Power Measurement Techniques on Standard Compute Nodes: A Quantitative Comparison

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***Abstract*—Energy efficiency is of steadily growing importance in virtually all areas from mobile to high performance computing. Therefore, lots of research projects focus on this topic and strongly rely on power measurements from their test platforms. The need for finer grained measurement data–both in terms of temporal and spatial resolution (component breakdown)–often collides with very rudimentary measurement setups that rely e.g., on non-professional power meters, IMPI based platform data or model-based interfaces such as RAPL or APM. This paper presents an in-depth study of several different AC and DC measurement methodologies as well as model approaches on test systems with the latest processor generations from both Intel and AMD. We analyze most important aspects such as signal quality, time resolution, accuracy, and measurement overhead and use a calibrated, professional power analyzer as our reference.**

I. Introduction

The increasing importance of energy efficiency currently pushes many academic research projects. Optimizing software applications for low energy consumption may soon be an integral part of the performance optimization process. This generates a need to measure system power consumption not as an average of full application runs, but individually for specific code sections, thereby increasing the demand for a high temporal resolution of the measurement. Another requirement often is to increase the spatial resolution by isolating the power consumption of dominant components, e.g. the CPU or memory, from less interesting aspects such as nearly static HDD power consumption or temperature-dependent fans.

HPC systems with large numbers of compute nodes are particularly challenging. The analysis of parallel applications that are not homogeneous enough to extrapolate from a single node, as well as energy-accounting purposes can drive the demand for cost-efficient large-scale power measurement techniques. Therefore, the power measurement methodology is a critical aspect of any energy efficiency research project–often driven by computer scientists rather than electrical engineers. This paper presents an in-depth analysis of several different power measurement approaches. A careful consideration of the trade-offs between high temporal resolution, measurement accuracy, and overhead is an essential part of this work.

We address common misconceptions and undocumented details regarding the *modeling approaches* of Intel and AMD. This includes aspects of accuracy, temporal resolution, and measurement overhead. We analyze *power consumption data from power supplies* that is often available through the Intelligent Platform Management Interface (IPMI). While this measurement method is rarely the first choice, it is attractive when the research focus is energy efficiency of large high performance computing systems. In these cases, power distribution units (PDUs) or power supplies (PSUs) with integrated power measurement features might be the only reasonable or affordable alternative for a system-wide analysis. However, data from such devices has limited temporal resolution and its reliability is questionable, as they are designed for data center power management use cases. We also include a prototype of our own *DC measurement* approach that is designed to increase both temporal and spatial resolution of our power measurements. Moreover, we address the important question of the highest sampling rate that can still deliver useful data for energy efficiency research–both for AC and DC measurements.

II. Related Work

The urgent need of gather information about power consumption has been covered by previous research activities which can be distinguished in physical measurement and modeling. One representative of the former is the PowerPack [9] framework, which consists of hardware devices used for measurement and software components to integrate the measurement and hand the information over to a software level. Another is the Intel Energy Checker SDK [24], which allows users to integrate energy measurement in applications. Hoever, the sampling rate is only 1 Sample per second (1 Sa/s). Knapp et al. [17] integrated temperature and power measurement for an AMD Opteron Cluster with PerfTrack. While the temperature is sampled once per 10 seconds, the power sampling rate is not defined. System vendors support measuring power consumption for example by implementing power sampling options in PDUs [2] and PSUs [3]. The BlueGene/P voltage regulators offer an interface to read power consumption information. Hennecke et al. [12] developed a tool to read these information at a rate of 4 Sa/s. Laros used and adapted the Cray Reliability Availability and Serviceability Management System to measure the voltage regulator power information at a sampling rate of 100 Sa/s [18].

Model-based power consumption estimates have shown to be reasonably accurate [10], [23], [15], [6] and are provided by current x86 microprocessors. The processor manuals describe some details for Intel's Running Average Power Limiting (RAPL) [13] and AMD's Application Power Management (APM) [4]. Dongarra et al. [8] compared RAPL using PAPI [25] to real power measurements using PowerPack with a sampling interval of 100 ms. Their conclusion is that RAPL presents a viable alternative to physical measurements. To the authors knowledge no such analysis is available for APM.

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III. Experimental Setup

A. Test systems

Our experimental setup includes three test systems that feature the latest processor generations from Intel and AMD (see Table I). We include 1P, 2P and 4P systems in our analysis. The systems have been picked due to the variety of different available instrumentations which are also listed in Table I.

The first system features a single socket Intel Sandy Bridge Xeon E3 server processor, which is closely related to desktop Core i7 counterparts, with the main differences being ECC support and disabled graphics unit. We use this system to compare the reference AC measurement to two types of DC instrumentation and processor power consumption reported by the Intel RAPL counters.

The second system is a two socket Dell server with two Sandy Bridge-EP based Intel Xeon E5 processors. Here we compare the reference AC measurement with IPMI based power consumption information and the Intel RAPL counters for processor and DRAM power consumption.

The third system is a four socket SuperMicro node with four 16-core AMD Bulldozer processors. We use this machine to compare the reference AC measurement with another AC measurement that is provided by a MEGWARE ClustSafe "intelligent" PDU. Moreover, we also include AMD's model-based power monitoring feature, the APM counters, in our comparison.

B. AC Instrumentation

ZES: The baseline power consumption is measured using a calibrated ZES ZIMMER LMG450 device located between the power supply of the inspected system and the electrical outlet. We use a fixed voltage range of 250 V and a current range of 0.6 A, 1.2 A, and 5 A for the Sandy Bridge 1P, the Sandy Bridge 2P, and the Bulldozer 4P system, respectively. The ZES power meter also features an option to automatically adapt to adequate voltage and current ranges. Any readjustment requires more than one second to finish. We deem this overhead to be unacceptable, considering the quickly changing power demands of applications. The power deviation for AC readings is defined in [1, sec. 12.1.1] as

$$\Delta P = \pm(0.07\%\ of\ Rdg.\ +\ 0.04\%\ of\ Rng.).$$

$Rdg.$: specific power reading from the ZES
$Rng.$: power range, computed from the peak values for the voltage and current ranges

The approximated deviation for the individual test systems is presented in Table II. In the following we will use the ZES LMG450 as a reference for the correctness of other power monitoring sources due to its high accuracy and calibration.

IPMI: The *Intelligent Platform Management Interface* is a collection of standardized interfaces to manage and monitor computer systems. Our Sandy Bridge 2P system provides an *integrated Dell Remote Access Controller (iDRAC7)*, which implements IPMI 2.0. We gather this data from a remote system via TCP/IP, thereby avoiding any overhead on the measured system. Dell claims a 1 % accuracy for the PSU's power monitoring capabilities [3]. The update rate is 1 sample/s.

PDU: Our Bulldozer 4P test system is part of a Megware Cluster of quad socket AMD Opteron nodes. All nodes of this cluster are connected to Megware ClustSafe Power Distribution Units (PDUs). The PDU data of the Bulldozer 4P system is gathered using a python script on a dedicated administration node. The data update rate is 1 Hz and the accuracy is within 2 % according to Megware [2].

C. DC Instrumentation

We have performed a custom DC side instrumentation of our Sandy Bridge 1P test system as depicted in Figure 1. The 8-pole 12V lane (so-called P8 connector) is wired to our LMG450 power meter to gain a reference power measurement. Moreover, we use a FHS 40-P/SP600 Hall-effect based current transducer that is connected to a National Instruments PCI-6255 Data Acquisition card in order to drastically increase the temporal resolution of our measurement. The data acquisition card supports sampling rates of several hundred kS/s, which means the bandwidth limitation of our signal is determined either by components on the main board (e.g., capacitors) or by the performance characteristics of our current sensor (max. frequency of ~10 kHz). From our measurements results we deduct that the P8 connector powers the CPU and its DRAM interface, but not the DRAM refresh.

TABLE I: Hardware Configuration and Power Measurement Setup

Name	Sandy Bridge 1P	Sandy Bridge 2P	Bulldozer 4P
Vendor/System	Intel SDP	Dell R720	SuperMicro 1042G-LTF
CPU Sockets	1x Intel Xeon E3-1280	2x Intel Xeon E5-2670	4x AMD Opteron 6274
Cores/Threads	4/8	16/32	64/64
Frequency	3.5 GHz (Turbo: 3.9)	2.6 GHz (Turbo: 3.3)	2.2 GHz (Turbo: 3.1)
TDP	95 W	2x 115 W	4x 115 W
Memory	4x 2 GiB DDR3-1333	8x 8 GiB DDR3-1600	16x 4 GiB DDR3-1600
Mainboard	Intel S1200BTL	Dell 0M1GCR	SuperMicro H8QGL
Disk	1x 500 GB SATA 7.2K Seagate ST3500514NS	1x 500 GB SATA 7.2K WDC WD5003ABYX	1x 250 GB SATA 7.2K WDC WD2503ABYX
PSU	1x 365W, 80Plus Silver Intel FS365HM1-00	1x 750W, 80Plus Platinum Dell D750E-S1	1x 1400W, 80Plus Gold PWS-1K41F-1R
AC Measurement	ZES LMG450	ZES LMG450, PSU (IPMI)	ZES LMG450, ClustSafe PDU
DC Measurement	ZES LMG450, NI PCI-6255	n/a	
Energy Model	RAPL (Desktop)	RAPL (Server)	APM

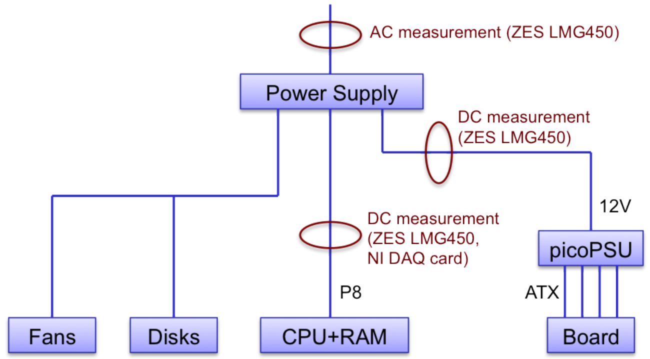


Fig. 1: DC instrumentation of our Sandy Bridge 1P test system.

In addition to the P8 instrumentation, we use a DC-DC converter (picoPSU-90-XLP) to generate all voltages of the 24-pole ATX connector. The picoPSU is powered by a single 12 V connector, which allows us to easily measure the DC main board power consumption with only one channel of our LMG450 power meter. There are no PCIe cards in the system, so this measurement includes all on-board components (chipset, network interfaces, graphics, etc.). It does not include hard disks or system fans, so that these rather invariant or temperature dependent loads cannot disturb the measurement.

The accuracy of DC measurements with the ZES power meter differs slightly from the AC measurements, as ΔP is calculated differently [1, sec 13.3.3]:
$\Delta P = \pm(0.05\%\ of\ Rdg.\ +\ 0.05\%\ of\ Rng.)$
The ranges are set to fixed values of 12.5 V and 5 A. Accuracy details can be found in Table II.

Our additional setup using a Hall sensor and a National Instruments data acquisition card only provides a current measurement. A voltage measurement of the 12V lane exceeds the voltage range of the NI card and we have avoided the effort of installing a voltage divider. We therefore assume this voltage to be constant at 12V for our power calculation. However, due to the existing ZES instrumentation of this DC channel, we were able to create several reference points at different load levels and use these to calibrate the power consumption reading that we gain from the NI card. This allows us to combine good accuracy with a high temporal resolution.

D. Energy-Model Instrumentation

Running Average Power Limit (RAPL): The RAPL interface has been introduced with the Intel Sandy Bridge processors. It enhances previous implementations [14] by providing an operating system access to energy consumption information. Several papers use RAPL to measure the energy consumption of functions and systems [11], [5]. Its actual purpose, however, is to set a limitation of the processors power consumption and modify this at runtime. The RAPL interface allows the definition of a maximal power consumption over a certain time window for several domains on a processor. Each domain provides an accumulating counter that holds the corresponding energy consumption. The available domains depend on the processor version. While processor models 0x2A provide an interface for package, core and GPU, server processors (model number 0x2D) provide package, core and DRAM domains. The registers holding these counters are updated approximately every 1 ms [13, Chapter 14.7.4]. The granularity defined in the *RAPL_POWER_UNIT* MSR is about 15,3 uJ for our test systems. For an update rate of about 1 ms this results in a power granularity of 15.3 mW.

Overall, there are two very important aspects that need to be considered when working with RAPL. First, the RAPL values are not a result of an actual (physical) measurement. Instead, they are based on a modeling approach that uses a "set of architectural events from each [...] core, the processor graphics, and I/O, and combines them with energy weights to predict the package's active power consumption" [21]. Previous research has demonstrated that using a counter-based model can be reasonably accurate [15], [6], [23], [10]. A model for the DRAM domain is described in [7]. Second, the RAPL interface returns energy data, not power data. There is no timestamp attached to the individual updates of the RAPL registers, and no assumptions besides the average update interval can be made regarding this timing. This means that no deduction of the power consumption is possible other than averaging over a fairly large number of updates. For example, averaging over only 10 ms would result in an unacceptable inaccuracy of at least 10 % due to the fact that either 9, 10, or 11 updates may have occurred during this time.

Application Power Management (APM): With processor family 15h, AMD also introduced an on-chip energy-consumption estimation. APM is used for TDP limiting and to calculate available power budgets for turbo modes. Average power for the last time frame can be calculated using several northbridge registers [4]. The default update rate on our test systems is approx. 10 ms. The granularity of the power estimation is defined in the northbridge register *TDP Limit3* (*TDP2Watt*, 3.8 mW in our case).

Providing the average power of the last time frame has both advantages and disadvantages compared to the Intel "energy accumulator" design. For larger time scales (in seconds), RAPL provides information about the overall energy consumption since the last reading; APM only holds information of the last 10 ms capture. For smaller time scales however, APM does not suffer from the previously described disadvantage of the RAPL approach. In our measurements, we therefore read the APM values every 10 ms.

TABLE II: Measurement accuracy for ZES measurements, ΔP_{range} is the range fraction of the power deviation equation; ΔP_{idle} and ΔP_{max} define the theoretical maximal deviation for an idling or fully used system in Watt and percentile of the actual reading

Test System	ΔP_{range}	ΔP_{idle}	ΔP_{max}
Sandy Bridge 1P	0.3 W	0.33 W / 0.75 %	0.40 W / 0.29 %
Sandy Bridge 2P	0.6 W	0.65 W / 0.87 %	0.81 W / 0.27 %
Bulldozer 4P	2.4 W	2.56 W / 1.09 %	2.91 W / 0.40 %
Sandy Bridge 1P (DC)	0.19 W	0.19 W / 9.99 %	0.23 W / 0.26 %

E. Synthetic Workload Kernels

The goal of this paper is to determine which instrumentation provides the best information about a system's power consumption at a given time during the execution of an application. A good instrumentation will expose the impact of application execution (e.g. specific code paths) on power consumption. In a first step, we compare the measurement results of different instrumentation types using synthetic code sequences. These synthetic kernels are specifically designed to provide a tightly controllable workload with particularly diverse characteristics:

- `sleep`, measuring an idle processor.
- A highly optimized matrix multiplication (`dgemm`) that maximizes the use of processing resources and power consumption.
- Memory bound data streaming. This especially stresses the memory subsystem.
- A complex mathematical function (`sin`) performed in a loop. The result of one operation is used as input of the next operation. This data dependency leads to an inefficient use of the arithmetic pipeline.
- The square root operation performed in a loop. The `sqrtsd` x86 instruction has been shown to be a particularly low power consuming operation [19].
- A simple in-cache computation (multiply-add) loop. This specifically stresses the computational resources.
- An OpenMP ping-pong loop between threads. This provokes high frequent load changes on the different cores as well as cache line transfers.
- A busy-waiting implementation that uses `gettimeofday`.

This set of different workloads enables a detailed comparison of the different power measurement methodologies. Except for the sleep kernel, we conduct all experiments using a varying number of threads via OpenMP. We run all combinations of thread number and benchmark type consecutively for 10 seconds each, of which the first and last second are omitted from the analysis. This hides effects of inaccurate timing during measurement. Furthermore, the average over the multiple measurements of a constant workload allows to compare measurements made with different sampling rates and removes noise from the comparison.

Another synthetic workload is used to evaluate the measurement methodologies with respect to varying frequencies of workload changes (caused by e.g., varying code path lengths). This benchmark alternates between a compute intense and a square root kernel. We use sqrt computations rather than the sleep functionality provided by the operating system. Even though the latter would result in a much greater difference in absolute power usage, it would introduce unwanted and less predictable effects and delays due to C-state changes. A variant of this workload has different times for the high and low period (pulse-width modulation) to analyze aliasing effects and the energy-correctness of different measurement types.

F. Data Processing and Measurement Overhead

We use the Vampir performance analysis toolset to integrate the benchmarking process and the power consumption measurement as well as to evaluate the results [20]. The VampirTrace performance monitor collects application traces that we enrich with power consumption data. The tracing overhead is application dependent and is in our case negligible due to the long duration of the traced functions. VampirTrace features a plugin interface that we use to add energy information to the traces [22]. Our plugin connects to the Dataheap infrastructure to integrate ZES, iDRAC and PDU power consumption information [16]. All Dataheap components besides the plugin itself run on separate servers to eliminate measurement overhead. The plugin collects the samples post mortem, i.e. after the experiment has finished, and therefore does not influence the system under test. This is true for both the ZES LMG450 (AC+DC) and the NI DAQ (DC) measurement.

However, the overhead of the model-based energy estimation is existent and measurable. It can be divided into the VampirTrace overhead and the overhead for accessing the processor registers. The latter is predominant. While we use `pread` in conjunction with the `msr` kernel module to access RAPL data, the APM values are gathered using `libpci`. Reading a single RAPL MSR requires about $0.46\,\mu$s. Reading all RAPL domains on our single socket test system (core, gpu, package) requires $1.4\,\mu$s. On the dual socket system, OS scheduling of the measurement task to the second socket cannot be avoided, thereby increasing the overhead to $8.6\,\mu$s for a full scan (both sockets, each with core, package and dram). For obtaining a single APM value, we read the current TDP capture as well as the TDP-to-Watt translation, and perform a small conversion. This adds up to about $2.4\,\mu$s. However, reading all four APM values consecutively takes about $70\,\mu$s on our 4P test system. The `fam15h_power` kernel module can also be used to access APM via sysfs entries. This does not need privileged access rights but creates an overhead of about $3\,\mu$s. All overheads have been measured at the reference frequency of the systems and are frequency dependent.

An important aspect of the measurement infrastructure is to associate the measured value with a correct timestamp. For RAPL and APM this is straight forward - since the measurement is done on the observed system itself, a local timestamp can be used. This would use the same clock as application instrumentation, so the two can be combined. The only remaining uncertainty is the time it takes to read the actual values and the time to read the local timestamp. This can be mitigated by reading a timestamp before and after the measurement and using an average of both timestamps. The other measurements are taken on different systems that have different clocks. For measurement periods of many milliseconds, as is the case with LMG450, iDRAC and ClustSafe, a synchronization with NTP is sufficient. However a local network time source should be used on all participating systems. The 5 microsecond sampling interval of the NI measurements is way beyond NTP accuracy. To achieve a better synchronization, we generate a defined workload signal before starting each experiment, and detect the resulting signal in the power measurement. The timestamps are then shifted appropriately so that the measured power consumption pattern matches the causal application execution.

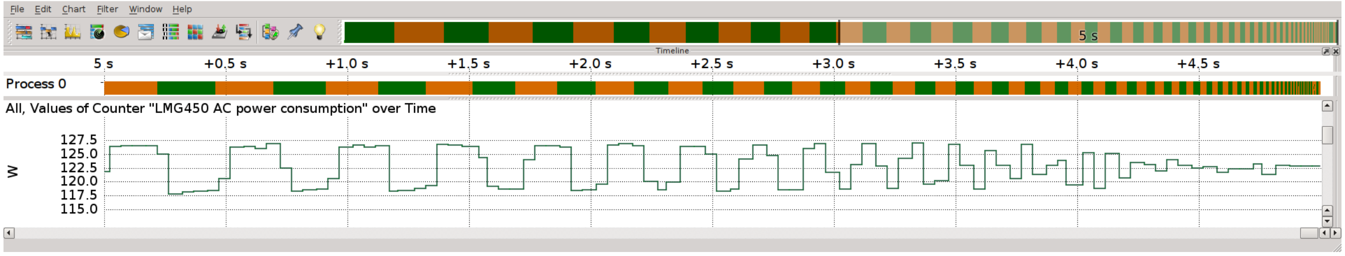


Fig. 2: Measurement on Sandy Bridge 1P using the LMG450 on AC power input with increasing frequency of synthetic workload changes. Orange in the top chart is the high power load (compute), green the low power load (sqrt).

IV. Signal Quality Comparison

In the following we use 'Sa/s' for the number of power samples per second. This always refers to what is exposed to us, e.g. we can gain a maximum of 20 Sa/s from the LMG450, even though the internal sampling rate is at least 50 kSa/s. In case of the NI DAQ card, the sampling rate of e.g., 100 kSa/s refers to the actual physical sampling rate.

As described in Section III-B, the LMG power meter has well-defined specifications, is calibrated and highly accurate. This makes it suitable to provide the reference for other measurement methodologies. We use it for all test systems to measure the AC power consumption with 20 Sa/s. Figure 2 shows for our Sandy Bridge 1P test system that load details of only 50 ms are actually visible with an AC measurement. We have seen identical results on many more test systems than included in this paper. Load details that are shorter than 50 ms are not visible, but the samples provided by this power meter are correct averages. Therefore, integrating over the individual power consumption samples will return a correct result for the energy consumption. This is an important property that can not be taken for granted when using other techniques.

We use the synthetic workloads described in Section III-E to compare the different measurements approaches to our reference power meter. For each workload configuration we average the results of an 8 second window. It is not feasible to compare individual samples, as different measurement methods have different frequencies or timestamps for their samples. The averaging approach also removes noise and aliasing.

A. AC Instrumentation

For the different constant workloads both the IPMI (iDRAC) measurement on Sandy Bridge 2P and the ClustSafe PDU power measurement on Bulldozer 4P are very close to the LMG AC reference measurement, as shown in Figures 3 and 4. The maximum difference between iDRAC and LMG measurement averages is 5 W at a load of 80 W, but 95 % of the measurement averages differ by less than 2 W. For the ClustSafe PDU on the other hand, the biggest difference to LMG measurement averages was 12 W at 732 W total consumption, and 96 % of the measurement averages were within 2 W. In this setup, the measurements of iDRAC and ClustSafe are reasonably exact. However, this can be significantly different in other scenarios with non-constant workloads or individual measurement points rather than 8 s averages.

In order to create a particularly challenging test, we use a workload with 1 s intervals of low power consumption (sqrt kernel) and 0.2 s intervals of high compute load. We set the LMG450 to 20 Sa/s and compute the 1 Sa/s average manually. However, we have verified that this average is not any different from what the LMG450 returns when setting it directly to 1 Sa/s. The LMG450 20 Sa/s measurement (0.05 s sampling interval) shows that the actual AC power consumption fits well to the workload. The LMG450 1 Sa/s plot shows an energy-correct average over 1 s periods. The pattern includes five values that average a 0.2 s peak with 0.8 s of low power consumption followed by one value that does not include

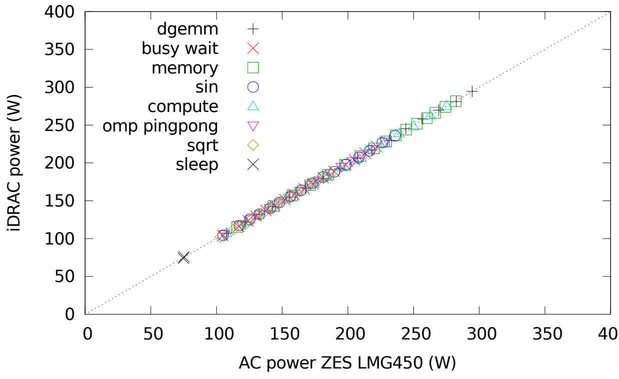


Fig. 3: Correlation between iDRAC power measurement and LMG AC reference measurement on average for different workloads on Sandy Bridge 2P

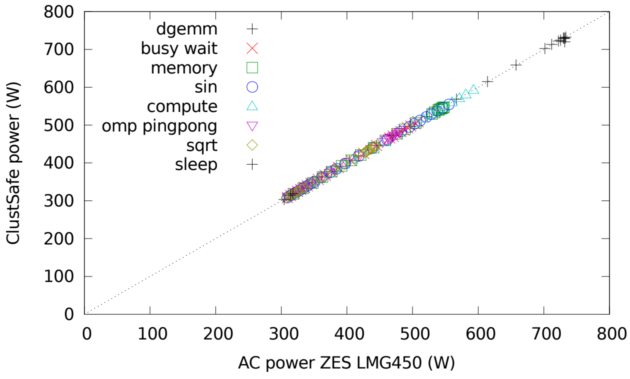


Fig. 4: Correlation between ClustSafe power measurement and LMG AC reference measurement on average for different workloads on Bulldozer 4P

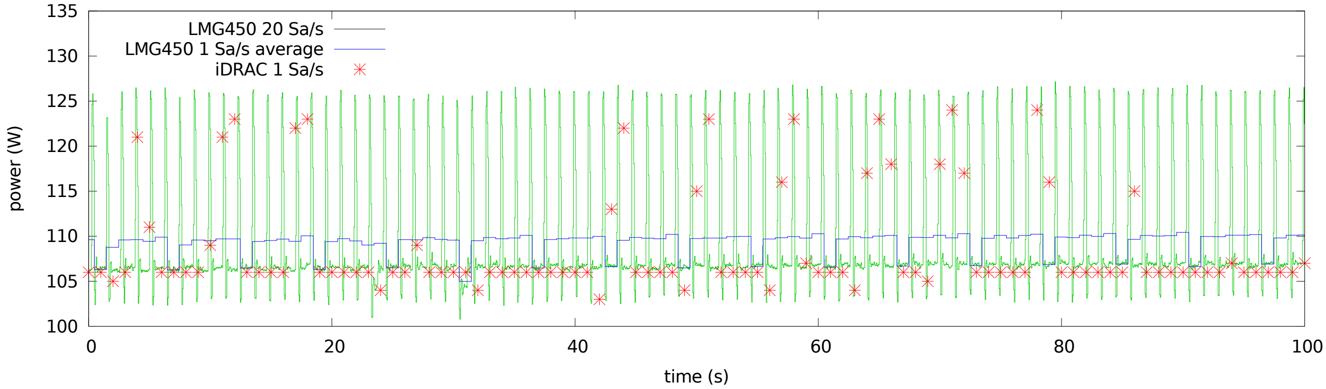


Fig. 5: iDRAC and LMG measurement on Sandy Bridge 2P. LMG 1 Sa/s is computed from LMG 20 Sa/s as average.

the high compute load. This result is correct, even though it naturally can not show the 0.83 Hz workload signal directly. In contrast, the iDRAC measurement shows an irregular pattern that we cannot explain. For the ClustSafe PDU measurements we observe very similar effects. Both devices are clearly not designed for these use cases. In contrast, our extensive tests did never result in any unexplainable data from the professional power meter LMG450. Figure 5 shows the result of the iDRAC measurement and the LMG450 measurement.

B. DC Instrumentation

LMG450: The power consumption of the mainboard (excluding the 12V P8 connector) on our Sandy Bridge 1P test system is almost static. Our measurements range from 33.6 W (idle) to 35.7 W (memory intense workloads). All other workloads average around 34.8 W. It is therefore reasonable to assume the board power consumption as constant. In contrast, the DC measurement of the 12V P8 connector ranges from 1.6 W (idle) to 100 W (Linpack). To better understand the influence of the power supply, we compare the sum of both DC measurements with the AC reference measurement in Figure 6. There is a strongly linear correlation between the two, and the DC power approximation $P_{DC} = 0.948 \times P_{AC} - 6.64W$ is correct within $\pm 0.2W$ for all our measured values.

Hall sensor and data acquisition card: In our setup, the 12V P8 power lane is wired through both the LMG450 and a Hall-effect based current transducer (which is attached to the DAQ card). We use the former to calibrate the latter simply with an offset and a factor. This also compensates the drawback that we only measure current, not voltage, with the DAQ card. Figure 7 shows that the measurements from the Hall sensor are very close to the reference data for constant workloads. Only a minor deviation remains due to the fact that the Hall sensor is highly sensible to changes of external magnetic fields.

The main reason for our use of the Hall sensor is that we can increase the sampling rate by 4 orders of magnitude – from 20 Sa/s to 200 kSa/s. This potentially reveals much more detail regarding the power consumption of small application phases. However, the high sampling rate also captures unwanted small-scale effects such as interrupts. Moreover, the measurement setup introduces significant noise to the measurement signal. Our experiments show that the spectral density is very similar for different workloads, including non-constant ones. It has significant components at 90-100 kHz and about 8 kHz. This is disadvantageous for an energy efficiency analysis of the system and should therefore be removed from the measurement with adequate post processing of the data.

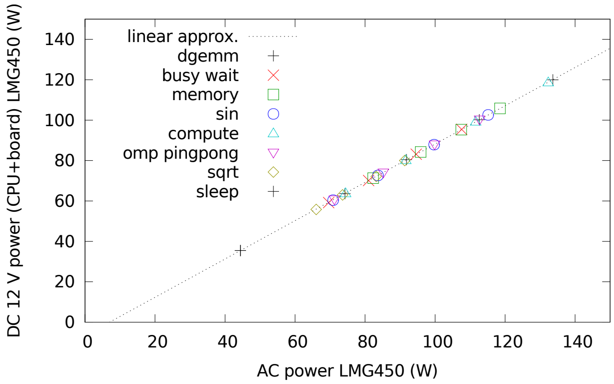


Fig. 6: Correlation between the AC and the DC (CPU/RAM + mainboard) average power measurement (both with LMG450) for constant workloads on Sandy Bridge 1P.

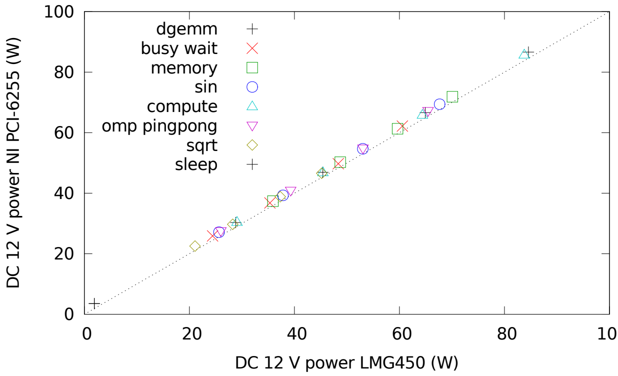


Fig. 7: Correlation between two DC average power measurements for constant workloads on Sandy Bridge 1P: Hall current transducer with NI PCI-6255 DAQ card vs. LMG450.

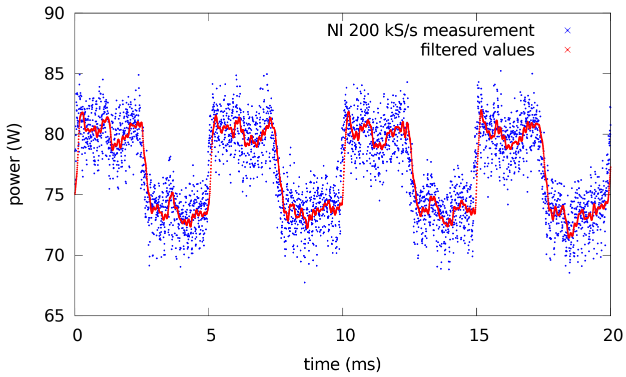


Fig. 8: Filtered and unfiltered power measurement samples on a repeating high/low workload with 2.5 ms each. Filter: Butterworth, 4th order, corner frequency 4.5 kHz

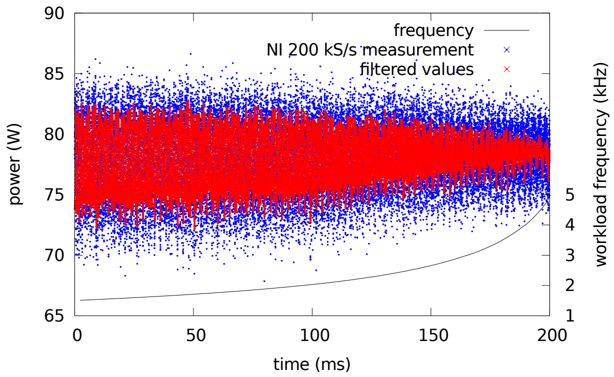


Fig. 9: Filtered and unfiltered power samples on a repeating high/low workload with increasing workload frequency. Filter: Butterworth, 4th order, corner frequency 4.5 kHz

A straight-forward way to deal with this noise is to apply a moving average, which serves as a very simple low-pass filter. However, filters of better quality are available. We use a 4th order Butterworth filter with a corner frequency of 4.5 kHz. It removes high frequency noise well while keeping lower frequencies unaffected. Figure 8 shows the filtered signal and the original with a 2.5 ms high / 2.5 ms low power alternating workload. No vital information is removed by the filter. Other components on the mainboard act as low-pass filter as well. Figure 9 illustrates this effect: Starting from approx. 2 kHz, the amplitude drops even for the unfiltered signal.

C. Energy Model Instrumentation

RAPL: On our Sandy Bridge 1P test system we use the 12V P8 LMG450 measurement as a reference to evaluate the accuracy of the RAPL data. Figure 10 compares the average RAPL package power consumption for different workloads to the reference measurement. The correlation between the RAPL and the reference measurement apparently depends on the workload type. While the computationally intense `dgemm` calculation only shows a small deviation, other workload types–in particular memory workloads–are underestimated by RAPL. This is not entirely surprising, as the Sandy Bridge 1P does not include the DRAM domain for RAPL measurements. It can be noted that RAPL slightly overestimates the idle power consumption compared to the 12 V reference measurement.

For our Sandy Bridge 2P test system we plot the sum of the estimated RAPL package and DRAM power for both sockets in Figure 11. The reference is now the AC power consumption and therefore includes mainboard power, fans, HDDs, and PSU losses. Consequently, the RAPL estimation is significantly lower than the reference on this test system. This offset is consistently 50 W for all workloads. Apart from this offset, the correlation is actually better than on the 1P system. The DRAM power domain significantly improves the correctness of the power consumption prediction.

However, Figure 11 already indicates that even with the DRAM domain, the accuracy of the RAPL extrapolation still depends on the workload being executed. Moreover, there are other options to expose the limitations of the RAPL modeling approach. While we only used physical cores in our previous experiments, Figure 12 highlights workload thread counts that use HyperThreading (by increasing the thread count from 16 to 18, 20, ..., 32). RAPL apparently does not correctly account for the influence of HyperThreading on the power consumption. For the sqrt workload, the reference power consumption decreases with an increasing number of logical threads, but the

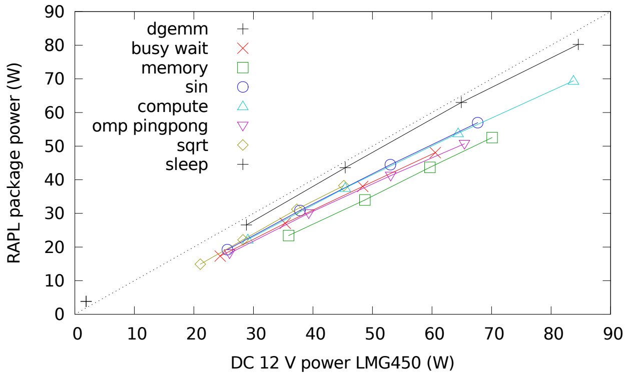


Fig. 10: Correlation between the RAPL measurement and DC power (LMG450) on average for constant workloads. Sandy Bridge 1P, RAPL package, single socket, turbo enabled

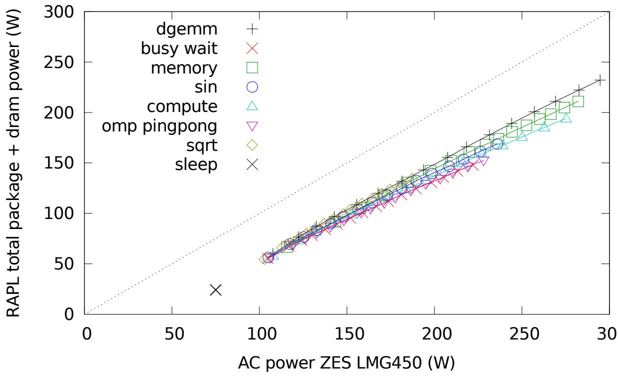


Fig. 11: Correlation between the RAPL and AC power (LMG450) on average for constant workloads. Sandy Bridge 2P, RAPL package + dram, sum of two sockets, turbo disabled

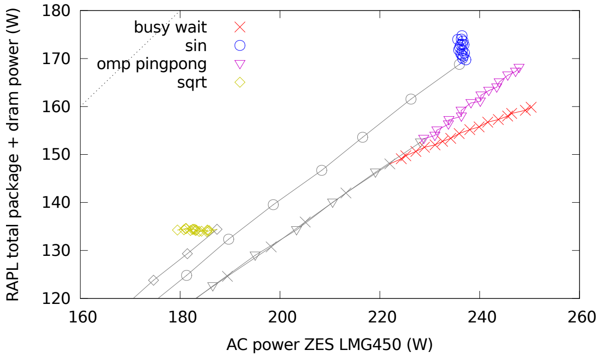


Fig. 12: Correlation between the RAPL measurement and AC power (LMG450). Sandy Bridge 2P, RAPL package + dram, sum of two sockets, hyperthreading

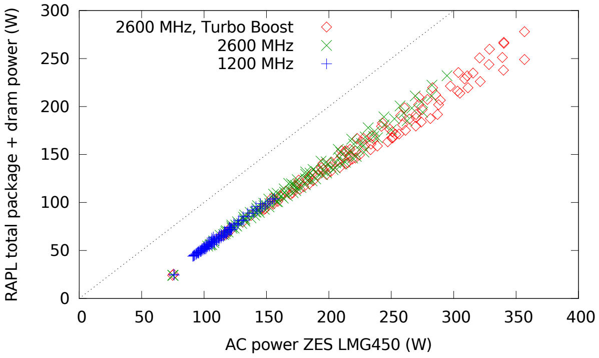
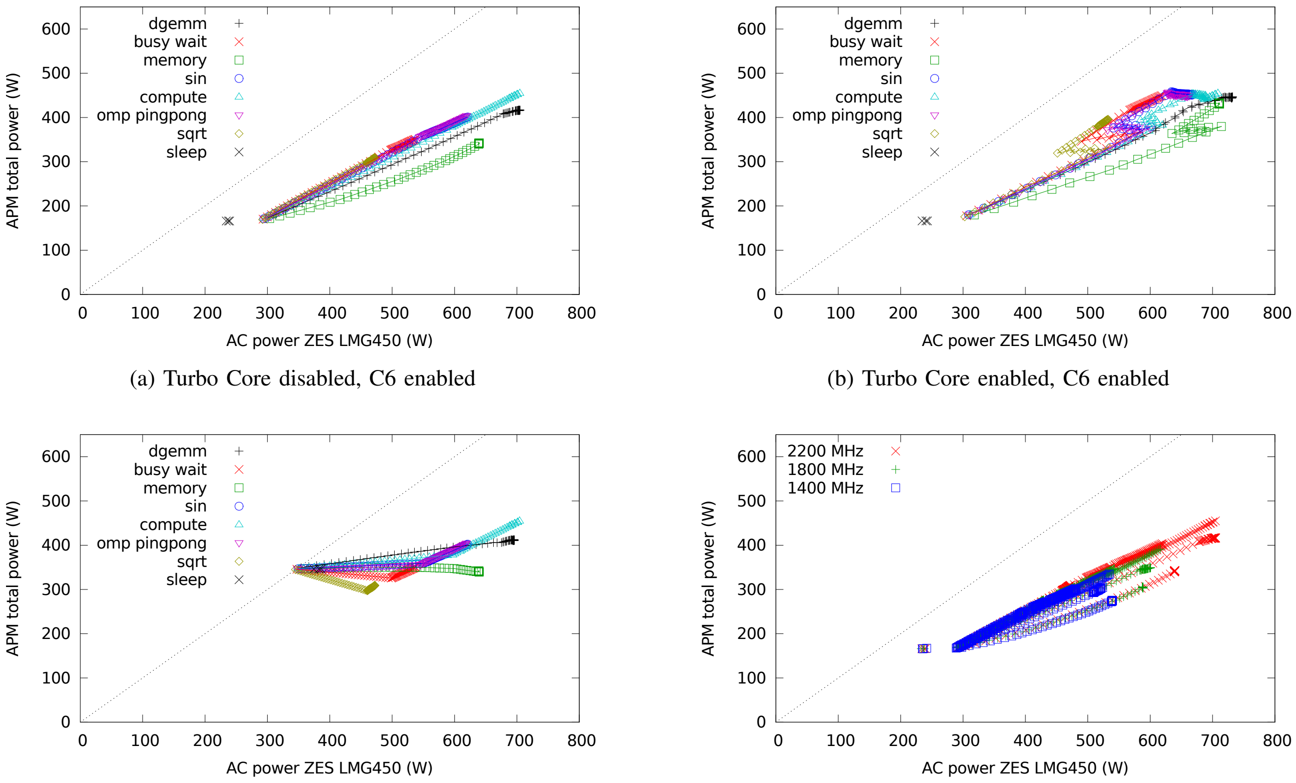


Fig. 13: Correlation between the RAPL measurement and AC power (LMG450). Sandy Bridge 2P, RAPL package + dram, sum of two sockets, different frequency/turbo modes



(a) Turbo Core disabled, C6 enabled

(b) Turbo Core enabled, C6 enabled

(c) Turbo Core disabled, C6 disabled

(d) Turbo Core disabled, C6 enabled, different frequencies

Fig. 14: Correlation between APM (sum of 4 sockets) and AC reference power for constant workloads on Bulldozer 4P.

RAPL estimation remains constant. For the sine workload, the reference power consumption remains constant, while RAPL estimates an increase in power consumption. Although these discrepancies are not large in terms of total watts, they are evidently systematic. Another experiment compares different CPU frequencies (including Turbo Boost) on our Sandy Bridge 2P test system. Since frequency changes are of much interest to optimize energy consumption, it is important that their impact on power consumption is accounted for correctly by the power measurement. The results are summarized in Figure 13 and indicate that RAPL handles Turbo Boost and frequency changes correctly.

APM: Figure 14 shows the results of our experiments with AMD's solution APM. The accuracy of the APM data strongly depends on the system configuration, and we observe the best power estimation with Turbo Core disabled and c-state C6 enabled. As depicted in Figure 14a most of the measurement points show a nearly linear correlation to the reference measurement. Some workload dependency can be observed, as APM systematically underestimates the memory kernel and–to a lesser extend–the dgemm workload. For all other workloads, APM provides a consistent power estimation. Figure 14b shows the same measurements with enabled Turbo Core. For our analysis, the important point to take from this

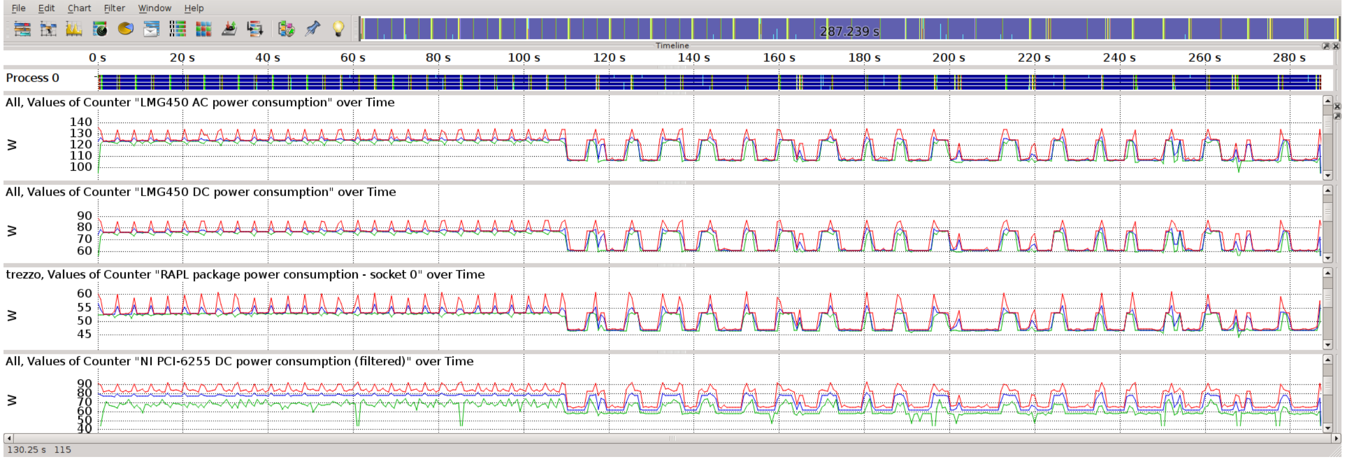

File Edit Chart Filter Window Help
287.239 s
Timeline
0 s 20 s 40 s 60 s 80 s 100 s 120 s 140 s 160 s 180 s 200 s 220 s 240 s 260 s 280 s
Process 0
All, Values of Counter "LMG450 AC power consumption" over Time
W
140 130 120 110 100
All, Values of Counter "LMG450 DC power consumption" over Time
W
90 80 70 60
trezzo, Values of Counter "RAPL package power consumption - socket 0" over Time
W
60 55 50 45
All, Values of Counter "NI PCI-6255 DC power consumption (filtered)" over Time
W
90 80 70 60 50 40
130.25 s 115

Fig. 15: Vampir screenshot of applu with power measurements (full view)

is that APM does not reflect the difference between active and inactive Turbo Core correctly. This results in the specific pattern depicted in Figure 14b. A complete understanding of this pattern would require extensive discussion, but we argue that this pattern is simply a result of the Turbo Core control strategy. In another experiment we have disabled Turbo Core and the C6 state. The result is shown in Figure 14c. In this case, APM fails to give a useful prediction of the processor's power consumption when inactive cores are involved. APM obviously does not account for at least some of the power savings that are enabled through the C-states. One possible explanation is that APM is unaware of the L2 cache flushes and subsequent power gating that occur in C1 state. Similar to the RAPL analysis, our last APM experiment evaluates if different processor frequencies are accounted for correctly by the power consumption model. We disable Turbo Core and use the standard P states of the Bulldozer CPU. The results are summarized in Figure 14d. As with RAPL, the power consumption of different frequencies is estimated correctly by APM.

V. Application Analysis

To optimize the energy usage of complex applications, it is vital to understand how different parts of the application (e.g. functions, parallel regions or different iterations) influence the power consumption of the system. We therefore shift our focus from synthetic workloads to more complex, real-life applications from the SPEC OMP2001 benchmark suite. The Sandy Bridge 1P system is used for this analysis because it has the most detailed instrumentation. Calibrated AC and DC instrumentation, RAPL counters and high resolution 12 V DC NI measurements are available for comparison. The previously described Butterworth filter is applied to the 12 V DC NI measurement data. For the combined analysis of both application behavior and power consumption we use the tools described in Section III-F and examine our traces graphically with Vampir.

Figure 15 shows an overview of the full 287 s application run of the applu benchmark. The top display shows color coded application activity for the four executing threads. Below are the four power measurements with LMG450 (AC,

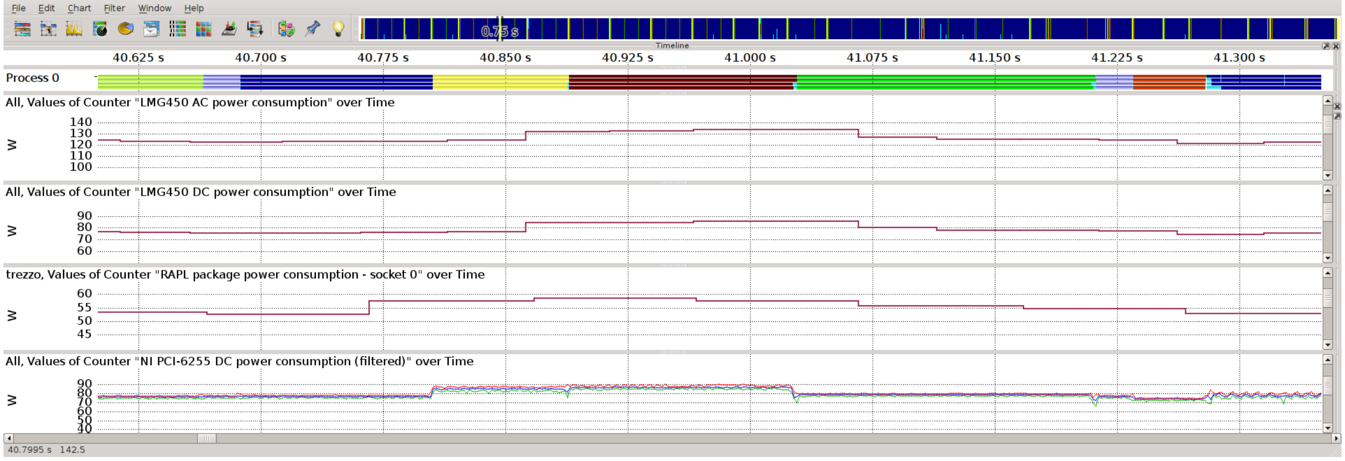

File Edit Chart Filter Window Help
0.75 s
Timeline
40.625 s 40.700 s 40.775 s 40.850 s 40.925 s 41.000 s 41.075 s 41.150 s 41.225 s 41.300 s
Process 0
All, Values of Counter "LMG450 AC power consumption" over Time
W
140 130 120 110 100
All, Values of Counter "LMG450 DC power consumption" over Time
W
90 80 70 60
trezzo, Values of Counter "RAPL package power consumption - socket 0" over Time
W
60 55 50 45
All, Values of Counter "NI PCI-6255 DC power consumption (filtered)" over Time
W
90 80 70 60 50 30
40.7995 s 142.5

Fig. 16: Vampir screenshot of applu with power measurements (zoomed on a 750ms time range); despite the NTP synchronization between measurement and host systems, the measurement from the LMG450 appears to be shifted by several milliseconds.

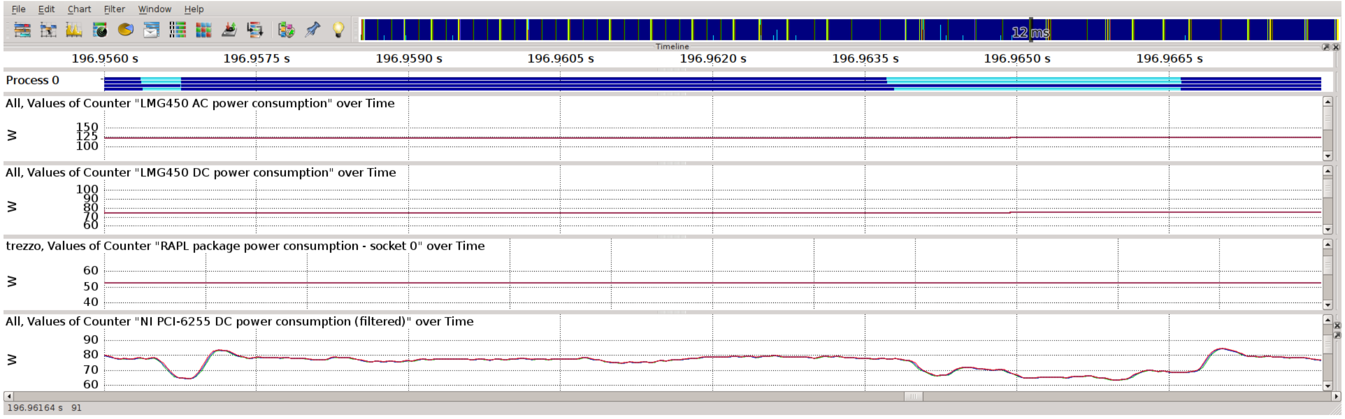

File Edit Chart Filter Window Help
12 ms
Timeline
196.9560 s
196.9575 s
196.9590 s
196.9605 s
196.9620 s
196.9635 s
196.9650 s
196.9665 s
Process 0
All, Values of Counter "LMG450 AC power consumption" over Time
W
150
125
100
All, Values of Counter "LMG450 DC power consumption" over Time
W
100
90
80
70
60
trezzo, Values of Counter "RAPL package power consumption - socket 0" over Time
W
60
50
40
All, Values of Counter "NI PCI-6255 DC power consumption (filtered)" over Time
W
90
80
70
60
196.96164 s 91

Fig. 17: 12ms window of applu; light blue in the top chart is an OMP barrier, dark blue application region.

DC), RAPL, and NI. The red/blue/green lines are the maximum/minimum/average values of time ranges that are to short to be illustrated fully due to the limited pixel resolution. In this view, the average power consumption reported by the different measurement methods is very similar. The NI measurement reveals different minimum and maximum measurement points, since its internal time resolution is much finer. It contains much shorter fluctuations, that are averaged in the 50 ms / 100 ms measurement periods of the LMG / RAPL measurements.

Figure 16 magnifies a 750 ms time frame that includes the execution of various application regions. Using the NI measurement, a specific power consumption profile can be associated to each region. However, this temporal granularity makes it very difficult to see these effects using the LMG450 or RAPL measurements. The temporal resolution of RAPL is too low to clearly identify short code regions. This impedes a clear region-to-power mapping based on measurement methods other than our DC-based NI DAQ card. While there is no IPMI or ClustSafe measurement available for this system, it is evident, that it would reveal no information on this time scale at all. The measurement interval of one second is even longer than the displayed time window.

Figure 17 highlights even more details, in this case a load imbalance between the four threads. The third thread requires more time to execute the 'dark blue' code region. As a result, the other threads wait for it in an OpenMP barrier. The application uses a passive wait policy, so the system power consumption drops significantly during that time. At this time scale, the pattern is only visible to the NI measurement.

VI. Lessons Learned and Best Practices

We have learned a number of lessons. The following are our recommendations for three different scenarios:

Energy consumption measurement of compute job: Temporal resolution is not an issue in this scenario. The best results will naturally be achieved with a professional power meter. The data covers all components, including Disks, Fans, and power supply losses. If this is not an option, data from PDUs or PSUs may be available. This power data is sufficiently accurate as well, but a computation of the energy consumption may be incorrect, particularly for small time spans and very regular workloads. For longer runs it is likely, but not guaranteed, that average values are statistically correct. Regarding Intel's software approach RAPL, our extensive tests with non-constant workloads confirm that the RAPL measurements are not samples but energy correct averages over the last measurement period. However, RAPL only covers the CPU and potentially the DRAM, ignoring other aspects such as fans, disks, and power supply losses. As these are often small and relatively static consumers, a reference measurement using a power meter may provide the necessary information to compute full node energy consumption. AMD's current implementation of APM shows extreme deviations due to highly inaccurate power assumptions during sleep modes.

Low resolution power consumption measurement: In this scenario we are interested in a continuous flow of power measurement data for e.g. a coarse-grained analysis of application phases. It requires a relatively low temporal resolution of about 1 to 20 Sa/s. A fairly common misconception is that AC measurements exceeding 1 Sa/s will not provide additional information due to the large capacitors within the power supply. Our experiments clearly show that load details of only 50 ms can actually be exposed with an AC measurement. We have experienced this on many more test systems than included in this paper, and therefore argue that professional AC power meters are suitable for this type of analysis. Regarding PDU/PSU measurements, our experiments have consistently shown that neither IPMI-based platform power measurements nor values from 'intelligent' PDUs should be used to analyze workloads with temporal effects near the sampling period of these devices. The software approaches RAPL and APM are suitable within the same limitations as described earlier.

High resolution power consumption measurement: This category includes measurement methodologies that capture 100 Sa/s or more. At this rate, an in-depth analysis of individual application phases becomes feasible. AC measurements are not sufficient, and even the applicability of DC measurements is not without dispute. However, our own experiments show surprisingly good results. Even with a simple DC measurement setup, power data with a temporal resolution of about 1 ms can be gathered. It is adequate to measure with at least 10 kSa/s and apply filter techniques to improve the signal quality. The limits in temporal resolution certainly depend on the mainboard design, e.g. capacitor ratings, but we have seen similar results on other test systems. A calibration using a second, more accurate DC measurement approach is advisable. Depending on the mainboard layout, measuring the 12V P8 connector can even increase the spatial resolution. In our case, only the CPU and the non-static part of the DRAM power are connected to this power lane. On this lane we measure a 60-fold variation in power consumption, giving a vague idea of how energy-proportional computing will look like when even more mainboard features move into the CPU. Another popular option is RAPL, as this data is updated roughly every millisecond. Unfortunately, any detailed application analysis is strongly hindered by the fact that RAPL provides energy (and not power) consumption data without timestamps associated to each counter update. This makes sampling rates above 20 Sa/s unfeasible if the systematic error should be below 5 %, effectively eliminating the advantage in temporal resolution that RAPL has compared to AC measurement techniques. Constantly polling the RAPL registers will both occupy a processor core and distort the measurement itself. However, this can be an option if the power consumption overhead and potential other side effects are considered carefully, and if the target application does not require all processor cores.

The value of the Intel RAPL interface could be greatly improved by either reporting both power and energy in the RAPL registers, or by associating timing information with every update of the energy counter. For the AMD APM interface, an improved accuracy–particularly regarding sleep state power consumption–is the most urgently needed improvement.

VII. Conclusion

This paper provides an overview of a number of different power consumption measurement methodologies that may be used primarily in academic, energy-efficiency related research projects. In this field, a number of different and often opposing requirements exist, as well as test setups that do typically not meet industry lab standards. We verify the data using a calibrated, professional power meter. Based on our experiences, we present recommendations for three typical research scenarios.

We find the AC power consumption data provided by PDUs and PSUs to be reasonably accurate. Deriving energy data from these power values, e.g. for energy-based job accounting on HPC systems, is suitable in most cases. The modeling approaches provided by Intel (RAPL) and AMD (APM) provide data of varying quality. APM suffers from systematic inaccuracies that we blame on the novelty of this interface and that will likely improve in the future. For RAPL, implementations that include the DRAM plane can be mostly accurate. Unfortunately, any detailed application analysis is strongly hindered by the fact that RAPL provides energy (and not power) consumption data without timestamps associated to each counter update. This mostly eliminates the advantage in temporal resolution that RAPL has compared to AC measurement techniques. Finally, our DC power measurement setup using a Hall sensor and a fast data acquisition card shows surprisingly good results. Even though the setup is relatively simple, accurate power data with a temporal resolution of about 1 ms can be gathered.

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