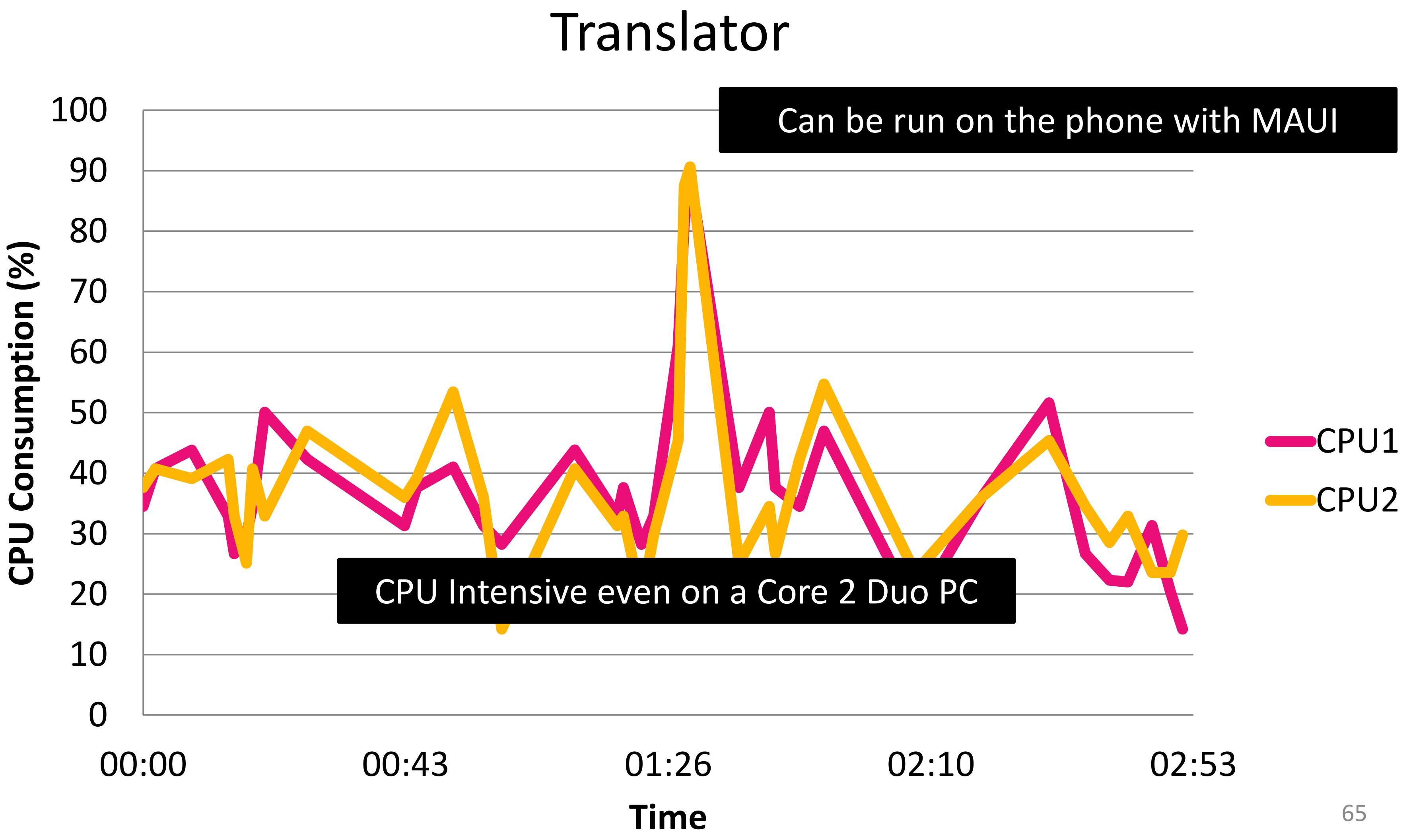
How much can MAUI improve performance?



Latency to server impacts opportunities for fine-grained offload



Can MAUI Run Resource-Intensive Applications?



SUMMARY

Looking ahead...

- Mechanisms are in place
  - Low power cores in the SoC
    - TI and others ...
  - Big.Little processors from ARM
    - Expected by end of year
  - Smart Web Services

- Offload Policies: the next big move?