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Gaskins

(54) **MICROPROCESSOR WITH IMPROVED PERFORMANCE DURING P-STATE TRANSITIONS**

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Continuation-in-part of application No. 10/646,988, filed on Aug. 22, 2003.
Continuation-in-part of application No. 10/816,004, filed on Apr. 1, 2004.

(60) Provisional application No. 60/544,206, filed on Feb. 12, 2004. Provisional application No. 60/415,942, filed on Oct. 3, 2002. Provisional application No. 60/530,323, filed on Dec. 17, 2003. Provisional application No. 60/892,300, filed on Mar. 1, 2007. Provisional application No. 60/892,303, filed on Mar. 1, 2007. Provisional application No. 60/892,306, filed on Mar. 1, 2007. Provisional application No. 60/892,548, filed on Mar. 2, 2007.

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(57) **ABSTRACT**

A microprocessor includes core logic that operates according to a core clock signal in order to execute program instructions, clock generation circuitry controllable to generate the core clock signal having one of N different possible frequencies, wherein N is more than two, and a control circuit. The control circuit, in response to a request to operate the core logic at a destination frequency, iteratively controls the clock generation circuitry to generate the core clock signal having a new frequency until the core clock signal frequency is the destination frequency. The new core clock signal frequency on each iteration is one of the N different possible frequencies monotonically closer to the destination frequency. The number of iterations is between zero and N−1 depending upon the destination frequency specified and the core clock signal frequency when the request is received.

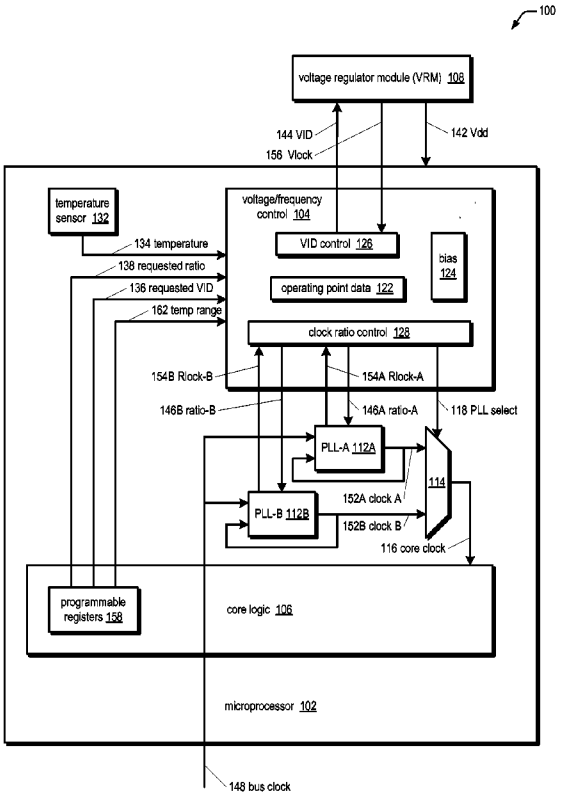


Fig. 1

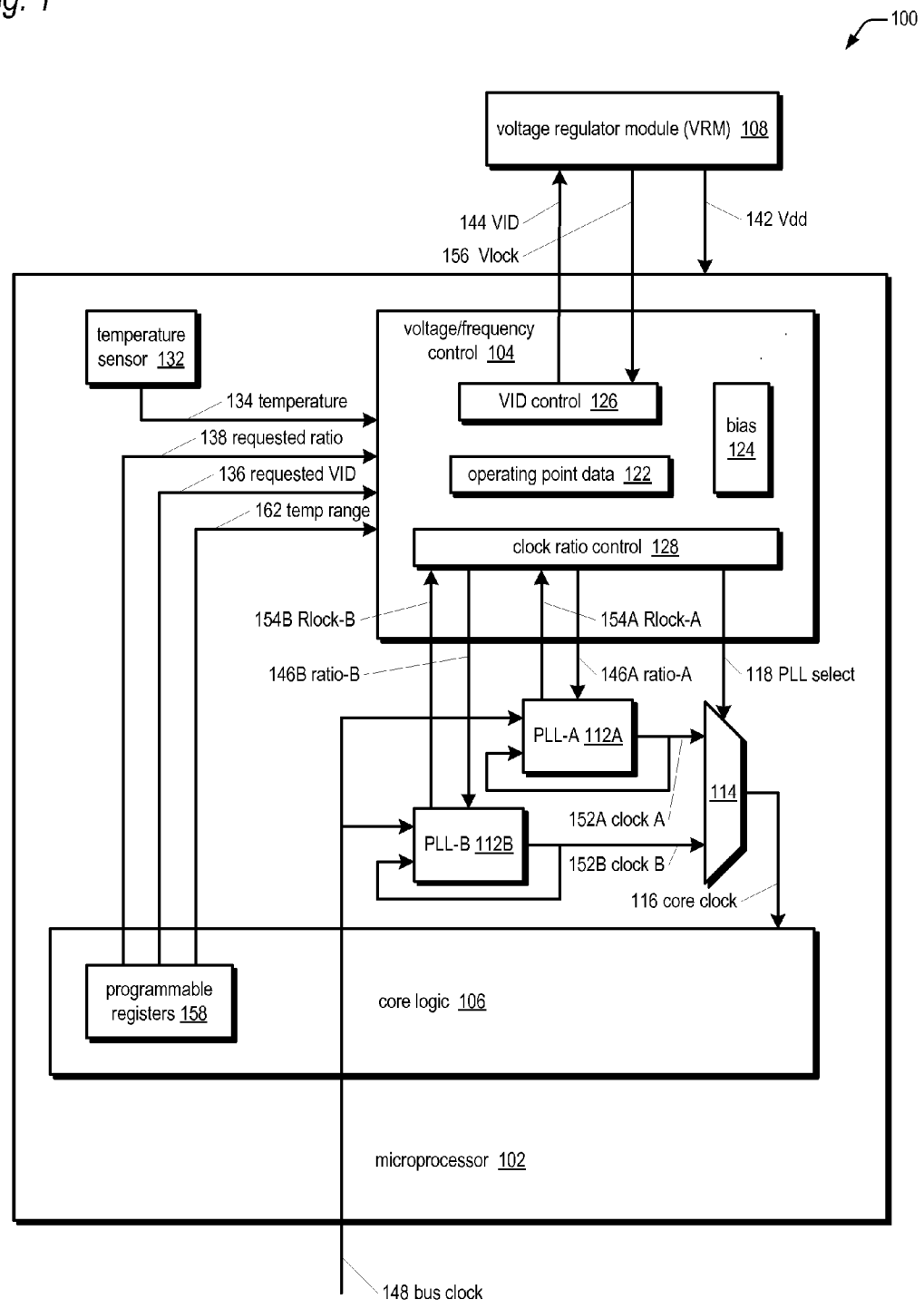

100
voltage regulator module (VRM) 108
144 VID
156 Vlock
142 Vdd
temperature sensor 132
voltage/frequency control 104
VID control 126
bias 124
134 temperature
138 requested ratio
136 requested VID
162 temp range
operating point data 122
clock ratio control 128
154B Rlock-B
154A Rlock-A
146B ratio-B
146A ratio-A
118 PLL select
PLL-A 112A
114
152A clock A
PLL-B 112B
152B clock B
116 core clock
programmable registers 158
core logic 106
microprocessor 102
148 bus clock

Fig. 2

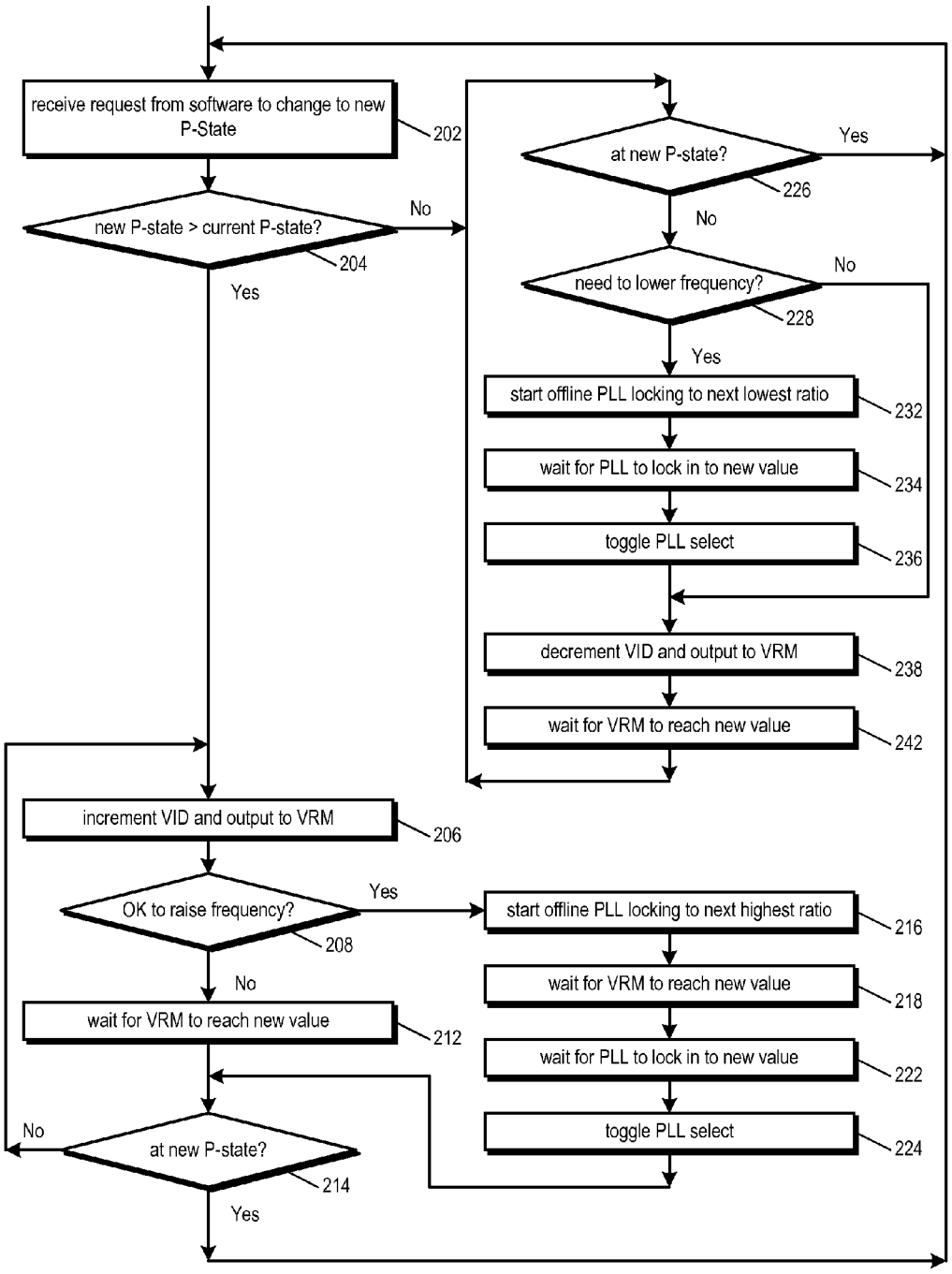
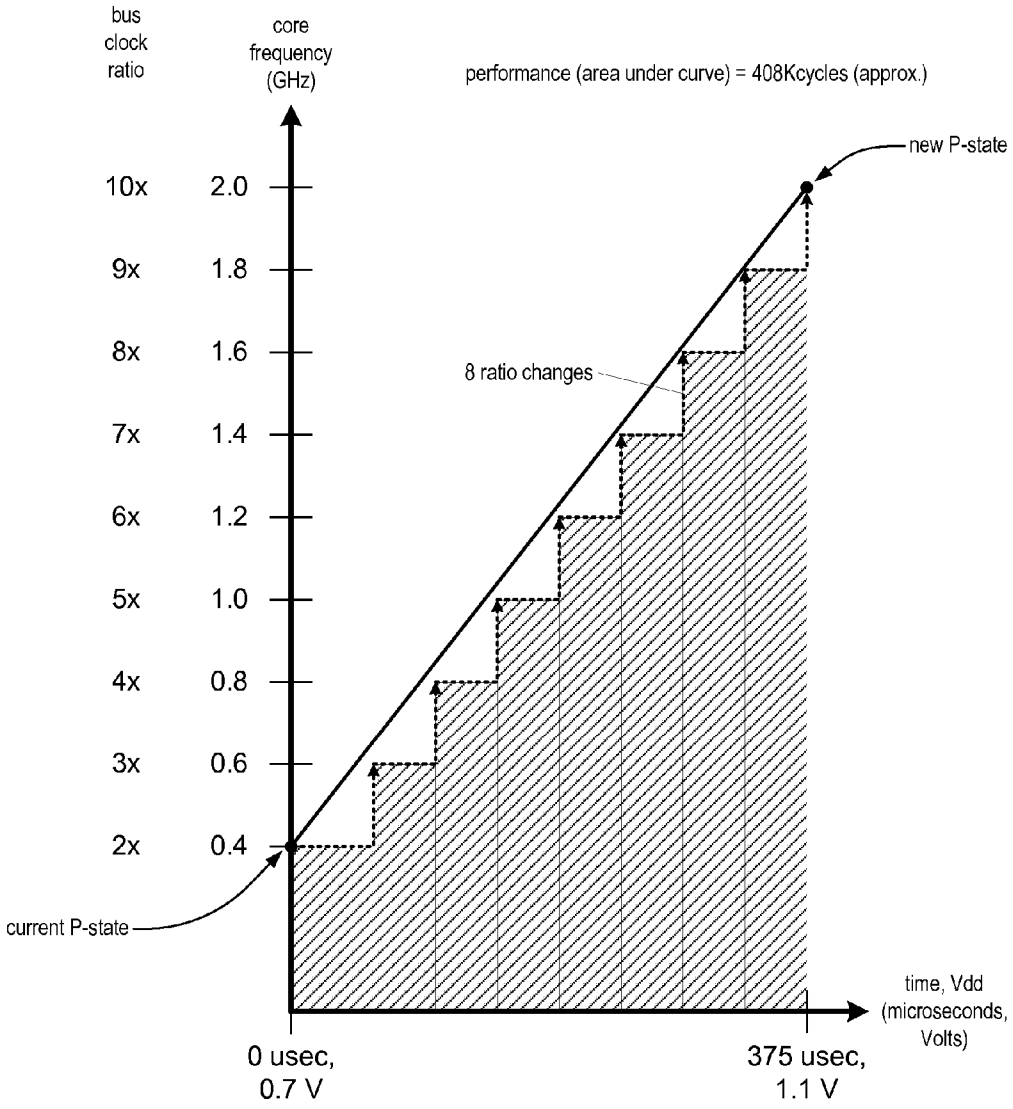

receive request from software to change to new P-State
202
new P-state > current P-state?
204
No
Yes
at new P-state?
226
Yes
No
need to lower frequency?
228
No
Yes
start offline PLL locking to next lowest ratio
232
wait for PLL to lock in to new value
234
toggle PLL select
236
decrement VID and output to VRM
238
wait for VRM to reach new value
242
increment VID and output to VRM
206
OK to raise frequency?
208
Yes
No
start offline PLL locking to next highest ratio
216
wait for VRM to reach new value
218
wait for PLL to lock in to new value
222
toggle PLL select
224
wait for VRM to reach new value
212
at new P-state?
214
No
Yes

Fig. 3



A P-state transition from the lowest P-state to the highest P-state requires 25 VID changes, each 16mV and each requiring approximately 15 microseconds for a total of approximately 375 microseconds.

Fig. 4

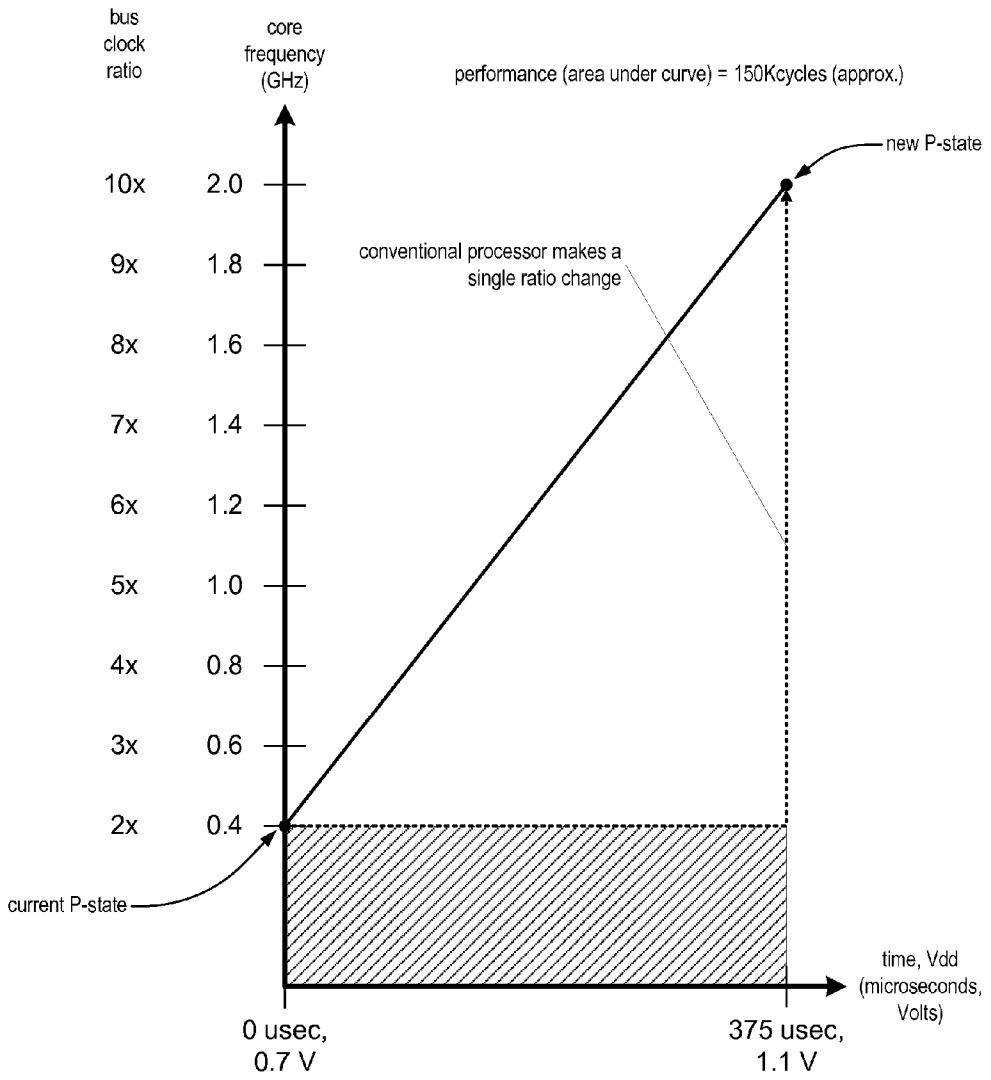

bus clock ratio
core frequency (GHz)
performance (area under curve) = 150Kcycles (approx.)
new P-state
10x 2.0
9x 1.8
8x 1.6
7x 1.4
6x 1.2
5x 1.0
4x 0.8
3x 0.6
2x 0.4
conventional processor makes a single ratio change
current P-state
time, Vdd (microseconds, Volts)
0 usec, 0.7 V
375 usec, 1.1 V

Fig. 5

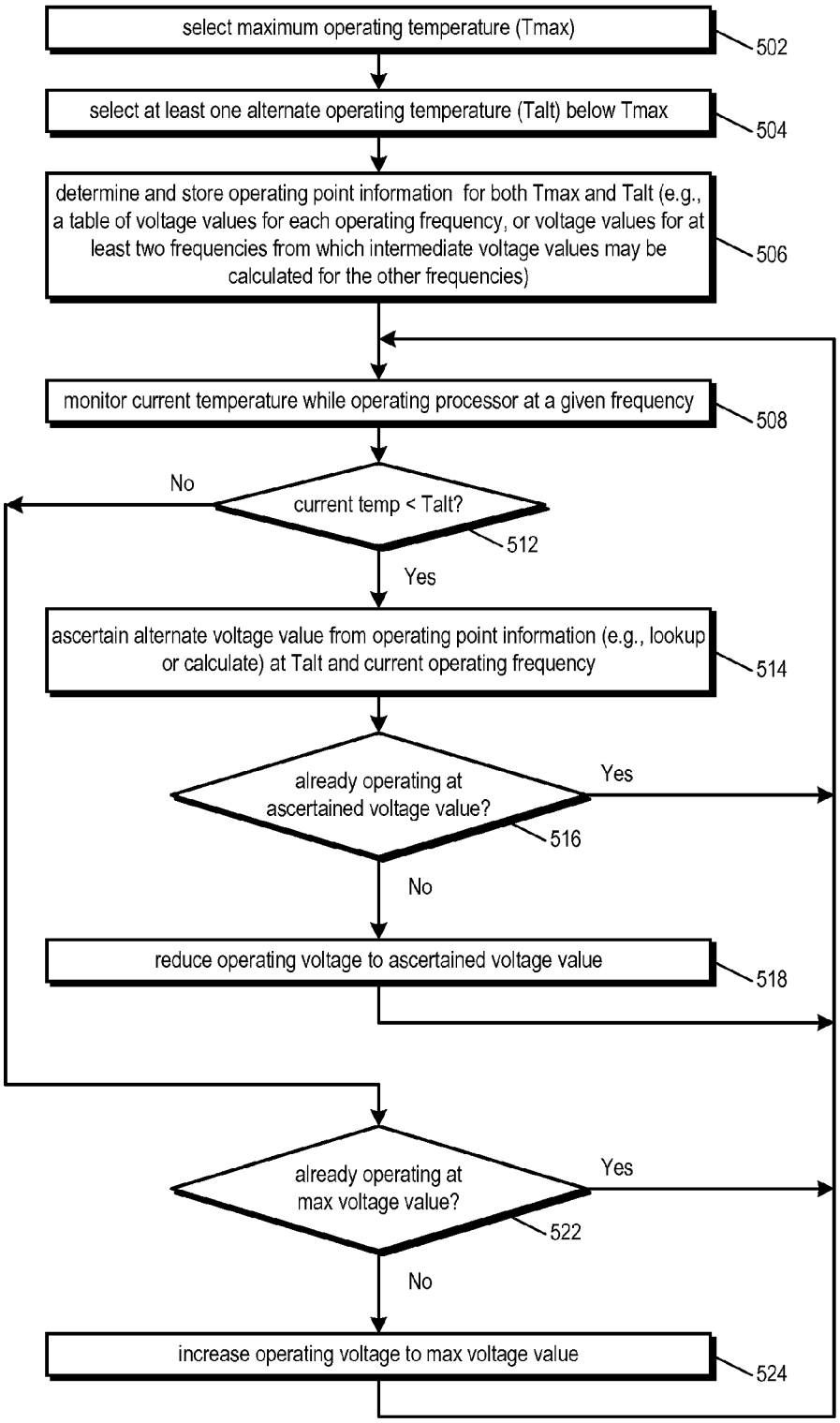

select maximum operating temperature (Tmax)
502
select at least one alternate operating temperature (Talt) below Tmax
504
determine and store operating point information for both Tmax and Talt (e.g., a table of voltage values for each operating frequency, or voltage values for at least two frequencies from which intermediate voltage values may be calculated for the other frequencies)
506
monitor current temperature while operating processor at a given frequency
508
current temp < Talt?
512
No
Yes
ascertain alternate voltage value from operating point information (e.g., lookup or calculate) at Talt and current operating frequency
514
already operating at ascertained voltage value?
516
Yes
No
reduce operating voltage to ascertained voltage value
518
already operating at max voltage value?
522
Yes
No
increase operating voltage to max voltage value
524

Fig. 6

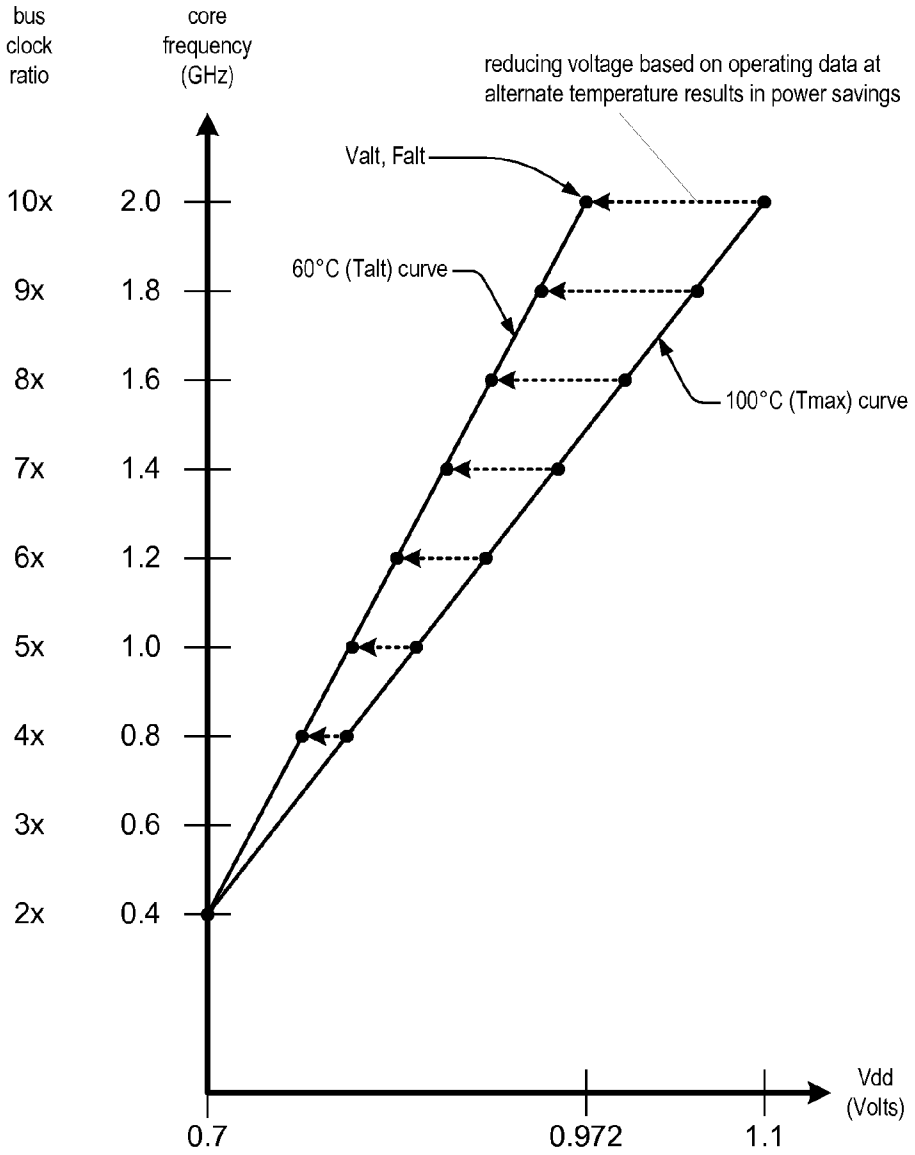

bus clock ratio
core frequency (GHz)
reducing voltage based on operating data at alternate temperature results in power savings
Valt, Falt
60°C (Talt) curve
100°C (Tmax) curve
10x
9x
8x
7x
6x
5x
4x
3x
2x
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.7
0.972
1.1
Vdd (Volts)

Fig. 7

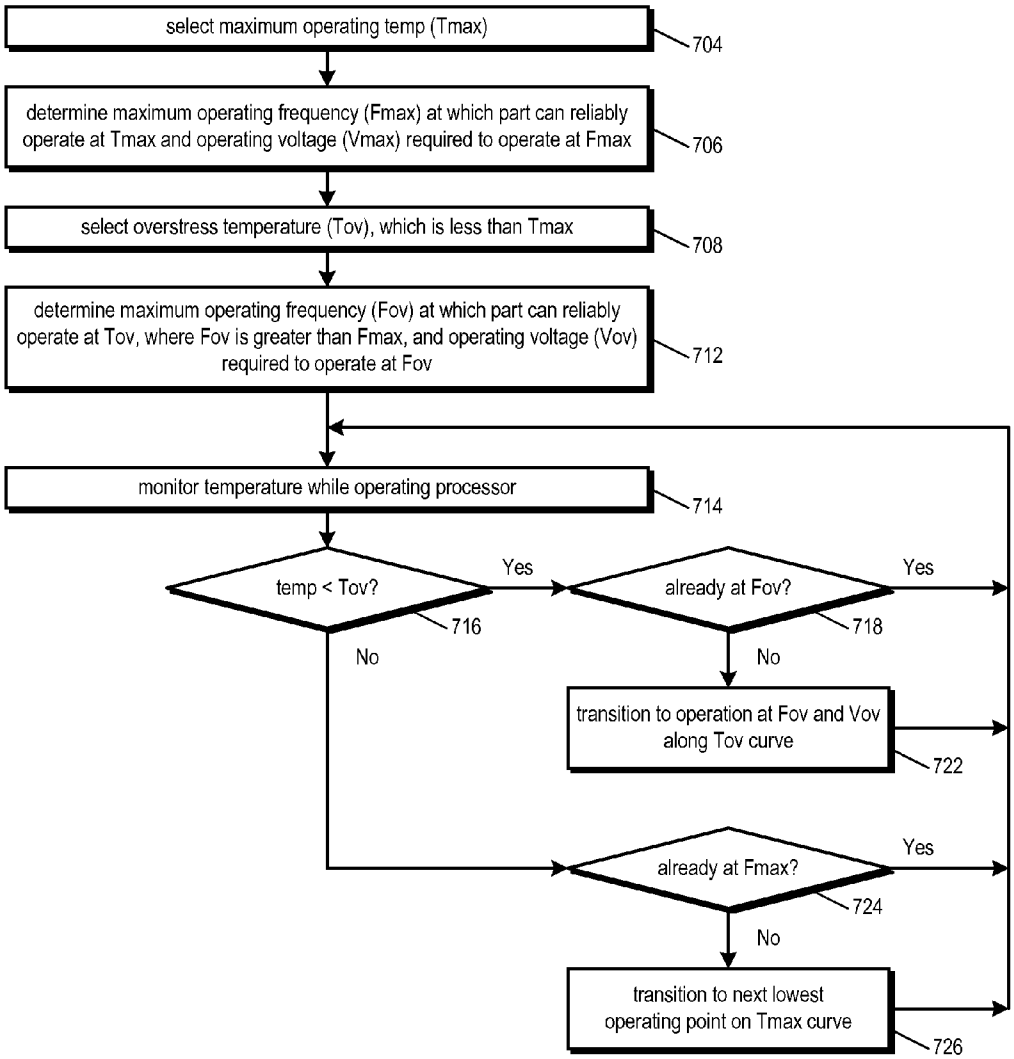

select maximum operating temp (Tmax)
704
determine maximum operating frequency (Fmax) at which part can reliably operate at Tmax and operating voltage (Vmax) required to operate at Fmax
706
select overstress temperature (Tov), which is less than Tmax
708
determine maximum operating frequency (Fov) at which part can reliably operate at Tov, where Fov is greater than Fmax, and operating voltage (Vov) required to operate at Fov
712
monitor temperature while operating processor
714
temp < Tov?
716
Yes
No
already at Fov?
718
Yes
No
transition to operation at Fov and Vov along Tov curve
722
already at Fmax?
724
Yes
No
transition to next lowest operating point on Tmax curve
726

Fig. 8

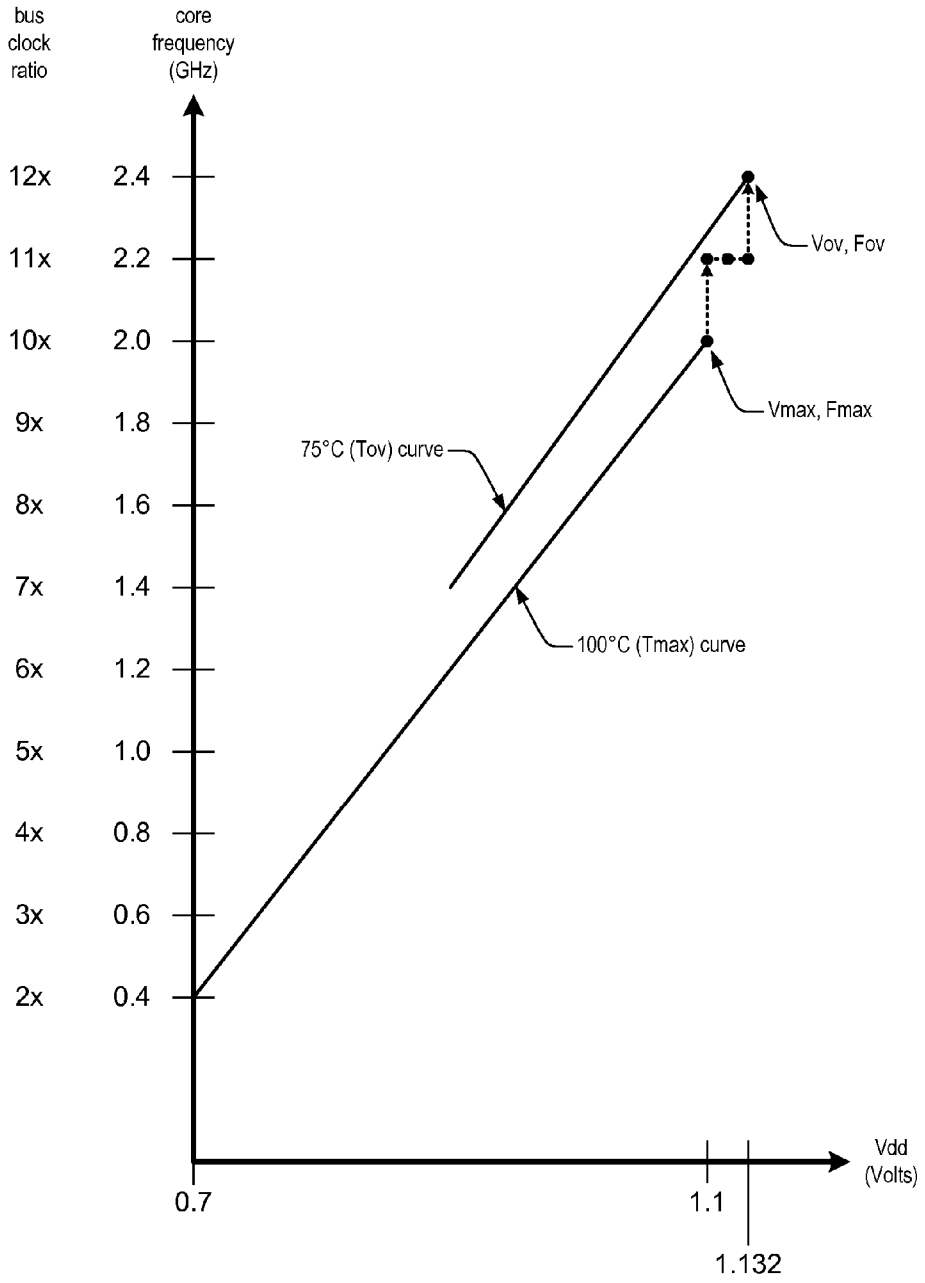

bus clock ratio
core frequency (GHz)
12x
2.4
11x
2.2
10x
2.0
9x
1.8
8x
1.6
7x
1.4
6x
1.2
5x
1.0
4x
0.8
3x
0.6
2x
0.4
Vov, Fov
Vmax, Fmax
75°C (Tov) curve
100°C (Tmax) curve
Vdd (Volts)
0.7
1.1
1.132

Fig. 9

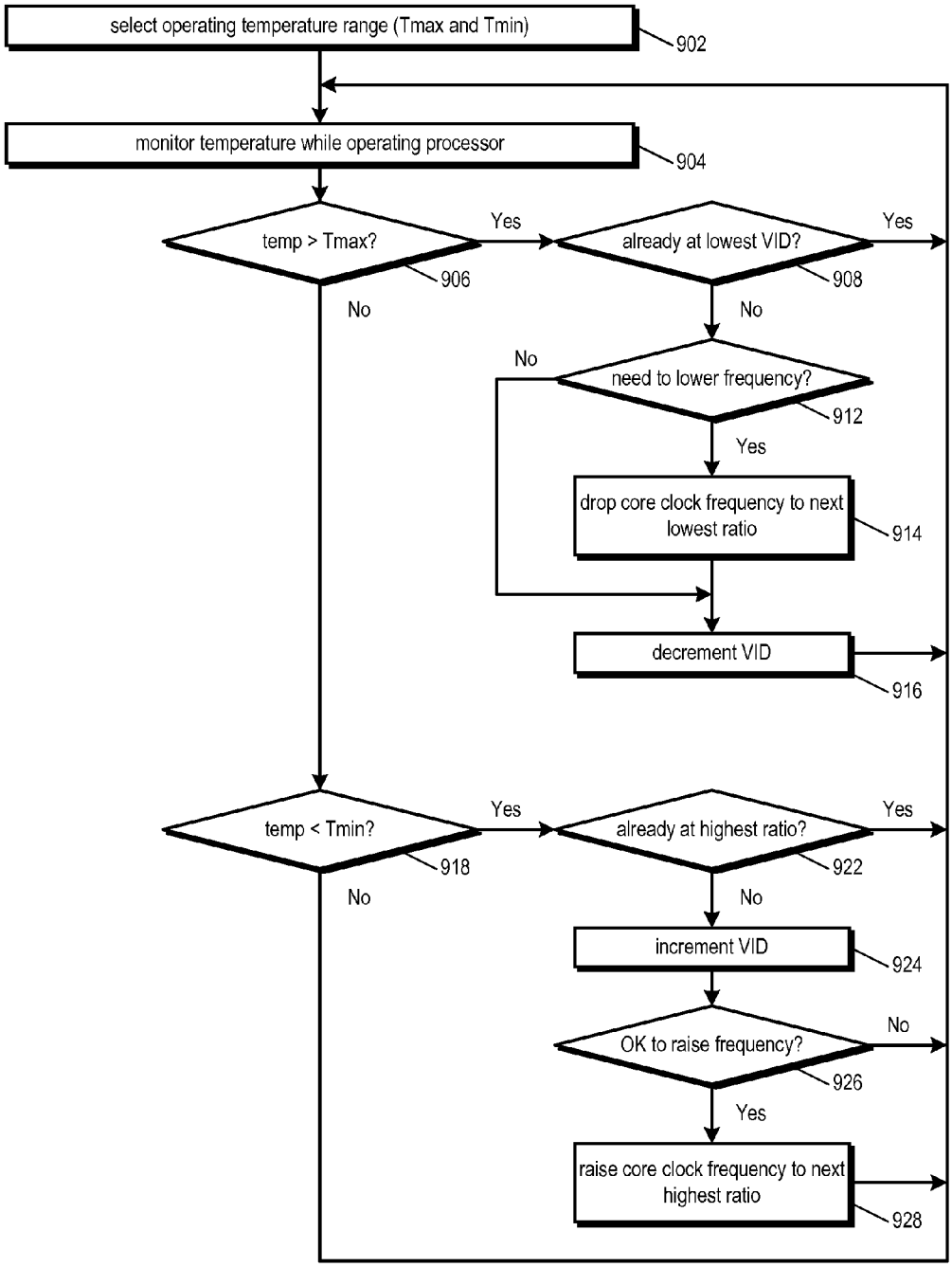

select operating temperature range (Tmax and Tmin)
902
monitor temperature while operating processor
904
temp > Tmax?
906
Yes
No
already at lowest VID?
908
Yes
No
need to lower frequency?
912
No
Yes
drop core clock frequency to next lowest ratio
914
decrement VID
916
temp < Tmin?
918
Yes
No
already at highest ratio?
922
Yes
No
increment VID
924
OK to raise frequency?
926
No
Yes
raise core clock frequency to next highest ratio
928

Fig. 10

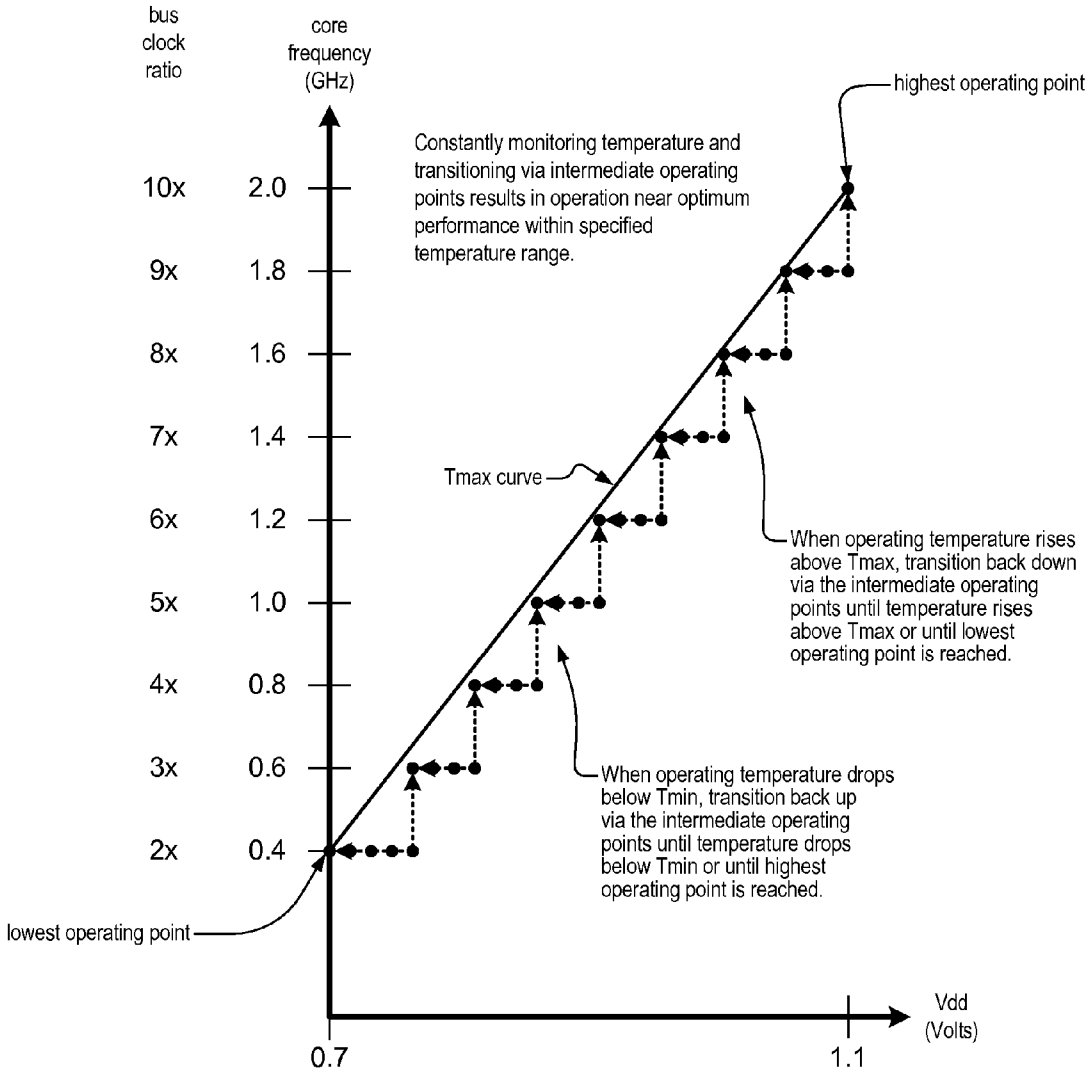

bus clock ratio
core frequency (GHz)
10x 2.0
9x 1.8
8x 1.6
7x 1.4
6x 1.2
5x 1.0
4x 0.8
3x 0.6
2x 0.4
highest operating point
Constantly monitoring temperature and transitioning via intermediate operating points results in operation near optimum performance within specified temperature range.
Tmax curve
When operating temperature rises above Tmax, transition back down via the intermediate operating points until temperature rises above Tmax or until lowest operating point is reached.
When operating temperature drops below Tmin, transition back up via the intermediate operating points until temperature drops below Tmin or until highest operating point is reached.
lowest operating point
Vdd (Volts)
0.7
1.1

Fig. 11

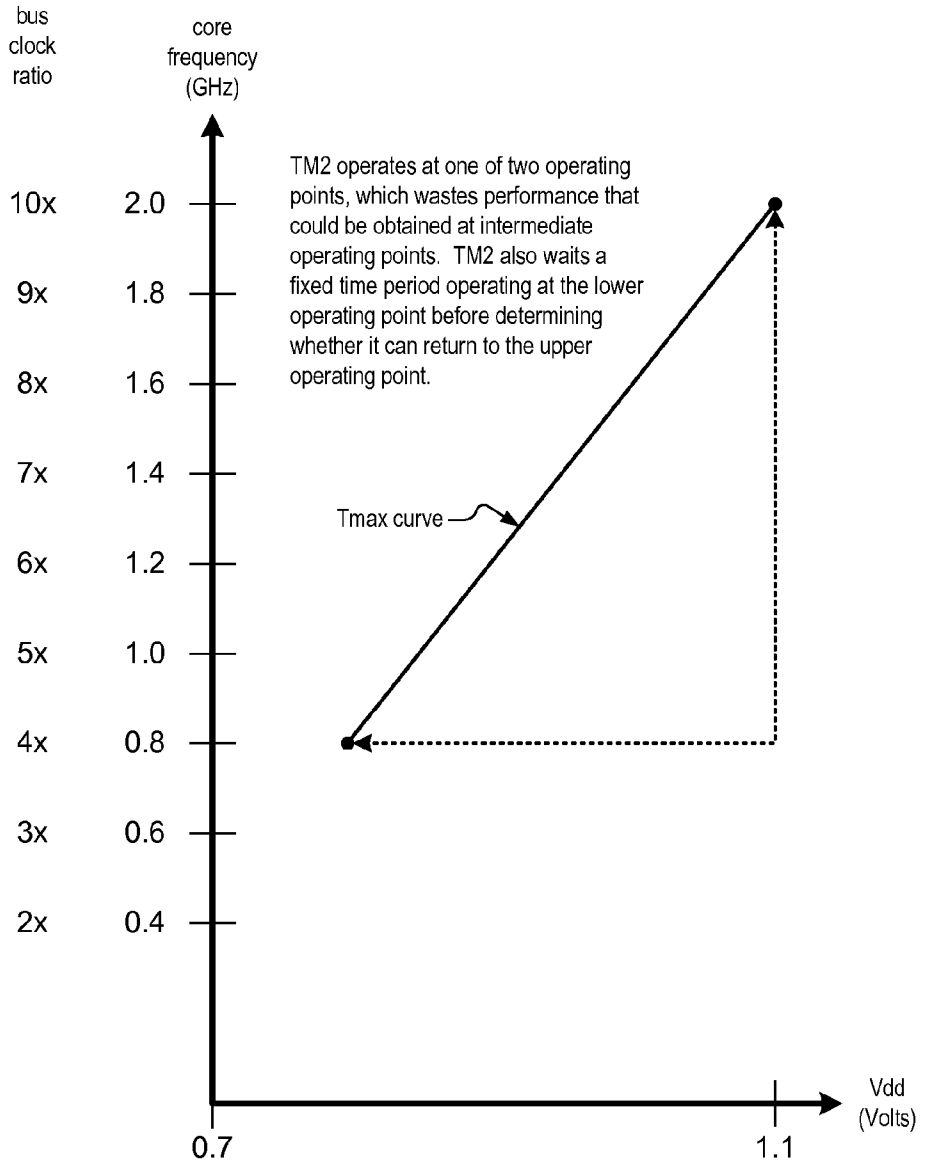

bus clock ratio
core frequency (GHz)
10x
2.0
9x
1.8
8x
1.6
7x
1.4
6x
1.2
5x
1.0
4x
0.8
3x
0.6
2x
0.4
TM2 operates at one of two operating points, which wastes performance that could be obtained at intermediate operating points. TM2 also waits a fixed time period operating at the lower operating point before determining whether it can return to the upper operating point.
Tmax curve
0.7
1.1
Vdd (Volts)

Fig. 12

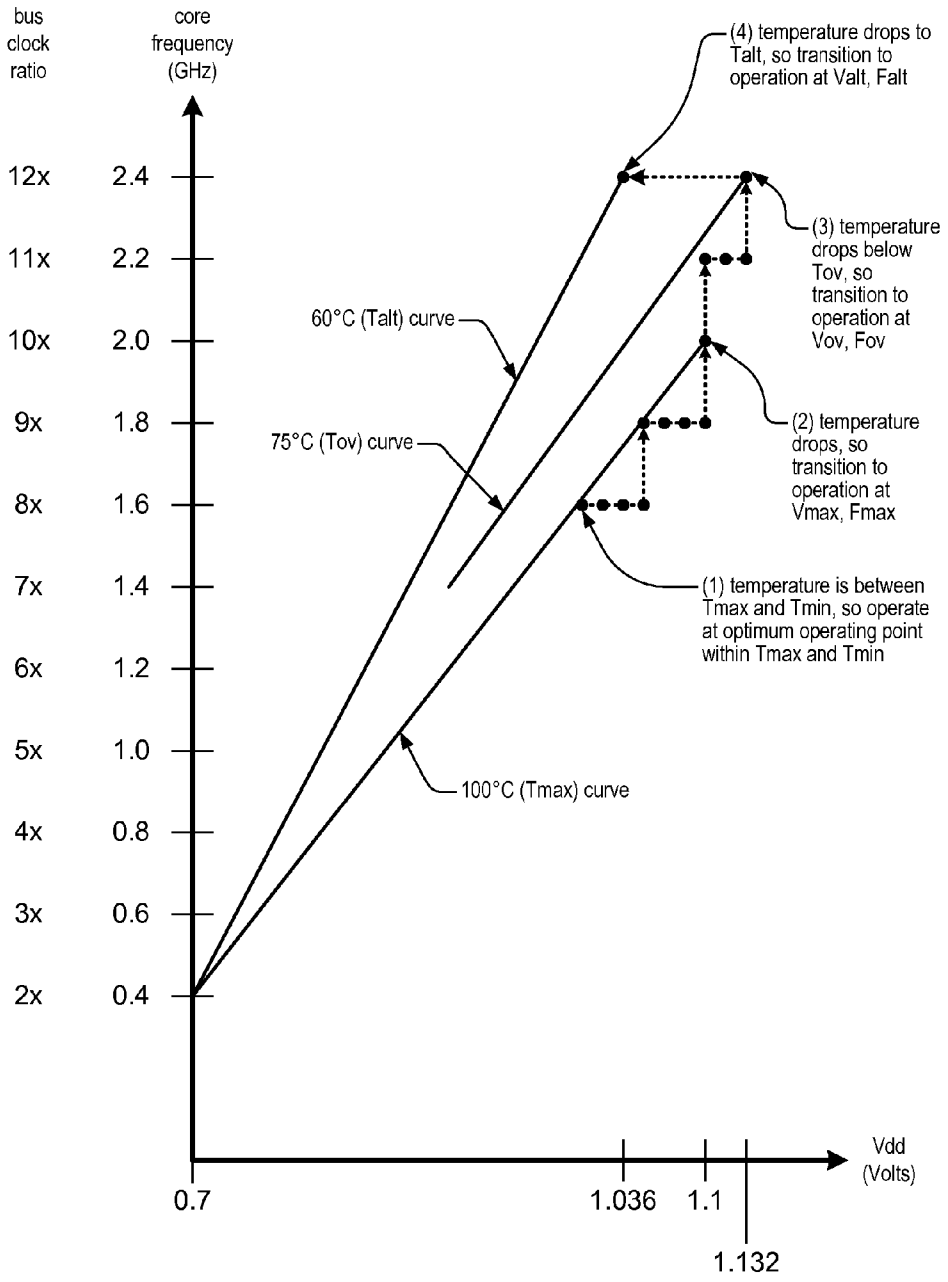

bus clock ratio
core frequency (GHz)
12x 2.4
11x 2.2
10x 2.0
9x 1.8
8x 1.6
7x 1.4
6x 1.2
5x 1.0
4x 0.8
3x 0.6
2x 0.4
(4) temperature drops to Talt, so transition to operation at Valt, Falt
(3) temperature drops below Tov, so transition to operation at Vov, Fov
(2) temperature drops, so transition to operation at Vmax, Fmax
(1) temperature is between Tmax and Tmin, so operate at optimum operating point within Tmax and Tmin
60°C (Talt) curve
75°C (Tov) curve
100°C (Tmax) curve
Vdd (Volts)
0.7
1.036
1.1
1.132

Fig. 13

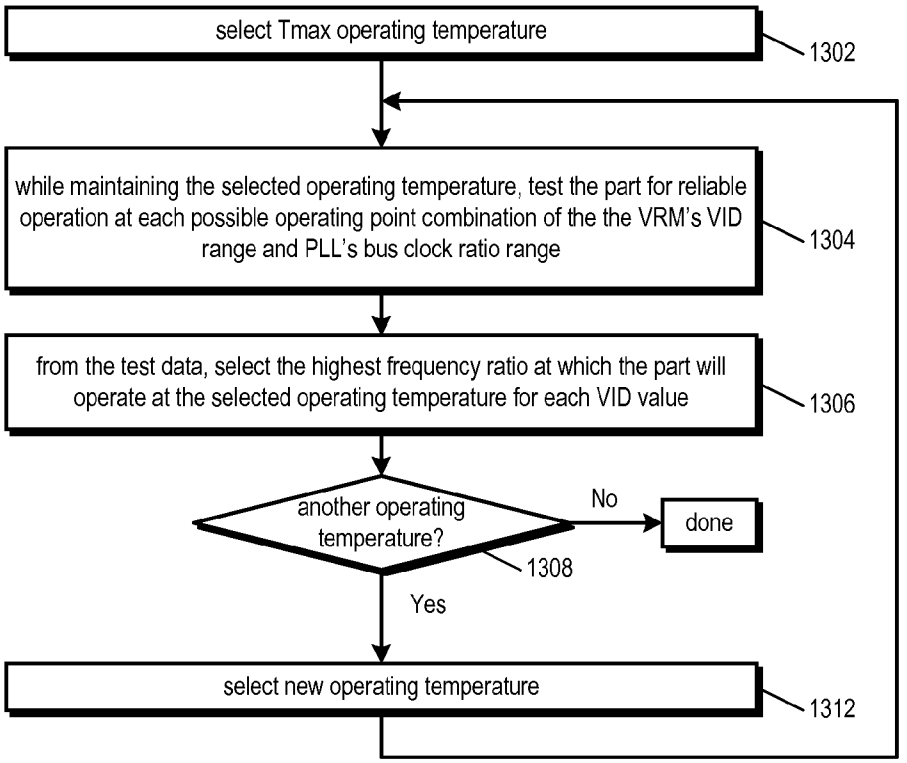

select Tmax operating temperature
1302
while maintaining the selected operating temperature, test the part for reliable operation at each possible operating point combination of the the VRM's VID range and PLL's bus clock ratio range
1304
from the test data, select the highest frequency ratio at which the part will operate at the selected operating temperature for each VID value
1306
another operating temperature?
1308
No
done
Yes
select new operating temperature
1312

Fig. 14

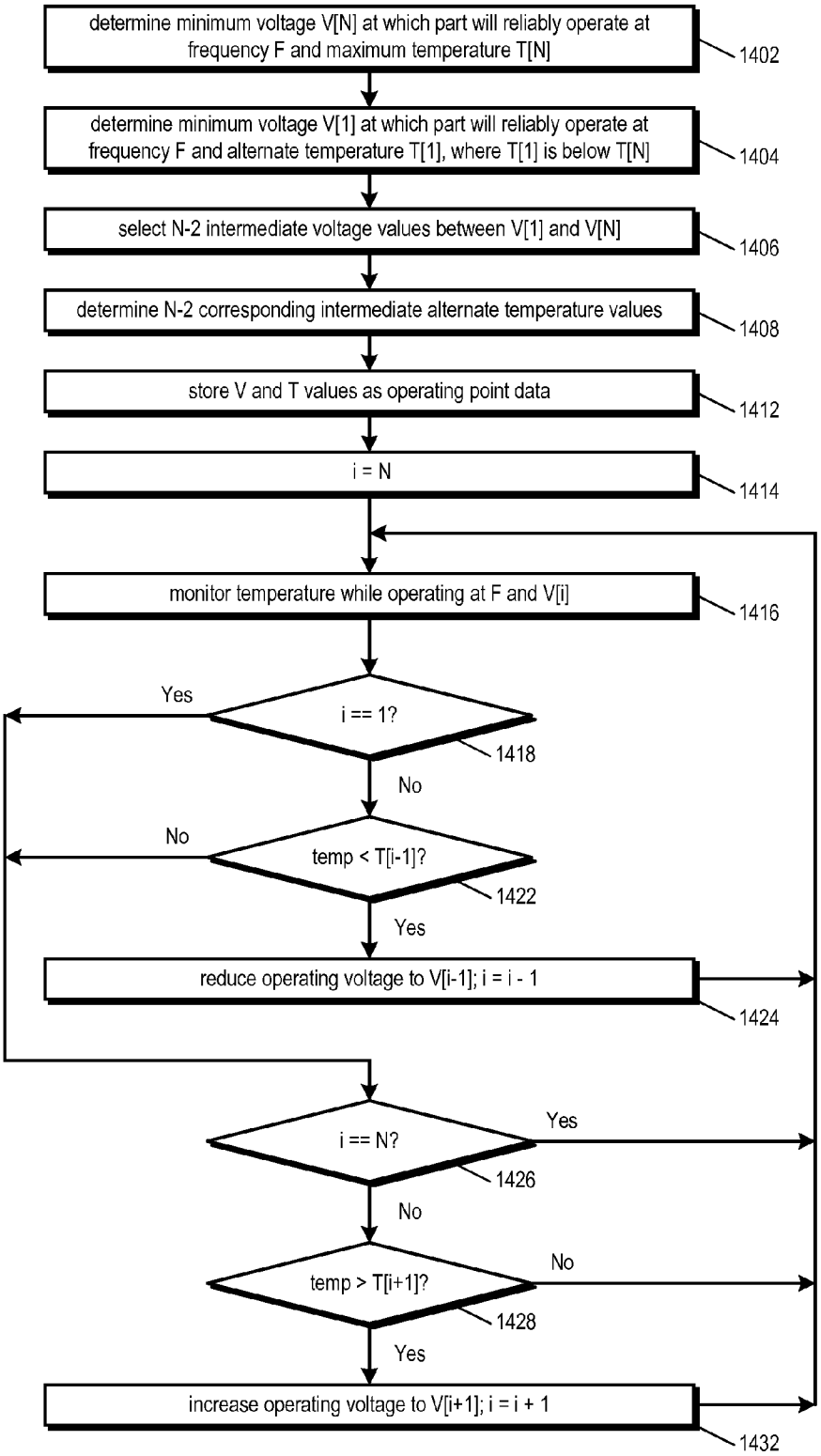
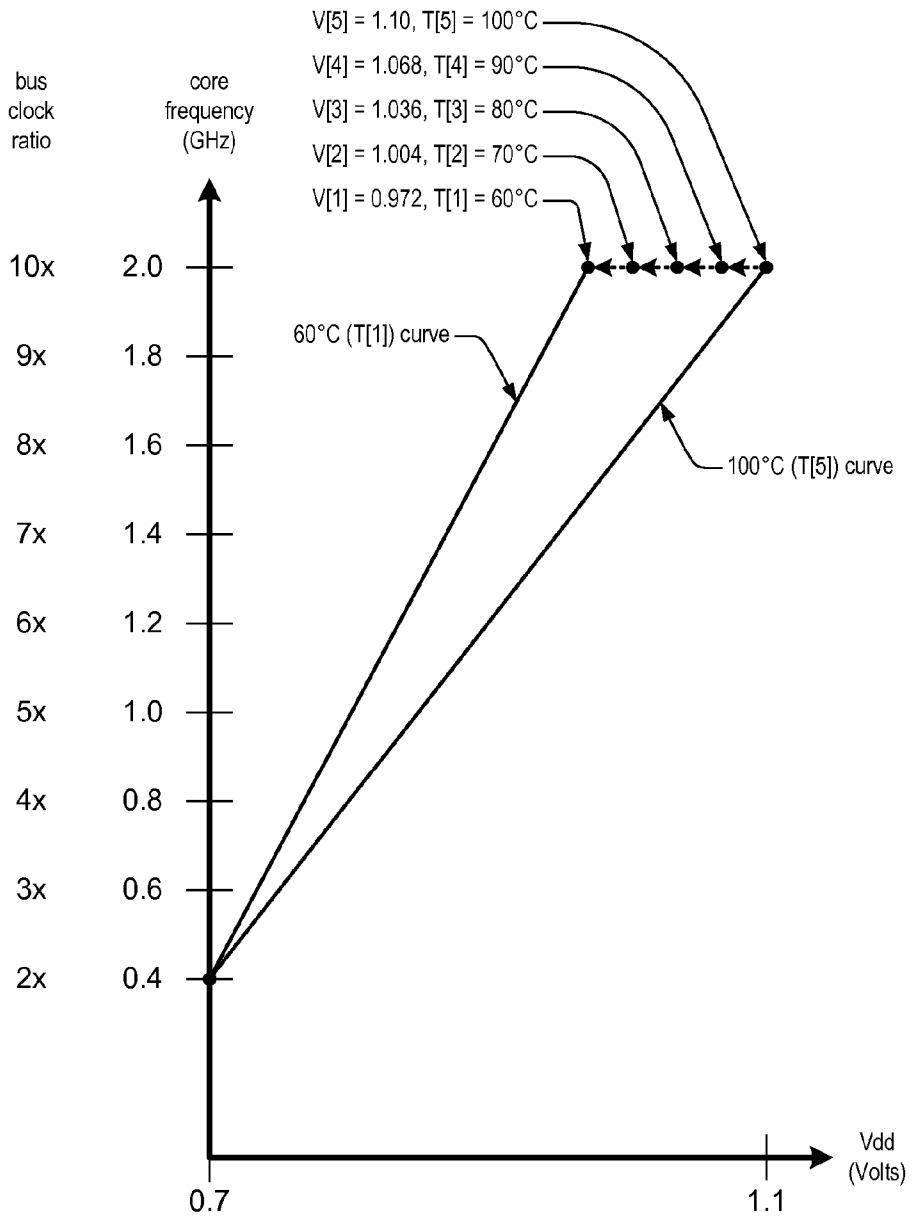

determine minimum voltage V[N] at which part will reliably operate at frequency F and maximum temperature T[N]
1402
determine minimum voltage V[1] at which part will reliably operate at frequency F and alternate temperature T[1], where T[1] is below T[N]
1404
select N-2 intermediate voltage values between V[1] and V[N]
1406
determine N-2 corresponding intermediate alternate temperature values
1408
store V and T values as operating point data
1412
i = N
1414
monitor temperature while operating at F and V[i]
1416
i == 1?
1418
Yes
No
temp < T[i-1]?
1422
No
Yes
reduce operating voltage to V[i-1]; i = i - 1
1424
i == N?
1426
Yes
No
temp > T[i+1]?
1428
No
Yes
increase operating voltage to V[i+1]; i = i + 1
1432

Fig. 15


V[5] = 1.10, T[5] = 100°C
V[4] = 1.068, T[4] = 90°C
V[3] = 1.036, T[3] = 80°C
V[2] = 1.004, T[2] = 70°C
V[1] = 0.972, T[1] = 60°C
bus clock ratio
core frequency (GHz)
10x 2.0
9x 1.8
8x 1.6
7x 1.4
6x 1.2
5x 1.0
4x 0.8
3x 0.6
2x 0.4
60°C (T[1]) curve
100°C (T[5]) curve
Vdd (Volts)
0.7
1.1

MICROPROCESSOR WITH IMPROVED PERFORMANCE DURING P-STATE TRANSITIONS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of the following Applications each of which is incorporated by reference herein in its entirety for all purposes and each of which was owned or subject to an obligation of assignment to VIA Technologies, Inc. or one of its wholly-owned subsidiaries at the time the invention claimed herein was made:

Ser. No.	Filing Date	Title
10/816020 (CNTR.2207)	Apr. 1, 2004	INSTANTANEOUS FREQUENCY-BASED MICROPROCESSOR POWER MANAGEMENT
10/646988 (CNTR.2209)	Aug. 22, 2003	RESOURCE UTILIZATION MECHANISM FOR MICROPROCESSOR POWER MANAGEMENT
10/816004 (CNTR.2216)	Apr. 1, 2004	FREQUENCY-VOLTAGE MECHANISM FOR MICROPROCESSOR POWER MANAGEMENT

[0002] Application Ser. No. 10/816,020 claims priority to Provisional Application 60/544,206, filed Feb. 12, 2004, which is hereby incorporated by reference in its entirety for all purposes.

[0003] Application Ser. No. 10/646,988 claims priority to Provisional Application 60/415,942, filed Oct. 3, 2002, which is hereby incorporated by reference in its entirety for all purposes.

[0004] Application Ser. No. 10/816,004 claims priority to Provisional Application 60/530,323, filed Dec. 17, 2003, which is hereby incorporated by reference in its entirety for all purposes.

[0005] This application claims priority to the following Provisional Applications, each of which is incorporated by reference herein in its entirety for all purposes:

Ser. No.	Filing Date	Title
60/892300 (CNTR.2308)	Mar. 1, 2007	A METHOD AND APPARATUS FOR CONSIDERING TEMPERATURE IN VOLTAGE AND FREQUENCY ADJUSTMENTS ON A MICROPROCESSOR (PARALLAX)
60/892303 (CNTR.2311)	Mar. 1, 2007	ITERATIVE APPROACH TO OPERATING POINT TRANSITIONS
60/892306 (CNTR.2318)	Mar. 1, 2007	TM3
60/892548 (CNTR.2325)	Mar. 2, 2007	OVERSTRESS MODE

[0006] This application is related to the following Applications which are concurrently filed herewith:

Ser. No.	Filing Date	Title
TBD (CNTR.2308)	herewith	MICROPROCESSOR CAPABLE OF DYNAMICALLY REDUCING ITS POWER CONSUMPTION IN RESPONSE TO VARYING OPERATING TEMPERATURE
TBD (CNTR.2318)	herewith	MICROPROCESSOR WITH IMPROVED THERMAL MONITORING AND PROTECTION MECHANISM
TBD (CNTR.2325)	herewith	MICROPROCESSOR CAPABLE OF DYNAMICALLY INCREASING ITS PERFORMANCE IN RESPONSE TO VARYING OPERATING TEMPERATURE

BACKGROUND OF THE INVENTION

Field of the Invention

[0007] The present invention relates in general to the field of the interplay between power consumption and performance in microprocessors, and particularly to the reduction of the former and the increase of the latter with respect to the operating temperature of the microprocessor.

[0008] Power consumption management is an important issue for several types of computing systems, including portable devices, laptop computers, desktops, and servers. Battery life, for example, is a significant issue for most laptop computer users. Furthermore, it has been reported that in many data centers the energy cost of operating a server over its lifetime is greater than the purchase price of the server itself. Furthermore, there is a demand for the so-called "green" computers. The microprocessor may consume a significant amount of the power consumed by the computing system. Therefore, the microprocessor is often the target of power reduction techniques.

[0009] For a given microprocessor design, the core clock frequency largely determines the performance the microprocessor delivers to its user, i.e., the amount of instructions the microprocessor can execute in a given amount of time. Many systems that employ microprocessors require a certain level of performance, and the level may vary over time during operation of the system. For example, many modern microprocessors include the ability for system software, such as the BIOS or operating system, to dynamically specify a particular performance level by specifying the operating frequency of the microprocessor.

[0010] The dynamic power consumption of a microprocessor is proportional to the frequency of its core clock signal and to the square of its operating voltage. However, it is well known that the physical properties of most modern microprocessors are such that for each frequency at which the microprocessor may be operated, a minimum voltage level at the frequency must be supplied to the microprocessor or else it will fail to operate properly. Therefore, what is needed is a way to reduce the power consumed by a microprocessor at a required performance/frequency level by reducing the operating voltage.

[0011] Furthermore, there is a constant demand from consumers to receive higher performance from microproces-

sors. As discussed herein, all other things being equal, the higher the frequency at which a microprocessor operates the higher the performance the microprocessor will deliver. Consequently, a popular method of increasing the performance of microprocessors is what is commonly referred to as "overclocking." Traditionally, computer enthusiasts overclock a system by increasing the clock frequency of the front side bus of the microprocessor, which causes the microprocessor and other circuits connected to the front side bus to operate at the higher clock frequency. Overclocking has several drawbacks. First, overclocking a system invariably requires the overclocker to augment or replace the standard cooling system provided by the computer system manufacturer with a higher capacity cooling system, such as higher velocity and/or larger (and often louder) fans, more heavy duty heat sinks, liquid coolants, phase change cooling, or even liquid nitrogen. Second, overclocking may result in unreliable operation of the microprocessor potentially resulting in loss or corruption of data, damage to the microprocessor, or even damage to the system. This is because overclocking typically exceeds the specifications of the manufacturer, who may not have tested the microprocessor at the overclocked speeds and therefore cannot guarantee proper operation thereat. Third, overclocking the front side bus implies that the other devices that may be connected to the front side bus, such as memory, chipsets, video cards, etc., are also operating at the higher clock frequency and may also be subject to the additional cooling and unreliability problems just mentioned. Therefore, what is needed is an improved method for increasing the operating frequency of a microprocessor that avoids the drawbacks of traditional overclocking.

[0012] Still further, as mentioned herein, some microprocessors provide a means for system software, such as the BIOS or operating system, to change the operating frequency of the microprocessor. For example, the Advanced Configuration and Power Interface (ACPI) Specification, Revision 3.0 defines a P-state in terms of a CPU core operating frequency, and provides a means for system software to request the microprocessor to transition to a specified P-state. In the case of a frequency increase, typically the microprocessor must increase its operating voltage in order to support the frequency increase according to the physical characteristics of the microprocessor. The time to perform the voltage increase may be significant, depending upon the amount of voltage increase required. Conventional microprocessors increase the voltage to the necessary level and then make a single frequency change from the current frequency to the requested frequency, as shown in FIG. **4** and discussed in more detail herein. According to the conventional method of transitioning from a current P-state to a new P-state, the microprocessor operates at the lowest frequency during the entire P-state transition, which is inefficient. Therefore, what is needed is an improved method for increasing microprocessor performance when making a P-state transition.

[0013] Finally, some microprocessors include thermal monitoring and protection mechanisms. For example, various Intel® processors include Enhanced Intel SpeedStep® Technology, which includes the Thermal Monitor 2 (TM2) automatic thermal protection mechanism. TM2 was introduced in the Pentium® M processor and is also incorporated into newer models of the Pentium 4 processor family. The Intel Pentium M Processor with 2-MB L2 Cache and 533-MHz Front Side Bus Datasheet of July 2005 described TM2 as follows: "When the on-die thermal sensor indicates that the die temperature is too high, the processor can automatically perform a transition to a lower frequency/voltage specified in a software programmable MSR. The processor waits for a fixed time period. If the die temperature is down to acceptable levels, an up transition to the previous frequency/voltage point occurs." This operation is illustrated by an example with respect to FIG. **11**, which is discussed in more detail herein.

[0014] The ability of the processor to operate according to the TM2 mechanism only within the two operating points, namely the default operating point and the system software-specified operating point, has drawbacks. In particular, if the gap between the two operating points is programmed to be relatively large, then for many workload level and environmental condition combinations the processor may not be operating at a performance-optimal frequency/voltage combination. On the other hand, the smaller the gap between the two operating points the less the mechanism is able to provide the desired thermal protection during heavy workloads and/or hot environmental conditions. Furthermore, a valuable performance opportunity may be lost while operating at the lower frequency/voltage point if the fixed time period is too long. Therefore, what is needed is a higher performance thermal monitoring and protection mechanism.

BRIEF SUMMARY OF INVENTION

[0015] The present invention provides an improved method for increasing microprocessor performance when making a P-state transition by, rather than making a single frequency change, iteratively making multiple frequency changes while transitioning from the current P-state voltage to the new P-state voltage.

[0016] In one aspect, the present invention provides a microprocessor. The microprocessor includes core logic, configured to operate according to a core clock signal in order to execute program instructions. The microprocessor also includes clock generation circuitry, controllable to generate the core clock signal having one of N different possible frequencies, wherein N is more than two. The microprocessor also includes a control circuit, coupled to the clock generation circuitry. The control circuit, in response to a request to operate the core logic at a destination frequency, iteratively controls the clock generation circuitry to generate the core clock signal having a new frequency on each of successive frequency iterations until the core clock signal frequency is the destination frequency. The new core clock signal frequency on each of the iterations is one of the N different possible frequencies monotonically closer to the destination frequency. The number of frequency iterations is between zero and N−1 depending upon the destination frequency specified and the core clock signal frequency when the request is received.

[0017] In another aspect, the present invention provides a method for improving the performance of a microprocessor having core logic configured operate according to a core clock signal in order to execute program instructions. The method includes receiving a request to operate the core logic at a destination frequency. The method also includes generating a new frequency on the core clock signal in response the receiving the request, the new frequency being closer to

the destination frequency than a current frequency. The method also includes iterating at least twice on the generating a new frequency, until the new frequency is the destination frequency.

[0018] In another aspect, the present invention provides an apparatus for improving the performance of a microprocessor. The apparatus includes a first output, configured to provide a signal to control an operating voltage of the microprocessor. The apparatus also includes a second output, configured to provide a signal to control an operating frequency of the microprocessor. The apparatus also includes an input, configured to receive a request to operate the microprocessor at a destination frequency. The apparatus also includes a control circuit. The control circuit, in response to receiving the request on the input, iteratively generates the signal on the second output to operate the microprocessor at a plurality of different values of the operating frequency between a current frequency and the destination frequency. The control circuit also, in response to receiving the request on the input, iteratively generates the signal on the first output to operate the microprocessor at a plurality of different values of the operating voltage between a current voltage and a destination voltage associated with the destination frequency, while transitioning the operating frequency from the current frequency to the destination frequency.

[0019] In another aspect, the present invention provides a computer program product for use with a computing device, the computer program product comprising a computer usable storage medium having computer readable program code embodied in the medium, for providing a microprocessor. The computer readable program code includes first program code for providing core logic, configured to operate according to a core clock signal in order to execute program instructions. The computer readable program code also includes second program code for providing clock generation circuitry, controllable to generate the core clock signal having one of N different possible frequencies, wherein N is more than two. The computer readable program code also includes third program code for providing a control circuit, coupled to the clock generation circuitry. The control circuit, in response to a request to operate the core logic at a destination frequency, iteratively controls the clock generation circuitry to generate the core clock signal having a new frequency on each of successive frequency iterations until the core clock signal frequency is the destination frequency. The new core clock signal frequency on each said frequency iteration is one of the N different possible frequencies monotonically closer to the destination frequency. The number of frequency iterations is between zero and N−1 depending upon the destination frequency specified and the core clock signal frequency when the request is received.

[0020] In another aspect, the present invention provides a method for improving the performance of a microprocessor. The method includes receiving a request to change from operating the microprocessor at a current frequency to a destination frequency. The method also includes transitioning an operating voltage of the microprocessor from a current voltage to a destination voltage associated with the destination frequency, in response to the receiving the request. The method also includes operating the microprocessor at a plurality of frequencies between the current frequency and the destination frequency while the transitioning the operating voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIG. **1** is a block diagram illustrating a computing system including a microprocessor according to the present invention.

[0022] FIG. **2** is a flowchart illustrating operation of the microprocessor of FIG. **1** to transition from a current P-state, or operating point, to a new P-state, or operating point, in a performance-optimizing manner according to the present invention.

[0023] FIG. **3** is a graph further illustrating, by an example, operation of the microprocessor of FIG. **1** making a P-state transition according to the embodiment of FIG. **2**.

[0024] FIG. **4** is a graph illustrating, by an example, operation of a conventional microprocessor making a P-state transition.

[0025] FIG. **5** is a flowchart illustrating operation of the microprocessor of FIG. **1** to reduce the operating voltage when the operating temperature of the microprocessor is below a temperature threshold in order to save power according to the present invention.

[0026] FIG. **6** is a graph further illustrating operation of the microprocessor as described with respect to the embodiment of FIG. **5**.

[0027] FIG. **7** is a flowchart illustrating operation of the microprocessor of FIG. **1** to increase the performance of the microprocessor when the operating temperature of the microprocessor is below a temperature threshold according to the present invention.

[0028] FIG. **8** is a graph further illustrating, by an example, the method of operating the microprocessor of FIG. **1** in overstress mode according to the embodiment of FIG. **7**.

[0029] FIG. **9** is a flowchart illustrating a method for dynamically operating the microprocessor of FIG. **1** at or near optimum performance within a specified temperature range according to the present invention.

[0030] FIG. **10** is a graph further illustrating, by an example, the method of dynamically optimizing the performance of the microprocessor of FIG. **1** within a specified temperature range according to the embodiment of FIG. **9**.

[0031] FIG. **11** is a graph illustrating operation of the TM2 thermal monitoring and protection mechanism.

[0032] FIG. **12** is a graph illustrating operation of the microprocessor according to an embodiment of the present invention in which the features described with respect to FIGS. **5**, **7**, and **9** are employed in combination.

[0033] FIG. **13** is a flowchart illustrating a process for creating operating point information included in the operating point data of the microprocessor of FIG. **1** according to an embodiment of the present invention.

[0034] FIG. **14** is a flowchart illustrating operation of the microprocessor **102** of FIG. **1** to successively reduce the operating voltage when the operating temperature of the microprocessor **102** is below corresponding successively

lower temperature thresholds in order to save power according to an alternate embodiment.

[0035] FIG. **15** is a graph further illustrating operation of the microprocessor **102** as described with respect to the embodiment of FIG. **14**.

DETAILED DESCRIPTION OF THE INVENTION

[0036] Referring now to FIG. **1**, a block diagram illustrating a computing system **100** including a microprocessor **102** according to the present invention is shown. The system **100** includes a voltage regulator module (VRM) **108** coupled to the microprocessor **102**. The VRM **108** includes a voltage identifier input, VID **144**, received from the microprocessor **102**, a Vlock output **156** provided to the microprocessor **102**, and a voltage supply output, V_{dd} **142**, provided to the microprocessor **102**. The microprocessor **102** outputs a value on the VID input **144** to control the VRM **108** to output a particular supply voltage V_{dd} **142** which serves as the power source to the microprocessor **102**. In response to a new value on the VID input **144**, the VRM **108** gradually changes the output voltage V_{dd} **142** until it reaches the requested value, at which time the VRM **108** outputs a true value on the Vlock signal **156** to indicate the V_{dd} **142** value has stabilized. In one embodiment, the VRM **108** takes approximately 15 microseconds to stabilize in response to a new value on the VID input **144**. In one embodiment, the VRM **108** changes the V_{dd} **142** value by 16 mV for each incremental value of the VID **144**.

[0037] The microprocessor **102** includes core logic **106**, a temperature sensor **132**, a voltage/frequency control circuit **104**, two phase-locked loops (PLLs) **112**A and **112**B operating in parallel, and a selection circuit **114**. The voltage/frequency control **104** includes a clock ratio control circuit **128**, a VID control circuit **126**, a bias bit **124**, and storage for operating point data **122**. The VID control **126** generates the VID signal **144** to the VRM **108** and receives the Vlock **156** signal from the VRM **108**. The bias bit **124** indicates whether there is a preference for lower power consumption or higher performance by the microprocessor **102**. In one embodiment, the bias bit **124** is programmable by system software, such as a system BIOS or the operating system.

[0038] The temperature sensor **132** senses the temperature of the microprocessor **102** and outputs the temperature **134** to the voltage/frequency control **104**. In one embodiment, the temperature sensor **132** comprises multiple temperature sensors that sense the temperature of various portions of the microprocessor **102** and provide the highest temperature **134** to the voltage/frequency control **104**. In one embodiment, the temperature sensor **132** is located near the portion or portions of the microprocessor **102** that are known by the manufacturer to generally operate at the highest temperature.

[0039] Each of the PLLs **112** outputs a respective clock signal **152**A and **152**B that are provided as inputs to the selection circuit **114**. The selection circuit **114** includes a third input, PLL select **118**, generated by the clock ratio control **128**, which serves as a select input to the selection circuit **114**. Based on the value of the PLL select **118** input, the selection circuit **114** selects one of the PLL **112** clocks **152**A or **152**B to output as core clock signal **116**. The core clock **116** serves as the clock signal for the core logic **106**. Each of the PLLs **112** receives a bus clock signal **148**, which is an external clock signal received by the microprocessor **102**. Preferably, the bus clock **148** is the clock signal for the external bus of the microprocessor **102**, such as may be generated by a motherboard of the system **100**, for example. The clock ratio control **128** also generates two ratio signals **146**A and **146**B that are provided to the respective PLLs **112**A and **112**B. The PLLs **112** generate their respective clock signals **152**A and **152**B that are a multiple of the bus clock **148**, such as the ratios shown in FIG. **3**. The PLLs **112** multiply the bus clock **148** by a factor specified by the respective ratio signal **146**A and **146**B. In response to a new value on the ratio input **146**, the PLL **112** gradually changes the output clock frequency **152** until it reaches the requested value, at which time the PLL **112** outputs a true value on the Rlock signal **154** to indicate the clock signal **152** has locked in to the requested frequency. The output clock signals **152** are fed back as inputs to their respective PLL **112** to maintain the core clock **116** frequency synchronized with the bus clock **148** frequency according to well known operation of PLLs. In one embodiment, the PLLs **112** take approximately 10 microseconds to lock in once they receive a new value on the ratio input **146**. In one embodiment, the PLLs **112** are capable of multiplying the bus clock **148** frequency by integer values from 2 to 12.

[0040] The core logic **106** performs the fetching and execution of program instructions and data. The core logic **106** may include, for example, caches, instruction fetch and issue logic, architectural and non-architectural register files, branch prediction units, address generators, result writeback logic, a bus interface unit, and execution units such as arithmetic logic units, integer units, floating point units, and SIMD units, such as are well known in the art of microprocessor design. In one embodiment, the core logic **106** comprises an x86 architecture microprocessor.

[0041] The core logic **106** may include various programmable registers, including programmable registers **158** that system software may program to request operation of the microprocessor **102** at a new operating point, operating temperature range, or other condition. An operating point is a voltage/frequency ordered pair at which the microprocessor **102** may reliably operate at a given temperature. For example, in one embodiment, the microprocessor **102** may reliably operate at an operating point of 1.0 GHz and 0.75V at 100° C. Data describing the various operating points of the processor is stored in operating point data store **122**, whose use is described in more detail herein with respect to the remaining Figures. In one embodiment, the system software may program the registers **158** with a P-state value in compliance with the Advanced Configuration and Power Interface (ACPI) Specification, Revision 3.0. The ACPI specification defines a P-state in terms of a CPU core operating frequency. Although an ACPI P-state does not specify an operating voltage value, according to the ACPI specification the CPU reports a value of the typical power dissipated by the microprocessor with each supported P-state. A requested VID **136** and a requested clock ratio **138** are provided by the programmable registers **158** to the voltage/frequency control **104**. The programmable registers **158** may also be programmed with an operating temperature range, which is provided to the voltage/frequency control **104** via signals **162**, and which is described in more detail herein with respect to FIGS. **9** and **10**. The VID control **126** and the clock ratio control **128** generate the VID **144**, ratio

146, and PLL select 118 signal values, among other things, in response to the requested VID 136 and requested clock ratio 138 values and in response to the temperature range 162 values, as described in more detail herein.

[0042] The operating point data 122 includes information specifying, for each of multiple operating temperatures, multiple operating points (i.e., voltage/frequency combinations) at which the microprocessor 102 may reliably operate at the given one of the multiple operating temperatures. FIG. 13 describes the process by which the operating point data 122 is determined according to one embodiment. In one embodiment, the operating point data 122 includes a table of operating points for each of the multiple operating temperatures. Each entry in the table comprises the maximum PLL 112 frequency ratio value at which the microprocessor 102 may reliably operate at a given VID 144 value at the specified one of the multiple operating temperatures. In one embodiment, the table includes, for each of the operating temperatures, a frequency ratio for each of the possible V_{dd} 142 values the VRM 108 is capable of outputting. In another embodiment, the operating point data 122 includes a frequency ratio for fewer than all the possible V_{dd} 142 values, and the microprocessor 102 calculates the frequency ratio value for the remaining possible V_{dd} 142 values using the included values. In one embodiment, the microprocessor 102 calculates the frequency ratio value for the remaining possible V_{dd} 142 values by extrapolating along a line between two endpoints of the line at the maximum and minimum V_{dd} 142 values. In another embodiment, the microprocessor 102 calculates the frequency ratio value for the remaining possible V_{dd} 142 values according to a predetermined polynomial expression stored within the microprocessor 102.

[0043] In one embodiment, the manufacturer stores the operating point data 122 in the microprocessor 102 during its fabrication, such as in hard-wired logic of the microprocessor 102. Additionally or alternatively, the operating point information is programmed into programmable fuses, programmable logic, or a non-volatile memory of the microprocessor 102 after fabrication of the microprocessor 102, such as during manufacturing configuration of the microprocessor 102 after testing of each microprocessor 102 part, or by system software during operation of the microprocessor 102.

[0044] Referring now to FIG. 2, a flowchart illustrating operation of the microprocessor 102 of FIG. 1 to transition from a current P-state, or operating point, to a new P-state, or operating point, in a performance-optimizing manner according to the present invention is shown. Flow begins at block 202.

[0045] At block 202, the microprocessor 102 receives a request from system software to change from the current P-state to a new P-state. In one embodiment, system software programs the registers 158 of FIG. 1 with a new value to request the change to the new P-state. In response, the requested VID 136 and requested core clock ratio 138 are provided to the voltage/frequency control 104 of FIG. 1. In one embodiment, only the requested core clock ratio 138 is provided to the voltage/frequency control 104, and the new V_{dd} 142 value is determined from the operating point data 122. In one embodiment, the voltage/frequency control 104 accesses the operating point information for a predetermined temperature, such as the maximum operating temperature, to determine the minimum V_{dd} 142 value at which the microprocessor 102 may reliably operate at the requested ratio 138. Flow proceeds to decision block 204.

[0046] At decision block 204, the voltage/frequency control 104 of FIG. 1 determines whether the operating frequency specified by the new P-state requested at block 202 is greater than the current operating frequency. If not, flow proceeds to block 226; otherwise, flow proceeds to block 206.

[0047] At block 206, the VID control 126 increments the VID 144 to cause the VRM 108 to begin raising the V_{dd} 142 value. That is, the VID control 126 outputs a new value on the VID 144 that is one greater than the current value. Preferably, the VRM 108 is capable of increasing the V_{dd} 142 to the new level in a steady manner such that the microprocessor 102 may continue to operate during the V_{dd} 142 output transition. That is, operation of the microprocessor 102 need not be suspended while the VRM 108 is changing the V_{dd} 142. Flow proceeds to decision block 208.

[0048] At decision block 208, the voltage/frequency control 104 determines from the operating point data 122 associated with the T_{max} operating temperature whether it is permissible to raise the operating core clock 116 frequency based on the fact that the operating voltage V_{dd} 142 is being raised to the next highest VID 144. If so, flow proceeds to block 216; otherwise, flow proceeds to block 212.

[0049] At block 212, the VID control 126 waits for the Vlock signal 156 to indicate that the V_{dd} 142 has reached the new value requested at block 206. Flow proceeds to decision block 214.

[0050] At decision block 214, the voltage/frequency control 104 determines whether the new P-state requested at block 202 has been reached. If not, flow proceeds to block 206 to continue increasing the voltage V_{dd} 142 and, as necessary, the core clock frequency 116 until reaching the P-state requested at block 202; otherwise, flow proceeds to block 202 to await another P-state change request.

[0051] At block 216, the clock ratio control 128 outputs a new value on the ratio control signal 146 of the offline PLL 112 to start the offline PLL 112 locking in to the next highest ratio of the bus clock 148 than the current core clock frequency 116 that is supported by the soon-to-be new V_{dd} 142 value corresponding to the VID 144 value output at block 206. Typically, the new value on the ratio control signal 146 of the offline PLL 112 will be one greater than the current value of the ratio control signal 146 of the online PLL 112; however, if the slope of the operating point curve is relatively steep, then the new ratio may be two or more ratios above the current ratio. If the output 152A of PLL-A 112A is currently selected by the selection circuit 114 to be the core clock 116 output, then PLL-A 112A is the online PLL 112 and PLL-B 112B is the offline PLL 112, and vice versa. Flow proceeds to block 218.

[0052] At block 218, the VID control 126 waits for the Vlock signal 156 to indicate that the V_{dd} 142 has reached the new value requested at block 206. Flow proceeds to decision block 222.

[0053] At block 222, the ratio control 146 waits for the Rlock signal 154 of the offline PLL 112 to indicate that its

output clock signal **152** has locked in on the new frequency requested at block **216**. Flow proceeds to block **224**.

[**0054**] At block **224**, the ratio control **146** toggles the value on the PLL select signal **118** to select the offline PLL **112** clock output **152** as the core clock **116**, thus making the offline PLL **112** now the online PLL **112** and the online PLL **112** the offline PLL **112**. When the clock ratio of a PLL is being changed, the output of the PLL **112** cannot be used until the PLL has locked in to the new frequency. Advantageously, because the microprocessor **102** includes two PLLs **112**A and **112**B that can be alternated between being the online PLL **112** and the offline PLL **112**, the core clock frequency **116** can be changed effectively instantaneously, as described herein, and as described in U.S. patent application Ser. No. 10/816,004 (CNTR.2216), filed Apr. 1, 2004. In one embodiment, the core clock frequency **116** may be changed within a single cycle of the bus clock **148**. In one embodiment, the core clock frequency **116** may not be changed during certain phases of an active transaction on the processor bus; thus, the clock ratio control **128** makes an additional check and waits until the bus transaction phase completes before toggling the PLL select signal **118**. In the embodiment of FIG. **2**, performing steps **206** through **224** achieves proper operation of the microprocessor **102** because the VID **144** increments are relatively small, such as on the order of 16 mV. However, other embodiments are contemplated in which the VID **144** increments are relatively large, in which case the order of steps **216** and **218** are reversed to allow the VRM **108** to stabilize first before starting the offline PLL **112** locking to the next higher ratio. Flow proceeds to decision block **214**.

[**0055**] At decision block **226**, the voltage/frequency control **104** determines whether the new P-state requested at block **202** has been reached. If so, flow proceeds to block **202** to await another P-state change request; otherwise, flow proceeds to decision block **228**.

[**0056**] At decision block **228**, the voltage/frequency control **104** determines from the operating point data **122** associated with the T_{max} operating temperature whether the operating core clock **116** frequency needs to be lowered based on the fact that the operating voltage V_{dd} **142** is about to be lowered to the next lowest VID **144**. If not, flow proceeds to block **238**; otherwise, flow proceeds to block **232**.

[**0057**] At block **232**, the clock ratio control **128** outputs a new value on the ratio control signal **146** of the offline PLL **112** to start the offline PLL **112** locking in to the next lowest ratio of the bus clock **148** than the current core clock frequency **116** that is required by the soon-to-be new V_{dd} **142** value corresponding to the VID **144** value that will be output at block **238**. Typically, the new value on the ratio control signal **146** of the offline PLL **112** will be one less than the current value of the ratio control signal **146** of the online PLL **112**; however, if the slope of the operating point curve is relatively steep, then the new ratio may be two or more ratios below the current ratio. Flow proceeds to block **234**.

[**0058**] At block **234**, the ratio control **146** waits for the Rlock signal **154** of the offline PLL **112** to indicate that its output clock signal **152** has locked in on the new frequency requested at block **232**. In one embodiment, when waiting to receive a request to change to a new P-state at block **202** the offline PLL **112** is pre-locked in to the next lowest ratio. This is an optimization because when transitioning to a higher P-state, the voltage/frequency control **104** must wait a period for the VRM **108** to complete increasing the V_{dd} **142** which is greater than the period required to lock in the offline PLL **112** to the next highest ratio; whereas, when transitioning to a lower P-state, the voltage/frequency control **104** can immediately reduce the ratio without waiting for the VRM **108** to complete lowering the V_{dd} **142**. Flow proceeds to block **236**.

[**0059**] At block **236**, the ratio control **146** toggles the value on the PLL select signal **118** to select the offline PLL **112** clock output **152** as the core clock **116**, thus making the offline PLL **112** now the online PLL **112** and the online PLL **112** the offline PLL **112**. Flow proceeds to block **238**.

[**0060**] At block **238**, the VID control **126** decrements the VID **144** to cause the VRM **108** to begin lowering the V_{dd} **142** value. That is, the VID control **126** outputs a new value on the VID **144** that is one less than the current value. Preferably, the VRM **108** is capable of decreasing the V_{dd} **142** to the new level in a steady manner such that the microprocessor **102** may continue to operate during the V_{dd} **142** output transition. Flow proceeds to block **242**.

[**0061**] At block **242**, the VID control **126** waits for the Vlock signal **156** to indicate that the V_{dd} **142** has reached the new value requested at block **238**. Flow proceeds to decision block **226**.

[**0062**] Referring now to FIG. **3**, a graph further illustrating, by an example, operation of the microprocessor **102** of FIG. **1** making a P-state transition according to the embodiment of FIG. **2** is shown. The independent variables on the horizontal axis of the graph are time measured in microseconds and the operating voltage V_{dd} **142** measured in Volts. The domain of the time is 0 to 375 microseconds, which represents 25 VID **144** increments of the V_{dd} **142** value and corresponds to the domain of V_{dd} **142** from 0.7 V to 1.1 V, where each of the 25 V_{dd} **142** increments is 16 mV. The dependent variable on the vertical axis of the graph is the core clock frequency **116** measured in GHz. In the embodiment of FIG. **3**, the bus clock frequency is 200 MHz, the range of bus clock ratios is 2× to 10×, resulting in a corresponding core clock frequency **116** range of 400 MHz to 2.0 GHz. The graph shows a transition according to FIG. **2** from a lowest P-state at 400 MHz (2× ratio) and corresponding 0.7 V V_{dd} **142** value to the highest P-state at 2.0 GHz (10× ratio) and corresponding 1.1 V V_{dd} **142** value. The performance during the 375 microsecond transition period is the number of core clock **116** cycles, which is the area of the rectangles under the curve between the lowest and highest P-states, which in the example of FIG. **3** is a line between the lowest and highest P-states. As the time and V_{dd} **142** values increase, a new rectangle is formed each time the core clock **116** frequency is increased. In the example of FIG. **3**, employing the steps of FIG. **2**, the performance is approximately 408,000 core clock **116** cycles.

[**0063**] FIG. **3** illustrates a transition from one P-state to a higher P-state using the iterative approach of FIG. **2** to optimize performance during the transition. As described in FIG. **2**, the iterative approach may also be used to make a transition from one P-state to a lower P-state to optimize performance during the transition. However, in an alternate embodiment, when transitioning to a lower P-state, opera-

tion is optimized for reduced power, viz, the transition is made by immediately reducing the operating frequency to the low P-state and remaining at the low P-state frequency while the voltage value is transitioned to the specified voltage value.

[0064] Referring now to FIG. **4**, a graph illustrating, by an example, operation of a conventional microprocessor making a P-state transition is shown. The graph of FIG. **4** is similar to the graph of FIG. **3**, except that the microprocessor continues to operate at the 400 MHz (2× ratio) frequency throughout the transition of the supply voltage value up to the highest P-state value of 1.1 V, at which time a single change of the core clock frequency to 2.0 GHz (10× ratio) is made. Accordingly, in the example of FIG. **4**, the performance is only approximately 150,000 core clock cycles.

[0065] As may be observed from FIGS. **3** and **4**, the amount of time required to transition from a current P-state to another P-state (or vice versa) may be relatively large, on the order of hundreds of microseconds. The microprocessor **102** of FIG. **1** operating according to the embodiment of FIG. **2** has the advantage that it does not require any stopping of the core clock **116** to the core logic **106** to make the P-state transition by virtue of the dual PLL **112** arrangement, which facilitates effectively instantaneous core clock **116** frequency changes. That is, the voltage/frequency control **104** advantageously makes the multiple intermediate operating point transitions without suspending operation of the core logic **106** from executing program instructions. This is in contrast to conventional microprocessors which must incur at least the delay of waiting for their single PLL **112** to lock in to the new frequency (for example, approximately 10 microseconds). Additionally, as may be observed by comparing FIGS. **3** and **4**, the core logic **106** of the microprocessor **102** operating according to the embodiment of FIG. **2** has the advantage that it enjoys almost three times the number of clock cycles for execution of instructions than the conventional method during the P-state transition time, which may potentially be hundreds of microseconds. These two additional performance advantages may be significant, particularly in environments in which the operating system is requesting relatively frequent P-state changes due to rapidly varying temperature conditions.

[0066] It is noted that while according to steps **206** through **224** or **228** through **242** of FIG. **2**, with some VID **144** increments or decrements, the voltage/frequency control **104** may not perform a corresponding ratio increase or decrease, and vice versa. This depends upon the single VID **144** change amount (e.g., 16 mV), upon the frequency amount of a single ratio change (e.g., 200 MHz), and upon the valid operating point values stored in the operating point data **122** or calculated from the operating point data **122**. Thus, for example, assume the microprocessor **102** is currently operating at 1.2 GHz (6× ratio) and 0.9 V while transitioning to a higher P-state. The voltage/frequency control **104** will perform step **206** to increase the V_{dd} **142** to 0.916 V. If the operating point data **122** indicates that at 0.916 V the microprocessor **102** can reliably operate at 1.2 GHz (6× ratio), but not at 1.4 GHz (7× ratio), then the voltage/frequency control **104** foregoes performing steps **216** through **224** and continues operating at 1.2 GHz until the V_{dd} **142** reaches a value at which the operating point data **122** indicates the microprocessor **102** may reliably operate at 1.4 GHz, in which case the voltage/frequency control **104** will perform steps **216** through **224** during that iteration of the loop. In the example of FIG. **3**, the voltage/frequency control **104** performs twenty-five VID **144** changes and eight core clock **116** ratio changes; thus, approximately every three VID **144** changes the voltage/frequency control **104** will perform a core clock **116** ratio change.

[0067] In the example of FIG. **3**, a single maximum operating temperature curve is assumed. However, as discussed herein with respect to the remaining Figures, the steps of FIG. **2** may be advantageously employed in the embodiments of FIGS. **5** through **10**, **12**, and **14** to make operating point transitions that involve multiple operating temperatures.

[0068] Referring now to FIG. **5**, a flowchart illustrating operation of the microprocessor **102** of FIG. **1** to reduce the operating voltage when the operating temperature of the microprocessor **102** is below a temperature threshold in order to save power according to the present invention is shown. Flow begins at block **502**.

[0069] At block **502**, the microprocessor **102** manufacturer selects the maximum operating temperature at which the user may operate the microprocessor **102**, referred to as T_{max}, and includes the T_{max} value in the operating point data **122**. The maximum operating temperature may be determined based on device technology and customer requirements, among other factors, as well as expected typical cooling systems provided by computer system manufacturers. In one embodiment, the maximum operating temperature selected is 100° C., although other values may be chosen. In one embodiment, the manufacturer selects the T_{max} value based on market requirements. In one embodiment, the manufacturer selects the T_{max} value as the temperature at which the user may reliably operate the microprocessor **102** at T_{max} for a lifetime over which the manufacturer wishes to guarantee to consumers proper operation of the microprocessor **102**. In one embodiment, the manufacturer provides a 10 year guarantee of the parts, although other values may be chosen. In one embodiment, the manufacturer determines the T_{max} value based on accelerated life testing of the microprocessor **102**. In one embodiment, the T_{max} value is programmed into a programmable fuse of the microprocessor **102**. Flow proceeds to block **504**.

[0070] At block **504**, the microprocessor **102** manufacturer selects at least one alternate operating temperature of the microprocessor **102**, referred to as T_{alt}, which is less than the T_{max} value, and includes the T_{alt} value in the operating point data **122**. In one embodiment, the microprocessor **102** manufacturer may select multiple T_{alt} values for which to determine operating point information as described herein with respect to block **506**, as described herein with respect to FIGS. **14** and **15**. In one embodiment, the microprocessor **102** operates with a default T_{alt} value that system software may override by programming another T_{alt} value into a register used by the voltage/frequency control **104**. In one embodiment, the default T_{alt} value is programmed into a programmable fuse of the microprocessor **102**. Flow proceeds to block **506**.

[0071] At block **506**, the microprocessor **102** manufacturer determines the operating point information for each of the T_{max} and T_{alt} values. According to one embodiment, the operating point information for the T_{max} and T_{alt} values is determined according to the embodiment of FIG. **13**. Flow proceeds to block **508**.

[0072] At block **508**, the microprocessor **102** monitors its temperature while operating at a given frequency. That is, the temperature sensor **132** senses the current operating temperature and provides the temperature **134** to the voltage/frequency control **104** of FIG. **1**. In one embodiment, the given operating frequency is a default value, which may be a single operating frequency at which the microprocessor **102** is enabled to operate. In one embodiment, system software instructs the microprocessor **102** to operate at the given operating frequency. The system software may be the system BIOS or operating system, for example. In one embodiment, the system software instructs the microprocessor **102** to operate at the given operating frequency by programming a performance state (P-state) value into the microprocessor **102**. In one embodiment, the P-state value conforms to the Advanced Configuration and Power Interface (ACPI) Specification, such as Revision 3.0 of the ACPI Specification. Flow proceeds to decision block **512**.

[0073] At decision block **512**, the voltage/frequency control **104** determines whether the current temperature **134** is less than the T_{alt} value. The current operating temperature **134** may drop below the T_{alt} value for various reasons, such as a reduction in the workload placed upon the microprocessor **102** by the programs executing thereon or changes in the operating environment such as an air conditioning unit in the machine room turning on or the removal of an obstruction to airflow around the microprocessor **102**. Advantageously, as shown in FIG. **5**, the voltage/frequency control **104** may take advantage of the drop in the temperature **134** by reducing the operating voltage V_{dd} **142** to reduce the power consumed by the microprocessor **102**. Furthermore, because the microprocessor **102** is more likely to be consuming less power while operating at the lower voltage, its operating temperature **134** will likely remain below the T_{alt} value, thus advantageously prolonging operation at the lower voltage and the commensurate power savings. If the current temperature **134** is not less than the T_{alt} value, flow proceeds to decision block **522**; otherwise, flow proceeds to block **514**.

[0074] At block **514**, the voltage/frequency control **104** determines from the operating point information **122** the voltage value specified for operating the microprocessor **102** at the current operating frequency at the T_{alt} value. As discussed herein, the voltage/frequency control **104** may look up the voltage value in a table, or may calculate the voltage value based on operating point values stored in the operating point information **122**. Flow proceeds to decision block **516**.

[0075] At decision block **516**, the voltage/frequency control **104** determines whether the microprocessor **102** is currently operating at the voltage value determined at block **514**. If so, flow returns to block **508**; otherwise, flow proceeds to block **518**.

[0076] At block **518**, the voltage/frequency control **104** reduces the operating voltage to the value determined at block **514**, namely by outputting the appropriate VID value **144** to the VRM **108** of FIG. **1**, which responsively provides the reduced value of V_{dd} **142** to the microprocessor **102**. In one embodiment, the voltage/frequency control **104** reduces the operating voltage V_{dd} **142** in relatively small increments, such as 16 mV, until it reaches the value determined at block **514**. Flow returns to block **508**.

[0077] At decision block **522**, the voltage/frequency control **104** determines whether the microprocessor **102** is currently operating at the maximum voltage value for the current operating frequency, i.e., the voltage value for the current operating frequency at the T_{max} value. If so, flow returns to block **508**; otherwise, flow proceeds to block **524**.

[0078] At block **524**, the voltage/frequency control **104** increases the operating voltage to the maximum voltage value. In one embodiment, the voltage/frequency control **104** increases the operating voltage V_{dd} **142** in relatively small increments, such as 16 mV, until it reaches the maximum voltage value. Flow returns to block **508**.

[0079] In an alternate embodiment described herein with respect to FIGS. **14** and **15**, the microprocessor **102** manufacturer determines multiple alternate temperatures and determines and stores operating point information for multiple alternate temperatures, rather than just a single alternate temperature. In this embodiment, the microprocessor **102** may advantageously transition operation between the voltages associated with the maximum and multiple alternate temperatures as the temperature varies according to workload and environmental conditions, thereby operating the microprocessor **102** at the lowest power consumption level for the required frequency/performance level, which may be specified by the operating system or other system software, for example.

[0080] Referring now to FIG. **6**, a graph further illustrating operation of the microprocessor **102** as described with respect to the embodiment of FIG. **5** is shown. The independent variable of the graph is the operating voltage V_{dd} **142** on the horizontal axis measured in Volts. The dependent variable of the graph is the core clock frequency **116** on the vertical axis measured in GHz. In the embodiment of FIG. **6**, the bus clock frequency is 200 MHz, the range of bus clock ratios is 2× to 10×, resulting in a core clock frequency **116** range of 400 MHz (2× ratio) to 2.0 GHz (10× ratio). The graph shows two voltage/frequency curves, one for the T_{max} value (which is 100° C. in the embodiment) and one for the T_{alt} value (which is 60° C. in the embodiment). In the embodiment of FIG. **6**, an operating point of 1.1 V is shown for the 2.0 GHz operating frequency at the T_{max} value and an operating point of 0.972 V is shown for the 2.0 GHz frequency at the T_{alt} value. Thus, for example, according to FIG. **6**, if while operating at 2.0 GHz the voltage/frequency control **104** determines that the temperature **134** has dropped below 60° C., the voltage/frequency control **104** may reduce the V_{dd} **142** value from 1.1 V to 0.972 V. As shown in the graph, the operating voltage V_{dd} **142** may be reduced to a lower value at each of the core clock frequency **116** values if the operating temperature **134** is below the T_{alt} value, thereby advantageously resulting in lower power consumption by the microprocessor **102** than when operating at the maximum voltage V_{dd} **142** at the core clock frequency **116**.

[0081] As may be observed from FIGS. **5** and **6**, the embodiments may reduce the amount of power consumed by the microprocessor **102** at a given required performance level. The following example provides further illustration. Assume the system **100** is being used only to watch a DVD and the operating system responsively determines that a relatively low level of performance is required and power savings may be achieved. Consequently, the operating system programs the microprocessor **102** to operate at a 1.2

GHz clock frequency, for example. Assume the operating temperature **134** of the microprocessor **102** drops below the T_{alt} value of 60° C. In this case, according to FIGS. **5** and **6**, the voltage/frequency control **104** reduces the operating voltage V_{dd} **142** to a lower value to further reduce the microprocessor **102** power consumption.

[**0082**] Another advantage of the embodiment of FIGS. **5** and **6** is that it not only potentially reduces the dynamic power consumption of the microprocessor **102**, but it also potentially reduces the static power consumption of the microprocessor **102**. The static power consumption is primarily attributed to the amount of leakage power consumed by a transistor even when not making a transition. The leakage power is directly proportional to the operating voltage value. Thus, by reducing the operating voltage V_{dd} **142** according to FIGS. **5** and **6**, the static power consumption may also be advantageously reduced. Thus, advantageously, even a relatively small reduction in the V_{dd} **142** value may result in significant power reduction.

[**0083**] Referring now to FIG. **7**, a flowchart illustrating operation of the microprocessor **102** of FIG. **1** to increase the performance of the microprocessor when the operating temperature of the microprocessor **102** is below a temperature threshold according to the present invention is shown. The method illustrated in FIG. **7** is referred to herein as "overstress" or "overstress mode" to distinguish it from traditional overclocking, which does not include the microprocessor **102** monitoring its own operating temperature and automatically dynamically varying the operating frequency ratio between a maximum ratio and an overstress ratio based on the operating temperature, as described herein. Flow begins at block **704**.

[**0084**] At block **704**, the manufacturer selects the maximum operating temperature at which the user may operate the microprocessor **102**, referred to as T_{max}, and includes the T_{max} value in the operating point data **122**. The maximum operating temperature may be determined based on device technology and customer requirements, among other factors, as well as expected typical cooling systems provided by computer system manufacturers. In one embodiment, the maximum operating temperature selected is 100° C., although other values may be chosen. In one embodiment, the manufacturer selects the T_{max} value based on market requirements. In one embodiment, the manufacturer selects the T_{max} value as the temperature at which the user may reliably operate the microprocessor **102** at T_{max} for a lifetime over which the manufacturer wishes to guarantee to consumers proper operation of the microprocessor **102**. In one embodiment, the manufacturer provides a 10 year guarantee of the parts, although other values may be chosen. In one embodiment, the manufacturer determines the T_{max} value based on accelerated life testing of the microprocessor **102**. In one embodiment, the T_{max} value is programmed into a programmable fuse of the microprocessor **102**. Flow proceeds to block **706**.

[**0085**] At block **706**, the manufacturer determines the maximum operating frequency, referred to as F_{max}, at which the part **102** can reliably operate at T_{max}. The manufacturer also determines the operating voltage, V_{max}, required for the part **102** to reliably operate at F_{max} and T_{max}. According to one embodiment, the operating point information for the T_{max} values is determined according to the embodiment of FIG. **13**. In the embodiment of FIG. **8**, the values of V_{max} and F_{max} are 1.1 V and 2.0 GHz (10× ratio), respectively. Flow proceeds to block **708**.

[**0086**] At block **708**, the manufacturer selects an overstress operating temperature, referred to as T_{ov}, and includes the T_{ov} value in the operating point data **122**. The T_{ov} value is less than the T_{max} value. The T_{ov} value may also be determined based on device technology and customer requirements, among other factors, as well as expected typical cooling systems provided by computer system manufacturers. In one embodiment, the T_{ov} value is 75° C., as shown in FIG. **8**, although other values may be chosen. Flow proceeds to block **712**.

[**0087**] At block **712**, the manufacturer determines the maximum operating frequency, referred to as F_{ov}, at which the part **102** can reliably operate at T_{ov}. The manufacturer also determines the operating voltage, V_{ov}, required for the part **102** to reliably operate at F_{ov} and T_{ov}. According to one embodiment, the operating point information for the T_{ov} values is determined according to the embodiment of FIG. **13**. In the embodiment of FIG. **8**, the values of V_{ov} and F_{ov} are 1.132 V and 2.4 GHz (12× ratio), respectively. The various values required to operate the microprocessor **102** in overstress mode, such as T_{max}, T_{ov}, V_{max}, V_{ov}, F_{max}, and F_{ov}, are stored within the microprocessor **102** and may be included as part of the operating point data **122** of FIG. **1**. Flow proceeds to block **714**.

[**0088**] At block **714**, the microprocessor **102** monitors its temperature while operating. That is, the temperature sensor **132** senses the current operating temperature and provides the temperature **134** to the voltage/frequency control **104** of FIG. **1**. Initially, the microprocessor **102** operates at V_{max} and F_{max}. In one embodiment, system software may program the microprocessor **102** to enable or disable operation of the overstress mode. Flow proceeds to decision block **716**.

[**0089**] At decision block **716**, the voltage/frequency control **104** determines whether the current temperature **134** is less than the T_{ov} value determined at block **708**. The current operating temperature **134** may drop below the T_{ov} value for various reasons, such as a reduction in the workload placed upon the microprocessor **102** or changes in the ambient conditions or cooling system. Advantageously, as shown in FIG. **7**, the voltage/frequency control **104** may take advantage of the drop in the temperature **134** by increasing the core clock frequency **116** to increase the performance of the microprocessor **102**. If the current temperature **134** is not less than the T_{ov} value, flow proceeds to decision block **724**; otherwise, flow proceeds to decision block **718**.

[**0090**] At decision block **718**, the voltage/frequency control **104** determines whether the core clock frequency **116** is already at the overstress frequency F_{ov}. If so, flow returns to block **714** to continue monitoring the temperature **134**; otherwise, flow proceeds to block **722**.

[**0091**] At block **722**, the voltage/frequency control **104** controls the VRM **108** and PLLs **112** to cause the microprocessor **102** to operate at the F_{ov} and V_{ov} values, as shown in FIG. **8**. Preferably, the voltage/frequency control **104** transitions to operation at F_{ov} and V_{ov} in a manner similar to that described herein with respect to steps **206** through **224** of FIG. **2** proceeding along the T_{ov} curve, i.e., on the curve

at which the microprocessor **102** is capable of operating at the overstress temperature value T_{ov}. Flow returns to block **714** to continue monitoring the temperature **134**.

[**0092**] At decision block **724**, the voltage/frequency control **104** determines whether the core clock frequency **116** is already at the maximum frequency F_{max}. If so, flow returns to block **714** to continue monitoring the temperature **134**; otherwise, flow proceeds to block **726**. As discussed herein, embodiments are contemplated in which the TM3 mechanism of FIG. **9** may be used in combination with the overstress mechanism of FIG. **7**, in which case, flow may proceed from decision block **724** to decision block **918** of FIG. **9**.

[**0093**] At block **726**, the voltage/frequency control **104** controls the VRM **108** and PLLs **112** to cause the microprocessor **102** to operate at the F_{max} and V_{max} values, as shown in FIG. **8**. Preferably, the voltage/frequency control **104** transitions to operation at F_{max} and V_{max} in a manner similar to that described herein with respect to steps **226** through **242** of FIG. **2** proceeding along the T_{max} curve, i.e., on the curve at which the microprocessor **102** is capable of operating at the T_{max} value. The current operating temperature **134** may rise above the T_{ov} value as detected at decision block **716** for various reasons, such as an increase in the workload placed upon of the microprocessor **102** or changes in the operating environment. Advantageously, according to the steps at blocks **724** and **726**, the voltage/frequency control **104** may avoid overheating the microprocessor **102** by sensing the increase in the temperature **134** and reducing the core clock frequency **116** when necessary, thereby enabling at other times the microprocessor **102** to take advantage of operating in overstress mode when possible. Flow returns to block **714** to continue monitoring the temperature **134**.

[**0094**] Referring now to FIG. **8**, a graph further illustrating, by an example, the method of operating the microprocessor **102** of FIG. **1** in overstress mode according to the embodiment of FIG. **7** is shown. The independent variable on the horizontal axis of the graph is the operating voltage V_{dd} **142** measured in Volts. The domain of the V_{dd} **142** value is from 0.7 V to 1.1 V. The dependent variable on the vertical axis of the graph is the core clock frequency **116** measured in GHz. In the example of FIG. **10**, the bus clock frequency is 200 MHz, the range of bus clock ratios is 2× to 10×, resulting in a corresponding core clock frequency **116** range of 400 MHz to 2.0 GHz. The graph, according to FIG. **7**, shows a transition from the operating point values of V_{max} and F_{max} at 1.1 V and 2.0 GHz (10× ratio), respectively, to the overstress operating point values of V_{ov} and F_{ov} at 1.132 V and 2.4 GHz (12× ratio), respectively, on the 75° C. T_{ov} value curve.

[**0095**] An advantage of the overstress mode operation described herein is that it may operate with the conventional cooling system provided in a computer system **100** incorporating the microprocessor **102**. The overstress mode enables the microprocessor **102** to dynamically operate at the overstress frequency or below the overstress frequency at different times depending upon whether the workload and/or operating environment are such that the cooling system may adequately cool the microprocessor **102**. In contrast, conventional overclocking methods do not monitor the temperature of the microprocessor **102** in order to automatically dynamically change the frequency. That is, the frequency is fixed at the overclock frequency, or at best changeable by the user via the BIOS, which is not amenable to guaranteeing reliable operation of the microprocessor. Overstress mode provides a similar advantage over conventional overclocking schemes that unlock the bus frequency ratio by connecting electrical contacts across points on the outer surface of the microprocessor, such as provided by certain AMD Athlon parts. Another advantage of overstress mode is that the other devices that may be connected to the front side bus need not operate at the higher clock frequency and therefore are not subject to the additional cooling and unreliability problems. Another advantage of overstress mode is that because the frequency changes are internal to the microprocessor **102**, there is no requirement to stop the external processor bus when changing frequencies. Another advantage is that the overstress method described herein enables the microprocessor **102** manufacturer to test operation in the overstress mode to guarantee reliable operation of the microprocessor at the overstress operating point, whereas conventional after market overclocking schemes do not.

[**0096**] Referring now to FIG. **9**, a flowchart illustrating a method for dynamically operating the microprocessor **102** of FIG. **1** at or near optimum performance within a specified temperature range according to the present invention is shown. The method illustrated in FIG. **9** is referred to herein as "TM3" because it is an improvement over the well-known Intel "TM2" (Thermal Monitor 2) feature. Flow begins at block **902**.

[**0097**] At block **902**, an operating temperature range is selected. This is the temperature range in which it is desired that the microprocessor **102** should operate, but at the optimum performance within the temperature range. The temperature range is defined by a minimum temperature (T_{min}) and a maximum temperature (T_{max}). In one embodiment, the T_{max} and T_{min} values may be specified by either a T_{max} or T_{min} value and a delta, or range width, value from the T_{max} or T_{min} value. In one embodiment, system software programs the range into the programmable registers **158**. In one embodiment, the programmed values may be selectable by a user. The temperature range values **162** are provided to the voltage/frequency control **104** of FIG. **1**. In one embodiment, the temperature range is predetermined by the microprocessor **102** manufacturer. In one embodiment, the predetermined range operates as the default temperature range, which may be changed by programming of the registers **158**. In one embodiment, the T_{max} value is predetermined by the microprocessor **102** manufacturer and the T_{min} value is programmable by system software. In one embodiment, the TM3 feature may be enabled or disabled by system software. Flow proceeds to block **904**.

[**0098**] At block **904**, the microprocessor **102** monitors its operating temperature. That is, the temperature sensor **132** senses the current operating temperature and provides the temperature **134** to the voltage/frequency control **104** of FIG. **1**. Initially the microprocessor **102** operates at a default core clock **116** frequency and voltage V_{dd} **142** operating point. However, over time the voltage/frequency control **104** transitions to many different operating points as the operating temperature **134** varies, as described herein. As discussed herein, the operating temperature **134** may vary over

time based on a number of factors, including workload, ambient conditions, and cooling systems. Flow proceeds to decision block **906**.

[**0099**] At decision block **906**, the voltage/frequency control **104** determines whether the current temperature **134** is greater than the T_{max} value determined at block **902**. If not, flow proceeds to decision block **918**; otherwise, flow proceeds to decision block **908**.

[**0100**] At decision block **908**, the voltage/frequency control **104** determines whether the operating voltage V_{dd} **142** is already at the lowest VID **144** value supported by the VRM **108**. In the example shown in FIG. **10**, the operating voltage V_{dd} **142** at 0.7 V is the lowest value supported by the VRM **108**. If the operating voltage V_{dd} **142** is already at the lowest supported VID **144** value, flow returns to block **904** to continue monitoring the temperature **134**; otherwise, flow proceeds to decision block **912**.

[**0101**] At decision block **912**, the voltage/frequency control **104** determines from the operating point data **122** whether the operating core clock **116** frequency needs to be lowered based on the fact that the operating voltage V_{dd} **142** is about to be lowered at block **916** to the next lowest VID **144**. If not, flow proceeds to block **916**; otherwise, flow proceeds to block **914**.

[**0102**] At block **914**, the clock ratio control **128** causes a transition of the core clock **116** frequency to the next lowest ratio of the bus clock **148** below the current core clock **116** frequency required by the new VID **144** which will be output at block **916**. Advantageously, the transition is performed as described herein with respect to steps **226** through **242** of FIG. **2**, thereby avoiding the loss of performance incurred by conventional methods that stop the core clock while waiting for the PLL to lock in. That is, because the microprocessor **102** can effectively make operating point transitions without penalty (i.e., it can perform effectively instantaneous core clock **116** frequency changes with the dual PLLs **112** and can continue to operate reliably while the VRM **108** changes the V_{dd} **142** value), the voltage/frequency control **104** can afford to make relatively frequent operating point transitions when necessary, such as when the workload varies widely and frequently, to keep the microprocessor **102** operating within the temperature range specified at block **902**. Flow proceeds to block **916**.

[**0103**] At block **916**, the VID control **126** decrements the VID **144** value to cause the VRM **108** to transition to the next lowest V_{dd} **142** output level. Advantageously, the transition is performed as described herein with respect to steps **226** through **242** of FIG. **2**, thereby avoiding any loss of performance because the microprocessor **102** can continue to operate reliably while the VRM **108** changes the V_{dd} **142** value. Thus, the voltage/frequency control **104** can afford to make relatively frequent operating point transitions if necessary to keep the microprocessor **102** operating within the temperature range specified at block **902**. Flow returns to block **904** to continue monitoring the temperature **134**.

[**0104**] At decision block **918**, the voltage/frequency control **104** determines whether the current temperature **134** is less than the T_{min} value determined at block **902**. If not, flow returns to block **904** to continue monitoring the temperature **134**; otherwise, flow proceeds to decision block **922**.

[**0105**] At decision block **922**, the voltage/frequency control **104** determines whether the core clock frequency **116** is already at the highest operating frequency supported by the PLLs **112**. In the example shown in FIG. **10**, the operating frequency at 2.0 GHz (10× ratio) is the highest operating frequency supported by the microprocessor **102**. However, it is noted that the steps of FIG. **9** may also be incorporated with the steps of FIG. **7** such that the highest operating point supported by the microprocessor **102** is an overstress operating point, such as the operating point at 2.4 GHz (12× ratio) and 1.132 V shown in FIG. **8**. If the core clock frequency **116** is already at the highest operating frequency, flow returns to block **904** to continue monitoring the temperature **134**; otherwise, flow proceeds to block **924**.

[**0106**] At block **924**, the VID control **126** increments the VID **144** value to cause the VRM **108** to transition to the next highest V_{dd} **142** output level. Advantageously, the transition is performed as described herein with respect to steps **206** through **224** of FIG. **2**. Flow proceeds to decision block **926**.

[**0107**] At decision block **926**, the voltage/frequency control **104** determines from the operating point data **122** whether it is permissible to raise the operating core clock **116** frequency based on the fact that the operating voltage V_{dd} **142** was raised at block **924** to the next highest VID **144**. If not, flow returns to block **904** to continue monitoring the temperature **134**; otherwise, flow proceeds to block **928**.

[**0108**] At block **928**, the clock ratio control **128** causes a transition of the core clock **116** frequency to the next highest ratio of the bus clock **148** above the current core clock **116** frequency that is allowed by the new VID **144** output at block **924**. Advantageously, the transition is performed as described herein with respect to steps **206** through **224** of FIG. **2**, thereby avoiding the loss of performance incurred by conventional methods that stop the core clock while waiting for the PLL to lock in. Flow returns to block **904** to continue monitoring the temperature **134**.

[**0109**] Referring now to FIG. **10**, a graph further illustrating, by an example, the method of dynamically optimizing the performance of the microprocessor **102** of FIG. **1** within a specified temperature range according to the embodiment of FIG. **9** is shown. The independent variable on the horizontal axis of the graph is the operating voltage V_{dd} **142** measured in Volts. The domain of the V_{dd} **142** value is from 0.7 V to 1.1 V. The dependent variable on the vertical axis of the graph is the core clock frequency **116** measured in GHz. In the example of FIG. **10**, the bus clock frequency is 200 MHz, the range of bus clock ratios is 2× to 10×, resulting in a corresponding core clock frequency **116** range of 400 MHz to 2.0 GHz. The graph, according to FIG. **9**, shows transitions between the lowest and highest operating points via a plurality of intermediate operating points. As shown, the voltage/frequency control **104** constantly monitors the operating temperature **134** and transitions between the various adjacent operating points, without stopping the core clock **116**, in order to maintain the operating temperature **134** within the specified range. Thus, the embodiment of FIG. **9** advantageously keeps the core logic **106** operating close to the optimum performance level possible for the workload level, ambient conditions, and cooling system at a given time.

[**0110**] Referring now to FIG. **11**, a graph illustrating operation of the TM2 thermal monitoring and protection mechanism is shown. Operation of the TM2 mechanism, as

described in the Intel documentation, is provided above near the end of the Background section. It is noted that the operating point values provided in the example of FIG. **11** are not intended to represent values employed in a particular Intel processor. Rather, the values provided in FIG. **11** are selected for ease of comparison with the values shown in FIG. **10**.

[**0111**] As discussed herein, if with the TM2 method the system software programs the lower operating point to a location relatively close to the upper operating point, then the TM2 mechanism may not be able to provide the necessary thermal protection during heavy workloads and/or hot environmental conditions. Alternatively, as the system software programs the lower operating point to a location relatively farther from the upper operating point, the TM2 mechanism potentially wastes a large amount of performance in terms of clock cycles because it only transitions between two distant operating points. Stated alternatively, the TM2 mechanism forces the system software to make a tradeoff between operating point granularity (which translates into performance granularity) and thermal protection during possible hot conditions. In contrast, as may be observed by examining FIG. **9** and by comparing FIGS. **10** and **11**, the TM3 mechanism does not force the system software to make the performance thermal protection tradeoff; rather, the TM3 mechanism provides both: performance-capturing fine-grained operating point transitions (effectively the entire range of possible operating point combinations of the VRM **108** VID **144** range and the PLL **112** ratio range) and a large range of operating points in order to provide the needed thermal protection during heavy workloads and/or hot environmental conditions. Stated alternatively, once the TM2 method reaches its maximum operating temperature, it immediately transitions down to the low performance operating point, which is potentially unnecessary because a transition to an intermediate operating point might be sufficient to reduce the operating temperature below the maximum temperature. In contrast, the TM3 mechanism advantageously captures the additional performance by transitioning to intermediate operating points only as far as necessary to keep the operating temperature within the selected range.

[**0112**] Another advantage of the TM3 approach over the TM2 approach is that it does not suffer the potential performance disadvantage of operating the fixed time period at the lower operating point before transitioning to a higher operating point like the TM2 mechanism. Rather, the TM3 mechanism transitions up to a higher operating point when the temperature reaches the lower bound of the specified temperature range. Advantageously, the microprocessor **102** includes a clock generation circuit, namely the dual-PLL configuration, which facilitates transitions from a current operating frequency to a new operating frequency without stopping operation of the processor core, thereby avoiding a negative performance impact of relatively frequent operating frequency transitions if the workload and operating environment dictate them.

[**0113**] Another advantage of the TM3 approach is that it may provide an alternative to existing thermal management approaches that have undesirable side effects. For example, some systems implement variable speed fans that speed up when the operating temperature of the microprocessor exceeds a threshold in order to reduce the operating temperature. Typically, an undesirable side effect of the fan speed increase is additional noise. The TM3 approach advantageously provides an alternative approach for keeping the operating temperature down without the added fan noise.

[**0114**] Furthermore, the Intel documentation states that the trip temperature for TM2 is factory set. In contrast, according to one embodiment of the TM3 mechanism, the temperature range is user-selectable. Thus, if there is a desire to prolong battery life, for example, by reducing the battery temperature, which may be affected by the heat the microprocessor generates, the embodiment of TM3 advantageously allows the system software to program the microprocessor **102** with a relatively low temperature range.

[**0115**] Finally, the present inventors have observed that due to the physical characteristics of CMOS semiconductor integrated circuits, in a given manufactured lot of parts, counter-intuitively there may be some parts that fail the corner case of operating at the highest voltage and lowest frequency. When transitioning from the high operating point to the low operating point, the TM2 mechanism first reduces the frequency, then the voltage. Because the possibility exists within a processor implementing the TM2 mechanism that the lower operating point may be programmed at the lowest frequency, the parts that fail the corner case may need to be discarded from the yield because they might fail when TM2 was performed. Thus, an advantage of TM3 is that a yield increase may be realized since the frequency is reduced in a piecewise fashion such that the microprocessor **102** is not operating at the lowest frequency while operating at the highest voltage.

[**0116**] Referring now to FIG. **12**, a graph illustrating operation of the microprocessor **102** according to an embodiment of the present invention in which the features described with respect to FIGS. **5**, **7**, and **9** are employed in combination is shown. That is, FIG. **12** provides an example that illustrates that the TM3 technique of FIG. **9**, the overstress technique of FIG. **7**, and the power consumption reduction technique of FIG. **5** may all be employed in combination to improve the performance and/or reduce the power consumption of the microprocessor **102**. Furthermore, the various operating point transitions may be performed in an iterative manner similar to the technique described with respect to FIG. **2** in order to improve the performance of the microprocessor **102** during the operating point transitions where possible.

[**0117**] In the example of FIG. **12**, the temperature had risen to T_{max} as referred to with respect to FIGS. **9** and **10**. Consequently, the voltage/frequency control **104** is causing the microprocessor **102** to operate at an intermediate operating point between the highest operating point and the lowest operating point that is at or near the optimum performance operating point that the workload and operating environment will permit while keeping the operating temperature between the T_{max} and T_{min} values as referred to herein with respect to the TM3 technique of FIGS. **9** and **10**. Subsequently, the workload and/or operating environment change such that the temperature drops, and the voltage/frequency control **104** responsively transitions operation of the microprocessor **102** to the V_{max}/F_{max} operating point according to the steps of FIG. **9**.

[**0118**] Subsequently, the workload and/or operating environment change such that the temperature drops below the

T_{ov} value as referred to with respect to FIGS. **7** and **8**, and the voltage/frequency control **104** responsively transitions operation of the microprocessor **102** to the V_{ov}/F_{ov} operating point according to the steps of the overstress technique of FIG. **7**.

[**0119**] Subsequently, the workload and/or operating environment change such that the temperature drops below the T_{alt} value as referred to with respect to FIGS. **5** and **6**, and the voltage/frequency control **104** responsively transitions operation of the microprocessor **102** to the V_{alt}/F_{alt} operating point according to the steps of the power consumption reduction technique of FIG. **5**.

[**0120**] In addition to the embodiment of FIG. **12** in which all of the techniques are employed in combination, it should be understood that other embodiments are contemplated which employ fewer than all of the techniques in various combinations in the microprocessor **102**. For example, in one embodiment, the steps of FIG. **5** are performed in conjunction with the steps of FIG. **7**. That is, once the microprocessor **102** has been set to operate at the overstress operating point, if the T_{alt} temperature is less than the overstress temperature and the operating temperature reaches T_{alt}, then the operating voltage may be reduced from the overstress operating point voltage to the T_{alt} operating point voltage, in order to reduce the power consumption while enjoying the performance benefit of operating in overstress mode. In one embodiment, the steps of FIG. **5** are performed in conjunction with the steps of FIG. **9**. That is, while the microprocessor **102** is operating within the selected operating temperature range defined by T_{max} and T_{min}, if the T_{alt} temperature is less than T_{min} and the operating temperature reaches T_{alt}, then the operating voltage may be reduced from the current operating point voltage to the T_{alt} operating point voltage, in order to reduce the power consumption while enjoying the benefit of operating at or near the optimum performance within the specified temperature range. Other combinations of the techniques are contemplated.

[**0121**] Referring now to FIG. **13**, a flowchart illustrating a process for creating operating point information included in the operating point data **122** of the microprocessor **102** of FIG. **1** according to an embodiment of the present invention is shown. Flow begins at block **1302**.

[**0122**] At block **1302**, the manufacturer selects the maximum operating temperature at which the microprocessor **102** is specified to reliably operate, such as T_{max} discussed with respect to FIGS. **5**, **7**, and **9**. Flow proceeds to block **1304**.

[**0123**] At block **1304**, the manufacturer tests a microprocessor **102** part at each possible operating point combination of the VRM **108** V_{dd} **142** values (i.e., VID **144** values) and PLL **112** clock frequency **152** values (i.e., ratio **146** values), while maintaining operation of the part at the selected operating temperature, to determine whether the part will reliably operate at the operating point and selected temperature. Flow proceeds to block **1306**.

[**0124**] At block **1306**, the manufacturer selects, for each of the VID **144** values, the highest frequency ratio **146** at which the part reliably operated. The manufacturer may generate an operating point curve for the selected operating temperature using the selected operating points. The operating point curves are commonly referred to as shmoo curves, or shmoos. Examples of the operating point curves are shown in FIGS. **3**, **6**, **8**, **12** and **14**, in which cases the curves are lines. By determining the operating point data **122**, the manufacturer can insure reliable operation of the microprocessor **102** at or below the operating point curves. In particular, the microprocessor **102** may use the operating point data **122** to make power management decisions, such as those at decision boxes **208**, **228**, **912** and **926** of FIGS. **2** and **9**. Additionally, the manufacturer may use the results of the testing at block **1304** to sort the parts into different marketability categories, or bins. Flow proceeds to decision block **1308**.

[**0125**] At decision block **1308**, the manufacturer determines whether there are more operating temperatures for which it desires to test the part for reliable operation. If so, flow proceeds to block **1312**; otherwise, flow ends.

[**0126**] At block **1312**, the microprocessor **102** manufacturer selects a new operating temperature for which it desires to obtain operating point information. In particular, the manufacturer may select the T_{alt} value of FIG. **5**, the T_{ov} value of FIG. **7**, and the T_{min} value of FIG. **9**. Additionally, or alternatively, the manufacturer may select several different operating temperature values for which to perform steps **1304** and **1306**, and may select the default T_{ov}, T_{alt} and T_{min} values based on the data obtained from those steps, rather than selecting the T_{ov}, T_{alt} and T_{min} values a priori. Flow proceeds to block **1304**.

[**0127**] Referring now to FIG. **14**, a flowchart illustrating operation of the microprocessor **102** of FIG. **1** to successively reduce the operating voltage when the operating temperature of the microprocessor **102** is below corresponding successively lower temperature thresholds in order to save power according to an alternate embodiment is shown. In contrast to the embodiment of FIG. **5** which includes only a single alternate operating temperature threshold, the embodiment of FIG. **14** includes multiple alternate operating temperature thresholds to facilitate reduced power consumption on a more fine-grained temperature variation basis as described below. Flow begins at block **1402**.

[**0128**] At block **1402**, the microprocessor **102** manufacturer tests the microprocessor **102** to determine a minimum voltage, V[N], at which the microprocessor **102** will reliably operate at a given frequency, F, and at a maximum operating temperature, T[N], which is also referred to herein as T_{max}. In particular, the manufacturer determines the maximum VID **144** value at which the microprocessor **102** will reliably operate at F and T[N]. In this embodiment, N refers to the number of different VID **144** values at the frequency F (i.e., the number of operating points) at which the voltage/frequency control **104** may cause the microprocessor **102** to operate as the operating temperature **134** drops below N−1 different successive values. The manufacturer determines the V[N] value for each core clock **116** frequency value (i.e., for each of the possible ratios **146**). Flow proceeds to block **1404**.

[**0129**] At block **1404**, the microprocessor **102** manufacturer tests the microprocessor **102** to determine a minimum voltage, V[**1**], at which the microprocessor **102** will reliably operate at frequency F and at an alternate operating temperature, T[**1**], which is less than the T[N] value. The manufacturer determines the V[**1**] value for each core clock **116** frequency value. Flow proceeds to block **1406**.

[0130] At block **1406**, the manufacturer selects N−2 intermediate VID **144** values between the V[N] and V[**1**] values determined at blocks **1402** and **1404**. In one embodiment, the manufacturer computes the difference between V[N] and V[**1**] and then divides by N−1 to determine the incremental distance between each successive intermediate voltage value, which may require rounding down to the nearest VID **144** value. In one embodiment, the manufacturer selects N−2 intermediate VID **144** values that are not necessarily evenly spaced. In one embodiment, all the VID **144** values between V[N] and V[**1**] are included. For some values of F, the difference between V[N] and V[**1**] may not be sufficient to accommodate N different VID **144** values. More generally, the value of N may be different for different values of F. Flow proceeds to block **1408**.

[0131] At block **1408**, the manufacturer determines N−2 intermediate alternate operating temperature **134** values at which the microprocessor **102** may reliably operate at the frequency F that correspond to the intermediate VID **144** values determined at block **1406**. In one embodiment, the manufacturer computes each intermediate alternate temperature value relative to the T[N] and T[**1**] values proportionate to the location of its corresponding voltage value between the V[N] and V[**1**] values. Other embodiments are contemplated in which the computation of the corresponding intermediate alternate temperature values is non-proportionate based on empirical testing. Other embodiments are contemplated in which the manufacturer tests each part at each of the intermediate alternate temperature values to determine the corresponding intermediate voltage values, rather than computing them. Flow proceeds to block **1412**.

[0132] At block **1412**, the VID **144** and corresponding temperature values, referred to as V[i] and T[i], determined at blocks **1402** through **1408** are included as a table in the operating point data **122** of FIG. **1**. The operating point data **122** includes a table for each of the F values. Herein, reference is made to an entry in the table via an index value, "i", in which a value of i=N indexes the table entry specifying the T_{max} value and its corresponding V[N] VID **144** determined at block **1402**, a value of i=1 indexes the table entry specifying the values determined at block **1404**, and a value of i between 1 and N indexes a table entry specifying one of the intermediate V[i]/T[i] pairs determined at blocks **1406** and **1408**. Flow proceeds to block **1414**.

[0133] At block **1414**, the index value is initialized to N when the microprocessor **102** is reset so that the voltage/frequency control **104** will cause the microprocessor **102** to operate at the V[n] value. Flow proceeds to block **1416**.

[0134] At block **1416**, the microprocessor **102** monitors its temperature while operating at frequency F and voltage V[i], which is the V_{dd} **142** value output by the VRM **108** of FIG. **1** in response to the VID control **126** outputting a VID **144** value from the operating point data **122** table entry selected by the index value that was initialized at block **1414**. Flow proceeds to decision block **1418**.

[0135] At decision block **1418**, the voltage/frequency control **104** determines whether the index value is equal to 1. If so, flow proceeds to decision block **1426**; otherwise, flow proceeds to decision block **1422**.

[0136] At decision block **1422**, the voltage/frequency control **104** determines whether the current temperature **134** is less than the temperature value T[i−1] specified in the operating point data **122** table entry selected by the index value minus 1. If the current temperature **134** is not less than the T[i−1] value, flow proceeds to decision block **1426**; otherwise, flow proceeds to block **1424**.

[0137] At block **1424**, the voltage/frequency control **104** outputs to the VRM **108** the VID value **144** specified in the operating point data **122** table entry selected by the index value minus 1 to reduce the operating voltage V_{dd} **142**. Also, the voltage/frequency control **104** decrements the index value. Flow returns to block **1416**.

[0138] At decision block **1426**, the voltage/frequency control **104** determines whether the index value is equal to N. If so, flow returns to block **1416**; otherwise, flow proceeds to decision block **1428**.

[0139] At decision block **1428**, the voltage/frequency control **104** determines whether the current temperature **134** is greater than the temperature value T[i+1] specified in the operating point data **122** table entry selected by the index value plus 1. If the current temperature **134** is not greater than the T[i+1] value, flow returns to block **1416**; otherwise, flow proceeds to block **1432**.

[0140] At block **1432**, the voltage/frequency control **104** outputs to the VRM **108** of FIG. **1** the VID value **144** specified in the operating point data **122** table entry selected by the index value plus 1 to increase the operating voltage V_{dd} **142**. Also, the voltage/frequency control **104** increments the index value. Flow returns to block **1416**.

[0141] Referring now to FIG. **15**, a graph further illustrating operation of the microprocessor **102** as described with respect to the embodiment of FIG. **14** is shown. The independent variable of the graph is the operating voltage V_{dd} **142** on the horizontal axis measured in Volts. The dependent variable of the graph is the core clock frequency **116** on the vertical axis measured in GHz. In the embodiment of FIG. **6**, the bus clock frequency is 200 MHz, the range of bus clock ratios is 2× to 10×, resulting in a core clock frequency **116** range of 400 MHz (2× ratio) to 2.0 GHz (10× ratio). The example shown in FIG. **15** illustrates values for the 2.0 GHz frequency only. The example shown in FIG. **15** illustrates an embodiment in which there are five (5) different possible operating temperature **134** thresholds, T[**1**]=60° C., T[**2**]=70° C., T[**3**]=80° C., T[**4**]=90° C., and T[**5**]=100° C., and five corresponding operating voltage values, denoted V[**1**]=0.972V, V[**2**]=1.004V, V[**3**]=1.036V, V [**4**]=1.068V, and V [**5**]=1.10V. The graph shows two voltage/frequency curves, one for the highest operating temperature **134** value and one for the lowest operating temperature **134** value. In the example of FIG. **15**, if while operating at 2.0 GHz at 1.1V the voltage/frequency control **104** determines that the temperature **134** has dropped below 90° C., the voltage/frequency control **104** reduces the V_{dd} **142** value from 1.1 V to 1.068 V; if the temperature **134** subsequently drops below 80° C., the voltage/frequency control **104** reduces the V_{dd} **142** value to 1.036 V; if the temperature **134** subsequently drops below 70° C., the voltage/frequency control **104** reduces the V_{dd} **142** value to 1.004 V; if the temperature **134** subsequently drops below 60° C., the voltage/frequency control **104** reduces the V_{dd} **142** value to 0.972 V. Conversely, if while operating at 2.0 GHz at 0.972V the voltage/frequency control **104** determines that the temperature **134** has risen above 70° C., the voltage/frequency control **104**

increases the V_{dd} **142** value to 1.004 V; if the temperature **134** subsequently rises above 80° C., the voltage/frequency control **104** increases the V_{dd} **142** value to 1.036 V; if the temperature **134** subsequently rises above 90° C., the voltage/frequency control **104** increases the V_{dd} **142** value to 1.068 V; if the temperature **134** subsequently rises above 90° C., the voltage/frequency control **104** increases the V_{dd} **142** value to 1.10 V. As shown in the graph of FIG. **15**, the operation of the microprocessor **102** according to the embodiment of FIG. **14** has advantages similar to those of the embodiment of FIG. **5**. In addition, the embodiment of FIG. **14** has the advantage of potentially capturing additional power consumption savings over the embodiment of FIG. **5** by providing finer-grained transitions to a lower operating voltage V_{dd} **142** as the operating temperature **134** drops below the successive T[i] values, particularly in operating environments in which the operating temperature **134** rarely reaches the T_{alt} value of FIG. **5**. Furthermore, the dual PLL **112** arrangement of the microprocessor **102** advantageously enables making the relatively more frequent operating point transitions of the embodiment of FIG. **14** at effectively no performance cost since the core clock **116** to the core logic **106** does not need to be stopped during the transitions.

[**0142**] Although the present invention and its objects, features, and advantages have been described in detail, other embodiments are encompassed by the invention. For example, although embodiments have been described in which various operating frequencies, voltages, and temperatures have been specified, other embodiments are contemplated in which other values may be employed.

[**0143**] While various embodiments of the present invention have been described herein, it should be understood that they have been presented by way of example, and not limitation. It will be apparent to persons skilled in the relevant computer arts that various changes in form and detail can be made therein without departing from the scope of the invention. For example, in addition to using hardware (e.g., within or coupled to a Central Processing Unit ("CPU"), microprocessor, microcontroller, digital signal processor, processor core, System on Chip ("SOC"), or any other device), implementations may also be embodied in software (e.g., computer readable code, program code, and instructions disposed in any form, such as source, object or machine language) disposed, for example, in a computer usable (e.g., readable) medium configured to store the software. Such software can enable, for example, the function, fabrication, modeling, simulation, description and/or testing of the apparatus and methods described herein. For example, this can be accomplished through the use of general programming languages (e.g., C, C++), hardware description languages (HDL) including Verilog HDL, VHDL, and so on, or other available programs. Such software can be disposed in any known computer usable medium such as semiconductor, magnetic disk, or optical disc (e.g., CD-ROM, DVD-ROM, etc.). The software can also be disposed as a computer data signal embodied in a computer usable (e.g., readable) transmission medium (e.g., carrier wave or any other medium including digital, optical, or analog-based medium). Embodiments of the present invention may include methods of providing a microprocessor described herein by providing software describing the design of the microprocessor and subsequently transmitting the software as a computer data signal over a communication network including the Internet and intranets. It is understood that the apparatus and method described herein may be included in a semiconductor intellectual property core, such as a microprocessor core (e.g., embodied in HDL) and transformed to hardware in the production of integrated circuits. Additionally, the apparatus and methods described herein may be embodied as a combination of hardware and software. Thus, the present invention should not be limited by any of the herein-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

[**0144**] Finally, those skilled in the art should appreciate that they can readily use the disclosed conception and specific embodiments as a basis for designing or modifying other structures for carrying out the same purposes of the present invention without departing from the scope of the invention as defined by the appended claims.

We claim:

1. A microprocessor, comprising:

core logic, configured to operate according to a core clock signal in order to execute program instructions;

clock generation circuitry, controllable to generate the core clock signal having one of N different possible frequencies, wherein N is more than two; and

a control circuit, coupled to the clock generation circuitry, and configured, in response to a request to operate the core logic at a destination frequency, to iteratively control the clock generation circuitry to generate the core clock signal having a new frequency on each of successive frequency iterations until the core clock signal frequency is the destination frequency, wherein the new core clock signal frequency on each of said frequency iterations is one of the N different possible frequencies monotonically closer to the destination frequency, wherein the number of said frequency iterations is between zero and N−1 depending upon the destination frequency specified and the core clock signal frequency when the request is received.

2. The microprocessor as recited in claim 1, further comprising:

an output, configured to provide a signal for controlling an operating voltage of the microprocessor;

wherein the control circuit is further configured, in response to said receiving the request, to iteratively generate the signal on the output to cause the operating voltage to have a new voltage on each of successive voltage iterations until the operating voltage is a destination voltage associated with the destination frequency.

3. The microprocessor as recited in claim 2, wherein the new voltage on each of said voltage iterations is monotonically closer to the destination voltage.

4. The microprocessor as recited in claim 1, wherein the clock generation circuitry comprises:

two phase-locked loops (PLLs), each controllable to generate a clock signal having one of N different possible frequencies; and

a selection circuit, controllable to select one of said PLL clock signals for provision to said core logic as said core clock signal.

5. The microprocessor as recited in claim 4, wherein said control circuit is configured, on each said frequency itera-

tion, to control a non-selected one of the PLLs to generate its clock signal having the new frequency, and to subsequently select the non-selected PLL to provide its clock signal as the core clock signal to the core logic when the non-selected PLL has locked in to the new clock frequency.

6. The microprocessor as recited in claim 1, wherein the clock generation circuitry is configured to receive a bus clock signal having a bus clock frequency, wherein the clock generation circuitry is configured to generate the core clock signal as a multiple of the bus clock frequency.

7. The apparatus as recited in claim 1, wherein the control circuit is configured to iteratively control the clock generation circuitry to generate the core clock signal having a new frequency on each of said successive frequency iterations until the core clock signal frequency is the destination frequency, without suspending operation of the core logic.

8. A method for improving the performance of a microprocessor having core logic configured operate according to a core clock signal in order to execute program instructions, the method comprising:

receiving a request to operate the core logic at a destination frequency;

generating a new frequency on the core clock signal, in response said receiving the request, the new frequency being closer to the destination frequency than a current frequency; and

iterating on said generating a new frequency, until the new frequency is the destination frequency, wherein said iterating comprises at least two iterations.

9. The method as recited in claim 8, further comprising:

iteratively generating a signal to cause an operating voltage of the microprocessor to have a new voltage until the operating voltage is a destination voltage associated with the destination frequency.

10. The method as recited in claim 9, wherein the new voltage on each iteration of said voltage is monotonically closer to the destination voltage.

11. The method as recited in claim 8, wherein the new frequency is one of N different possible frequencies, wherein N is more than two.

12. The method as recited in claim 11, wherein the new frequency on each of said iterations is one of the N different possible frequencies monotonically closer to the destination frequency, wherein the number of said iterations is between zero and N−1 depending upon the destination frequency specified and the core clock signal frequency when the request is received.

13. The method as recited in claim 8, wherein the microprocessor includes two PLLs each configured to generate a respective clock signal, wherein said generating a new frequency comprises:

causing a non-selected one of the two PLLs to generate the new frequency; and

selecting the non-selected one of the two PLLs to provide its clock signal as the core clock signal to the core logic.

14. The method as recited in claim 8, wherein said generating and said iterating are performed without suspending operation of the core logic.

15. An apparatus for improving the performance of a microprocessor, comprising:

a first output, configured to provide a signal to control an operating voltage of the microprocessor;

a second output, configured to provide a signal to control an operating frequency of the microprocessor;

an input, configured to receive a request to operate the microprocessor at a destination frequency; and

a control circuit, configured, in response to receiving the request on the input, to:

iteratively generate the signal on the second output to operate the microprocessor at a plurality of different values of the operating frequency between a current frequency and the destination frequency; and

iteratively generate the signal on the first output to operate the microprocessor at a plurality of different values of the operating voltage between a current voltage and a destination voltage associated with the destination frequency, while transitioning the operating frequency from the current frequency to the destination frequency.

16. The apparatus as recited in claim 15, wherein the control circuit is configured to monotonically change the plurality of the different values of the operating frequency in a direction toward the destination frequency.

17. The apparatus as recited in claim 15, wherein the control circuit is configured to monotonically change the plurality of the different values of the operating voltage in a direction toward the destination voltage.

18. The apparatus as recited in claim 15, wherein the control circuit is configured to transition between the plurality of values of the operating frequency without suspending operation of core logic of the microprocessor.

19. The apparatus as recited in claim 15, further comprising:

an input, configured to receive a bus clock used to generate the plurality of values of the operating frequency;

wherein the control circuit is configured to transition the operating frequency within a cycle of the bus clock on each iteration of the operating frequency.

20. The apparatus as recited in claim 15, wherein the control circuit is configured to transition the operating frequency in less than one hundred nanoseconds on each iteration of the operating frequency.

21. The apparatus as recited in claim 15, wherein the control circuit is configured to alternately select between two phase-locked loops (PLLs) to provide a core clock signal at the current frequency to core logic of the microprocessor.

22. The apparatus as recited in claim 15, wherein the control circuit is configured to store information for associating each of the plurality of different values of the operating frequency with one of the plurality of different values of the operating voltage.

23. A computer program product for use with a computing device, the computer program product comprising:

a computer usable storage medium, having computer readable program code embodied in said medium, for providing a microprocessor, said computer readable program code comprising:

first program code for providing core logic, configured to operate according to a core clock signal in order to execute program instructions;

second program code for providing clock generation circuitry, controllable to generate the core clock signal having one of N different possible frequencies, wherein N is more than two; and

third program code for providing coupled to the clock generation circuitry, and configured, in response to a request to operate the core logic at a destination frequency, to iteratively control the clock generation circuitry to generate the core clock signal having a new frequency on each of successive frequency iterations until the core clock signal frequency is the destination frequency, wherein the new core clock signal frequency on each of said frequency iterations is one of the N different possible frequencies monotonically closer to the destination frequency, wherein the number of said frequency iterations is between zero and N−1 depending upon the destination frequency specified and the core clock signal frequency when the request is received.

24. The computer program product as recited in claim 23, said computer readable program code further comprising:

fourth program code for providing an output, configured to provide a signal for controlling an operating voltage of the microprocessor;

wherein the control circuit is further configured, in response to said receiving the request, to iteratively generate the signal on the output to cause the operating voltage to have a new voltage until the operating voltage is a destination voltage associated with the destination frequency.

25. The computer program product as recited in claim 23, wherein the control circuit is configured to iteratively control the clock generation circuitry to generate the core clock signal having a new frequency until the core clock signal frequency is the destination frequency, without suspending operation of the core logic.

26. A method for improving the performance of a microprocessor, the method comprising:

receiving a request to change from operating the microprocessor at a current frequency to a destination frequency;

transitioning an operating voltage of the microprocessor from a current voltage to a destination voltage associated with the destination frequency, in response to said receiving the request; and

operating the microprocessor at a plurality of frequencies between the current frequency and the destination frequency while said transitioning the operating voltage.

27. The method as recited in claim 26, wherein the plurality of frequencies are monotonically changing in a direction toward the destination frequency.

28. The method as recited in claim 26, wherein said operating the microprocessor at the plurality of frequencies comprises transitioning between each of the plurality of frequencies without suspending operation of core logic of the microprocessor.

29. The method as recited in claim 26, wherein said operating the microprocessor at the plurality of frequencies comprises alternately selecting between two phase-locked loops (PLLs) to provide a core clock signal of the current frequency to core logic of the microprocessor.

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