Analysis of The Enhanced Intel® Speedstep® Technology of the Pentium® M Processor

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Overview

- Mobile computers challenges
  - Energy and Average power
  - Thermal Design Power
- Intel® Pentium® M power management
- The experiments
- Test results
- Conclusions
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Power & Density increases

- Think Watts/Cm²
  - Complex architecture at faster and smaller technology
  - Denser power is harder to cool

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The Mobile Environment

- Maximize performance & features within given constraints
  - Power / Thermal
  - Size – form factor
  - Noise
  - Energy / Battery life
  - etc.

- Mobile platforms offer Tradeoff preferences
  - User defined or built-in scheme
    - Compromise performance for longer battery life, lower acoustic noise, cool box etc.
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Die Temperature measurements

- Temperature based control mechanisms
- A diode connected to an external A/D - reports temperature
- Fixed temperature sensors
  - Max spec junction temperature
  - Critical temperature detector

\[
T = \frac{\Delta V_{BE}}{n \cdot \ln(N) \cdot \frac{k}{q}}
\]

- \(n\): diode ideality factor
- \(k\): Boltzmann constant
- \(q\): electron charge constant
- \(T\): diode temperature (Kelvin)
- \(V_{BE}\): Voltage from base to emitter
- \(I_c\): Collector current
- \(I_s\): Saturation current
- \(N\): Ratio of collector currents
Controlling TDP - Linear

- P states and T states

Temp.

Power

Clock

TDP

Trigger

P>TDP
Controlling TDP - Linear

- Self or S/W trigger – Stop clock asserted, Power and temperature drop

Diagram showing:
- Trigger
- Temperature (Temp.)
- Power (P>TDP)
- Clock
- STOPCLK
Controlling TDP - Linear

- STOPCLOCK continues toggling for a pre defined time
- Average power and temperature drop – performance drops

Trigger

Thermal significant time

Average Temperature

Average Power Reduced
Controlling TDP - Linear

- STOPCLOCK continues toggling for a pre defined time
- Average power and temperature drop – performance drops

Trigger

Thermal significant time

Average Temperature

Full Power

Leakage

Average Power Reduced

Linear dependency (<1:1)
Power to Performance
Energy = P*t → no gain
Leakage impacts energy
Dynamic Voltage Scaling (DVS)

- One μ ARCH implementation – Power and energy control

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Clock

Vcc

Power

Switch

Thermal or Utilization

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Dynamic Voltage Scaling (DVS)

- PLL relock at lower frequency at same Vcc
- Fast change – no user experience impact

Short time O.K with S/W
Dynamic Voltage Scaling (DVS)

- Vcc drops gradually while CPU active
- Power savings changes from linear to $F^3$

Power savings > time increase
Energy net savings

Clock

Vcc

Power

Performance drops by Function of F (Frequency)

CPU power drops by $P=C*V^2*F \Rightarrow \text{function of } F^3$

Power savings > time increase
Energy net savings
Dynamic Voltage Scaling (DVS)

- Vcc is ramped up increasing power
- Once stable – PLL relock at high frequency
Adaptive Energy Control

- Applications have wide dynamic power range
- Require high power high performance bursts
  - Determine user experience
- Trade power performance as needed
  - Driven by Operating system ACPI
  - Average power control on the fly - ADAPTIVE
ACPI Control

- Operating system feature – Industry standard
  - Supported by MS and Linux
  - Passive and active policies defined for each zone
  - User preference – Max performance or Max battery
    - Switches _PSV and _ACx
  - DVS or clock throttling used for passive power control
    - Available Power states published by BIOS
    - DVS and once reached min Vcc - linear
    - Implements PD controller algorithm
  - Fan on/off and speed used for active cooling

- Diagram showing temperature and frequency over time.
Duty cycle: 0.8

Test name: Adjustable power test (duty cycle: 0.8)
Test version: 1.1
Utils version: 1.1
Compiler: Visual C++, Win32
Press escape to stop
On loops: 80000, Off loops: 239

PO: 600 MHz
Duty cycle: 0.9
Test name: Adjustable power test (duty cycle: 0.9)
Test version: 1.1
Tools version: 1.1
Compiler: Visual C++, Win32
Press escape to stop
On loops: 80000, Off loops: 239

Processor Frequency:
Start Control
Start Workload

Results:

Writing to C:\Program Files\Intel Corporation\TAT\Results.txt
Writing to C:\Program Files\Intel Corporation\TAT\Results.txt

Temperature

100°C
0°C
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Test Setup

Thermal control

- CPU temperature is a function of power and ambient temp.
  - Long time to heat the ambient and heat sink
- Case temperature control formed stable environment
  - Heating plate and fan to keep temperature at fixed temperature
  - Force extreme conditions

Test cases

- SPEC-Int and SPEC-FP components
- Used the self trigger mechanism
  - For repeatable & consistent results
- Collected power temperature and performance

Testing on real silicon the theoretical expected behavior

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Lineal vs. DVS control

Thermal Throttle impact

SPEC2K Performance [% of max]

Cooling [% of max]

Start Throttle

Higher temp. Less cooling

Linear

DVS
Lineal vs. DVS control

Thermal Throttle impact

SPEC2K Performance [%]

Cooling [% of max]

- Higher temp. Less cooling -

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Lineal vs. DVS control

Thermal Throttle impact

- Shallow Slope: More cooling at same performance
- Higher temp. Less cooling

SPEC2K Performance [%] vs. Cooling [% of max]

- Linear
  - ~3%
  - ~4%
  - ~5%
  - ~6%

- DVS

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DVS set point

Throttle impact on performance

Optimal point (performance) is at the highest frequency that does not exceed $T_{j\text{max}}$ with no transitions up and down.

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Average Power management

- Average CPU Power [W]
  - 0.37: Lowest freq.
  - 0.6: 66% Power Efficiency 1:1.4 - Static
  - 1.1: 48% Performance

- Mobile Mark 02 [Score]
  - 112: 600 MHz Power saving (Battery)
  - 216: 1600 MHz Performance (AC)
Average Power management

- 48% Performance, 66% Power Efficiency 1:1.4 - Static
- 10% Performance, 43% Power Efficiency 1:4

600 MHz Power saving (Battery)
600 – 1600 ADAPTIVE
1600 MHz Performance (AC)

Average Power Score

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Energy efficiency

- Energy consumed for the SPEC-Int and SPEC-FP
  - We measured energy as $E = \int P(t)$
  - Energy consumed at 1600 MHz defined as 100%

![Energy efficiency graph]

Lowest energy at lowest frequency
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Summary and Conclusions

- **Intel Pentium M** Specifically designed for mobile
  - Targeting energy and power efficiency

- **Mobile systems trade performance for power**
  - To meet user preference

- **Enhanced Intel SpeedStep Technology** provides significantly improved power to performance and energy control scheme
  - Silicon measurement confirm the theoretical work
  - Optimal point for performance to power is at the highest frequency that does not exceed $T_{j\_max}$
    - Policy implemented into ACPI algorithm
  - Optimal point for energy and battery life is at the minimum frequency possible with DVS
Thanks

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Die Temperature measurements

- A diode connected to an external A/D reports temperature
- Fixed temperature

\[ V_{BE} = \frac{n k T}{q} \cdot \ln \left( \frac{I_C}{I_S} \right) \]

\[ T = \frac{\Delta V_{BE}}{n \cdot \ln(N) \cdot \frac{k}{q}} \]

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Controlling TDP - Linear

- STOPCLOCK continues toggling for a pre defined time
- Average power and temperature drop – performance drops

![Diagram showing temperature, power, clock, and STOPCLK signals over time.]

**Trigger**

**Thermal significant time**

- Temp.
- Power
- Clock
- STOPCLK

**P>TDP**
Dynamic Voltage Scaling (DVS)

- Vcc drops gradually while CPU active
- Power savings changes from linear to $F^3$

CPU power drops by $P=C\cdot V^2\cdot F \propto function of F^3$

Performance drops by Function of $F$ (Frequency)
The Pentium M Power Control Schemes

**Linear power scaling**
- Change CPU frequency only
  - reduces both power and performance linearly with frequency
  - Saves power, No energy savings

**New Dynamic Voltage Scaling (DVS)**
- Reduces Voltage and frequency on the fly
  - Frequency is dependent ~ linearly on Voltage
  - Power is a function of $C*F*V^2$
- Reduction of both voltage and frequency provides $F^3$
  - power reduction for linear performance reduction
  - Also results with energy savings
ACPI Interface

Power Scheme settings
Shut off devices and timers you don’t need.

Use extended power schemes to manage power according to your needs. Select an extended power scheme and click OK, or click Create New Power Scheme to create a customized scheme.

List of Predefined Power Schemes
- Personal
- Super Power Saver
- ThinkPad Default
- High Battery Performance
- High Battery Performance
- CD Audio
- Word Processing/E-mail
- Dark Room
- Word Processing/E-mail
- High System Performance
- High System Performance

Super Power Saver
When using battery power:
- System standby: 5 mins.
- Turn off monitor: 3 mins.
- LCD brightness: Level 0 (Low)
- Turn off hard disks: 3 mins.
- CPU speed: Slow

Maximizes your power savings.
The Pentium M Power Control Schemes

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**New Dynamic Voltage Scaling (DVS)**
- Reduces Voltage and frequency on the fly
- Reduction of both voltage and frequency provides $F^3$ power reduction for linear performance reduction

- See details…