Cahners
MICROPROCESSOR REPORT
www.MPRonline.com
THE INSIDER'S GUIDE TO MICROPROCESSOR HARDWARE

Top PC Vendors Adopt Crusoe

Transmeta Reveals Roadmap; New TM5600 Has 512K L2 Cache

By Tom R. Halfhill {7/10/00-02}

Four top-tier vendors at PC Expo announced their intention to make notebook computers based on Transmeta's Crusoe processors. Some of these systems will use a new version of Crusoe that has twice as much on-chip L2 cache. Transmeta has also revealed a two-year roadmap of processors with higher clock speeds, greater integration, lower power consumption, and new VLIW cores, as Figure 1 shows.

The four PC vendors throwing their weight behind Transmeta's unusual x86-compatible processors (see *MPR 2/14/00*, "Transmeta Breaks x86 Low-Power Barrier") are Fujitsu, Hitachi, IBM, and NEC. All the vendors plan to introduce notebooks in the ultralight class, ranging in weight from 2.8 to 3.5 pounds, with TFT screens ranging in size from 10.4 to 12.1 inches. The notebooks are scheduled to ship this fall.

Crusoe processors are well suited for lightweight notebooks, because their low power consumption eliminates the need for cooling fans and large heat sinks. Furthermore, ultralight notebooks don't compete in the same performance class as larger, heavier laptops, where Intel's mobile processors have a speed advantage.

Some of the new notebooks will use the Crusoe TM5600, which has 512K of on-chip L2 cache—twice as much as the TM5400 announced in February. In other respects, the TM5600 is identical to the TM5400. It will be manufactured by Transmeta's foundry partner, IBM Microelectronics, in a 0.18-micron copper process and packaged in a 474-pin ceramic BGA. Doubling the L2 cache increased the die size to 88mm^2, which is 20% larger than the TM5400's die (73mm^2).

According to Transmeta, the TM5600 is 5–15% faster than the TM5400 and consumes 2–17% less power. Although doubling the size of the L2 cache and enlarging the die would normally increase power consumption, Transmeta says the TM5600 actually uses less power when running typical Windows software, because it makes fewer accesses to main memory over the 3.3V I/O bus.

However, Transmeta still has not released any results of common industry benchmark tests, such as Ziff-Davis

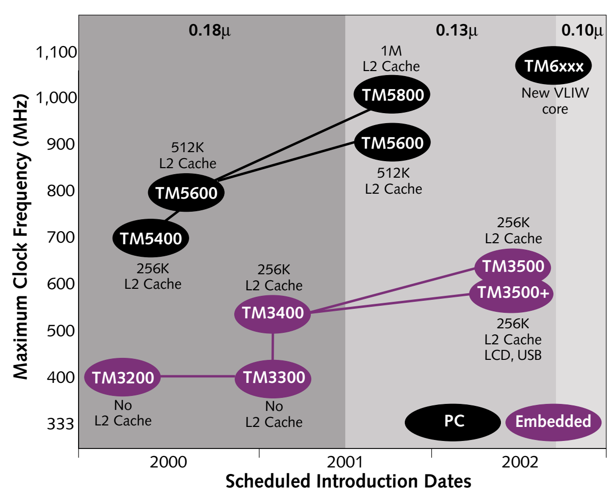


Figure 1. Transmeta's two-year roadmap calls for several new chips based on the existing TM3200 and TM5400 CPU cores, followed by an entirely new core in 2002.

Media's Winstone. Transmeta claims—with some credibility—that existing benchmark programs are misled by the unusual caching and dynamic-recompilation behavior of Crusoe's code-morphing (x86 emulation) software. According to Transmeta's estimates, a TM5400 Crusoe running at 700MHz delivers about the same raw performance as an Intel Pentium III at 500MHz.

Surprising Power Measurements

To back up its claims that Crusoe processors typically consume only 500mW to 1.5W—including the integrated north-bridge controller—Transmeta showed MDR a test system that graphically displays a constant measurement of minimum, maximum, and average power consumption. We experimented with several Windows applications, including Microsoft Word, Internet Explorer, an MP3 audio player, and a DVD movie player. As Figure 2 shows, average power consumption is indeed in the range promised by Transmeta and rarely spikes above 6W. And the test system revealed startling differences in power consumption among applications. For example, merely selecting a paragraph of text in Word briefly gobbled more power than decoding the MPEG-2 stream of a DVD movie.

Faster Crusoe processors are coming next year, according to Transmeta's roadmap. In 2H01, Transmeta will migrate its cores to IBM's 0.13-micron copper process, which offers the option of silicon-on-insulator (SOI) technology (see *MPR 5/1/00-01*, "IBM Paving the Way to 0.10 Micron"). The process shrink will reduce core voltage to 1.2V and boost clock speeds about 25%, even if Transmeta doesn't use SOI. The TM5600 would move into the 700–900MHz frequency range at this geometry.

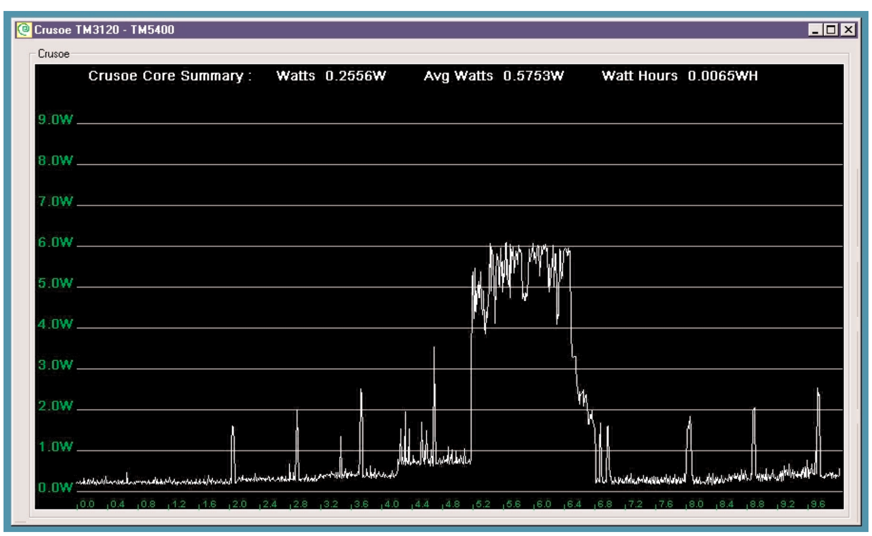


Figure 2. Transmeta's instrumented test system continuously plots power consumption while other software is running. This trace plots the playback of a DVD movie, with regularly spaced spikes marking the decompression and display of each video frame. The large but brief power surge was caused by launching another Windows application.

To take further advantage of the 0.13-micron process, Transmeta plans to introduce another new processor, the Crusoe TM5800, which will have 1M of on-chip L2 cache. It will use the same core as the TM5600 and TM5400 and retain the 474-pin CBGA package.

In 2002, Transmeta plans to revamp its Crusoe line with an entirely new CPU core based on an enhanced VLIW architecture. This core will have a faster FPU and will target a 0.13- or 0.10-micron process. Transmeta expects this unnamed chip (probably TM6xxx) to have twice the performance of existing Crusoe processors while reducing typical power consumption below 500mW.

The code-morphing software will also get an overhaul. Because that software translates x86 instructions into native VLIW instructions on the fly, Transmeta has virtually unlimited freedom to change the inner workings of the CPU core without breaking compatibility with operating systems and applications.

Equally Aggressive Embedded Roadmap

Transmeta's roadmap calls for similar improvements to the company's line of Crusoe processors for Mobile Linux information appliances. The current product is the TM3200, formerly known as the TM3120 (renamed because of a trademark conflict).

Next year, Transmeta plans to introduce two new chips, the TM3300 and TM3400. Both will come in smaller packages (360-pin CBGAs instead of 474-pin CBGAs), achieved by eliminating the unused pads reserved for the DDR-SDRAM interface on TM5xxx-series chips, but they will retain their SDR-SDRAM interfaces. The downsized package will allow Transmeta to sell the TM3300 for less than $50. The TM3400 will be the higher-end model, adding a 256K on-chip L2 cache and LongRun power manager.

In 2002, Transmeta plans to introduce the TM3500, which migrates the existing core to a 0.13-micron process. That will reduce the core voltage to 1.2V and boost the clock frequency to 600MHz. There will also be a more integrated version of the TM3500 that has 256K of on-chip L2 cache, LongRun power management, an LCD controller, a USB interface, and a PCI interface. Those additions will bump the pin count back up to 474 but provide system vendors with a more complete system solution. Table 1 summarizes the features of Transmeta's current and future chips.

Less than six months after its much-hyped public debut, Transmeta has gained the crucial support of some

Feature	TM5400	TM5600	TM5800	TM6xxx	TM3200	TM3300	TM3400	TM3500
CPU Core	5400	5400	5400	6xxx	3200	3200	3200	3200
Core Freq*	500–700MHz	500–800MHz	700MHz–1GHz	>1GHz	333–400MHz	333–400MHz	400–533MHz	400–600MHz
L1 Cache (I/D)	64K/64K	64K/64K	64K/64K	n/a	64K/32K	64K/64K	64K/64K	64K/64K
L2 Cache	256K	512K	1M	n/a	None	None	256K	256K
LongRun?	Yes	Yes	Yes	Yes	No	No	Yes	Yes
SDRAM Ctrl?	SDR+DDR	SDR+DDR	SDR+DDR	n/a	SDR	SDR	SDR	SDR
LCD Ctrl?	No	No	No	n/a	No	No	No	Yes
USB Ctrl?	No	No	No	n/a	No	No	No	Yes
PCI Ctrl?	Yes	Yes	Yes	n/a	Yes	Yes	Yes	Yes
IC Process	0.18µ 5LM	0.18µ 5LM	0.13µ	0.10–0.13µ	0.18µ 5LM	0.18µ 5LM	0.18µ 5LM	0.13µ
Core Voltage	1.6V	1.6V	1.2V	1.2V	1.5V	1.5V	1.5V	1.2V
Die Size	73mm^2	88mm^2	n/a	n/a	77mm^2	77mm^2	n/a	n/a
Package	CBGA-474	CBGA-474	CBGA-474	n/a	CBGA-474	CBGA-360	CBGA-360	CBGA-474
Power (typ)	<1.5W	<1.5W	<1W	<500mW	<1.5W	<1.5W	<1.5W	<1W
Price (1K)	$119–$329	n/a	n/a	n/a	$65–$89	<$50	n/a	n/a
Availability	Now	Aug-00	2H01	2002	Now	1Q01	1Q01	2002

Table 1. Transmeta has aggressive plans to expand its Crusoe line over the next two years while taking advantage of IBM's latest semiconductor process. (*In this table, "core frequency" refers to the maximum clock-frequency ratings of individual Crusoe processors, not to the range of frequencies supported by LongRun power management. n/a = information not available.)

top-tier PC vendors and major financial backers. In addition to the PC vendors that announced Crusoe-based notebooks at PC Expo, Gateway has committed to using a Crusoe chip in a Linux-compatible information appliance designed for AOL (see *MPR 6/5/00-04*, "Transmeta Lands Gateway-AOL IA"), and several high-profile investors have kicked in $88 million of funding (see *MPR 5/1/00-06*, "Transmeta Lands $88M").

Although Transmeta's performance and power-consumption claims haven't been independently verified, this situation is clearly not hurting the company's ability to attract key customers and investors. And Transmeta's early success is exerting pressure on Intel to come up with a comparable line of low-power processors.

Telling Watt's Right From Wrong

No doubt in response to Transmeta's challenge, Intel says its latest mobile PC processors come close to matching the average power consumption of the TM5400. On June 19, Intel announced five mobile Pentium III and Celeron processors and claimed their average power consumption to be 0.8–1.6W for the 500/600MHz Pentium III and 1.6–2.8W for the 600/750MHz Pentium III (see *MPR 7/3/00-02*, "Intel Strikes Back at Transmeta").

Those numbers are far below Intel's own thermal design power (TDP) specifications, which represent worst-case design points for engineers who want to ensure that their systems won't overheat. The disparity between Intel's average-power estimates and the TDP specifications provoked a quick reaction from Transmeta. The company accused Intel of manipulating the average-power figures by basing them on tests with Ziff-Davis Media's BatteryMark program, which typically spends 80% of its time in idle states.

Sorting out these claims and counterclaims isn't easy. Intel's TDP specification is 9.5W for the 500/600MHz mobile Pentium III and 15.8W for the 600/750MHz mobile Pentium III. However, those numbers don't include a north-bridge controller, which is integrated on Crusoe chips and included in their power ratings. Intel does offer mobile

Feature	Transmeta Crusoe TM5400	Transmeta Crusoe TM5600	Intel Mobile Pentium III	Intel Mobile Pentium III
CPU Core	5400	5400	Coppermine	Coppermine
Freq Range*	200–700MHz	200–800MHz	600/750MHz	500/600MHz
L1 Cache (I/D)	64K/64K	64K/64K	16K/16K	16K/16K
L2 Cache	256K On-Chip	512K On-Chip	256K On-Chip	256K On-Chip
North Bridge	Yes	Yes	No	No
SDRAM Ctrl	SDR+DDR	SDR+DDR	No	No
PCI Ctrl?	Yes	Yes	No	No
MMX?	Yes†	Yes†	Yes	Yes
SSE?	No	No	Yes	Yes
IC Process	0.18µ 5LM	0.18µ 5LM	0.18µ 6LM	0.18µ 6LM
Metal Layers	Copper	Copper	Aluminum	Aluminum
Core Voltage	1.1–1.65V	1.1–1.7V	1.35/1.6V	1.1/1.35V
Die Size	73mm^2	88mm^2	106mm^2	106mm^2
Power Modes	LongRun	LongRun	SpeedStep	SpeedStep
Power (typ)	0.5–1.5W	0.5–1.5W	1.6–2.8W	0.8–1.6W
Power (max)	~6W	~6W	13.9/20W	12.2/16.6W
Price (1K)	$329	n/a	$562	$316
Availability	Now	Aug-00	Now	Now

Table 2. Transmeta's Crusoe processors have an advantage in power consumption, whereas Intel's mobile Pentium III processors have an advantage in performance: Transmeta says a 700MHz TM5400 is about as fast as a 500MHz Pentium III. (*In this table, "frequency range" refers to the variable clock rates of an individual chip in its different operating modes. The TM5400 and TM5600 can vary their frequencies within these ranges in increments of 33MHz, while the mobile Pentium III chips are limited to the two frequencies shown. †Not including north bridge. n/a = information not available.)

Price & Availability

Transmeta will begin shipping production volumes of the Crusoe TM5600 with 512K L2 cache in August. The price has yet to be announced. The TM5400 and TM3200 are shipping now. TM5400 prices range from $119 at 500MHz to $329 at 700MHz, and TM3200 prices range from $65 at 333MHz to $89 at 400MHz (all for 1,000-unit quantities). For more information, go to *www.transmeta.com*.

Pentium III processors in MMC-2 cartridges with a north bridge, but that feature increases the TDP to 12.8W for the 500/600MHz mobile Pentium III and 19.1W for the 600/750MHz mobile Pentium III.

There are two clock-frequency numbers for each mobile Pentium III processor because they automatically reduce their core voltage and clock rate when unplugged from AC power, a feature Intel calls SpeedStep. For example, the 500/600MHz mobile Pentium III normally operates at 600MHz and 1.35V on AC power, but it steps down to 500MHz and 1.1V on batteries. Likewise, the 600/750MHz mobile Pentium III normally operates at 750MHz and 1.6V on AC power; however, it then steps down to 600MHz and 1.35V on batteries. Table 2 compares the specifications of Intel's and Transmeta's mobile processors for PC notebooks.

The differences between Intel's TDP specifications and average-power estimates are roughly an order of magnitude, which implies the average-power figure is based on a 10% duty cycle. ZD Media's eTesting Labs (formerly ZD Labs) told MDR that BatteryMark does indeed leave a system in idle states about 80% of the time, because that's how ZD Media's engineers think real people use notebook computers. So, as Transmeta alleges, BatteryMark's light duty cycle could explain the gap between Intel's average and worst-case power numbers. Figure 3 shows a power-consumption trace of the 500/600MHz mobile Pentium III in battery mode (500MHz).

The Quest for Better Benchmarks

The truth about Intel's and Transmeta's power-consumption claims is more elusive, however. For one thing, Intel didn't base its average-power estimates solely on BatteryMark. The company tested a wide range of desktop PC applications, as did Transmeta.

Not by coincidence, one application Intel tested was a DVD movie player, which is Transmeta's favorite demo. Playing a DVD movie on a 600/750MHz mobile Pentium III at 600MHz consumes an average of less than 2W, says Intel, and the same task consumes less than 1W on a 500/600MHz mobile Pentium III at 500MHz. But the screen photo in Figure 4 (supplied by Intel) traces the latter processor during DVD playback in battery mode, and it appears to show average power consumption in the 2.3W range. And Intel's TDP specifications clearly indicate that, to avoid meltdowns, system engineers must design for brief periods of much higher power consumption.

Unfortunately, Transmeta has been less forthcoming with power-consumption benchmarks than Intel. Transmeta criticizes Intel's BatteryMark score but won't release one of its own, saying that conventional tests like BatteryMark don't yield accurate results, because of the TM5400's unique LongRun technology. LongRun can vary the chip's core voltage from 1.1V to 1.65V and the clock frequency from 200MHz to 700MHz in 33MHz increments—all while running on battery power and in response to soft-

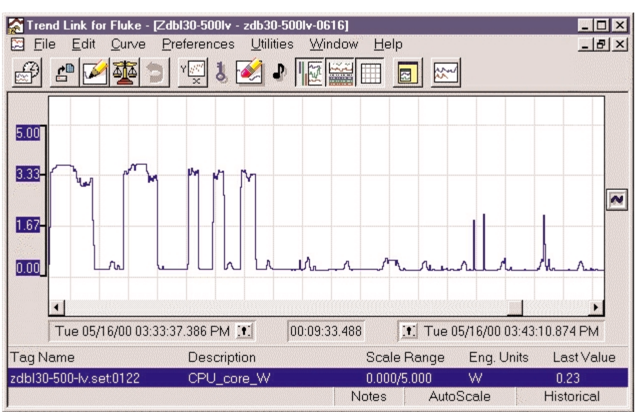


Figure 3. This power-consumption trace shows a 500/600MHz mobile Pentium III processor running the ZD Media BatteryMark 3.0 program, which keeps the CPU idle most of the time. That allows Intel's QuickStart power manager to reduce average power consumption well below 3W.

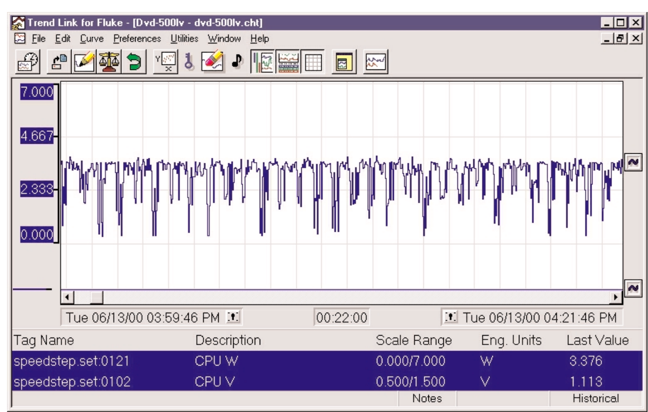


Figure 4. This trace shows a 500/600MHz mobile Pentium III processor playing a DVD movie in battery-optimized (500MHz) mode. Compared with the similar trace from Transmeta in Figure 2, the Intel processor appears to be consuming at least twice as much power—even without a north bridge, which would add about 4W.

Transmeta Explains LongRun

The last mysteries of Transmeta's LongRun technology were explained in a presentation at **Embedded Processor Forum** last month by Marc Fleischmann, the company's director of low-power programs. Although LongRun is somewhat less sophisticated than we imagined after Transmeta's public announcement in February, it is nonetheless effective.

MICHAEL MUSTACCHI

Marc Fleischmann, Transmeta's director of low-power programs, explains LongRun at EPF2000.

At that time, Transmeta said LongRun scales a Crusoe processor's core voltage and clock frequency up or down in response to software demands, allocating just enough performance to handle the varying workload while conserving power. That sounds like a neat trick, but we wondered how LongRun could tell the difference between a true workload and a tight event loop that's simply waiting for something to happen. Answer: it can't. At least, not without a clue from the operating system in the form of an idle command.

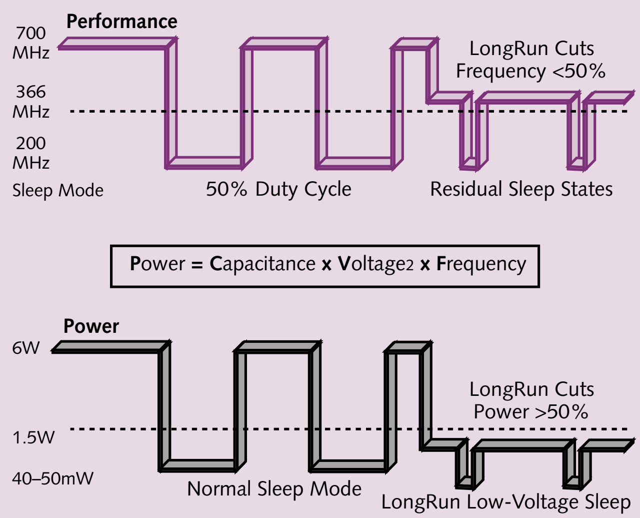
To conserve power, modern operating systems periodically issue idle commands to the CPU during brief periods when the need for processing power is low. Those periods might occur between the frames of an MPEG video stream, or even between a user's keystrokes. The idle command triggers the CPU's power-saving mode. The CPU goes to sleep until it needs to process an interrupt, then wakes up.

It turns out that Transmeta's code-morphing (x86 emulation) software constantly tracks the amount of time the CPU spends in sleep mode and uses that information to help LongRun regulate the chip's core voltage and clock frequency. For example, if the code-morphing software discovers the CPU is asleep half the time (e.g., a 50% duty cycle), it tells LongRun to cut the chip's voltage and frequency by a little less than 50%—say, 366MHz in the case of a 700MHz TM5400. As the figure below shows, that leaves enough performance to handle the software workload while boosting the duty cycle to near 100%.

By itself, reducing the clock rate would save little or no power, because the CPU is now working twice as hard at half the frequency to do the same amount of work. But LongRun also reduces the core voltage, which significantly cuts power consumption. That's because $W={}^1/_2CV^2F$, where W is watts, C is capacitance, V is voltage (squared), and F is frequency. Therefore, power consumption drops faster than the linear reduction in frequency.

The CPU still gets a few catnaps after the clock-rate adjustment, because LongRun chooses a clock frequency that leaves some performance headroom. During those naps, the TM5400 enters a special low-voltage sleep mode that reduces power consumption to 40–50mW. The TM5400 consumes even less power in this mode than it does during the normal sleep mode.

LongRun is a clever and innovative approach to power management that does have the effect of scaling power consumption to software demands. And unlike AMD's similar PowerNow feature (see *MPR 5/1/00-05*, "AMD's K6 Family on the Move"), LongRun requires no modifications to the BIOS or operating system, because it takes advantage of existing power-management technology.



ware workloads, unlike SpeedStep (see sidebar "Transmeta Explains LongRun"). The TM5400 would probably fare better with tests that simulate a heavier workload than BatteryMark, because LongRun could scale the core to some intermediate voltage and frequency within its broad range. A mobile Pentium III with SpeedStep would, however, be limited to its single battery-mode voltage and frequency.

On the other hand, a mobile Pentium III is likely to deliver more performance than a TM5400, and not just because the TM5400 has to emulate the x86. At its lowest LongRun-controlled power level of 1.1V, the 700MHz

TM5400 cuts back its clock frequency to a pedestrian 200MHz. At that same voltage, the 500/600MHz mobile Pentium III sprints at 500MHz.

We agree with Transmeta that existing power-consumption and performance benchmarks aren't the best way to evaluate the TM5400's unique abilities. Still, it would be nice to have more data points. Our experiments with Transmeta's power-monitoring system lead us to believe that the brief 6W power spikes we observed roughly correspond to Intel's TDP ratings, and that the TM5400's average power consumption is indeed in the 1.5W range. If our casual observations are confirmed by more rigorous tests on the Crusoe-based notebook computers soon to hit the market, Transmeta's promise of "all-day computing" could be realized.

One good sign is that Transmeta has joined EEMBC (EDN Embedded Microprocessor Benchmark Consortium) to help define a new suite of power-consumption tests and is working with other benchmarking organizations to refine their existing suites. Those efforts could benefit all CPU vendors, not just Transmeta. As more CPU architects turn to unusual techniques like LongRun to prolong battery life, power-consumption benchmarks will need to get more sophisticated—and now is not too early to start. ◇