Energy Management in Mobile Devices with the Cinder Operating System

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Abstract- **We present Cinder, an operating system for mobile phones and devices, that allows users and applications to control and manage limited device resources such as energy. We argue that controlling energy allocation is an important and increasingly useful feature for operating systems, especially on mobile devices. We present two new low-level abstractions in the Cinder operating system, taps and reserves, which store and distribute energy for application use. We identify three key properties of control isolation, delegation, and subdivision and show how using these abstractions can achieve them. We also show how the architecture of the HiStar information flow control kernel lends itself well to control energy. We prototype and evaluate Cinder on a popular smartphone, the Android G1.**

Index Terms- **Energy, mobile phones, power management.**

I. INTRODUCTION

In the past decade, mobile phones have emerged as a dominant computing platform for end users. These very personal computers depend heavily on graphical user interfaces, always-on connectivity, and long battery life, yet in essence run operating systems originally designed for workstations (Mac OS X/Mach) or time-sharing systems (Linux/Unix). Historically, operating systems have had poor energy management and accounting. This is not surprising, as their APIs standardized before energy was an issue. This limited control and visibility of energy is especially problematic for mobile phones, where energy and power define system lifetime. In the past decade, phones have evolved from low-function proprietary applications to robust multi- programmed systems with applications from thousands of sources. Apple announced that as their App Store houses 185,000 apps for the iPhone with more than 4 billion application downloads. This shift away from single-vendor software to complex application platforms means that the phone's software must provide effective mechanisms to manage and control energy as a resource. Such control will be even more important as the danger grows from buggy or poorly designed applications to potentially malicious ones.

In the past year, mobile phone operating systems began providing better support for understanding system energy use. Android, for example, added a UI that estimates application energy consumption with system call and event instrumentation, such as processor scheduling and packet counts. This is a step forward, helping users understand the mysteries of mobile device lifetime.

This paper presents Cinder, a new operating system de- signed for mobile phones and other energy-constrained computing devices. Cinder extends the HiStar secure kernel to provide new abstractions for controlling and accounting for energy: reserves and taps. Taps and reserves compose together to allow applications to express their intentions, enabling policy enforcement by the operating system.

II. A CASE FOR ENERGY CONTROL

This section motivates the need for low-level, fine-grained energy control in a mobile device operating system. It starts by reviewing some of the prior work on energy visibility and the few examples of coarse energy control. The next section describes reserves and taps, abstractions which provide these mechanisms at a fine granularity.

There is rich prior work on addressing the visibility problem of attributing consumption to application principals. Control, in contrast, has seen much less effort. Early systems like EcoSystem proposed highlevel application power limits. Mobile applications today, however, are much more complex: they spawn and invoke other services and have a much richer set of peripherals to manage. We believe that for users and applications to effectively control power, an operating system must provide three mechanisms: isolation, subdivision, and delegation. We motivate these mechanisms through

three application examples that we follow through the rest of the paper. Isolation is a fundamental part of an operating system. Memory and IPC isolation provide security, while cpu and disk space isolation ensure that processes cannot starve others by hogging needed resources.

III. DESIGN

Cinder is based on the HiStar operating system which is a secure exo-kernel that controls information flow using a label mechanism. The kernel provides a small set of kernel object types to applications, from which the rest of system is built: threads, address spaces, segments, gates, containers, and devices. Cinder adds two new kernel object types: reserves and taps. This section gives an overview of HiStar, describes reserves and taps, gives examples of how they can be used, and provides details on their security and information flow.

3.1 HISTAR

HiStar is composed of six first-class kernel objects, all protected by a security label. Its segments, threads, address spaces, and devices are similar to those of conventional kernels. Containers enable hierarchical control over deallocation of kernel objects – objects must be referenced by a container or face garbage collection. Gates provide protected control transfer of a thread from one address space to a named offset in another; they are the basis for all IPC.

3.2 RESERVES

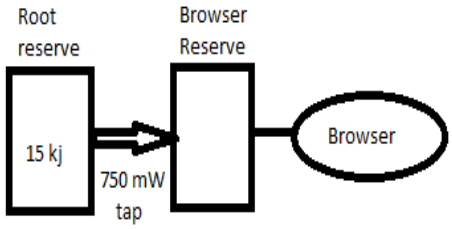
A reserve describes a right to use a given quantity of a resource, such as energy. When an application consumes a resource the Cinder kernel reduces the values in the corre- sponding reserve. The kernel prevents threads from performing actions for which their reserves do not have sufficient resources. Reserves, like all other kernel objects, are protected by a security label (§3.5) that controls which threads can ob- serve, use, and manipulate it.

3.3 TAPS

A tap transfers a fixed quantity of resources between two reserves per unit time, which controls the maximum rate at which a resource can be consumed. For example, an appli- cation reserve may be connected to the system battery via a tap supplying 1 mJ/s (1 mW).

Taps aid in subdividing resources between applications since partitioning fixed quantities is impractical for most policies. A user may want her phone to last at least 5 hours if she is surfing the web; the amount of energy the browser should receive is relative to the length of time it is used. Providing resources as a rate naturally addresses this. Taps are made up of four pieces of state: a rate, a source reserve, a sink reserve, and a security label containing the privileges necessary to transfer the resources between the source and sink

FIGURE:



A 15 kJ battery, or root reserve, connected to a reserve via a tap. The battery is protected from being misused by the web browser. The web browser draws energy from an isolated reserve which is fed by a 750 mW tap**.**

5.4 ACCESS CONTOL & SECURITY

Any thread can create and share reserves or taps to subdivide and delegate its resources. This ability introduces a problem of fine grained access control. To solve this, reserves and taps are protected by a security label, like all other kernel objects. The label describes the privileges needed to observe, modify, and use the reserve or tap. Since a tap actively moves resources between a source and sink reserve, it needs privileges to observe and modify both reserve levels; to aid with this, taps can have privileges embedded in them.

VI. CINDER ON HTC DREAM

Controlling energy requires measuring or estimating its consumption. This section describes Cinder's implementation and its energy model. The Cinder kernel runs on AMD64, i386, and ARM architectures. All source code is freely avail- able under open-source licenses. Our principal experimental platform is the HTC Dream (Google G1), a modern smart- phone based on the Qualcomm MSM7201A chipset.

6.1 ENERGY ACCOUNTING

Energy accounting on the HTC Dream is difficult due to the closed nature of its hardware. It has a two-processor design. The operating system and applications run on an ARM11 processor. A secure, closed ARM9 coprocessor manages the most energy hungry, dynamic, and informative components (e.g. GPS, radio, and battery sensors). The ARM9, for example, exposes the battery level as an integer from 0 to 100.

6.2 POWER MODEL

Our energy model uses device states and their duration to estimate energy consumption. We measured the Dream's energy consumption during various states and operations. All measurements were taken using an Agilent Technologies E3644A, a DC power supply with a current sense resistor that can be sampled remotely via an RS-232 interface. We sampled both voltage and current approximately every 200 ms, and aggregated our results from this data. While idling in Cinder, the Dream uses about 699 mW and another 555 mW when the backlight is on. Spinning the CPU increases consumption by 137 mW. Memory-intensive instruction streams increase CPU power draw by 13% over a simple arithmetic loop.

6.3 PERIPHERAL POWER

The baseline cost of activating the radio is exceptionally high: small isolated transfers are about 1000 times more expensive, per byte, than large transfers. Results demonstrate that the overhead involved dominates the total power cost for flows lasting less than 10 seconds in duration, regardless of the bitrate.

An application powers up the radio by sending a single 1-byte UDP packet. The secure ARM9 automatically returns to a low power mode after 20 seconds of inactivity. Because the ARM9 is closed, Cinder cannot change this inactivity timeout. With this workload, it costs 9.5 joules to send a single byte! One lesson from this is that coordinating applications to amortize energy start-up costs could greatly improve energy efficiency. In x5.5 we demonstrate how Cinder can use reserves and taps for exactly this purpose.

6.4 MOBILITY AND POWER MODEL IMPROVEMENTS

Cinder's aim is to leverage advances in energy accounting to allow users and applications to provision and manage their limited budgets. Accurate energy accounting is an orthogonal and active area of research. Cinder is adaptable and can take advantage of new accounting techniques
or information exposed by device manufacturers.

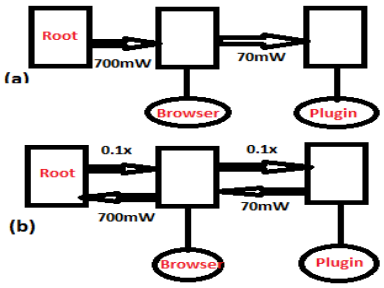
VII.APPLICATIONS

To gain experience with Cinder's abstractions, we developed applications using reserves and taps.

7.1 ENERGYWRAP

Taking advantage of the composability of Cinder's resource graph, the energy wrap utility allows any application to be sandboxed even if it is buggy or malicious. Energywrap takes a rate limit and a path to an application binary. The utility creates a new reserve and attaches it to the reserve in which energywrap started by a tap with the rate given as input. After forking, energywrap begins drawing resources from the newly allocated reserve rather than the original re- serve of the parent process and executes the specified program.

Figure.



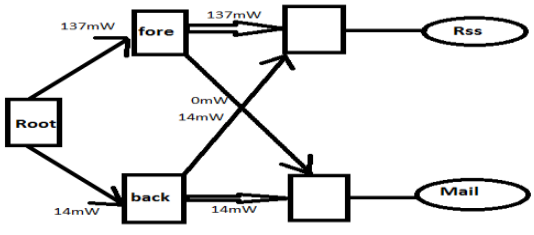
(a) A web browser configured to run for at least 6 hours on a 15 kJ battery. The web browser further ensures that its plugin cannot use more than 10% of its energy.

(b) (b) Adding 0.1x backward proportional taps promotes sharing of excess energy unused by the browser and plugin.

7.2 ENERGY-AWARE APPLICATIONS

Using Cinder, developers can gain fine grained control of resources within their applications, providing a better experience to end users. This includes adaptive policies for pro- grams where partial or degraded results are still useful, andoffer a compromise between battery life and user experience. For example, smart applications may scale the quality of streaming video or reduce texture quality in a game when available energy is low, since the user can still watch a video or play a game when insufficient resources are available to run at full fidelity.

FIGURE.



RSS is running in the foreground so the task manager has set its tap to give it additional power. Mail is running in the background, and can only draw energy from the background reserve. This ensures that actual battery consumption matches the user's expectation that the visible application is responsible for most energy consumption.

VIII. EXPREIENCE DEVLPOING ON A MOBILE

We ported Cinder to the HTC Dream mobile phone. Because developing a kernel for a mobile phone platform is a nontrivial task that is rarely attempted, we describe our process here in detail. To run Cinder on the HTC Dream, we first ported the kernel to the generic ARM architecture (2,380 additional lines of C and assembly).MSM7201A-specific kernel device support for timers, serial ports, framebuffer, interrupts, GPIO pins, and keypad required another 1,690 lines of C. Cinder implements the GSM/GPRS/EDGE radio functionality in userspace with Android driver ports.

8.1CINDER-LINUX VS CINDER-HISTAR

Cinder was initially implemented on HiStar because several key behaviors of the platform are naturally expressible using HiStar's abstractions. One such feature of Cinder is resource delegation between principals. Consider a common situation where a client process P requires work to be performed on its behalf by a daemon process D. A real world example is the radio interface layer daemon on the Android platform. Cinder must ensure P is charged for any work D performs on its behalf – or, equivalently, it must ensure that P provides the resources that D's code uses to run. HiStar's abstractions achieve this behavior cleanly and simply. A process in HiStar is a container, containing an address space and one or more threads. IPC is performed through special gates defined by the process – a thread belonging to process P can enter a gate defined by process D, after which the thread has access to D's address space, though while under control of D's code text. When process P requires service from daemon D a thread, T, belonging to P enters D's address space via a gate. Cinder debits T for work it performs as usual even though it executes under the control of D's code, correctly billing consumption to P.

IX. RELATED WORK

We group related work into three categories: resource management, energy accounting, and energy efficiency.

9.1 RESOURCE MANAGMENT

Cinder's taps and reserves build on the abstraction of resource containers [Banga 1999]. Like resource containers, they provide a platform for attributing resource consumption to a specific principal. By separating resource management into rates and quantities, however, Cinder allows applications to delegate with reserves, yet reclaim unused resources. This separation also makes policy decisions much easier. Since resource containers serve both as limits and reservations, hierarchical composition either requires a single policy (limit or reserve) or ad hoc rules (a guaranteed CPU slot cannot be the child of a CPU usage limit). Linux has recently incorporated "cgroups" [Menage 2008] into the mainline kernel, which are similar to resource containers, but group processes rather than threads.

9.2 MEASUREMENT,MODELLING AND ACCOUNTING

Accurately estimating a device's energy consumption is an ongoing area of research. Early systems, such as ECOSystem [Zeng 2002], use a simple linear combination of device states. Most modern phone operating systems, such as Symbian and OS X, follow this approach. PowerScope improves CPU energy accuracy by correlating instrumented traces of basic blocks with program execution [Flinn 1999b].

9.3 ENERGY EFFICIENCY

There is rich prior work on improving the energy efficiency of individual components, such as CPU voltage and frequency scaling [Flautner 2002; Govil 1995], spinning down disks [Douglis 1995; Helmbold 1996], or carefully selecting memory pages [Lebeck 2000]. Phone operating systems today tend to depend on much simpler, but still effective optimization schemes than in the research literature, such as hard timeouts for turning off devices. The exact models or mechanisms used for energy efficiency are orthogonal to Cinder: they allow applications to complete more work within a given power budget. The image viewer described in x5.3 is an example of an energy-adaptive application, as is typical in the Odyssey system [Flinn 1999a].

X. FUTURE WORK

We believe that the reserve and tap abstractions may be fruitfully applied to other resource allocation problems beyond energy consumption. For instance, the high cost of mobile data plans makes network bits a precious resource. Applications should not be able to run up a user's bill due to expensive data tariffs, just as they should not be able to run down the battery unexpectedly. Since data plans are frequently offered in terms of megabyte quotas, Cinder's mechanisms could be repurposed to limit application network access by replacing the logical battery with a pool of network bytes.

XI. CONCLUSION

Cinder is an operating system for modern mobile devices. It uses techniques similar to existing systems to model device energy use, while going beyond the capabilities of current operating systems by providing an IPC system that fundamentally accounts for resource usage on behalf of principals. It extends this accounting to add subdivision and delegation, using its reserve and tap abstractions.We have described and applied this system to a variety of applications demonstrating, in particular, their ability to partition applications to energy bounds even with complex policies. Additionally, we showed Cinder facilitates policies which enable efficient use of expensive peripherals despite non-linear power models.

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