Title
The Atom LEAP Platform For Energy-Efficient Embedded Computing

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The Atom LEAP Platform For Energy-Efficient Embedded Computing

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1. Abstract

This Technical Report provides a review of a new embedded computing platform enabling research, education and training, and product development based on the Intel Atom processor architecture. This introduces a dramatic advance in the capability for direct characterization of energy and power dissipation in embedded computing platforms and the associated capabilities for optimization of performance and energy. This report includes development, usage, and example operation and results with platform applications in mobile computing, distributed sensing, network routing, and wireless access point implementation. In each case, Atom LEAP is intended to provide both a reference design and a high throughput, easily implemented solution with an unprecedented advance in the capability for characterizing energy usage at a level of computing task and operating system detail substantially superior to prior methods.

2. Overview of Low-power Energy Aware Platform (LEAP) Systems

A broad range of embedded networked sensor applications have appeared for large-scale systems focused on the most urgent demands in environmental monitoring, security, and other applications. These applications not only introduce important demand for Embedded Networked Sensing (ENS) systems, they also introduce fundamental new requirements that lead to the need for new ENS embedded architectures, associated algorithms, and supporting software systems. New requirements include the need for diverse and complex sensor systems that present demands for energy and computational resources as well as for broadband communication. Sensing resources include imaging devices, chemical and biological sensors, and others. Computational system demands for new ENS applications now include image processing, statistical computing, and optimization algorithms required for selection of proper sensor sampling.

The LEAP platform has introduced a new embedded system design where components are not selected exclusively for low average power dissipation, but instead are selected with both energy and performance criteria to achieve highest energy efficiency and lowest system energy dissipation for a specific measurement objective.

LEAP technology has been applied to embedded networked sensing, [McIntire2006] energy-aware routing, [Stathopoulos2007] energy-efficient embedded computing, [Stathopoulos2008] and energy-efficient multicore computing [Ryffel2009].

This platform includes a new energy accounting capability necessary for in-field, adaptive optimization of energy and performance, including methods that may only operate if provided with real-time knowledge of subsystem energy dissipation. LEAP energy accounting is a process of both energy measurement and attribution to the responsible system task or application. Through the use of synchronized energy measurements across the platform's power domains, the LEAP architecture is able to assign energy usage to high level system operations, often spanning multiple hardware resources. This energy accounting feature allows runtime assessment of energy costs, enabling adaptive behavior based upon energy specific goals. This architecture also includes energy management through scheduling of component operation. Thus, it is then possible to select the most energy efficient components to meet the demands of each sensing task.

It is important to note that the LEAP architecture is necessary since, run-time measurement of energy integrated with the platform is required for optimization of energy and performance for many important applications. A series of critical characteristics for determining platform energy dissipation and sensor node platform performance are in fact only known only at runtime. For example, the dynamic nature of events means that as time evolves, data-dependent processing requirements will demand that platform schedules adapt. As an example, processor resource conflicts resulting from the requirements for both processing sensor data (in order to derive event information) while also maintaining network communication between nodes, presents a resource conflict that can be determined only at runtime due to the inherently unpredictable nature of events.

3. LEAP Platform Development

The LEAP platform has proceeded through generations beginning with LEAP-1 based on the PXA255 ARM processor [McIntire2006], and then LEAP-2 based on the PXA270 processor and ARM11 architecture [Stathopoulos2008]. The LEAP Server system then was developed to provide support for server-class computing platforms.[Ryffel2009]

The enabling components for LEAP2 included an ASIC (implemented with a low power ASIC sampling system accessible to the ARM11 address/data bus). This sampling systems enabled all memory, storage, processor, and peripheral component current levels to be be sampled at a rate greater than 1 kHz per channel.

LEAP-1 and LEAP-2 have been successful in research and instruction in many programs. LEAP-2 is entering a commercial product in seismic monitoring.

4. The Atom LEAP Platform

The Intel Atom processor is appearing in a broad range of embedded products ranging from mobile devices to network appliances. Its support in the Green Edge Networking program provides the capability for development of a wide range of testbeds and development systems.

The development of Atom LEAP is intended to provide the following benefits:

4.1. Distribution and Community Access:

1) Low cost:
    a. The Atom Intel motherboard is low cost and readily available.
2) Accessible
    a. The components for Atom LEAP are low cost and are easily added to the platform.
3) Extensible
    a. The Atom LEAP motherboard provides a reference design with a wide range of peripheral and network interfaces and storage system interfaces. The construction of energy-aware network appliances, energy-aware sensing platforms and testbeds is quite practical now.

4.2. Performance:

1) The Atom LEAP system departs from prior LEAP architectures by relying on peripheral, USB-interface, high speed analog sampling system.
    a. Today, this uses the National Instruments 780105 USB DAQ system providing high speed analog sampling in both single-ended and differential forms.
2) This system enables an advance in sampling speed over prior platforms
3) The new architecture also presents a challenge for event synchronized sampling. This challenge has been addressed and the solution adopted enables a dramatic step forward in platform capability.

4.3. New Deep Inspection of Computing Platform Energy-Sensitive Operation

Atom LEAP introduces new high resolution synchronization methods that improve both performance and ease of use.

LEAP architectures enable sampling at high speed integrated with kernel systems. However, these kernel systems were not configurable at run time. Further previous LEAP systems did not enable resolution of energy usage for the combination of user space and kernel space computing including interrupt and system call energy investments. (This did not affect past research since these can be accounted for in careful experimental design.) Also,Previous LEAP systems were required to develop an indirect method for resolving energy dissipation by individual cores in a multicore platform.

The Atom LEAP system has adopted several new architecture advances. First, the Atom LEAP system leverages the Linux kprobes technology.[Panchamukh2004] Extensions of this system to include the Linux Trace Tookit and SystemTap are straightforward. This permits the runtime insertion of an inspection module that enables LEAP “energy calipers” to be placed at any location in the kernel code sequence of control. This enables fast instrumentation of a new system. There are many, diverse and fundamental measurements that were not previously possible that may now be accessible.

Second, the sampling system and platform are synchronized through an event mechanism that enables instrumentation of short time scale, ephemeral events including kernel services (system calls and interrupts). This is a significant breakthrough for Green Edge in that we are aware of no prior work that has quantified energy investment by these kernel services or further have provided attribution of them to specific tasks and users.

4.4. Architecture

The Atom LEAP platform is shown below in Figure 1. This is based on the Intel Atom N330 Motherboard with documentation here:

http://www.intel.com/products/desktop/motherboards/d945gclf2-d945gclf2d/d945gclf2-d945gclf2d-overview.htm

This includes support for:

1) The Intel Atom N330 dual core processor.
2) Dual and multicore embedded systems are now becoming common for their performance and energy efficiency advantages. This platform permits us direct access to each core's energy dissipation. This is a breakthrough for many research opportunities.
3) Eight USB 2.0 ports
4) This affords many extension
5) Two Serial SATA ports
6) Ethernet interfaces
7) This enables research on energy efficient storage and IO scheduling
8) One parallel ATA IDE interface
9) One serial port
10) One parallel port
11) One PCI port
12) Graphics and audio interfaces

Support and drivers are available for a wide range of wireless network interfaces.

The Atom LEAP architecture is shown in Figure 1. The N330 dual core processor, SDRAM, Storage, and Network interfaces, are monitored by the high speed sampling system. Synchronization methods, to be discussed, enable access to power dissipation data that is then synchronized with kernel events. Very soon, this will be available with synchronization for events in *each core*.

The components and finally a complete system is shown in Figures 2 and 3. It should be noted that the platform can be packaged in a small module.

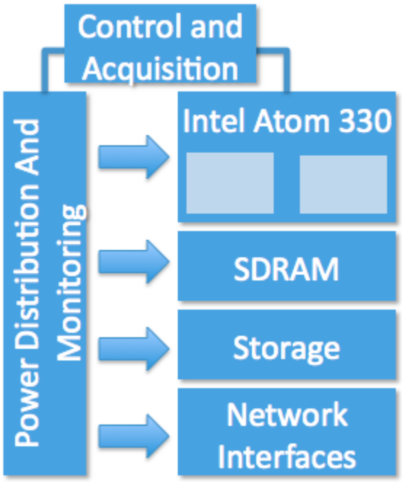


Figure 1. The Atom LEAP Platform architecture for the dual core Atom N330 processor

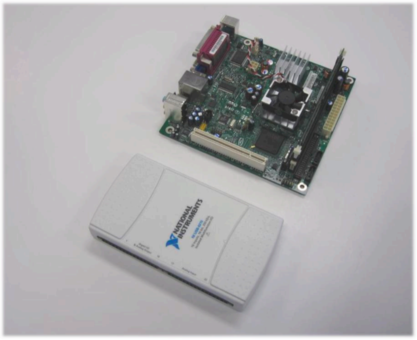


Figure 2. The Atom LEAP Platform primary components including embedded motherboard with a wide range of diverse interface options as well as the analog sampling module at lower left.

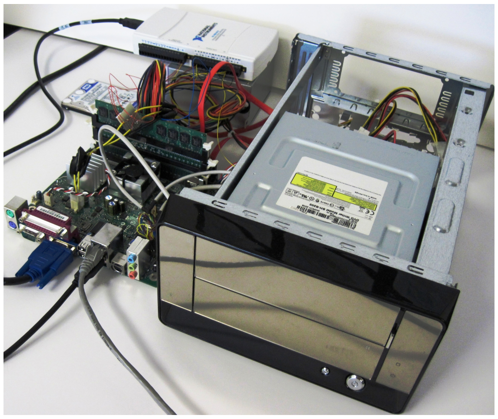


Figure 3. The Atom LEAP Platform. The Atom platform is shown next to the optional chassis. Wiring between the DAQ and platform is shown. The Atom LEAP wiring harness can be supplied as a kit item or constructed.

4.5. Atom LEAP Software Systems

For this development of the LEAP platform, we have sought to provide a system that is as accessible as possible to users, permits instrumentation of both user space and kernel systems, and finally enables energy attribution of system calls and interrupts as well as kernel services never previously accounted for.

The synchronization method between high speed sampling (up to 10 kHz per channel for all channels) and each CPU is based on the instrumentation of the kernel, digital signal generation, and measurement. It is important to note that kernel events may be identified and included in analysis at *runtime.* Ultimately, each Time Stamp Counter (the 64b accumulator of CPU clock ticks in the x86 architecture) for each core is then synchronized with sampling.

Now, synchronization begins with the introduction of kprobe events. Many kprobe example implementations are available that provide ample design guidance. Kprobe technology enables the insertion of a breakpoint (illegal instruction) at any kernel location at runtime. The trap handler that services the illegal instruction trap is modified by kprobes to examine the state of the system, confirm the nature of the trap and the legitimate nature of the kprobe, and finally call a function that the user has inserted as a handler. The handler function examples for Atom LEAP include functions that will, for example, permit identification of the current process, access to any kernel symbol for inspection or manipulation, and many other features.

Most importantly, this will enable the insertion of "energy calipers" that measure the energy dissipated between events for all components synchronized with any event desired. A user space version of kprobes control (including one equipped with a web interface) was developed in the Green Edge program. This will enable research by developers of deep internals without the requirement to modify the kernel or write kernel modules.

Finally, another important feature of this system is now the ability for each core to produce a synchronization signal and then permit true multicore analysis. This will be another first.

5. Atom LEAP Testbeds

Atom LEAP individual units and testbeds can be constructed rapidly. A list of components is below with current pricing as of early 2010.

Part Number	Description	Unit Price	Quantity
WD160BEVS	SATA HDD 160GB	$48	1
KVR667D2/1GR	DDR2 1GB 240-pin 667MHz RAM	$30	1
D945GCLF2	Intel Atom Motherboard	$70	1
Apex MI-100	Chassis With Power Supply	$38	1
NI 780105-01	National Instruments DAQ USB 6215	$1,049	1
LT50J-.010-ND	0.01 Ohm Precision Resistor	$7	5
DDR2-INT-CSR	DDR2 Riser with Current Sensing Resistor	$49	1
Wiring Harness	Assembled cable harness	$10	1

6. Atom LEAP Example Power Dissipation Analysis

The Atom LEAP system may be distributed and complete software and hardware specifications will be made available at cvs.cens.ucla.edu. An example, convenient introductory application enables start and stop of sampling of power data at a rate of 10kHz per channel.

It is very important to note that there is not another platform available that provides the form of data shown below. Our discussions with the Intel Embedded group indicates that they have not created a platform of this type and exploited the combination of data and synchronization now available to the Green Edge team.

In particular, there are fascinating investigations that can now be performed. As an example, the Atom LEAP has many storage options. Currently, one of these is an SATA interface hard disk drive. Of course, NAND Flash storage is also available. It will be possible now to understand a wide range of processor, memory, storage, and network dependencies and usage tradeoffs that can be made in an energy-sensitive fashion. The following results demonstrate example data associated with this.

First, the Atom LEAP components being monitored include:

1) CPU Core 0 and CPU Core 1 of the Atom N330 (CPU0 and CPU1)
2) SDRAM Bank (SDRAM)
3) Hard Disk Drive (HDD)

As a straightforward first test, one can consider the power dissipation and energy investment associated with file transfer.

Digvijay performed an experiment using the facilities noted above and transferred a large file (600MB) from a remote web server (thus introducing the additional interesting features associated with latency and variable data delivery rate that will have a profound effect on energy efficiency of data transport).

The experiment included an initial 40 second quiescent period, the data download period of about 120 seconds, and a remaining period of 40 second quiescent (idle) operation.

Clearly, a vast number of important questions and optimization opportunities lie ahead. This experiment is simply intended to illustrate the characteristics of this platform that may be explored.

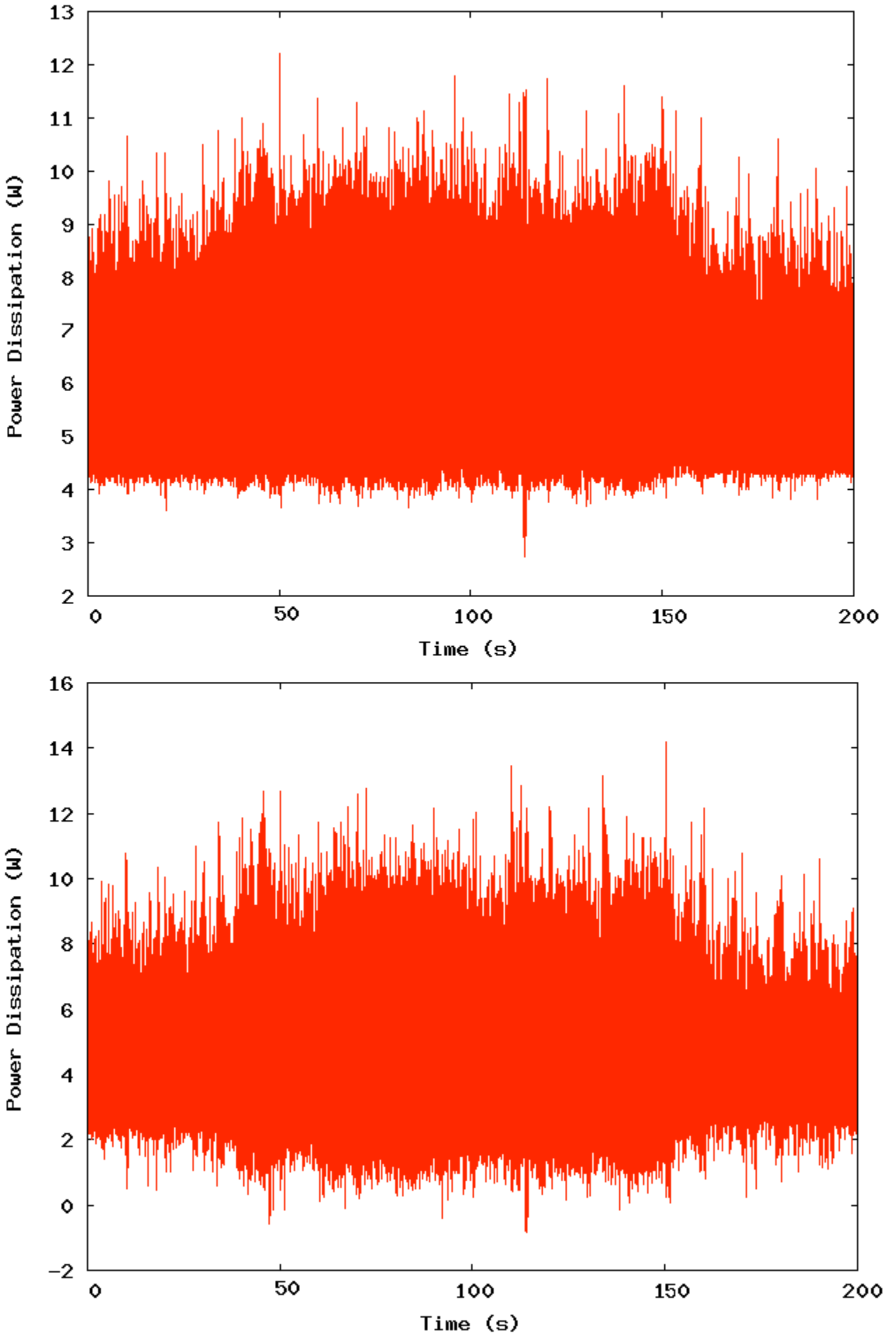


Figure 4. Power dissipation for CPU0 (upper) and CPU1 (lower) at full sampling bandwidth

Figures 4 and 5 display power dissipation for the two CPU cores. Note that Figure 5 shows low pass (first order at 1kHz corner frequency) filtered data. It is clear that the division of task assignments by the task scheduler effects the cores differently. The impact of data transfer, memory access, and data storage are visible.

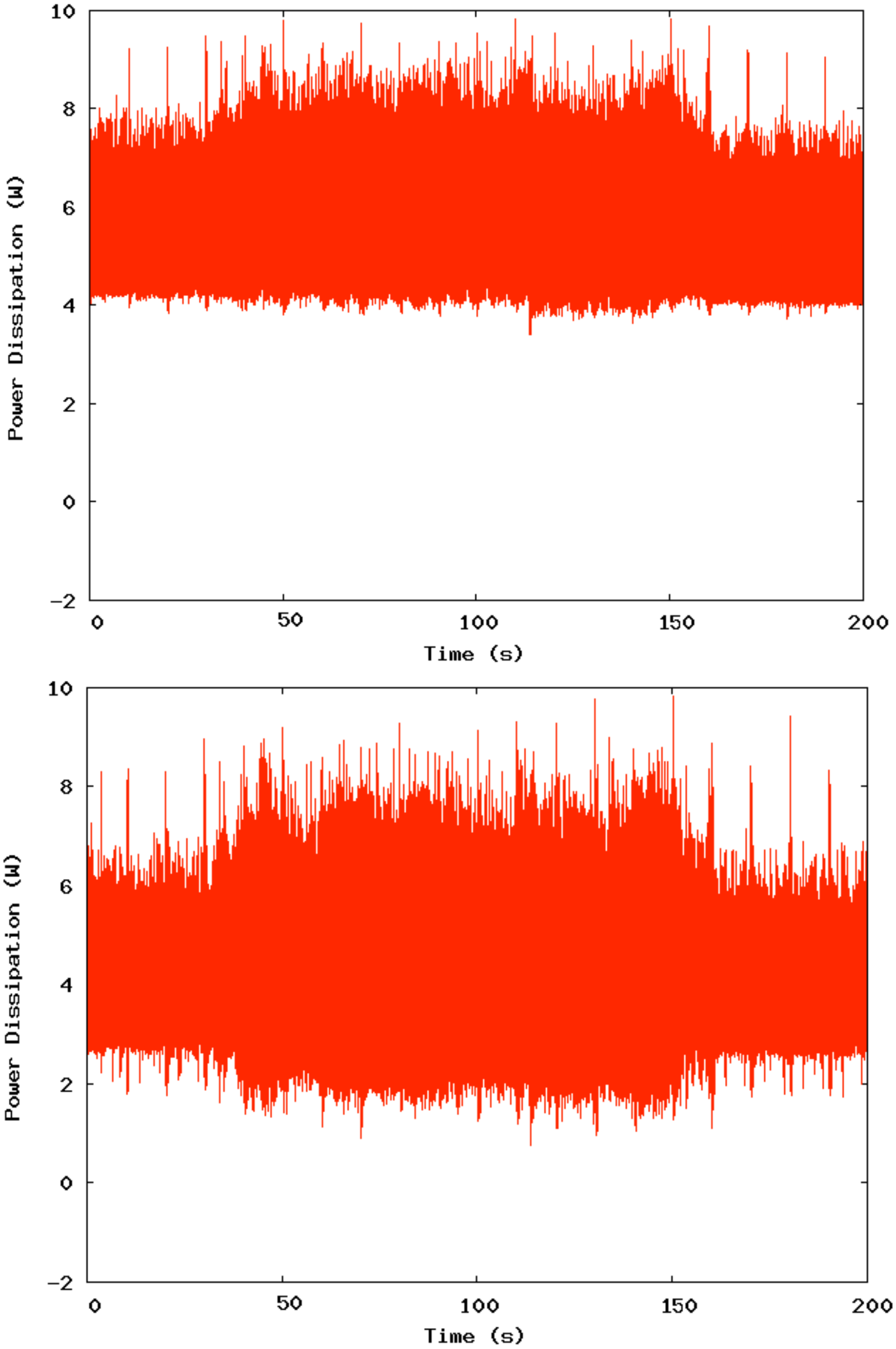


Figure 5. Power dissipation for CPU0 (upper) and CPU1 (lower) at full sampling bandwidth with a 1 kHz filter applied to the time series data.

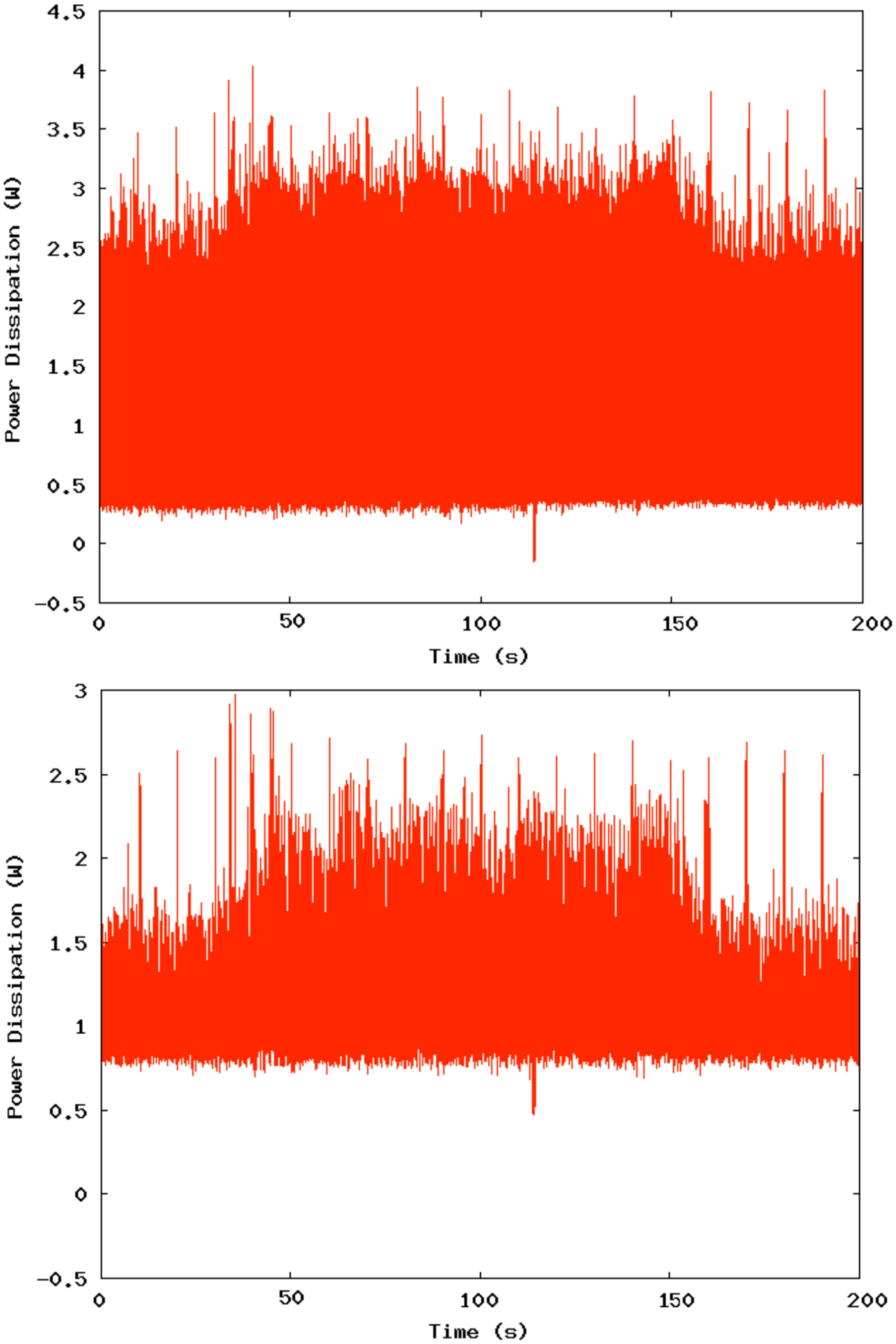


Figure 6. Power dissipation for memory at full sampling bandwidth (upper) and with a 1 kHz filter applied to the time series data (lower)

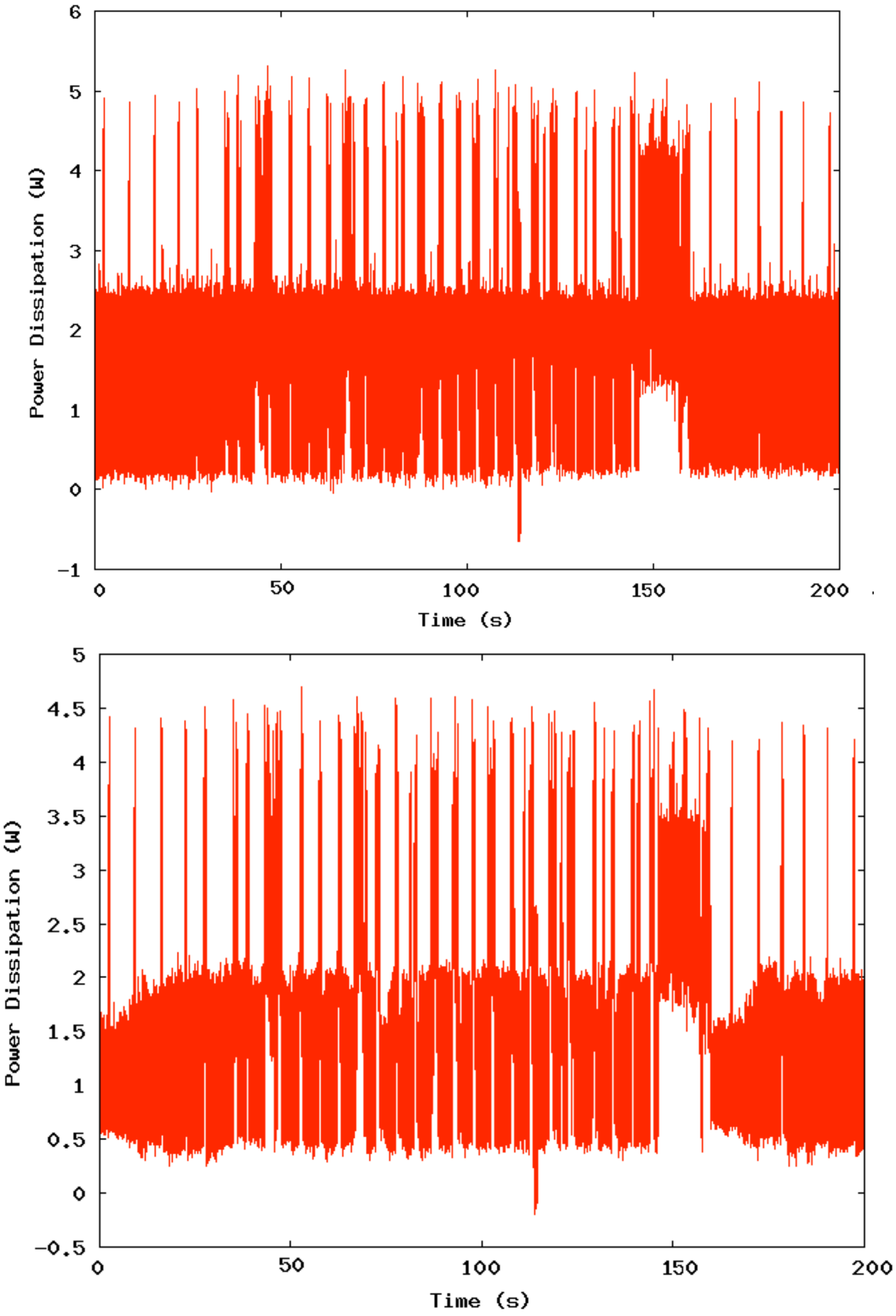
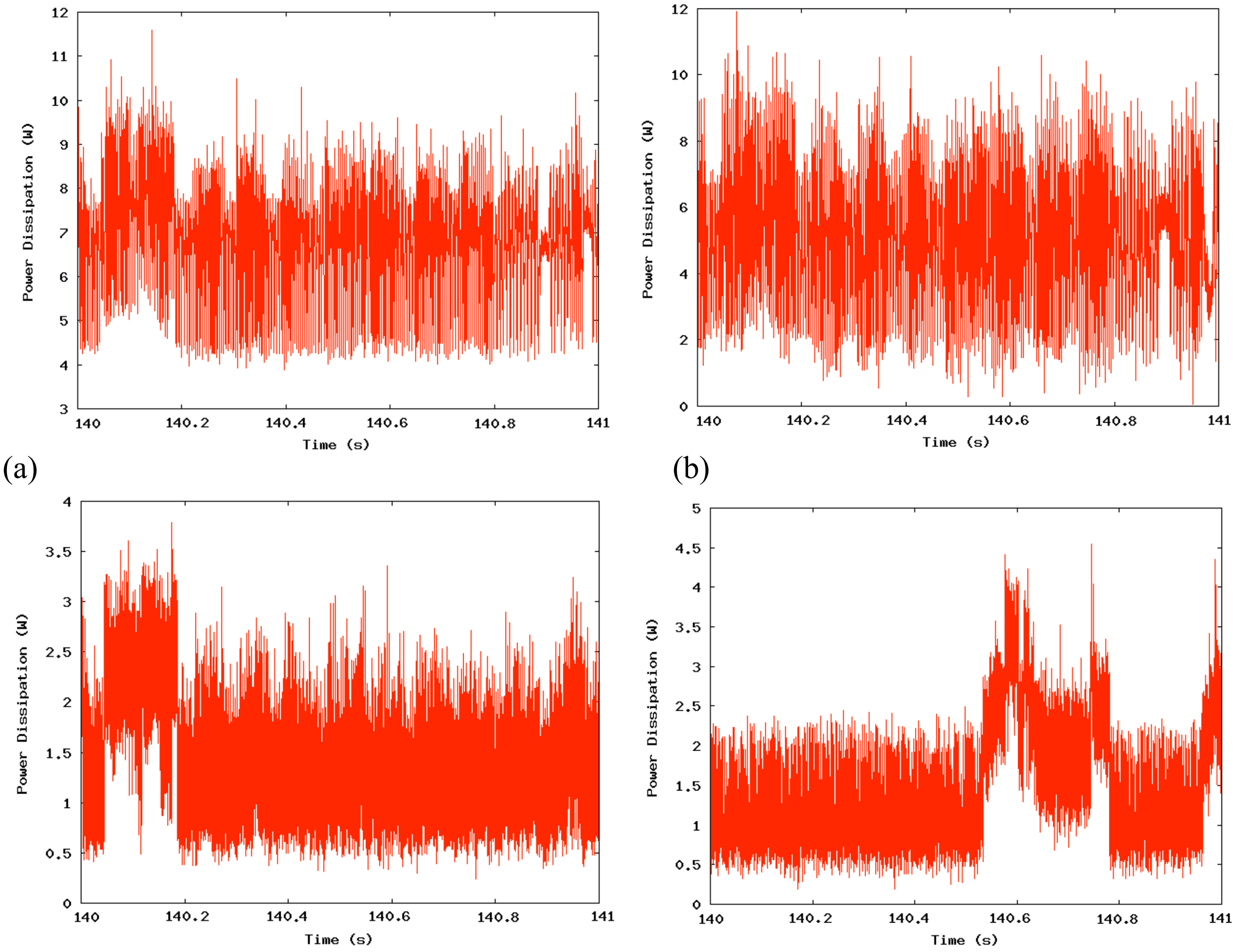


Figure 7. Power dissipation for HDD storage at full sampling bandwidth (upper) and with a 1 kHz filter applied to the time series data (lower)

Figures 6 and 7 display RAM and HDD data, while Figure 8 shows increased resolution plots of this data. Note that the HDD energy dissipation shows excursions due to its functions driven by platform demands that are, in fact, deferred and are anticipated by the platform.



(a) (b) (c) (d)

Figure 8. Power dissipation for (a) CPU0, (b) CPU1, (c) RAM, and (d) HDD storage at full sampling bandwidth over a 1 second interval.

7. Summary

The Atom LEAP platform provides a rapidly deployable, flexible, and readily extensible energy-efficient computing platform. The event synchronization and characterization capabilities provided by the Atom LEAP system enable direct access to operating system services and events that were previously not available for inspection. Atom dual core power monitoring offers additional characterization capability. Finally, the Atom LEAP system also provides a reference design for energy-efficient embedded computing products. In the near future, many Atom LEAP developments are planned for complete system testbeds, network routing, and wireless access point appliances. Atom LEAP hardware and software kit specifications will be included as well.

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