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(54) METHOD AND SCHEDULER IN AN OPERATING SYSTEM

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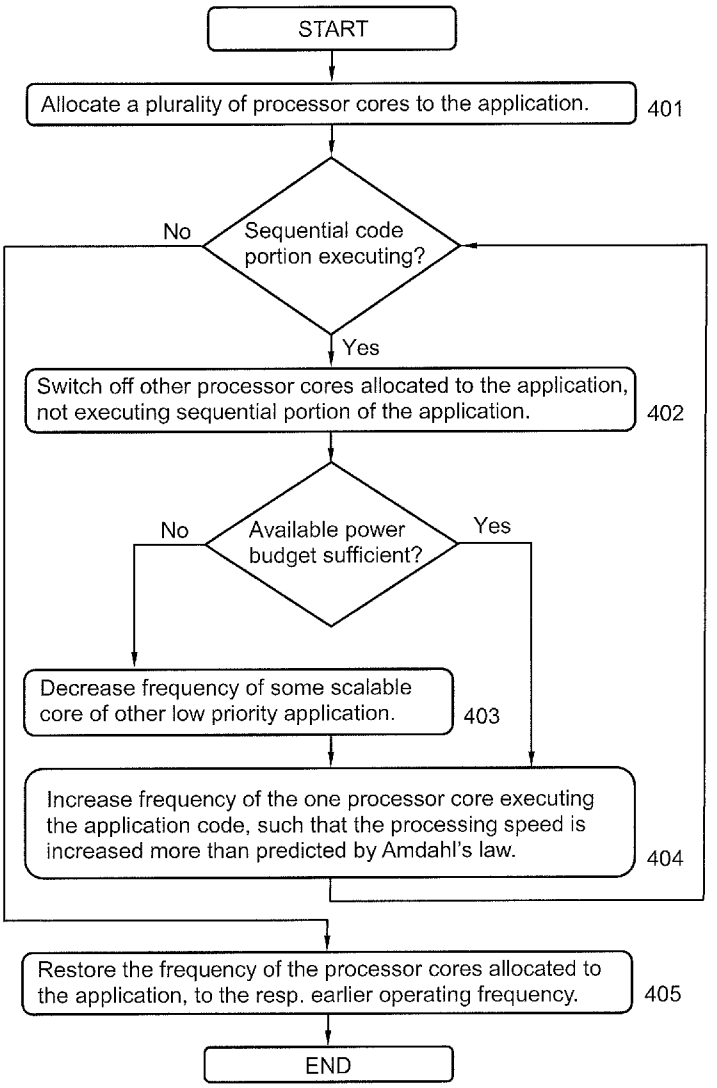
(57) **ABSTRACT**

Method and scheduler in an operating system, for scheduling processing resources on a multi-core chip. The multi-core chip comprises a plurality of processor cores. The operating system is configured to schedule processing resources to an application to be executed on the multi-core chip. The method comprises allocating a plurality of processor cores to the application. Also, the method comprises switching off another processor core allocated to the application, not executing the sequential portion of the application, when a sequential portion of the application is executing on only one processor core. In addition, the method comprises increasing the frequency of the one processor core executing the application to the second frequency, such that the processing speed is increased more than predicted by Amdahl's law.



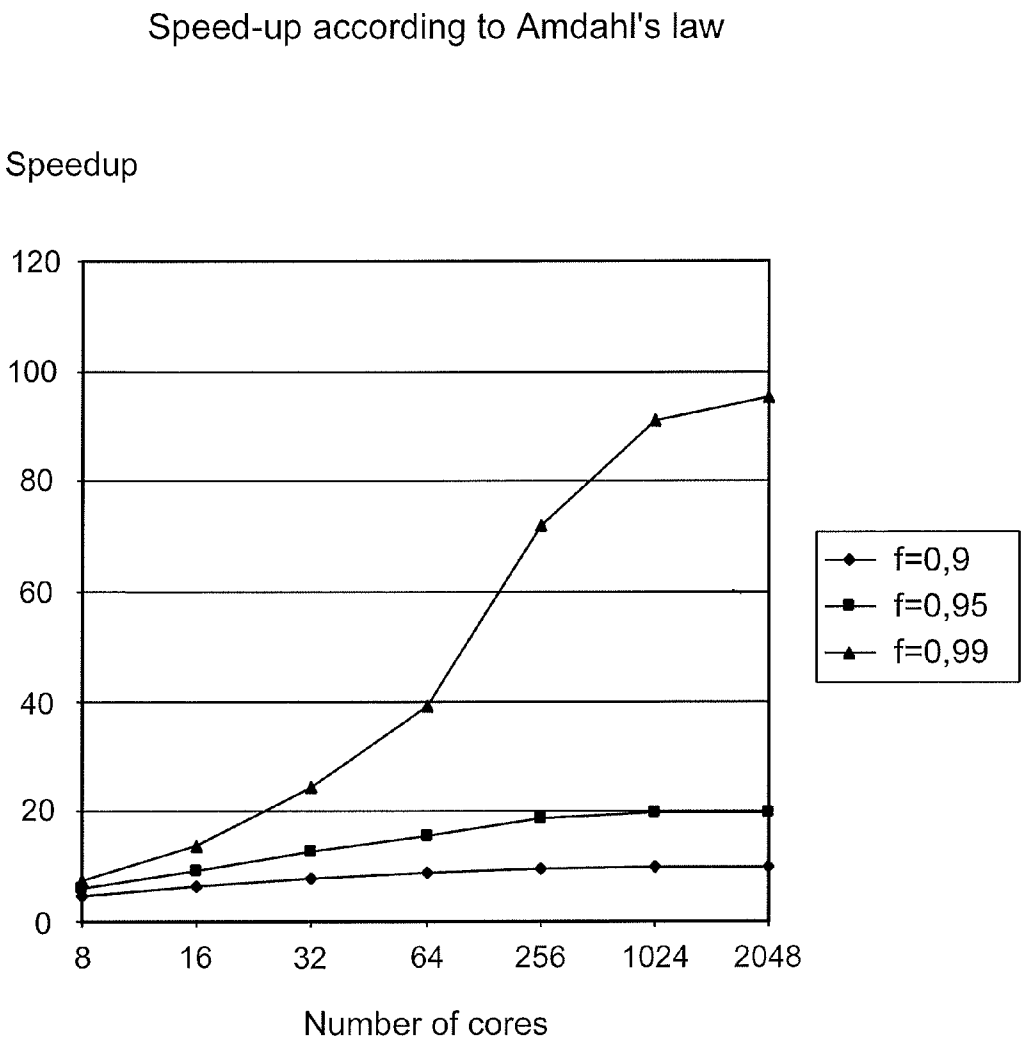

Speed-up according to Amdahl's law
Speedup
120
100
80
60
40
20
0
8
16
32
64
256
1024
2048
Number of cores
f=0,9
f=0,95
f=0,99

Fig. 1

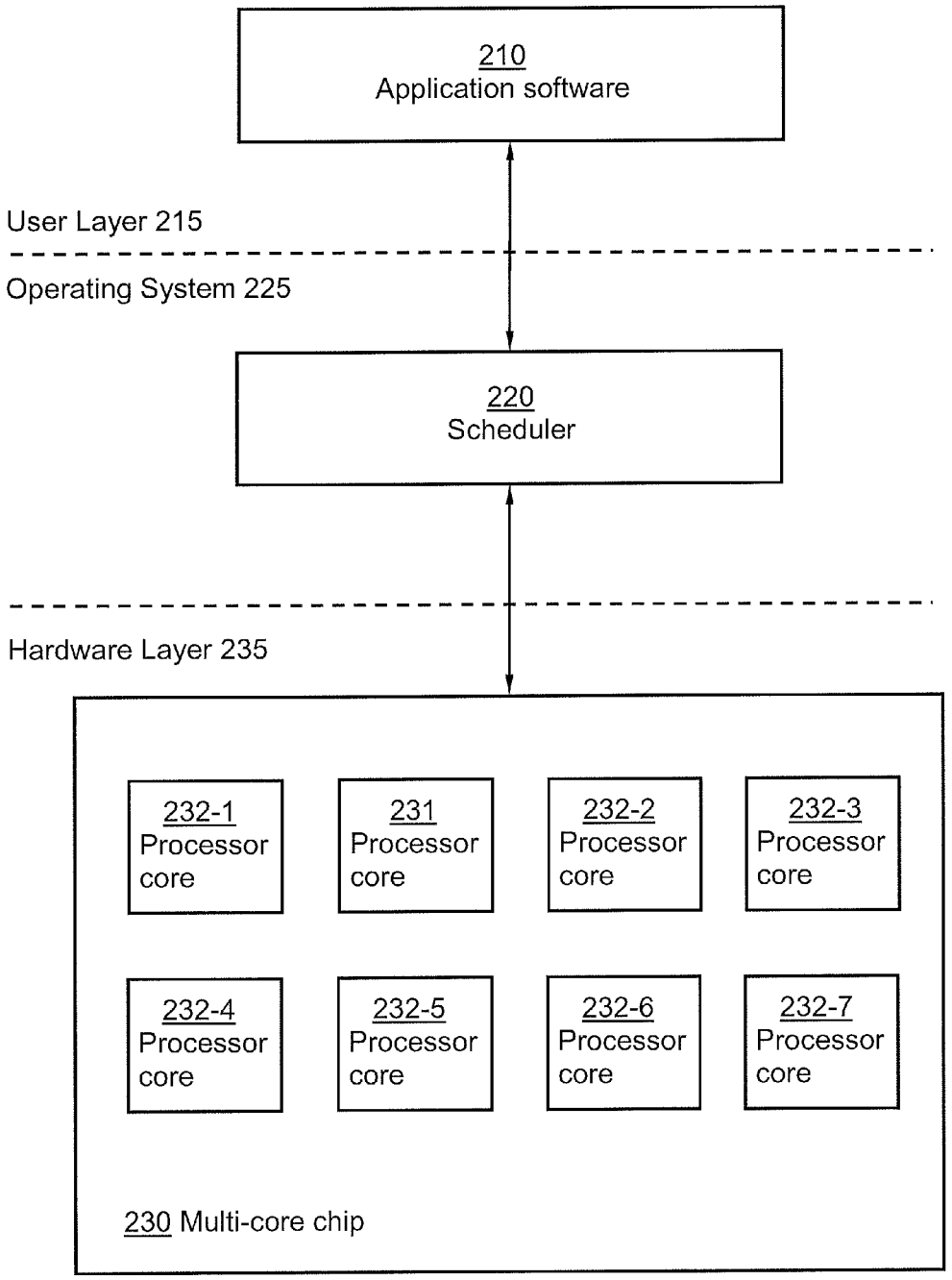

210
Application software
User Layer 215
Operating System 225
220
Scheduler
Hardware Layer 235
232-1
Processor core
231
Processor core
232-2
Processor core
232-3
Processor core
232-4
Processor core
232-5
Processor core
232-6
Processor core
232-7
Processor core
230 Multi-core chip

Fig. 2

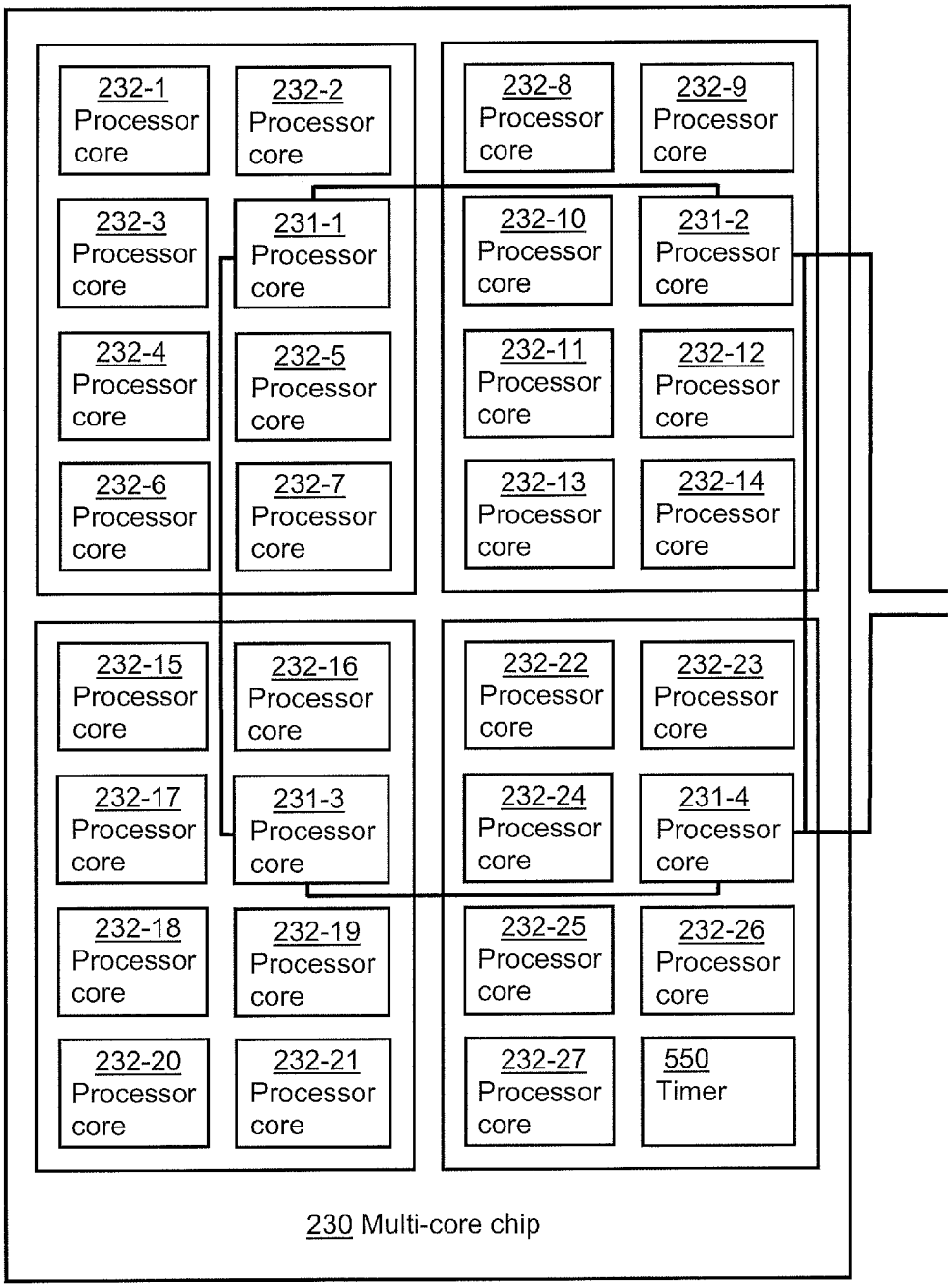

232-1 Processor core
232-2 Processor core
232-8 Processor core
232-9 Processor core
232-3 Processor core
231-1 Processor core
232-10 Processor core
231-2 Processor core
232-4 Processor core
232-5 Processor core
232-11 Processor core
232-12 Processor core
232-6 Processor core
232-7 Processor core
232-13 Processor core
232-14 Processor core
232-15 Processor core
232-16 Processor core
232-22 Processor core
232-23 Processor core
232-17 Processor core
231-3 Processor core
232-24 Processor core
231-4 Processor core
232-18 Processor core
232-19 Processor core
232-25 Processor core
232-26 Processor core
232-20 Processor core
232-21 Processor core
232-27 Processor core
550 Timer
230 Multi-core chip

Fig. 3

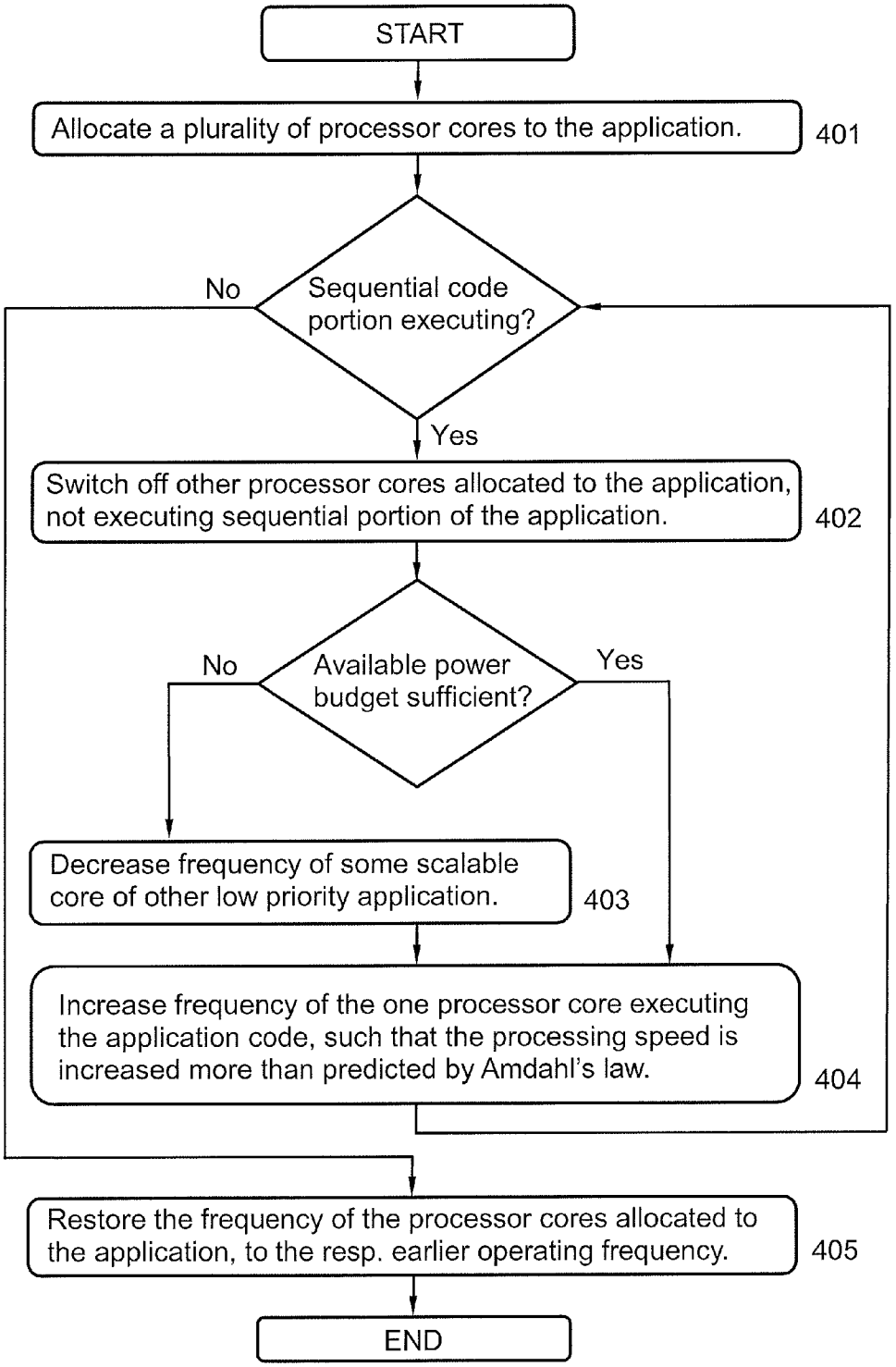

START
Allocate a plurality of processor cores to the application.
401
Sequential code portion executing?
No
Yes
Switch off other processor cores allocated to the application, not executing sequential portion of the application.
402
Available power budget sufficient?
No
Yes
Decrease frequency of some scalable core of other low priority application.
403
Increase frequency of the one processor core executing the application code, such that the processing speed is increased more than predicted by Amdahl's law.
404
Restore the frequency of the processor cores allocated to the application, to the resp. earlier operating frequency.
405
END

Fig. 4

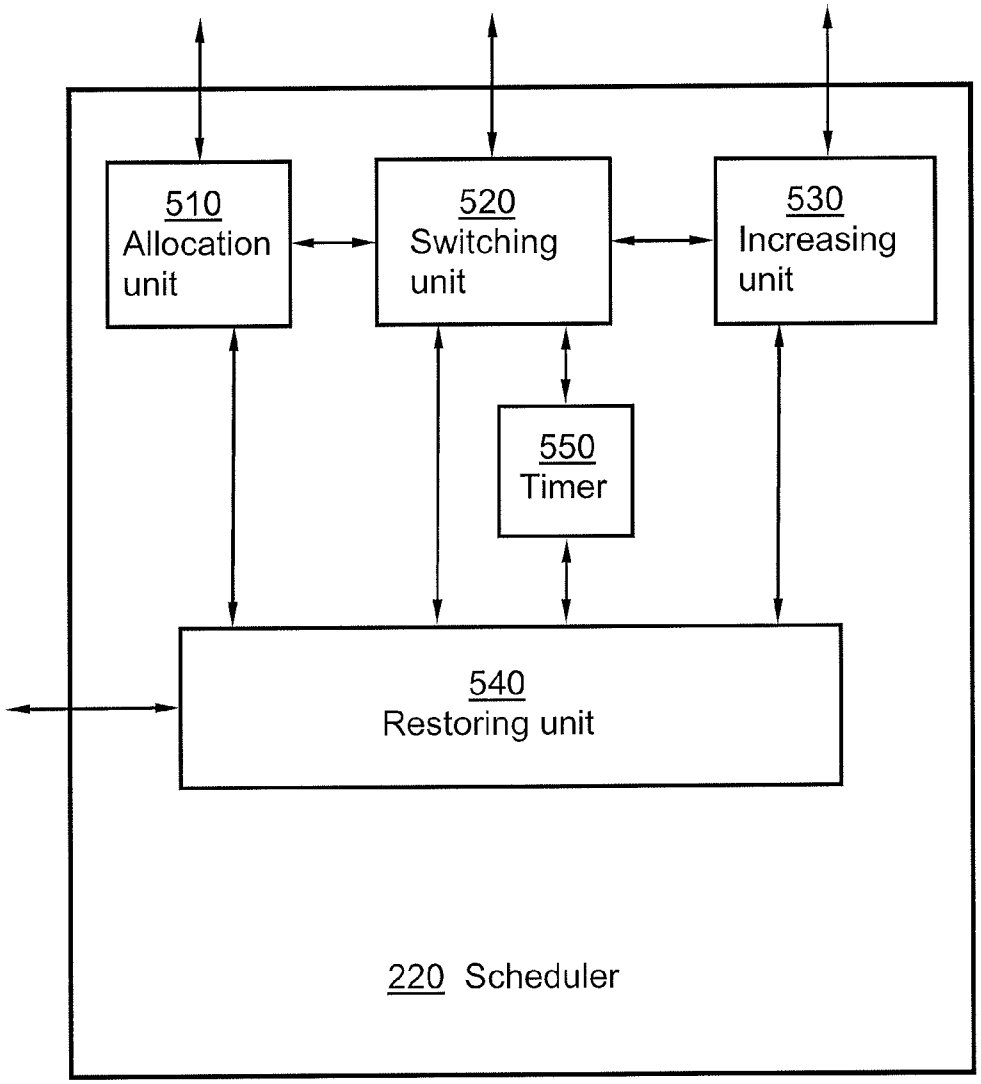

510
Allocation unit
520
Switching unit
530
Increasing unit
550
Timer
540
Restoring unit
220 Scheduler

Fig. 5

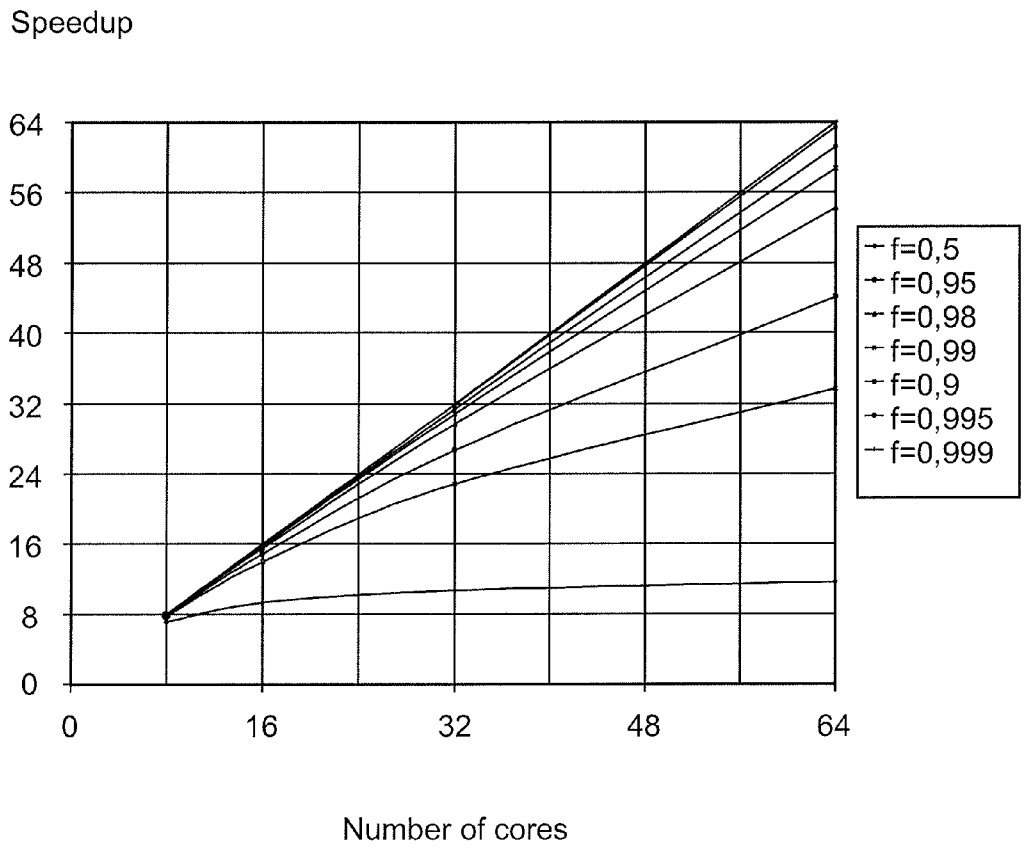

Speedup
64
56
48
40
32
24
16
8
0
0
16
32
48
64
Number of cores
f=0,5
f=0,95
f=0,98
f=0,99
f=0,9
f=0,995
f=0,999

Fig. 6

METHOD AND SCHEDULER IN AN OPERATING SYSTEM

TECHNICAL FIELD

[0001] The present invention relates to a method and a scheduler in an operating system and, more in particular, to a mechanism for scheduling processing resources on a multi-core chip.

BACKGROUND

[0002] The computing industry's development over the last decades has been largely defined by a dramatic increase of the available computing power, driven primarily by the self-fulfilment of Moore's law. However, recently this development has been heavily impacted by the inability of scaling performance further through increased frequency and complexity of processor devices, due primarily to power and cooling issues; as an answer, the industry turned to Chip-MultiProcessors (CMP) or multi-core devices. It is predicted that the advancement of manufacturing technology, in fact, the continued development according to Moore's law, will allow for chips comprising 100s or even 1000s of processor cores.

[0003] Currently operating system schedulers work on the principle of assigning tasks to available hardware resources such as processor cores or hardware threads and sharing a core among multiple applications.

[0004] Current approaches have a number of limitations. They do not scale well to high number of cores within the same chip. Micro-managing each core does not pay off well and may not be economical for simple cores. Further, current solutions do not consider dynamic variations in the processing requirements of applications. An application may be at different point in time executing in single threaded mode, while at other moments may require multiple threads of execution.

[0005] Chip multiprocessors pose however new requirements on operating systems and applications. It appears that current symmetric multi-processing, time-shared operating systems will not scale to several tens, less to hundreds or thousands of processor cores. On the application side, Amdahl's law, even it's version for chip multi-processors, will put a limit to the amount of performance increase that can be achieved even for highly parallelized applications, assuming static symmetric or static asymmetric multi-core chips as illustrated in FIG. **1**. For example, an application with only 1% sequential code can achieve, according to Amdahl's law, a theoretical speed-up factor of 7.4 on 8 cores, 14 on 16 cores, but only 72 on 256 cores and 91 on 1024 cores, compared with running on a single core.

[0006] Amdahl's law for CMP is expressed as:

$$Speedup_{dynamic}(f, n, r) = \frac{1}{\frac{1-f}{perf(r)} + \frac{f}{n}}$$

[0007] Where f is the fraction of the code that can execute in parallel, n is the number of processor cores, r is the number of processor cores that can be used jointly to execute sequential portions and perf(r) is the resulting performance, assumed to be less than r.

[0008] Better scalability, approaching linear for highly parallelized applications, could theoretically be obtained with chips where computing resources could be utilized either as several cores executing in parallel, for the execution of the parallel sections of the applications; or as a single, fast, powerful core for running the single-threaded, sequential portions of the applications. However, so far there is no solution that would scale with the number of cores.

[0009] Thus there is a problem to increase the processing speed of application code in a computer.

SUMMARY

[0010] It is the object to obviate at least some of the above disadvantages and provide an improved performance of applications executing on a multi-core system.

[0011] According to a first aspect, the object is achieved by a method in an operating system for scheduling processing resources on a multi-core chip. The multi-core chip comprises a plurality of processor cores. The operating system is configured to schedule processing resources to an application to be executed on the multi-core chip. The method comprises allocating a plurality of processor cores to the application. Also, the method comprises switching off processor cores allocated to the application, not executing the sequential portion of the application, when a sequential portion of the application is executing on only one processor core. In addition, the method comprises increasing the frequency of the one processor core executing the application, such that the processing speed is increased more than predicted by Amdahl's law.

[0012] According to a second aspect, the object is also achieved by a scheduler in an operating system for scheduling processing resources on a multi-core chip. The processing resources are allocated to an application to be executed on the multi-core chip. The multi-core chip comprises a plurality of processor cores. The scheduler comprises an allocation unit. The allocation unit is adapted to allocate a plurality of processor cores to the application. Also, the scheduler comprises a switching unit. The switching unit is adapted to switch off a processor core, allocated to the application, not executing a sequential portion of the application. Further, the scheduler comprises an increasing unit. The increasing unit is adapted to increase the frequency of the one processor core executing the application, such that the processing speed is increased more than predicted by Amdahl's law.

[0013] The present solution is based on a space shared approach for scheduling multiple processes on a many core chip. Also, the present solution rely on adapting performance of individual cores and the chip as a whole by controlled and scheduled variation of the frequency at which different cores execute, in contrast with current thread migration strategies. Instead of trying to guess the best thread assignment policy in the operating system rely on application generated requests for computing resources, similarly to how memory is currently managed. Thereby is a near-linear scaling of speed with the number of processing cores achieved. Further, the present solution addresses the issue of dynamically adapting processing needs to the requirements of applications. In addition, as the present solution is not relying on thread migration, hence improving cache usage characteristics. Thereby is an improved performance within a wireless communication system achieved.

[0014] Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The present invention will now be described more in detail in relation to the enclosed drawings, in which:

[0016] FIG. **1** is a diagram illustrating Speed-up according to Amdahl's law.

[0017] FIG. **2** is a schematic block diagram illustrating a system according to some embodiments.

[0018] FIG. **3** is a schematic block diagram illustrating a Multi-core chip according to some embodiments.

[0019] FIG. **4** is a flow chart illustrating embodiments of method steps in an operating system.

[0020] FIG. **5** is a block diagram illustrating embodiments of a scheduler in an operating system.

[0021] FIG. **6** is a diagram illustrating Speed-up according to some embodiments of the present method.

DETAILED DESCRIPTION

[0022] The invention is defined as a method and a scheduler in an operating system, which may be put into practice in the embodiments described below. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. It should be understood that there is no intent to limit the present method and/or scheduler to any of the particular forms disclosed, but on the contrary, the present methods and schedulers are to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the claims.

[0023] The present invention may, of course, be carried out in other ways than those specifically set forth herein without departing from essential characteristics of the invention. The present embodiments are to be considered in all respects as illustrative and not restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.

[0024] FIG. **2** is a schematic illustration over a computer system **200**. The computer system **200** may be situated within a computing device.

[0025] The computer system **200** comprises a user layer **215**. An application software **210**, within the user layer **215**, may run in the computer system **200**.

[0026] The computer system **200** further comprises an operating system **225** and a hardware layer **235**.

[0027] The operating system **225** comprises a scheduler **220**. The scheduler **220** is configured to schedule processing resources.

[0028] The hardware layer **235** may comprise a multi-core chip **230**. The multi-core chip **230**, which may be referred to as a multi-core processor, comprises a plurality of processor cores **231** and **232** although the cores **231**, **232** in the multi-core chip **230** may vary in number in other embodiments. The processor cores **231** and **232** may further comprise further resources e.g. a cache memory, instruction processing engine, just to mention some arbitrary examples of core resources.

[0029] In the table below is summarized the expected speed-up as well as the suggested levels according to some embodiments. Even for **2048** core systems **200**, five frequency levels (0, 1x, 2x, 4x, 8x) may suffice, with an acceptable impact on the theoretical performance. The performance differences are in the range of 1%-25% for applications with degrees of parallelism between 0.5 and 0.999, higher for applications with less degree of parallelism. However, all cores **231**, **231**, scalable or not, shall support at least levels 0 and 1x, i.e. it may be possible to switch off any core **231**, **232**.

Number of cores	Theoretical speed-up	Suggested factor
8	2	2
16	2.6	2
32	3.2	2
64	4	4
256	6.4	4
1024	10.1	8
2048	12.7	8

[0030] Embodiments of the present invention are thus based on the concept of a space-shared operating system **225**, whereas the operating system **225** executes as service on some of the cores **231**, while other cores **232** execute just a microkernel without threading support. Cores **231**, **232** may further be allocated to applications **210** upon request. The total power the many-core chip may use to execute applications **210** is managed by the operating system **225**. This global resource is allocated to applications **210** through two resources; cores **231**, **232** and frequencies at which these cores **231**, **232** execute, i.e. each application may be allocated a number of processor cores **231**, **232**, but the total computing power of these allocated number of processor cores **231**, **232**, i.e. the frequency at which these will execute, may be adjusted based on application needs and competing resource requests, within the limits set by the amount of scalable cores allocated to an application **210**, the maximum frequency scaling factor that may be used for those cores **231**, **232** and the total power budget of the chip **230**.

[0031] In order to allow the scheduler **220** to allocate computing resources, each application **210** may provide the operating system **225** with three parallelism parameters. The first parameter is degree of parallelism. The degree of parallelism may be expressed as a fraction of the computation that may execute in parallel on multiple cores **231**, **232**. The second parameter is the minimum amount of cores **231**, **232** that the application **210** needs in order to execute. The third parameter is the priority level of the application **210**, which may appear quite similar to "process priority", as previously known.

[0032] Thus each application **210** may request two types of computing resources from the operating system **225**. The first type of resource is processor core resource, which may be of type non-scalable, i.e. fixed frequency, or scalable i.e. scalable frequency. In the herein described non-limiting exemplary embodiments, the cores **231** are scalable and the cores **232** non-scalable. The allocation of this type of resource can occur at any time, e.g. at application start-up based on the parallelism parameters and/or during execution based on workload changes.

[0033] The second type of resource is execution speed. There are two scenarios for an application **210** to request allocation/de-allocation of such resources. Temporary frequency boost/restore to normal for the scalable cores **231** allocated to it, or shut off/restore to normal for any core **231**, **232** allocated to the application **210**.

[0034] From application perspective, the present method may assume a behaviour similar to handling memory today. Thus the application **210** may specify its parallelism parameters at start-up according to some embodiments. Also, the application **210** may request shutting off cores **231**, **232** immediately when these are not needed, e.g. once a parallel computation has finished and a single-threaded sequence begins. Further, according to some embodiments, the application **210** may request frequency boosting as a resource allocation request. The application **210** may according to some embodiments be responsible for requesting restoring to normal operating frequency of any core **231**, **232** that was previously shut down. Further yet, the application **210** may be responsible for requesting allocation/release of processor cores **231**, **232** of various types i.e. scalable/non-scalable.

[0035] According to some embodiments, the application **210** may be responsible to decide on which processor core **231**, **232** a certain computation is to be executed, which requires a shift from today's approach where the application **210** just provides a set of threads that the operating system **225** will deploy on available resources

[0036] The present method is based on the following principal idea of having the processor cores **231**, **232** on the chip **230** space-shared rather than time-shared. Thus each processor core **231**, **232** may be allocated to one and only one application **210**. Also, the allocation of processor cores **231**, **232** may be geometry aware, in the sense that the operating system **225** may group resources allocated to the same application **210** close to each other. Further, the operating system **225** may only shut off or free up allocated processor cores **231**, **232** at the explicit request of the application **210** or when the application **210** exits. According to yet some embodiments, the operating system **225** may adjust the speed of individual scalable cores **231** if needed to accommodate new requests. All non-allocated cores **232** may be kept in shut-off state. Further yet, the processing resource requests may have a wait time attached, such that a request with a zero wait time may return immediately, either with allocated resources or a negative response. A request with a positive wait-time may either return immediately with successfully allocated resources or be queued by the operating system **225** until it can be fulfilled, or a timer expires.

[0037] The present method according to some embodiments may begin with shutting off all cores **231**, **232** that do not execute operating system code. When a new application **210** is started, it gets allocated, if possible, the amount of processor cores **231**, **232** that it has specified in its parallelism parameters. Initially, all cores **231**, **232** may be started at normal, 1x speed. Allocation of processor cores **231**, **232** may be possible if the current power usage and the power required by the cores **231**, **232** according to the application parallelism parameters is less than, or equal to, the total power budget, or the application **210** has a priority level that triggers re-scheduling of power budgets and the re-scheduling results in having enough power budget freed up.

[0038] When an application **210** requests the allocation of more processor cores **231**, **232**, the request may be fulfilled if the resulting power budget does not exceeds the total budget, or the application **210** has a priority level that triggers re-scheduling of power budgets and the re-scheduling results in having enough power budget freed up.

[0039] The operating system **225** actively re-calculates power budgets every time a application **210** requests shut off or restore of individual cores **231**, **232** and may process pending requests if possible. Restoring may only succeed if the resulting power budget does not exceeds the total budget, or the application **210** has a priority level that triggers re-scheduling of power budgets and the re-scheduling results in having enough power budget freed up.

[0040] Restoring of operation of already allocated cores operating system **225** may have higher priority than allocation of new resources according to some embodiments.

[0041] When an application **210** requests frequency boosting or restoring for a core **231**, **232**, the operating system **225** may fulfil the request if and to the extent that the result does not mean exceeding the overall power budget of the processor chip. If the application **210** has a priority level that may trigger re-scheduling of power budgets, such a re-scheduling may be performed. If the request was to reduce frequency, the operating system **225** may process pending resource requests.

[0042] The operating system **225** may keep track of the period for which a scalable core **231** was running at boosted frequency; in order to avoid over-heating of the chip **230**, the frequency may be scaled back after the pre-set maximum amount of time the core **231**, **232** is allowed to run at such high frequencies. The scale-back may also trigger re-scheduling and servicing of outstanding requests. The scalable core **231** may be kept running at low frequency for a certain amount of time so as to allow a decrease in the temperature of the chip in order to avoid physical damage to the hardware, according to some embodiments. Thus a timer **550** may be used in order to prevent the scalable core **231** from increasing the frequency before a certain predetermined time interval has passed. According to some embodiments the timer **550** may be activated at the moment when the scalable core **231** decreases the frequency from an increased frequency to a working frequency. A comparison between the measured timer value and a predetermined time limit may then be performed, such that the scalable core **231** is prevented from increasing the frequency before a certain predetermined cooling period has passed, according to some embodiments.

[0043] Re-scheduling of resource allocations may be regarded as an advantageous component of the present method. It may occur every time when a request cannot be fulfilled without over-stepping the power budget and the requesting application has a higher priority than at least some of the other executing applications **210**.

[0044] During re-scheduling, the operating system **225** may basically modify the clocking of frequency-boosted cores **231**, **232**. As stated before, an already allocated core **231**, **232** may not be taken away forcefully by the operating system **225**, neither may it be shut down. This may be a pre-requisite to allow applications **210** to perform correctly. However, modifying the frequency at which single-threaded portions of lower-prioritized applications execute is a sensible way of prioritizing applications, without starving any. Hence, the operating system **225** may calculate how much the frequency scaling factor of some of the scalable cores executing lower-prioritized applications is to be reduced in order to fit in the power budget the requirements of higher prioritized applications. The applications **210** may be notified about the change and the application **210** with higher priority get its resources allocated.

[0045] There may be several different policies used by the scheduler **220** such as spreading the scale-back as evenly as possible to several applications **210**, reducing the impact on each individual application **210**, but impacting several applications **210**. Also, the scheduler **220** may focus on just enough

applications **210**, the ones with the lowest priority, to free up sufficient amount of power budget to fulfil the request.

[0046] Requests with non-zero wait time that cannot be fulfilled may be queued and may be serviced based on the priority of the application **210** making the request. If a request cannot be fulfilled before its timer expires, the request may be rejected and the application **210** notified.

[0047] In the space-shared operating system **225**, the scheduling method outlined above may be implemented as two components, placed in the core-local micro-kernel and a central resource management service.

[0048] The core-local micro-kernel has the primary task of managing the hardware and interfacing the application **210** and the central resource management service. It provides e.g. the following services: Change the frequency of the core **231**, **232**, shut down the core **231**, **232**, receive and forward to the central resource management service requests from the application **210**.

[0049] In order to increase performance, replies from the central resource management service may be sent directly to the application **210**, bypassing the local micro-kernel, according to some embodiments.

[0050] The central resource management service may be responsible for keeping track of all the processing resources i.e. scalable cores **231** and non-scalable cores **232** and the overall power budget. It has the function of allocating processing resources to newly started applications **210**, re-calculating core frequencies and request adjustment from local micro-kernels, wake-up/shut-down cores **231**, **232** and managing and tracking pending resource requests.

[0051] The central resource management service itself may be implemented as an internally distributed service, i.e. executing on multiple cores **231**, **232**. "Central" in this context only means that there may be one such service running in the system, visible to the distributed micro-kernels.

[0052] The present scheduling method thus may handle two types of resources: non-scalable cores **232** and scalable-cores **231**. Both of these resources scale, quantity-wise, linearly with the total number of cores **231**, **232**. In fact, the maximum number of scalable cores **231** equals n/8, while the maximum number of non-scalable cores **232** may be, obviously, less than n, where n is the total number of processor cores **231**, **232** in the chip **230**.

[0053] The present scheduling method may perform two tasks: keeping track of allocated cores **231**, **232** i.e. which core **231**, **232** to which application **210**, and performing re-scheduling calculations.

[0054] The first task may complexity-wise be quite similar to memory management and there are algorithms with a constant complexity, not dependent upon the actual number of resources or users, i.e. number of cores **231**, **232** and amount of applications **210**.

[0055] The task of re-scheduling may depend on the number of scalable cores **231**, **232**, limited to n/8 according to some embodiments. In fact, when a re-scheduling is to be performed, the scheduler may perform the following two steps:

[0056] Step 1

[0057] Identify the number of scalable cores **231** that are candidate for scaling back. These are cores **231** allocated to applications **210** with priority lower than the application **210** issuing the request that triggered the re-scheduling. As this information may be stored for each active scalable core **231**, which may be limited to max n/8, according to some embodiments, this information may be obtained by traversing a list with n/8 elements, yielding a complexity of O(n/8).

[0058] Step 2

[0059] Out of the candidate scalable cores **231**, the method may select which core **231** have their frequency reduced and by how much. The gain with each frequency-step can be pre-calculated, hence the total number of frequency changes may be calculated as a simple calculation, which may be independent of the total number of cores **231**, **232**, but dependent on the chosen policy; in any case it will be limited to the number of scalable cores, hence O(n/8).

[0060] In conclusion, the complexity of the re-scheduling algorithm may be O(n/8) in best case, with a worst case complexity of O(n/4). The key point is though that it scales linearly with the potential number of scalable cores and involves, even for a 1024 core chip, working with tables of at most 128 elements.

[0061] Concerning memory, the scheduler may have to store only four pieces of information for each scalable core **231**, to which application **210** it is allocated, current frequency scaling factor, dead-line until it can execute at this frequency and application priority, for performance reasons, the amount of memory needed for even a 1024 core system may be just a few kilobytes. For each non-scalable cores information such as current state i.e. on/off and application information needs to be stored, adding a few extra kilobytes. Even on a 64 bit machine, the amount of memory required would be n/8*3*8+n*8, i.e. 11* n bytes, about 11 kilobytes for a 1024 core chip.

[0062] FIG. **3** illustrates a multi-core chip **230** according to some embodiments.

[0063] An aspect to be considered may be the geometry of the multi-core chip **230**. This may be an advantage primarily in order to avoid hot spots and over-heating of the multi-core chip **230**, thus the processor cores **231** that can execute at higher frequencies may be spread out as evenly as possible and surrounded by other processor cores **232**, running at lower frequencies. According to some optional embodiments, a hierarchical chip interconnect may be built, by connecting the scalable cores **231** with a high-speed interconnect and then connect groups of other cores **232** to each scalable core **231**. A possible solution, out of a plurality of possible solutions for a 32 core chip according to some embodiments is shown in FIG. **3**. Each square represents a non scalable core **232**, and/or scalable cores **231**, while the thick lines showing the high speed, top level interconnect.

[0064] FIG. **4** is a flow chart illustrating embodiments of method steps **401-405** performed in an operating system **225**. The method aims at scheduling processing resources on a multi-core chip **230**. The multi-core chip **230** comprises a plurality of processor cores **231**, **232**. The operating system **225** is configured to schedule processing resources to an application **210** to be executed on the multi-core chip **230**.

[0065] The multi-core chip **230** may comprise one or several processor cores **231** of a first type which may be adapted to operate on either a first operating frequency or at least one second frequency. Also, the multi-core chip **230** may comprise one or several processor cores **232** of a second type which are adapted to operate on either the first operating frequency or to be switched off, according to some embodiments.

[0066] The processor cores **231** of the first type may be referred to as scalable cores and the processor cores **232** of the second type may be referred to as non-scalable cores. The first

operating frequency of the processor cores **231** of the first type and the first operating frequency of the processor cores **232** of the second type may be different, according to some embodiments. However, according to some embodiments, the first operating frequency may be the same for the processor cores **231** of the first type and the processor cores **232** of the second type.

[0067] The processor cores **231** the first type which are adapted to operate on either a first operating frequency and at least one second frequency may be spread out over the multi-core chip **230** and surrounded by at least one processor core **232** of the second type which is adapted to operate on either the first operating frequency or to be switched off, such that hot spots on the multi-core chip **230** may be avoided.

[0068] All non-allocated processor cores **231**, **232** comprised on the multi-core chip **230** may be kept in shut off state, according to some embodiments.

[0069] The operating system **225** may be configured to schedule processing resources to a plurality of applications **210** to be executed on the multi-core chip **230**, according to some embodiments.

[0070] To appropriately schedule processing resources on a multi-core chip **230**, the method may comprise a number of method steps **401-405**.

[0071] It is however to be noted that some of the described method steps **401-405** are optional and only comprised within some embodiments. Further, it is to be noted that the method steps **401-405** may be performed in any arbitrary chronological order and that some of them, e.g. step **401** and step **403**, or even all steps may be performed simultaneously or in an altered, arbitrarily rearranged, decomposed or even completely reversed chronological order. The method may comprise the following steps:

[0072] Step **401**

[0073] A plurality of processor cores **231**, **232** are allocated to the application **210**.

[0074] The number of initial allocation of processor cores **231**, **232** to the application **210** may be based on at least one application related parameter of: degree of parallelism, minimum amount of needed processor cores **231**, **232** and/or priority level, according to some embodiments.

[0075] Step **402**

[0076] When a sequential portion of the application **210** is executing on only one processor core **231**, another processor core **232**, allocated to the application **210**, not executing the sequential portion of the application **210** is switched off.

[0077] Step **403**

[0078] The frequency of some of scalable cores allocated to other applications with a lower priority than the application **210** is decreased. Thereby the frequency increase of the core **231** executing the application **210** is possible to perform, within the overall power budget of the system.

[0079] Step **404**

[0080] The frequency of the one processor core **231** executing the application **210** is increased to a second frequency, such that the processing speed is increased more than predicted by Amdahl's law.

[0081] The frequency of one or several processor cores **231** may be increased to the second frequency, for the same application **210**, or for multiple applications according to some embodiments.

[0082] The second frequency may be set to any of: 2, 4 or 8 times the first operating frequency, based on the total number of processor cores **231**, **232** on the multi-core chip **230**.

[0083] According to some embodiments, a timer **550** may be set to a predetermined time value and switching the frequency of the one processor core **231** back to the first operating frequency when the predetermined time has passed. Thus overheating and physical damage of the processor core **231** may be avoided.

[0084] The processor core **231** may according to some embodiments be prevented to re-increase the frequency before a predetermined cooling period has expired. The cooling period may be monitored e.g. by the timer **550**. Thus the timer **550** may be set to a predetermined value at the moment of frequency decrease of the processor core **231** and a count down to zero may be initiated before the frequency of the processor core **231** is allowed to increase again, according to some embodiments. Alternatively, the timer **550** may be set to zero and start counting the time at the moment of frequency decrease of the processor core **231** and compared to a time threshold value. Thus the processor core **231** may be prevented to re-increase the frequency before the predetermined cooling period has passed. Thus overheating and physical damage of the processor core **231** may be avoided.

[0085] Further, the assumed total power consumption of the processor cores **231**, **232** comprised on the multi-core chip **230** may be computed after the frequency increase and the frequency increase may be adjusted such that a predetermined total power consumption limit is not exceeded, according to some embodiments.

[0086] Step **405**

[0087] This step is optional and may only be performed within some embodiments.

[0088] When the sequential portion of the application **210**, which portion is executing on only one processor core **231**, is terminated, the frequency of the processor cores **231**, **232** allocated to the application **210** may be restored to the respective first operating frequency, i.e. the frequency that was used before performing the step of increasing **404** the frequency.

[0089] However, according to some embodiments, the frequency may be restored to the first operating frequency when a predetermined time has expired, measured by the timer **550**.

[0090] FIG. **5** is a block diagram illustrating embodiments of a scheduler **220** situated in an operating system **225**. The scheduler **220** is configured to perform the method steps **401-405** for scheduling processing resources on a multi-core chip **230** to an application **210** to be executed on the multi-core chip **230**. The multi-core chip **230** comprises a plurality of processor cores **231**, **232**.

[0091] For the sake of clarity, any internal electronics of the scheduler **220**, not necessary for understanding the present solution has been omitted from FIG. **5**.

[0092] The scheduler **220** comprises an allocation unit **510**. The allocation unit **510** is adapted to allocate a plurality of processor cores **231**, **232** to the application **210**. Also, the scheduler **220** comprises a switching unit **520**. The switching unit **520** is adapted to switch off a processor core **232** allocated to the application **210**, not executing a sequential portion of the application **210**. Further, the scheduler **220** comprises an increasing unit **530**. The increasing unit **530** is adapted to increase the frequency of the one processor core **231** executing the application **210**, such that the processing speed is increased more than predicted by Amdahl's law.

[0093] The scheduler **220** may further comprise a restoring unit **540**. The optional restoring unit **540** is adapted to restore the frequency of the processor cores **231**, **232** allocated to the

application **210** when the sequential portion of the application **210**, which portion is executing on only one processor core **231**, is terminated.

[0094] According to some embodiments, the scheduler **220** may comprise a timer **550**. The timer **550** may be set to a predetermined time value and switching the frequency of the one processor core **231** back to the first operating frequency when the predetermined time has passed.

[0095] The timer **550** may further be configured to monitor the cooling period of the processor core **231**, such that the processor core **231** is prevented from re-increasing the frequency before a predetermined cooling period has expired.

[0096] It is to be noted that the described units **510-540** comprised within the scheduler **220** may be regarded as separate logical entities, but not with necessity as separate physical entities. Any, some or all of the units **510-540** may be comprised or co-arranged within the same physical unit. However, in order to facilitate the understanding of the functionality of the scheduler **220**, the comprised units **510-540** are illustrated as separate units in FIG. **5**.

[0097] FIG. **6** illustrates the results assuming a multi-core chip **230** comprising **256** processor cores **231**, **232** where a specific application has 8, 16, 32 and 64 cores allocated, respectively. A near linear increase in performance may be observed for even less parallelized applications, such as e.g. the speedup for f=0.5 is above 7 when using 8 processor cores **231**, **232**, but switching off all **256** processor cores **231**, **232** when executing the sequential portion according to some embodiments of the present scheduling and resource management method.

[0098] Computer Program Product in the Operating System **225**

[0099] The method steps **401-405** in the operating system **225** may be implemented through one or more processor cores **231**, **232** in the multi-core chip **230**, together with computer program code for performing the functions of the present method steps **401-405**. Thus a computer program product, comprising instructions for performing the method steps **401-405** in the operating system **225** may schedule processing resources on a multi-core chip **230**.

[0100] The computer program product mentioned above may be provided for instance in the form of a data carrier carrying computer program code for performing the method steps according to the present solution when being loaded into the processor core **231**, **232**. The data carrier may be e.g. a hard disk, a CD ROM disc, a memory stick, an optical storage device, a magnetic storage device or any other appropriate medium such as a disk or tape that can hold machine readable data. The computer program code may furthermore be provided as program code on a server and downloaded to the processor core **231**, **232** remotely, e.g. over an Internet or an intranet connection.

[0101] The present invention may be embodied as a method and a scheduler in an operating system **225**, and/or computer program products. Accordingly, the present invention may take the form of an entirely hardware embodiment, a software embodiment or an embodiment combining software and hardware aspects all generally referred to herein as a "circuit". Furthermore, the present invention may take the form of a computer program product on a computer-usable storage medium having computer-usable program code embodied in the medium. Any suitable computer readable medium may be utilized including hard disks, CD-ROMs, optical storage devices, a transmission media such as those supporting the Internet or an intranet, or magnetic storage devices etc.

[0102] The terminology used in the detailed description of the particular exemplary embodiments illustrated in the accompanying drawings is not intended to be limiting of the invention.

[0103] As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless expressly stated otherwise. It will be further understood that the terms "includes," "comprises," "including" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. It will be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. Furthermore, "connected" or "coupled" as used herein may include wirelessly connected or coupled. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

1. Method in an operating system (**225**) for scheduling processing resources on a multi-core chip (**230**), the multi-core chip (**230**) comprises a plurality of processor cores (**231**, **232**), the operating system (**225**) is configured to schedule processing resources to an application (**210**) to be executed on the multi-core chip (**230**), the method comprises the steps of:

allocating (**401**) a plurality of processor cores (**231**, **232**) to the application (**210**),

when a sequential portion of the application (**210**) is executing on only one processor core (**231**), switching off (**402**) at least one processor core (**232**) allocated to the application (**210**), not executing the sequential portion of the application (**210**), and

increasing (**404**) the frequency of the one processor core (**231**) executing the application (**210**), such that the processing speed is increased more than predicted by Amdahl's law.

2. Method according to claim **1**, wherein the method comprises the further step of:

when the sequential portion of the application (**210**) executing on only one processor core (**231**) is terminated, restoring (**405**) the frequency of the processor cores (**231**, **232**) allocated to the application (**210**), to the respective frequency performed before the step of increasing (**404**) the frequency.

3. Method according to any of the claim **1** or **2**, wherein the multi-core chip (**230**) comprises one or several processor cores (**231**) of a first type, which are adapted to operate on either a first operating frequency or at least one second frequency, and one or several processor cores (**232**) of a second type, which are adapted to operate on either the first operating frequency or to be switched off.

4. Method according to any of the claims **1-3**, wherein the frequency of one or several processor cores (**231**) are increased to the second frequency, for the same application (**210**), or for multiple applications.

5. Method according to any of the claim **3** or **4**, wherein the processor cores (**231**) which are adapted to operate on either a first operating frequency and at least one second frequency are spread out over the multi-core chip (**230**) and surrounded by at least one processor core (**232**) which is adapted to

operate on either the first operating frequency or to be switched off, such that hot spots on the multi-core chip (**230**) are avoided.

6. Method according to any of the claims **1-5**, wherein the second frequency is set to any of: 2, 4 or 8 times the first operating frequency, based on the total number of processor cores (**231**, **232**) on the multi-core chip (**230**).

7. Method according to any of the claims **1-6**, wherein all non-allocated processor cores (**231**, **232**) comprised on the multi-core chip (**230**) is kept in shut off state.

8. Method according to any of the claims **1-7**, wherein the number of initial allocation of processor cores (**231**, **232**) to the application (**210**) is based on at least one application related parameter of: degree of parallelism, minimum amount of needed processor cores (**231**, **232**) and/or priority level.

9. Method according to any of the claims **1-8**, wherein the step of increasing (**404**) the frequency of the one processor core (**231**) executing the application (**210**) comprises setting a timer (**550**) to a predetermined time value and switching the frequency of the one processor core (**231**) back to the first operating frequency when the predetermined time has passed, such that overheating and physical damage of the processor core (**231**) is avoided.

10. Method according to any of the claims **1-9**, wherein the step of increasing (**404**) the frequency of the one processor core (**231**) executing the application (**210**) comprises computing the assumed total power consumption of the processor cores (**231**, **232**) comprised on the multi-core chip (**230**), after the frequency increase and adjust the frequency increase such that a predetermined total power consumption limit is not exceeded.

11. Method according to any of the claims **1-10**, wherein the operating system (**225**) is configured to schedule processing resources to a plurality of applications (**210**) to be executed on the multi-core chip (**230**).

12. Method according to any of the claims **1-11**, wherein the method comprises the further step of:

decreasing (**403**) the frequency of some of scalable cores allocated to other applications with a lower priority than the application (**210**), such that the frequency increase of the processor core (**231**) executing the application (**210**) is possible to perform, within the overall power budget of the system.

13. Method according to any of the claims **1-12**, wherein the processor core (**231**) is prevented to re-increase the frequency before a predetermined cooling period has expired.

14. Scheduler (**220**) in an operating system (**225**) for scheduling processing resources on a multi-core chip (**230**) to an application (**210**) to be executed on the multi-core chip (**230**), the multi-core chip (**230**) comprises a plurality of processor cores (**231**, **232**), the scheduler (**220**) comprises:

an allocation unit (**510**), adapted to allocate a plurality of processor cores (**231**, **232**) to the application (**210**),

a switching unit (**520**), adapted to switch off a processor core (**232**) allocated to the application (**210**), not executing a sequential portion of the application (**210**), and

an increasing unit (**530**), adapted to increase the frequency of the one processor core (**231**) executing the application (**210**), such that the processing speed is increased more than predicted by Amdahl's law.

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