Foxton Technology

HotChips 2005

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Intel Corp.
The Power Problem

- Power consumption is a primary limiter in today’s processors and unfortunately, it varies a lot
  - Part to part (processing)
  - As a result of the application
  - Due to temperature

Measured data of multiple Montecito parts: Power vs. part speed
The Power Problem

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Measure Montecito core power vs. application
Current Approaches to Power Management and Reduction

• Split out the thermal power spec from the max electrical power spec
  – Use “Thermal Design Power” (TDP) to spec a sustained power that is lower than the true maximum (“electrical power”)
  – Counts on the rarity of very high power events
  – Relies on a thermal sensor to throttle the part if it’s too hot
  – Allows a lower cost thermal solution, but power supplies and power delivery must still handle the max electrical power

• Dynamic Voltage Scaling (C states/P states)
  – Conserve energy when the processor is under-utilized to reduce average power

• Fuse in a Vcc that is part-specific
  – Higher power but faster parts can use a lower voltage at the same frequency
The Ideal Power Management for Servers and Desktop

- We currently over-design our power supplies and thermal solutions for worst case parts and applications
- Most of the time the part isn’t fully using the watts we’ve allocated for it
  - Lower power applications only run as fast as the highest power ones

=> We want to maximize performance / Watt for all situations

=> We want a processor to adapt operating point dynamically to it’s situation

This is what Foxton Technology does
What is Foxton?

• An integrated system that dynamically maximizes performance per watt including
  – Accurate, integrated power measurement
  – Integrated temperature measurement
  – Frequency control to maximize hertz/volt
  – A microcontroller to incorporate instantaneous \{power, temperature, voltage, frequency\} and optimize the operating point

• The result is processor cores doing their computation at optimal power efficiency
High Level View of System

10s of µs

Power Sensor → Micro-Controller → Supply VRM

Thermal Sensor → Micro-Controller

100s of ps

Voltage Sensor → Voltage to Freq. Converter → Clock
Power Consumption Contour

Optimization point is for typical *integer* applications which have .6X the switching power of the worst case

⇒ Amdahl’s law

Manufacturing test is accomplished by observing the *self measured power*, and the *self-generated frequency* for typical code at the power limit
Measuring Power

- Use package resistance to measure power
- Avoids burning extra power in measurement
- Portable, self-contained solution
  - No dependence on external power supply
Power Control System

- $P_{\text{Limit}}$
- $V_{\text{Connector}}$
- $V_{\text{Die}}$
- $R_{\text{Package}}$

Blocks:
- IIR
- DAC
- Calc
- A/D
- Micro-Controller
- Power Supply
- Package/Die
Temperature Measurement

- Calibrate the voltage drop at test to $T_J$ target (90°C)
- Use the known -1.7mV per degree C temperature coefficient to calculate die temperature
- Measure the voltage drop across the diodes every 20ms

![Diagram of temperature measurement system]
Package Resistance Calibration

- Package resistance can be computed with two voltage measurements with processor stalled:
  - Pulling quiescent current $I_0$
  - Pulling $I_0 +$ a precision, on-die generated current $I_{\Delta}$
- On-package precision R for consistent $I_{\Delta}$
- 66ms recalibration rate

$$R_{Package} = \frac{(V_{c2} - V_{d2}) - (V_{c1} - V_{d1})}{I_{\Delta}}$$
Frequency vs. Power Limit
Measured Data
Core 0, Core 1, Avg Frequency vs. $P_{\text{Limit}}$

A 31% power redux for a 10% frequency hit
Managing Frequency

- Voltage variability costs frequency and hence performance/watt
- A clock system that can track rapid voltage changes will both maximize hertz/volt and provide smooth response to micro-controller induced voltage changes

Today: Minimum Vcc(t) determines maximum frequency.
Foxton: Average Vcc(t) determines average frequency.
A Variable Frequency Clock System

Bus Clock (200MHz) → PLL

1/M (M=10) → Fmax (2.0GHz)

DFD (D=16) → L0

DFD (D=16) → SLCB

I/Os (1.6GHz) → Bus Logic (1.6GHz)

Foxton µC (1.0GHz)

DFD (D=0) → +2

RVD → DFD

D = f(P, V, T)

VID = f(Power, T)

VID = f(V, T)

VCORE (dynamic)

Fmax (2.0GHz) → Core Logic

(.504 * Fmax ≤ Fcore ≤ Fmax)

MVR
Clock System Modes

- **Fixed Frequency (FFM)**
  - Cores/Uncore are frequency and phase aligned
  - Cores/Uncore interfaces synchronous

- **Variable Frequency (VFM)**
  - Core supply modulated by Foxton Controller to manage power envelope
  - Core frequencies track Vcore via Regional Voltage Detector (RVD) V-F curves
    - Respond to Foxton modulation and local transients
    - V-F curves match worst-scaling paths on chip
  - Core/Uncore interfaces asynchronous
RVD Delay Line

**FINE**

in

**COARSE**

c0arse_sel

Dynamic Mux

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RVD Delay Element

in

out

**metal1 resistor**

FET

Graph:

- x-axis: 0.60 to 1.40
- y-axis: 2.00E-10 to 1.60E-09
- Color codes:
  - Red: 1.60E-09
  - Orange: 1.40E-09
  - Yellow: 1.20E-09
  - Green: 1.00E-09
  - Blue: 8.00E-10
  - Cyan: 6.00E-10
  - Magenta: 4.00E-10
  - Brown: 2.00E-10

Dynamic behavior shown with curves representing different conditions.
Example VFC Supply Droop Response

Clock period increased
No Adjust needed this cycle

Droop increases RVD delay line delay
Increased delay asserts period “UP” for one cycle
Speed gains from Adaptive Frequency

B1-1086 / Supply Virus

detailed curves - pass only

Vdroop inferred ~100mV

Vdroop inferred ~125mV

Speed Gain From VFC

Test 1  Test 2  Test 3
Summary

• Foxton is a system comprised of several key components
  – Accurate power and temperature measurement
  – Fine grained voltage control
  – Dynamic fast-response frequency control
  – A micro-controller to manage the system
• It can be wrapped around any processor or ASIC which can be virtually unchanged except:
  – An asynchronous interface to the rest of the system
  – Must support a wider range of operating voltages
• The result is a self-optimizing chip dynamically delivering greatly improved performance/watt