COMPARATIVE ANALYSIS OF SINGLE-CORE AND MULTI-CORE SYSTEMS

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ABSTRACT

Overall performance of computer systems are better investigated and evaluated when its various components are considered, components such as the hardware, software and firmware. The comparative analysis of single-core and multi-core systems was carried out using Intel Pentium G640T 2.4GHz dual-core, Intel Pentium IV 2.4GHz single-core and Intel Pentium IV 2.8GHz single-core systems. The approach method was using hi-tech benchmarking and stress testing software(s) to examine systems' CPU and RAM for performance and stability. In all the tests, the components of dual-core had better rating when compared with single-core components; GFLOP result, and execution time for various processes rank G640T 2.4GHz dual-core above Pentium IV 2.4GHz and 2.8GHz single-core respectively.

KEYWORDS

FLOP, ILP, TLP, Multi-core, Single-core, Novabench & Linpack.

1. INTRODUCTION

Operational advancements of microprocessors over the years were primarily due to speed (frequency) and parallelism increment [1] [2] [3] [13]. The addition of more transistors has led to other ways and/or techniques of increasing parallelism and improving performance [13]. Subsequently, architects then sought to increase parallelism by executing multiple instructions simultaneously (instruction-level parallelism or ILP) through pipelining techniques and superscalar architectures and to reduce the latency of accessing memory with ever larger on-chip caches. Microprocessors further increased ILP by implementing out-of-order execution engines that completed useful work instead of stalling on data and control dependencies [4]. It is now obvious that ILP increment, due to energy, heat and wire delay issues can no longer provide performance improvements that track Moore's Law [5]. Therefore, vendors have shifted attention to exploring thread-level parallelism (TLP) by designing chips with multiple processors, otherwise known as Multi-core or Chip Multiprocessors (CMPs). The implementation of high level TLP on multi-core(s) will continue to provide performance improvement while dealing with the traditional technology issues faced by single-core performance [4]. These new designs are referred to as multi-core processors because it has minimum of two execution cores with distinct execution pipelines, functional units and usually one level of private cache [24].

A Multi-core processor consists of two or more cores on a single die [6] [9] [26]. The cores of CMPs are essential components usually computation units and caches [6]. The individual cores on a multi-core processor don't necessarily run as fast as the highest performing single-core processors, but they improve overall performance by handling more workloads in parallel [7] [8].

The performance of single-core and multi-core processors is better understood by observing how the two execute programs [9]. Single-core processors running multiple programs would assign different time slices for these programs; if one of the processes is taking longer time to complete then all the rest of the processes start lagging behind [9]. However, in the case of multi-core processors if you have multiple tasks that can be run in parallel at the same time, each of them will be executed by a separate core in parallel thus boosting the performance [8].

It is a general belief that multi-core processor, similar to many-core processor, has several advantages over single-core processor. First, multi-core processors have the advantage of shorter wiring which reduced the delay among cores instead of going off-chip [11]. Second, the issue of width and instruction window size incur linear increment on the chip area of multi-core processors whereas a quadratic increment is incurred in single-core processor design [10]. Third, the design-partition of multi-core processors are configured in such a way that idle cores can be powered down or powered up as and when needed by the application contributing to overall power dissipation savings [9]. The multiple cores inside the chip are not clocked at a higher frequency, however, their high-level parallelism potential is what responsible for its eventual overall performance making them more energy efficient and low power cores [8] [9]; whereas power consumption has been one of the critical concerns in single-core processors [11].
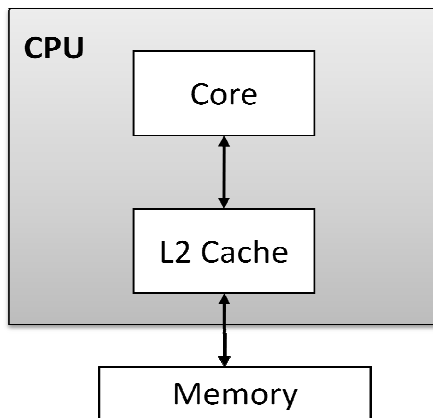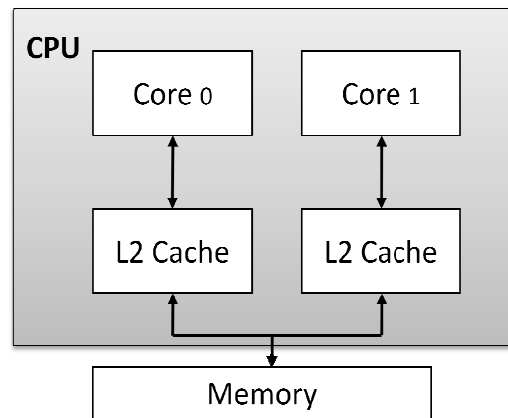
Figure 1:
Single-core Architecture

Figure 2:
 Multi-core Architecture

Figure 1 and 2 illustrates the architecture of a processing system with one core (single-core) and two cores (multi-core) respectively. A core in this context includes the following: instruction processing pipelines (integer and floating-point), instruction execution units, and the L1 instruction and data caches. Recently manufactured general-purpose computers appear like the dual-core (i.e. multi-core) system in that they have two separate but identical cores [12]. In some processing systems such as Intel Pentium-D and Opteron, each core has its own private L2 cache, while in others- Intel Core Duo, the L2 cache is shared between different cores. In multi-core(s), the option of a shared versus non-shared L2 cache have impacts on the performance of the system and a shared cache can be a possible source of vulnerability to Denial of Service (DoS) attacks because the memory system is disproportionately shared among multiple cores [12].

Despite the many advantages that multi-core processors have over single-core processors, there are a few major challenges the technology is facing [9]. Some software programs run slower on multi-core processors when compared to single-core processors. It has been correctly identified that increasing the cores of a processing system don't automatically get applications on multi-core systems to run faster [1]. Also, on-chip interconnects are becoming a critical logjam in meeting performance of multi-core chips [14]. With increasing number of cores comes along the huge

interconnect delays (wire delays) when data has to be moved across the multi-core chip from memories in particular [15]. The performance-effectiveness of a processor is a function of how fast a CPU can fetch data rather than how fast it can operate on it to avoid data starvation scenario [16].

The capability of multi-core processors to run applications more efficiently than single-core processors has given computer users the ability to keep working, at the same time running the most processor intensive tasks in the background [25]. A process with multiple threads has as many flows of controls as there are threads [26]. Each of these threads execute its own sequence of instructions independently and concurrently [26]. A process with multiple threads is called multithreaded [17] [26]. Thus the multi-cores improve multithreaded throughput, and delivers the advantages of parallel computing to properly thread mainstream applications [18]. Applications such as those use for wireless networking, computer vision, image processing, and multimedia possess great amount of functional and data parallelism, which can be exploited through a multi-core (System-on-Chip) [19] [25]. But for systems where single threaded applications dominate, multi-core systems offer very limited benefits [20]. It is on this note comparative analysis of single-core and multi-core system is being studied.

2. MATERIALS AND METHODS

Many researches have approached the comparative analysis of single-core and multi-core systems using diverse techniques, mostly as it concerns the area being studied. This involves the use of compiler or software tools like SPEC2006 to run test on certain components of the system-processor and RAM to see how it responds under specific or general condition per time. FLOP is commonly examined [21]. However, since FLOPs measure only raw execution rate, it can not be regarded as the best measurement of true speed. The true processor speed of a system is dependant on many other factors which include- pipeline length, register size, response time, cache size, cache latency, cache associativity, number of pipelines, instruction sets, number of registers, etc [28].

In this work, the comparative analysis of single-core and multi-core systems was approached by exploring firmware testing. This is done by using hi-tech software(s) to examine systems' CPU and RAM for performance and stability. The software(s) include: Intelburn Test - Stress testing software; Novabenchmark - Benchmarking software; and Performance Test - Benchmarking software. The stress testing software aims to test stability by trying to force a system to fail; and benchmarking aims to measure and assess the maximum performance possible at a given task or function [27]. Thereafter, a 33.3Gigabyte file-folder of 327 folders and 3480 files comprising videos, application software(s) and documents of different formats were copied from an external SATA-Hard Disk Drive, HDD to systems' internal HDD; features such as Number of processes, CPU usage, and Physical memory were observed and data collected for both the single-core and multi-core systems. The time taken to complete the transfer was however put under critical examination. Driverpack solutions and CPU-Z software tools were used to check for systems' CPU frequency, CPU temperature and core voltage. Apart from the information provided by these tools, it also envisages how multitasking affects the transfer process and its overall impart on the systems.

Table 1. Configuration of the Systems Under Test (SUT)

	HP COMPAQ DESKTOP PC, INTEL PENTIUM SINGLE-CORE SYSTEM	HP COMPAQ DESKTOP PC, INTEL PENTIUM SINGLE-CORE SYSTEM	HP DESKTOP PC, INTEL PENTIUM DUAL-CORE SYSTEM
CPU			
Vendor	GenuineIntel	GenuineIntel	GenuineIntel
Name	Intel Pentium 4	Intel Pentium 4	Intel Pentium G640T
Core Frequency (GHz)	2.4 GHz	2.8 GHz	2.4 GHz
Number of CPU	1	1	1
Number of cores	1	1	2
Number of threads	1	2	2
Processor type	Intel Pentium 4 Single-core processor	Intel Pentium 4 Single-core processor	Intel Pentium G640T Dual-core processor
PLATFORM			
BIOS Name & Version	BIOS F.3.4	BIOS F.3.4	BIOS AMI 7.12
BIOS Setting	Default	Default	Default
MEMORY MODULE(S)			
Vendor	Kingston	Kingston	Samsung
Type	DDR	DDR	DDR3
Size	2GB	2GB	2GB
Number of RAM modules	2 x 1024MB	2 x 1024MB	2048MB
Channels	Dual	Dual	Single
HARD DISK			
Vendor & model numbers	Maxtor and 6Y080L0	Maxtor and 6Y080L0	Seagate ST500DM002-1BD142
Type	IDE	IDE	SATA
Size	80GB	80GB	500GB
Number of Disk in System	1	1	1
OPERATING SYSTEM			
Name	Microsoft Windows 7 (32-bit)	Microsoft Windows 7 (32-bit)	Microsoft Windows 7 (64-bit)
Language	English	English	English

3. RESULTS AND DISCUSSION

3.1 Novabench

The table below shows an average of three-test score of CPU and RAM component for each system configuration: Intel Pentium IV 2.40GHz, Intel Pentium IV 2.80GHz, and Intel Pentium G640T 2.40GHz.

Table 2. Novabench Test Score of 2.4 GHz & 2.8 GHz Single-Core and 2.4 GHz Dual-Core Configurations

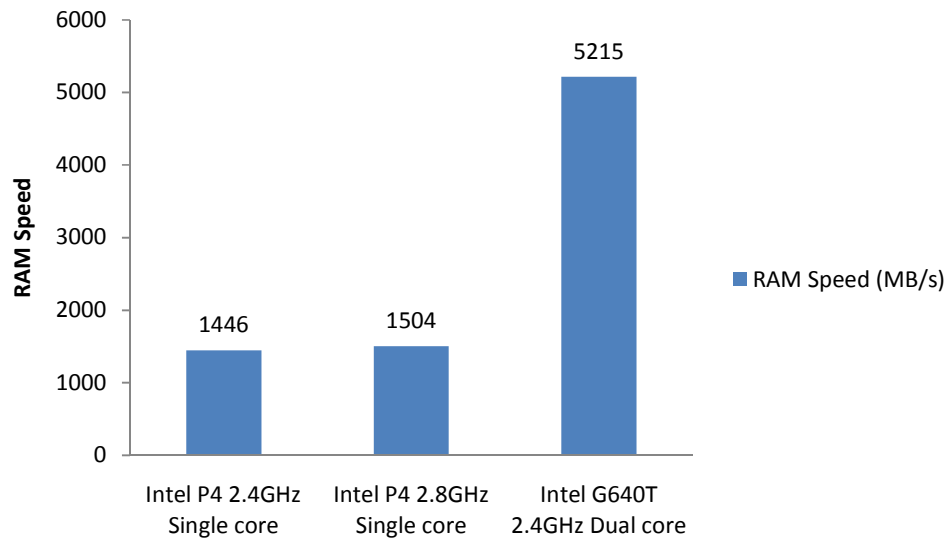|	Intel Pentium 4 2.40GHz	Intel Pentium 4 2.80GHz	Intel Pentium G640T 2.40GHz
2040 MB System RAM	**Score: 95**	**Score: 95**	**Score: 112**
RAM Speed (MB/s)	1446	1504	5215
CPU Tests	**Score: 55**	**Score: 100**	**Score: 229**
Floating Point Operations/Second	13453050	27492557	50843295
Integer Operations/Second	17622214	58554955	142977614
MD5 Hashes Generated/Second	3345501	297062	794837

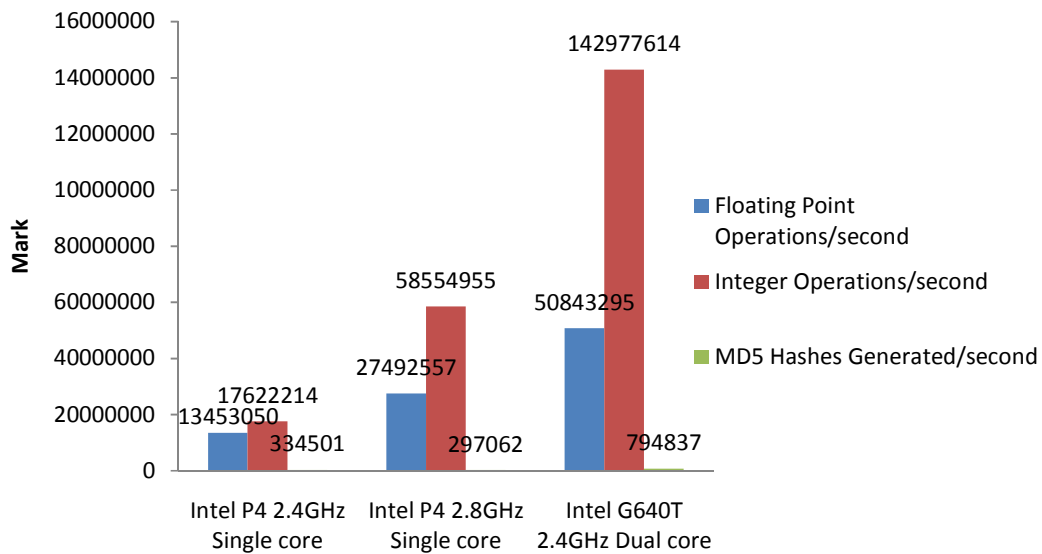Figure 3. RAM Speed (MB/s) of 2.4 GHz & 2.8 GHz Single-Core, and 2.4 GHz Dual-Core

Figure 4. CPU Operations per Second

3.2 Intelburn Test- Linpack

Linpack performs an operation from linear algebra called LU Factorization [22]. The three systems under experimental observation are found to be stable.

Table 3. Linpack Result of Intel P4 2.4 GHz Single-Core

	Time (s)	Speed (GFlops)	Result
Linpack Output Result for Intel Pentium 4 2.40GHz @ 2.394 MHz Single-core			
1	234.925	3.8050	2.908973e-002
2	233.757	3.8240	2.908973e-002
3	231.678	3.8583	2.908973e-002
4	232.552	3.8438	2.908973e-002
5	232.742	3.8407	2.908973e-002
6	231.629	3.8591	2.908973e-002
7	231.814	3.8560	2.908973e-002
8	231.602	3.8596	2.908973e-002
9	229.441	3.8959	2.908973e-002
10	229.924	3.8877	2.908973e-002
Test completed successfully in 2607.47seconds. Average GFlops: 3.85301			

Table 4. Linpack Result of Intel P4 2.8 GHz Single-Core

Linpack Output Result for Intel Pentium 4 2.80GHz @ 2.793 MHz Single-core			
	Time (s)	**Speed (GFlops)**	**Result**
1	281.094	3.1800	3.265950e-002
2	280.838	3.1829	3.265950e-002
3	284.360	3.1435	3.265950e-002
4	280.986	3.1812	3.265950e-002
5	280.581	3.1858	3.265950e-002
6	280.412	3.1878	3.265950e-002
7	281.230	3.1785	3.265950e-002
8	280.596	3.1857	3.265950e-002
9	280.848	3.1828	3.265950e-002
10	280.750	3.1839	3.265950e-002
Test completed successfully in 3169.20seconds Average GFlops: 3.17921			

Table 5. Linpack Result of Intel Pentium G640T 2.4 GHz Dual-Core

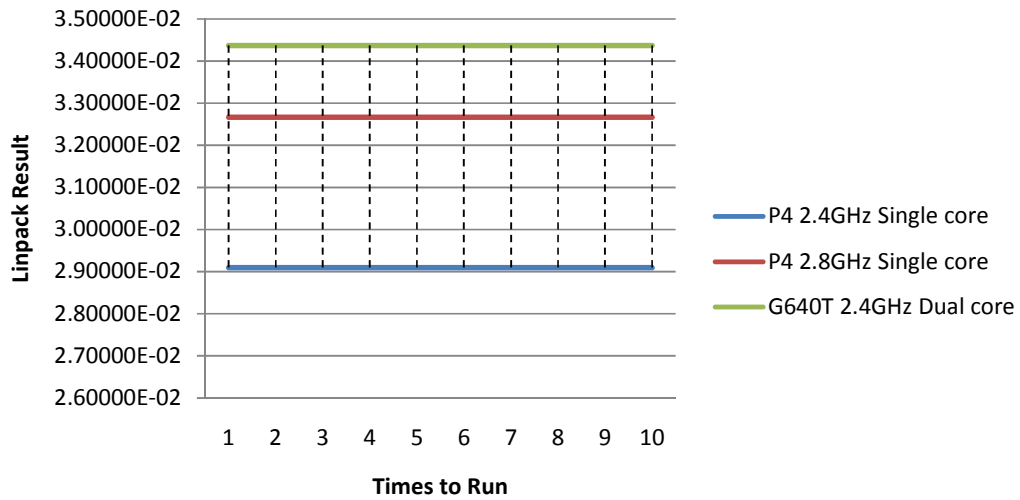| Linpack Output Result for Intel Pentium G640T 2.4GHz @ 2.394 MHz Dual-core			
	Time (s)	**Speed (GFlops)**	**Result**
1	53.876	16.5915	3.436777e-002
2	53.087	16.8381	3.436777e-002
3	53.018	16.8600	3.436777e-002
4	53.005	16.8641	3.436777e-002
5	52.935	16.8863	3.436777e-002
6	52.941	16.8844	3.436777e-002
7	52.951	16.8812	3.436777e-002
8	52.929	16.8883	3.436777e-002
9	52.938	16.8855	3.436777e-002
10	52.947	16.8827	3.436777e-002
Test completed successfully in 611.98seconds. Average GFlops: 16.84621			

Figure 5. Intel(R) Linpack Output Result for Single-Core and Dual-Core

3.3 Performance Test

Table 6. Performance for Pentium IV 2.4 GHz & 2.8 GHz Single-Core, and 2.4 GHz Dual-Core

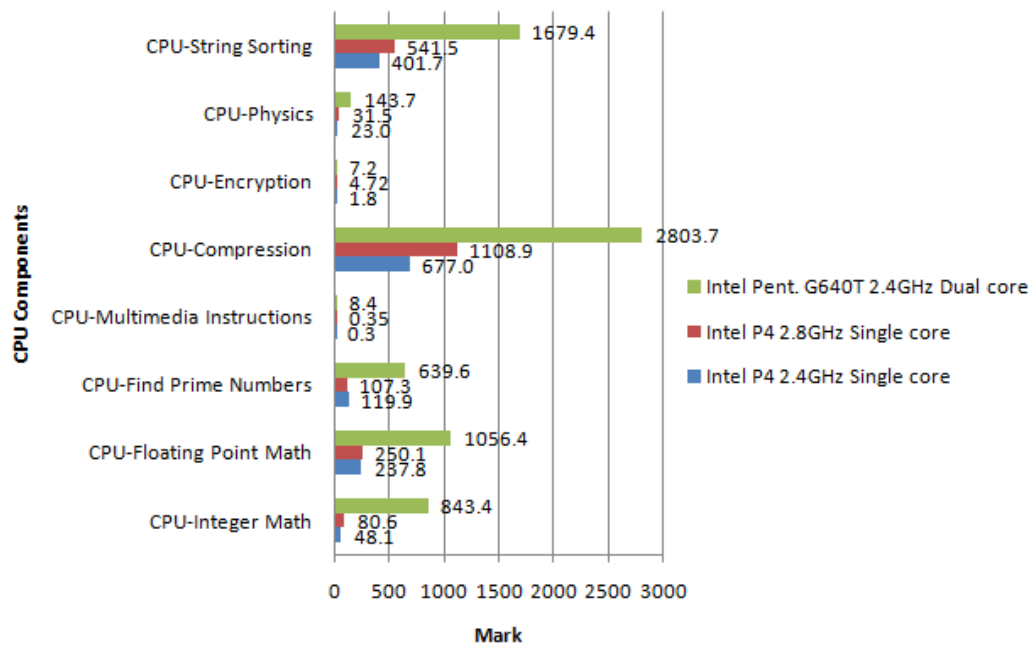|	Intel Pentium 4 2.40GHz @ 2.4 GHz	Intel Pentium 4 2.80GHz @ 2.8 GHz	Intel Pentium G640T 2.40GHz @ 2.4 GHz
CPU Mark	**317.2**	**452.0**	**2531.4**
CPU - Integer Math	48.1	80.6	843.4
CPU - Floating Point Math	237.8	250.1	1056.4
CPU - Find Prime Numbers	119.9	107.3	639.6
CPU - Multimedia Instructions	0.3	0.35	8.4
CPU - Compression	677.0	1108.9	2803.7
CPU – Encryption	1.80	4.72	7.2
CPU – Physics	23.0	31.5	143.7
CPU - String Sorting	401.7	541.5	1679.4
MEMORY Mark	**383.7**	**409.6**	**792.3**
Allocate Small Block	906.4	1238.6	4468.9
Read Cached	1562.9	1581.4	1920.0
Read Uncached	1267.9	1383.1	1778.5
Write	793.7	941.0	1730.7
Large RAM	365.8	324.6	805.8

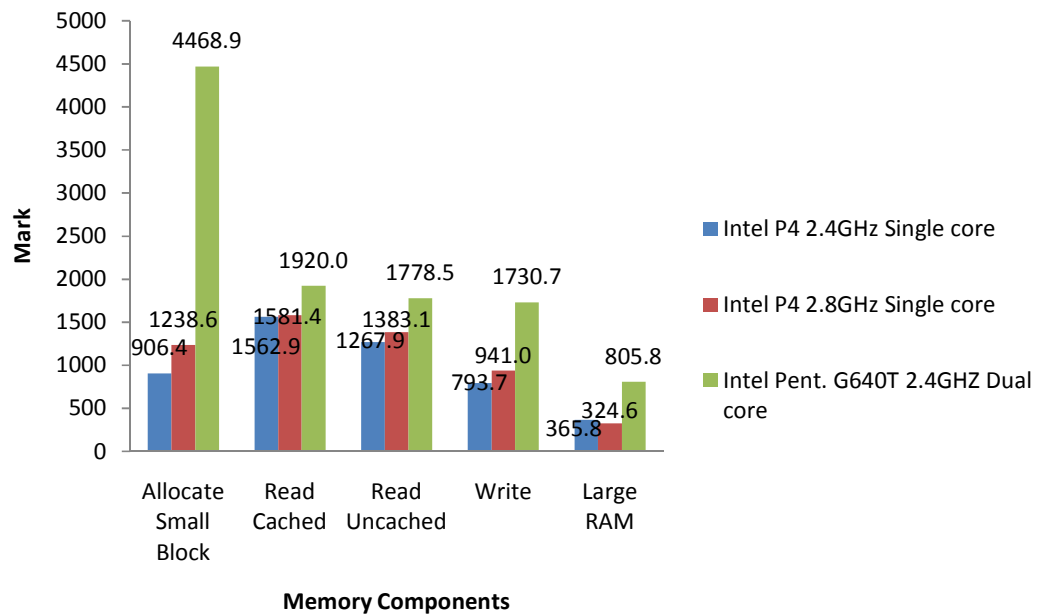Figure 6. CPU Performance Mark for Single-Core and Dual-Core Systems

Figure 7. Memory Performance Mark for Single-Core and Dual-Core Systems

Table 7. Transfer of 33.3GB File (Copy) from External SATA-HDD to the System

	Intel Pentium 4 2.4GHz Single-core	Intel Pentium 4 2.8GHz Single-core	Intel Pentium G640T 2.4GHz Dual-core
Number of Processes	38	38	38
CPU Usage	57%	40%	16%
Physical Memory	29% - 30% 611MB – 624MB	32% - 33% 620MB – 650MB	40% - 41% 795MB – 816MB
Maximum Frequency	100%	100%	60% - 69%
Time Taken to Copy files	1489 seconds	1446 seconds	1284 seconds
CPU Temperature Before Experiment	38°C	38°C	35°C
CPU Temperature After Experiment	41°C	41°C	39°C
Core Voltage	1.470volts	1.340volts	0.776volts
Maximum TDP	89W	89W	35W

Total Execution time of Intel Pentium IV 2.4 GHz Single-core system is 1489 seconds.
Total Execution time of Intel Pentium IV 2.8 GHz Single-core system is 1446 seconds.
Total Execution time of Intel Pentium G640T 2.4 GHz Dual-core system is 1284 seconds.

It is the usual norm to evaluate and relate the performance of two different computers, say, X and Y. When computer X is faster than computer Y, this means that the time taken to execute or complete a particular task and/or process on computer X is lower than on computer Y. Then, computer X is n times faster than computer Y [21].

Therefore,

$$\frac{Execution\ time\ of\ Y}{Execution\ time\ of\ X} = n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots (1)$$

$$n = \frac{Execution\ time\ of\ Y}{Execution\ time\ of\ X} = \frac{\frac{1}{Performance\ of\ Y}}{\frac{1}{Performance\ of\ X}} = \frac{Performance\ of\ X}{Performance\ of\ Y} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots (2)$$

The most significant approach for measuring performance is by considering the execution time of real programs/process. Performance and execution time are reciprocals, increasing performance decreases execution time [21].

Given,

$$n = \frac{Execution\ time\ of\ Single\ core\ system\ (Ex)}{Execution\ time\ of\ Dual\ core\ system\ (Ey)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

To calculate the percentage of the system execution time,

$$\frac{Execution\ time\ of\ Single\ core\ system\ (Ex)}{Execution\ time\ of\ Dual\ core\ system\ (Ey)} = 1 + \frac{n}{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots.. (4)$$

Therefore,

$$\frac{Execution\ time\ of\ Single\ core\ system\ (Ex)}{Execution\ time\ of\ Dual\ core\ system\ (Ey)} - 1 = \frac{n}{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$n = \frac{Ex(Pentium\ 4\ Single\ core\ system) - Ex(Pentium\ G640T\ Dual\ core\ system)}{Ey(Pentium\ G640T\ Dual\ core\ system)}$$
$$\times \frac{100}{1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (6)$$

Now to calculate n for the comparison of Intel Pentium IV 2.4GHz Single-core and Intel Pentium G640T 2.4GHz Dual-core:

$$n = \frac{1489 - 1284}{1284} \times \frac{100}{1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (7)$$

$$n = \frac{205 \times 100}{1284} = \frac{20500}{1284} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (8)$$

$$n = 15.966\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. . \ldots\ldots (9)$$

Then,

$$SpeedUp = \frac{1489}{1284} = 1.1597 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (10)$$

If we repeat steps (3) – (6) for the comparison of Intel Pentium IV 2.8GHz Single-core and Intel Pentium G640T 2.4GHz Dual-core systems:

$$n = \frac{1446 - 1284}{1284} \times \frac{100}{1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. . \ldots (11)$$

$$n = \frac{162 \times 100}{1284} = \frac{16200}{1284} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. . \ldots\ldots (12)$$

$$n = 12.6168\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. . \ldots\ldots (13)$$

Then,

$$SpeedUp = \frac{1446}{1284} = 1.1262 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. . (14)$$

Both single-core and multi-core systems responded to the test in sequential and exponential manner, thereby showing significant difference in the architectures as regard certain tasks. Components and devices like HDD, DVD-CD writer and graphic adapter were not considered because of reduced-functionality and technology gap between the periods these systems were introduced into the market. However, major emphasis was put into the CPU-components and RAM as they are the most prominent features of computer architecture.

The Novabench test score when examined showed astronomical difference in the performance of RAM speed and CPU components of 2.4GHz & 2.8GHz single-core, and 2.4GHz dual-core respectively. The techno-architecture of single-core processor is one major factor responsible for reduced functionality being experienced while carrying out this research. The chart representation can be found in figure 3 & 4.

The dual-core system further exhibit significant superiority over single-core when put under performance benchmark 7.0, the CPU and memory marks shows that the components of the dual-core system is well utilized and of high performance rating. The mark is available in figure 6 and 7 respectively.

The above results confirm that Intel Pentium G640T 2.4GHz Dual-core system is over 15.97% faster than Intel Pentium IV 2.4GHz Single-core system and 12.62% faster than Intel Pentium IV 2.8GHz Single-core system during the transfer of 33.3GB files from external HDD to these systems, with the speedup of 1.16 and 1.13 respectively. This is however synonymous to one of the various methods of comparing Single-core and Multi-core (Dual-core) systems [22], an explanation well-understood by an ordinary user; and in all cases of such and others the performance of multi-core will always surpass single-core except for single-threaded applications. Also, the table above shows the CPU Usage of 57% and 40% for Pentium IV 2.4GHz and 2.8GHz Single-core at Maximum Frequency 100%, this explains great differences between Single-core and Multi-core because at Maximum Frequency the systems were heat up and any attempt to perform additional operation (multitask) will drag the systems and if further intensify will breakdown the systems; in fact rendering could not be attempted because of reduced-functionality in Single-core. The Physical Memory result shows that there is a limit to what memory could do when the frequency is 100 percent utilized as we saw in the experiment. But this is not the case of Pentium G640T Dual-core as the CPU Usage was just 16%, Maximum Frequency 60% - 69% and Physical Memory 795MB – 816MB.

With all the astronomical performance display by dual-core in all test, one would have expected a faster rating and clear-cut speed when copying from an external HDD to the system, but this was not so as the time difference between the dual-core and single-core was not large; however, this is the peak of Intel Pentium IV 2.4GHz and 2.8GHz performance because the frequency was totally exhausted, temperature rising fast, and core voltage increasing thereby demanding more power. Therefore, the study envisages that communication overhead and memory latencies are still a limiting factor in multi-core performance. Finding good cache configurations would be helpful, thereby taking pressure off the main memory and reducing communication and cache coherence latencies, and increasing overall performance [23].

Linpack experiment clearly showed that all the systems being considered were stable and had operational capacity; the time taken to complete the looping for each system and the average GFLOPs obtained put Intel Pentium G640T 2.4GHz dual-core ahead of Intel Pentium IV 2.4GHz & 2.8GHz single-core, which comply with international benchmark. In all the test dual-core components had better rating, the linpack stress test was completed in 611.98 seconds with average GFLOPs 16.85 as against Intel Pentium IV 2.4GHz and 2.8GHz single-core systems which was completed in 2607.47 and 3169.20 seconds, and GFLOPs 3.85 and 3.18 respectively. Why the GFLOPs of Pentium IV 2.4GHz surpassed its 2.8GHz counterpart could not be ascertained as at the time of compiling this research. Intel Pentium G640T 2.4GHz dual-cores, unlike the single-core processors has maximum TDP of 35W, which makes it a low power consumption processor. It also utilizes the RAM memory more efficiently than the single-core, which necessitated the hypothesis that CPU architecture determines the limit of RAM utilization in a system and can not be stretched beyond this limit.

4. CONCLUSION

The study was able to show that G640T dual-core was 15.97% and 12.62% faster than Pentium IV 2.4GHz and 2.8GHz single-cores during the file transfer process, with the speedup of 1.16 and 1.13 respectively. The CPU usage for Pentium IV 2.4GHz and 2.8GHz were 57% and 40% at peak frequency while 16% CPU usage was observed in G640T dual-core; Novabench and Performance Test of CPU and Memory components rates G640T dual-core far above the single-core(s). After all investigation the research concludes that the success of multi-core so far can not be derived from its clock speed when placed side-by-side a single-core of same clock speed or higher but division of labour amongst cores, faster core-to-core communication, dynamic cache sharing between cores, smaller size of caches, lower core and bus frequencies, with significant

contribution from the memory as shown in the linpack experiment (average GFLOPs- 16.85), and the time taken to successfully complete ten loops (i.e. 611.98 second); this is the major reason they perform well in multi-threaded application and could not replicate the performance in single-threaded application.

This study points out the fact that despite the effectiveness and efficiency associated with multi-core system as against single-core system, which emanated as a result of technological advancement and architectural redesign, it still has certain deficiencies that must be overcome for optimal overall performance while the single-core which provided the need for more cores is still good and reliable for specific purposes.

5. RECOMMENDATION

Though single-core has made a mark and multi-core is taking over, increasing the frequency by all means and reducing the power at all cost in proportion to the core(s) of a processor is not the real solution to the problems facing multi-core but the need to channel more resources into coming up with better architectural design that would hasten synchronization between cores and memory, and relinquish unnecessary on-chip interconnect delay, latency & cache issue, and indecision that contributes to unwarranted slow pace of performance in multi-core processors.

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