MODELING SYSTEM POWER CONSUMPTION CONSIDERING DVFS AND THERMAL EFFECT

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Abstract: Increasing energy efficiency for a single system or data center is gaining much interest among IT operators and researchers. There has been lots of research focused on improving energy efficiency by analyzing existing systems and proposing a new system architecture. The most fundamental part of improving energy efficiency is to accurately and efficiently measure the power consumed by the servers. In this paper, we model the power consumption of a single server with resource utilization considering two factors, DVFS and thermal effect.

1 INTRODUCTION

Increasing energy efficiency of a single system or data center is gaining much interest among IT operators and researchers. Recent advances in cloud computing and distributed systems are accelerating the energy usage in data centers. This trend is causing increased operating cost and environmental concerns. Therefore, maximizing energy efficiency is a key issue for IT operators. There have been lots of research focused on improving energy efficiency by analyzing existing systems and proposing a new system architecture. Several research papers propose methods to use low power processors or SSDs to improve energy efficiency (Vasudevan et al., 2011; Andersen et al., 2009; Caulfield et al., 2009). Scaling down the cluster in distributed systems is another way to effectively improve energy efficiency (Chun et al., 2010; Harnik et al., 2009).

The most fundamental part of improving energy efficiency is to accurately and efficiently measure the power consumed by the servers. The simplest method is to directly measure the power consumption of the servers by using hardware such as power meters. However, it is not practical to attach power meters to all the running servers due to economical reasons. Therefore, there have been several research which use inference techniques to indirectly measure the power consumption of servers. Rivoire et al. analyzed several methods to model the power consumption of a single system (Rivoire et al., 2008). Initial effort was to use resource utilization to infer the power consumption (Fan et al., 2007; Qureshi et al., 2009). Recent research uses performance monitoring counters to measure the power consumption of servers (Kansal et al., 2010; Koller et al., 2010). We can obtain lots of information from the performance monitoring counters such as cycles per clock or number of L3 cache misses.

However, existing literature lacks the following. The first is that they do not consider the intrinsic power management of processors. Modern processors employ Dynamic Voltage and Frequency Scaling (DVFS) to dynamically adjust its frequency and voltage depending on the load. A few of previous literature mention that it is necessary to consider DVFS in the power consumption model. However, none of authors give any specific power model considering the DVFS. Secondly, there is no power model that considers thermal effect as well. Since the change in temperature affects the power consumption of CPU, this factor must be considered in modeling the power consumption.

In this paper, we model the power consumption of a single server with resource utilization. In our model, we consider two factors, DVFS states and thermal effect. Our assumption is that we can infer the power consumption of a single system by measuring the power consumption of the CPU since CPU consumes most of the power provided to the system. Several work already employ this assumption (Fan et al., 2007; Qureshi et al., 2009). To model the power consumption, we analyze the power consumption of a server while 1) changing the CPU frequency and 2) changing the temperature of the CPU. With this analysis, we propose a power model of a single sys-

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tem with CPU utilization and CPU temperature. Our model shows accurate estimation and similar trend to the actual power consumption.

2 MODELING POWER CONSUMPTION

We analyze the power consumption of a single server while varying the frequency and the temperature of the CPU.

2.1 DVFS and Thermal Effect

In current Linux, DVFS is controlled by a *governor*. Users can configure the governor as one of the followings, *performance*, *ondemand*, *conservative* and *powersave*. Under performance governor, CPU runs at its maximum frequency, whereas CPU runs at its minimum frequency under powersave governor. Ondemand governor periodically checks the current CPU load and maximizes its frequency if the current load is higher than the system threshold. Conservative governor is different from the ondemand governor in that it increases its frequency step by step. Since the ondemand governor shows the minimum frequency and the maximum frequency under idle and peak load, respectively, we configured the server with ondemand governor.

We show the power consumption and the temperature change of a single server in Fig. 1. Our target server has one quad-core processor with hyper threading disabled. We execute four CPU *stress* test programs simultaneously and measure the power consumption of the system with Yokogawa WT210 power meter. And we also measure the temperature of CPU from both inside and outside.

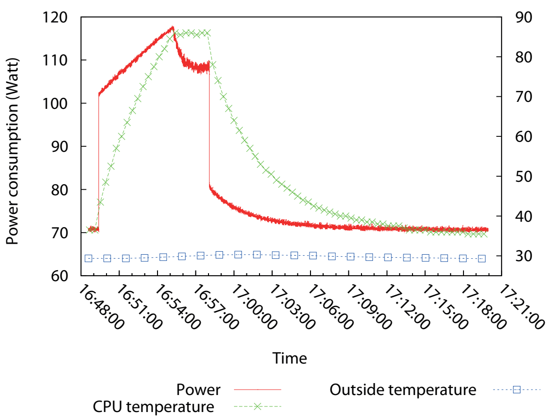


Figure 1: The change of power and temperature.

The server consumes about 70 W when it is in idle state. We executed CPU stress test processes at around 16:49 and killed them at around 16:58. Four processors run at their maximum frequency and the power increases up to 102 W. After that, the power consumption continuously rises until the power reaches around 117 W even though the utilization remains the same - 100%. This is due to the increased temperature of the CPU. In the figure, the temperature of the CPU increases from 35.5 °C to 86 °C. Even if all the processes are killed, the power consumption at that time is about 10 W higher than that of the initial power consumption. Note that the utilization of both of the cases is the same - 0%. This is caused by the increased CPU temperature.

When the power consumption reaches the maximum, the power suddenly drops to around 109 W and becomes stabilized. This is because the CPU temperature has reached the critical CPU temperature. As shown in the figure, the CPU temperature does not increase after the power consumption reaches the maximum. The CPU itself adjusts the frequency of the CPU cores in order to maintain the temperature of the CPU (this is called the CPU thermal throttling). This is shown in Table 1. In this table, we show the fraction of the time consumed in the frequency of the four cores while the CPU temperature stays at its critical value. Since the governor is set to the ondemand governor, the frequency of the cores should stay at their maximum frequency, which is 2.83 GHz in our case. However, the actual frequency of the cores shows abrupt changes so that the temperature is maintained in a certain level. For all the cores, the frequency was transitioned to its minimum about one fourth of the execution time. In this case, the temperature is maintained at around 86 °C.

We also show the power consumption when the cores run with different frequencies.

Table 1: The fraction of the time consumed in CPU frequencies during CPU throttling.

Core	2.83 GHz	2.33 GHz	2.00 GHz
0	0.74	0	0.26
1	0.72	0	0.28
2	0.70	0	0.30
3	0.74	0	0.26

Table 2: Power measurement with different CPU frequencies.

Frequency	idle	peak
2.00 GHz	70.2 W	85.2 W
2.83 GHz	71.2 W	102.5 W

We execute the same jobs and maintain the utilization of 100% for all the cores. The result is shown in Table 2. Although the utilization of both of the frequencies is the same, the difference of the power consumption is fairly large. The gap becomes larger if the difference of the frequency becomes larger.

From this observation, we claim the following results. First, the thermal effect on CPU power consumption is not ignorable since high temperature can result in extra power consumption and the CPU frequency throttling. Second, we cannot use the CPU utilization only as a metric to measure the system power consumption. This is due to the fact that even if the system is in full utilization, the DVFS can restrict the frequency depending on the DVFS governor. Since the power consumption of the full utilization under different frequencies is different, we should consider the DVFS states in the power consumption model.

2.2 Power Model

Our assumptions are as follows.

- CPU can have heterogeneous cores, which means that the available frequencies of each core in the same CPU packages can differ.
- We use the CPU utilization as our metric to measure the system power consumption. This assumption is generally used in previous literature.

We model the current power consumption of server n by the following equation.

$$P_n = P^r + \Delta P^t \,, \tag{1}$$

where P^r is the power consumed by the computing resources and ΔP^t is the change on power incurred by the thermal effect.

We first model the power contributed by the computing resources in the following equation. We model P^r as the sum of the per-core power consumption. The basic formula is similar to one presented by Fan et al (Fan et al., 2007). The basic power consumption formula has the following form,

$$P_n = P_i + u(t) \cdot (P_p - P_i) \,, \tag{2}$$

where P_i and P_p are the power consumption when the system is in idle and peak state, respectively. $u(t)$ is the utilization of the current time. Although Fan et al. use heuristics computing $u(t)$, the principle is the same - interpolating the idle and peak power consumption depending on the utilization. We modified their model to reflect the frequency of each core.

We modeled it as the following equation.

$$P^r = P_i + \sum_{c \in C_n} P^r(c) \,, \tag{3}$$

where P_i is the system idle power consumption, C_n is the set of CPU cores of node n and $P^r(c)$ is the power consumption contributed by the core c of node n. $P^r(c)$ can be computed as follows.

$$\begin{aligned} P^r(c) = {} & u(c) \cdot \{\Delta P_i(s(c)) + \\ & (P_p(s(c)) - P_i(s(c)))\} \,, \end{aligned} \tag{4}$$

where $u(c)$ is the utilization of the core c of node n and $s(c)$ is the DVFS state (frequency) of core c. Therefore, $\Delta P_i(s(c))$ is the increased idle power consumption when the core c is in state $s(c)$. Similarly, $P_i(s(c))$ and $P_p(s(c))$ denote the idle and peak power consumption when the core c is in state $s(c)$.

Now we elaborate more on the power model with the thermal effects. The basic model is similar to the model proposed by Fan et al. in that we interpolate the idle and peak power. In contrast to the power consumption contributed by the computation, we use system wide utilization to model the power consumption contributed by the thermal effect. The power consumption is shown in Eq. 5.

$$\Delta P^t = \Delta P_i{}^t + u_t \cdot (\Delta P_p{}^t - \Delta P_i{}^t) \,, \tag{5}$$

where $\Delta P_i{}^t$ is the least and $\Delta P_p{}^t$ is the highest power consumption incurred by the thermal effect. u_t is the ratio of the current temperature to the peak temperature, which we compute as the following equation.

$$u_t = \frac{t_p - t_c}{t_p - t_i} \,, \tag{6}$$

where t_c, t_i and t_p denote the current CPU temperature, the lowest and the highest CPU temperature, respectively. We normalize the temperature to the highest temperature so that we can obtain the power increase due to the thermal effect.

3 MODEL EVALUATION

We evaluated our model with several benchmark programs. First, we used the stress benchmark program for the first experiment which we used in Section 2, and also used SPECpower (SPECpower, 2011) for the second. SPECpower is a software benchmark tool to measure the power efficiency of the target system. The parameters used in our server are shown in Table 3. We obtain the values by measuring the power consumption with various CPU DVFS states.

Table 3: Parameters used in our server.

P_i	70.2 W
P_p	118.07 W
ΔP_i^t	0 W
ΔP_p^t	16 W
t_i	32 °C
t_p	86 °C
$\Delta p_i(2.00\text{ GHz})$	0 W
$\Delta p_p(2.00\text{ GHz})$	3.56 W
$\Delta p_i(2.33\text{ GHz})$	0.5 W
$\Delta p_p(2.33\text{ GHz})$	6.2 W
$\Delta p_i(2.83\text{ GHz})$	1 W
$\Delta p_p(2.83\text{ GHz})$	8.04 W

We first show the result when we execute the CPU intensive processes as we did in Section 2. We execute four CPU stress test programs simultaneously and measure the power consumption with the other model, which is proposed by Fan et al. The result is shown in Fig 2. As shown in the figure, Fan's model is very different from the actual power consumption since they do not consider DVFS and temperature. Their model maintains the maximum power consumption since utilization of the system is 100%. When the system utilization drops to zero, their model immediately drops the power consumption to the minimum. However, our model shows changes according to the frequency change and gradually increases the power consumption according to the CPU temperature. Our model also reduces the power consumption when the load is dropped to zero which shows similar pattern with the actual power consumption.

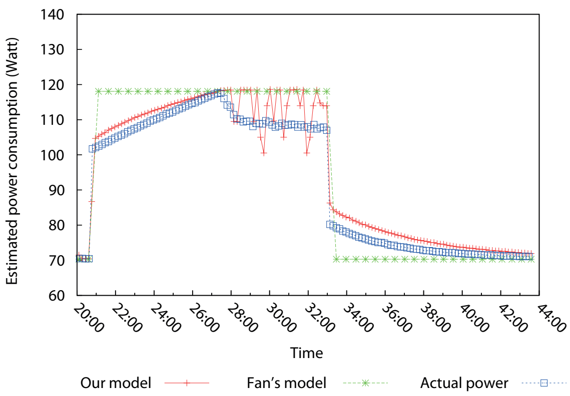


Figure 2: Comparison of estimated power consumption and actual power consumption when CPU stress test programs are executed.

In the next experiment, we use SPECpower to evaluate our model. During the execution, SPECpower maximally utilizes the system to obtain

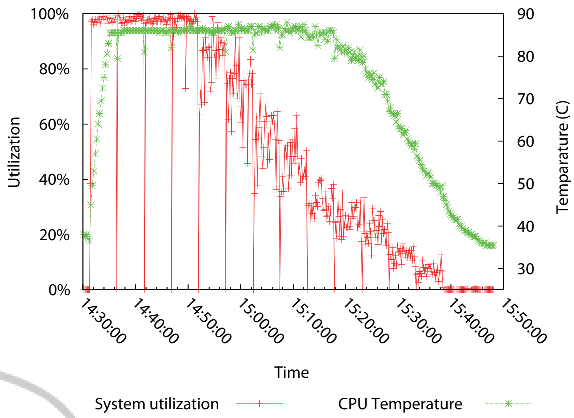
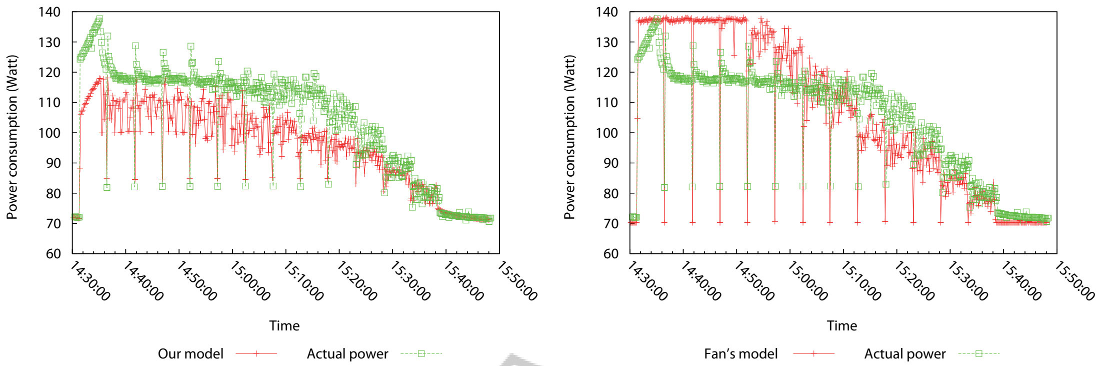


Figure 3: System utilization and CPU temperature when SPECpower is executed.

the maximum throughput of the target system. After that, SPECpower imposes specific load on the system so that it can obtain the throughput depending on the load. The system utilization and the temperature during the execution are shown in Fig. 3. After three calibration periods, SPECpower imposes load on the system by decreasing the load by 10% until the load reaches 0. The utilization curve shows this trend.

We show the estimated power consumption by our model and Fan's model in Fig. 4. Actual power consumption is also shown in the figure. First of all, the curve of actual power consumption is similar to the CPU temperature curve of Fig. 3. The utilization curve in Fig. 3 drops faster than the CPU temperature, which means the utilization curve is not similar to the actual power consumption curve. Although a lot of existing literature uses the utilization to measure the power consumption, this graph shows that the power consumption is more dependent on the CPU temperature. This proves that our model is more accurate than those use only utilization. The main difference between the actual power consumption and our estimated model is that our model does not count for other resources. Since SPECpower heavily uses disk and memory, actual power consumption is larger than the estimated power consumption by our model. Now we compare our model to the model proposed by Fan et al. Since Fan's model is solely dependent on the utilization, their model does not fit the actual power consumption. Even though their model considers other resources (ex. memory, disk, and network) as well, the estimated model does not go along with the curve of actual power consumption. Because it uses a heuristic method, it produces higher power consumption than the linear model in general.



(a) Our model and actual power consumption. (b) Fan's model and actual power consumption.

Figure 4: Comparison of estimated power consumption and actual power consumption when we execute the SPECpower.

4 CONCLUSIONS

Improving energy efficiency is becoming a key factor in distributed systems. The most fundamental part is to accurately and efficiently measure the power consumption of a single system. In this paper, we proposed a power consumption model which considers the intrinsic power management of processors and the thermal effect. Our model fairly fits the actual power consumption for CPU intensive and moderate benchmark programs. Our future work is to infer the CPU temperature through utilization so that we can support systems which do not have CPU temperature sensors.

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