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Influence of Long-Term Dependences on Hard Drives Performance during Human Computer Interaction

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Today, computer systems become one of the most important systems in technology and our life. They have a plenty of possible applications but most of them can be described as a transformation of (electrical) energy into useful work = calculations. This process is not so simple as it seems to be because the structure of computers hardware is very complicated and processed tasks are also very complex. Because the expectations of computer users are very high, a lot of computer resources are used only for operating systems normal work. Some existing solutions, especially in the memory system, guarantee that computer systems have acceptable performance but this parameter depends on many important system features. In this paper we will focus on one parameter, namely average disk time s/ transfer, in order to show the complex behavior of this memory system part during man–computer interaction. This is one of the most important counters in computer systems that works under Windows family operating systems and describes measurement related to hard drive based on the complete roundtrip time of any request.

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1. Introduction

Nowadays computer systems evolve towards beings that should be considered as the examples of complex systems. This is mostly related to the fact that their structure is much more complicated than their mathematical model related to the idea of Turing machine (on algorithmic (software) level) and the concept of von Neumann's architecture (on hardware level). This is especially well-visible when one considers the structure of computer memory [1] which in fact consists of many interdependent elements and is hierarchical (Fig. 1). But not only this hierarchy is important; let us note that the (computer) hardware alone does not mean anything special — this hardware should be governed by special software system (operating system) which is responsible not only for creating an interface between the user and computer elements but mostly for a management of limited system resources. Thus we have a hardware system with structure of connections between particular elements [2] and existing between them connections which are governed by special (software) relations. A hardware structure (network of connections) is for doing specified tasks (e.g., mathematical computations) according to given algorithms with reference to operating system management solutions.

Almost all nowadays operating systems for end users work under GUI interface. It is very convenient for users but this convenience requires quite big amount of available resources understood as memory, CPU, hard drive space. Taking into account the fact that generally computer systems resources are limited and this is a consequence of physical limitations and also economic costs for personal solutions, computer systems are general purpose and are built basing on solutions that allow for balance of costs and performance [3]. We show in next sections that computer memory subsystem is hierarchical and has special features which in fact can lead to the existence of dynamical phenomena. These phenomena are a part of interaction between computer user, limited hardware resources and mechanisms that are used in operating systems. We focus on one operating system, Windows 7, and show a spectral analysis of high-order phenomena for hard drives behavior during long term work of typical computer user.

The whole paper consists of 6 sections. After Introduction in Sect. 2 we show a hierarchical structure of computer memory system and describe it in terms of access time constants. Then, in Sect. 3, we present selected remarks about computer systems performance. Next section is devoted for description of our experiment. Basing on the experiment results we focus on some statistical properties of recorder time series and show in Sect. 5 how long-term dependences influence system performance. Last section shows conclusions and possible directions of future work.

2. Computer memory system

A typical computer user considers memory system as a linear structure which allows processing of different tasks [3, 4]. However, this view is very simplified because computer memory system consists of several levels which lead to the existence of hierarchical structure. Figure 1 presents some simplified version of this structure showing how the problem of limited resources is solved. The term limited resources should be considered at least in two dimensions. The first one is obvious — it focuses on physical (technological) limitations (available capacity),

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whereas the second one is related to economical limitations (cost per unit) — the cost of very quick memory levels is very high. There is also the third dimension connected with previous two — this is the problem of time dispersion during the access to successive levels and if CPU working frequency is 1 GHz such a dispersion can have 9 orders of magnitude.

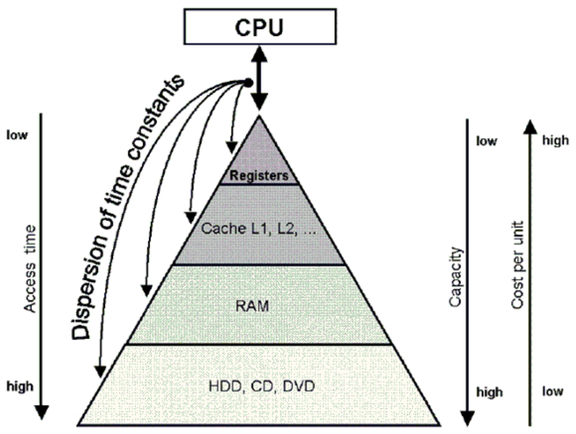

Fig. 1. Hierarchical structure of memory system [3, 4].

As one can see, each level of memory system has limited capacity. Because most of nowadays operating systems allow for multi-task processing the problem of limited amount of RAM memory is solved by the mechanism of virtual memory located on hard drive. This is very useful solution but it has some important influence on computer system performance. This is mostly connected with the fact that access time to RAM memory is between 50 and 150 ns whereas access time to hard drive is about 15–30 ms that is 5–6 orders of magnitude; each access to hard drive level is connected with huge latency. In fact, this can lead to several consequences. If many processed tasks required one-by-one access to hard drive its access time latency leads to still growing length of disk queue. If this access is connected with necessity of access to the operating system virtual memory this immediately can cause very low performance of the whole system. It is very important to have short roundtrip time of a I/O disk requests to ensure that disk response time will be as short as it is possible.

3. Selected remarks about measuring computer system performance

Performance is one of the most important parameters in description of computer systems. Generally, this term is evaluated in measurable, technical terms, using different metrics. But the simplest "metrics" is the answer to question: "How well is the computer doing the work it is supposed to do?" [5]. It is not easy to define which one aspect of computer processing should be taken into account, but in most cases it is assumed that one can use: response time, latency, completion time, channel capacity, scalability, performance per watt, availability, throughput, service time, instruction path length, bandwidth, relative efficiency, compression ratio, and speed up [6]. Because in this paper we consider hard drive behavior, we are interested in description of its performance in terms of time that is needed by hard disk during transfers (reading and writing). This time is related to the service time (dependent on hard drive features), but also on waiting time that is dependent on queueing (hard drive is a typical example of service point that is modeled by queuing theory). Let us note that these times are directly related to energy consumption by computer: the longest response time, the higher amount of energy is used for processing or even wasted.

It is not easy to measure in computer systems the above mentioned parameter remembering that computer system is a specific system in which such a measurement denotes the influence on measured parameter. For example, if one wants to measure any parameter of computer system, must have a computer program that allows this measurement and records obtained results of measurement. However, this computer program is processed by computer and influences recorded data. The only one possibility is to use solutions that are built inside operating systems and in the case of Windows operating systems this is done by the performance monitor tool (perfmon) [7]. This is very sophisticated application that allows presentation and recording of many interesting counters that are used by operating system for its normal work. Data are traced by different counters that are related to many important hardware and software components and this tracing is done always because this guarantees normal computer work. Obviously, perfmon as a computer program generates an additional workload and in the case of hard disks there is an additional latency associated with each input/output request to physical disk during perfmon processing. It was estimated that in computers under Windows ME with CPU 550 MHz, during 40k of input/output operations per second perfmon added about 5% ($\approx$ 2k); as a consequence the measurement layer added about 3 to 4 μm to the I/O manager path length for each I/O operation. But it is also expected that faster processors will have a proportionally less delay. If a disk I/O request normally lasts for 3 to 5 ms, this additional latency is hardly noticeable [7].

In next section we show results of experiment that was done basing on 60 different configurations of hardware. For each configuration we trace system counter average disk time s/ transfer to obtain as long as it was possible time series that represent dynamical behavior of hard disk (every traced disk has a Serial ATA bus). Justification for this choice will be presented below, now it is worth to write that we focus on a typical interaction between user and computer (any special benchmark tests were not done), because such an approach guaranteed that during experiment we had "real" workload — not an artificial one like in the case of special tests. Workload generated by benchmarks is extreme; normally it has almost never happened. Workload generated by special tests can be repeated, but it seems that more "natural" situation is when we trace behavior of typical user who works with computer for a necessary long time.

4. Results of experiment

In the case of hard drive it should be noted that one physical drive can have many logical disks. Taking into account the existing in Windows OS solutions if one wants to describe disk performance can focus on the set of different available counters. A first look on the list available under perfmon tool suggests that the most important should be % disk time that should measure disk utilization. But this counter is not measured directly. Its values are derived by special system driver on a software layer. During processing each I/O request packets (IRPs) pass through this layer, and timestamps of the duration for the IRPs are recorded. An average over the collection interval shows the counter average disk time s/transfer and this is a direct measure of disk response time from the hardware level [8]. Strictly speaking, this counter shows complete roundtrip time of each request and it is a direct measure of disk response time. This also means that it includes time of queuing when disk is busy with another request (in the case of SCSI this is also the bus busy time). A counter % disk time is calculated from the sum of all IRP roundtrip times (that is average disk time s/transfer) multiplied by values of another counter disk transfers/s, and divided by time interval duration, or essentially

$$\%\ \text{disk time} = \text{average disk time s/transfer} \times \text{disk transfers/s}$$

and in some cases this can cause values that exceed 100%. The above "formula" can be directly related to Little's law but as it is known that this law can be used only when system is in equilibrium state: the rate of requests arrived into the system does not exceed the rate of served (completed) tasks and this cannot be always guaranteed. A direct measure of disk response time basing on an average disk time s/transfer counter is a useful metric because it shows the most accurate values, including time of queuing caused by the fact that disk is busy and also caused by the situation when the bus is busy — for actually processed in CPU tasks this is the most important parameter causing any additional delays. Moreover, assuming that disk is $M/M/1$ queue a total disk roundtrip time measurement, instead of a simple disk service time measurement, helps better understanding of utilization factors.

During the experiment we use 60 different configurations of hardware (personal computers) working under Windows 7 operating system and trace their behavior during interaction between human and computer. This interaction can be considered as a normal, typical work of users who use office programs, internet browsers, communicators, media applications, etc. These tasks can be processed together or independently and we did not use any special scenarios for workload. The most important assumption was to reconstruct behavior of different users for different hardware configurations.

The shortest obtained time series has 200k observations while the longest ones > 1M. Because in perfmon the lowest possible resolution of data collection is 1 s in the case of time series that have more than one million records this means that we have records lasting for ≈280 h. For the shortest time series this was only ≈55 h. Data tracing was done only when computer was used by user (obviously, including short breaks during this interaction). Assuming that daily (on average) counter was traced for 8 h it is easy to check that for the longest time series our research was done by almost 35–40 days. Such long time was needed in order to collect valuable and reliable data. This was not possible in all cases but we have only several time series that were shorter than 500k observations. As it was written above we did not use any special tests assuming that such tests generate rather artificial workload that has little in common with workload generated by computer users. During processing we trace

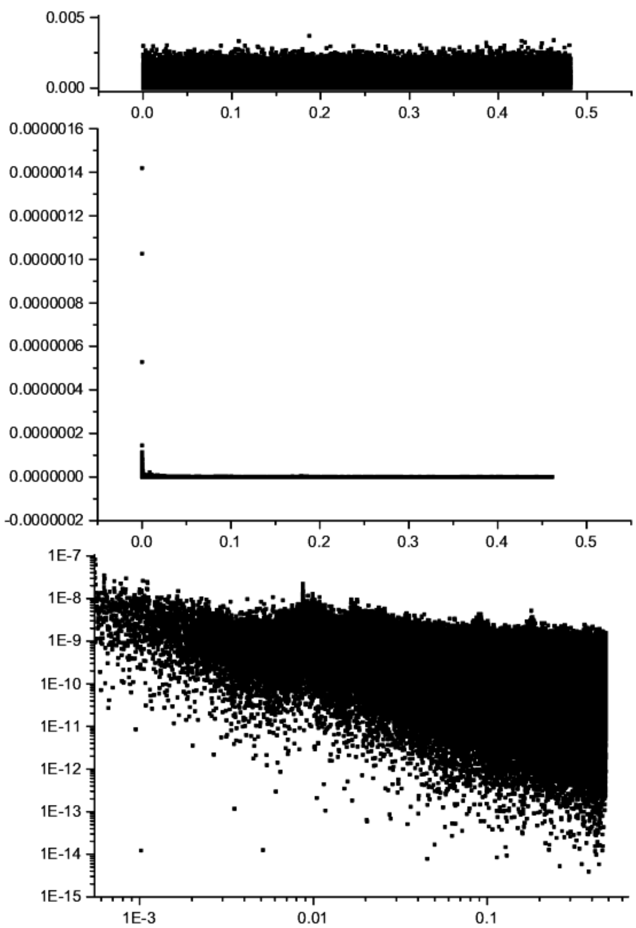

Fig. 2. Behavior of spectral density for different obtained time series during experiment. Top figure shows flat spectrum, middle one a spectrum with boost for low frequencies. Bottom figure is a log–log plot of middle figure showing the existence of $1/f$ noise.

by perfmon a system counter average disk time s/transfer and assume the following approach for analysis. Instead of considerations in the time domain we focus on frequency domain in order to check some typical frequencies and time constants in this counter behavior. This is related to the fact that the analysis in frequency domain typically allows to determine some interesting phenomena in terms of their periodic appearance. Such an approach is for example used in analysis of engine vibrations or seasonal analysis. A first look of obtained results showed that for some of obtained periodograms we have special features as it is shown in Fig. 2.

Spectrum can be flat for all frequencies indicating that there are not any distinctive periods of special phenomena appearance (Fig. 2, top), but it can also have a special shape — for low frequencies we have a boost of spectral density (Fig. 2, middle). The existence of such a situation is well-known in literature and usually it is referred to the fact that in analyzed time series we have long-term dependences [9]. This is especially visible if plot is done on a log-log scale (Fig. 2, bottom) where the spectral density states a law $S(f) \sim 1/f$ called $1/f^{\beta}$ noise. Usually calculations of β parameter (the slope of spectral density) are done by a linear fit — Table I shows the obtained results for all frequencies and also for 10% of lowest frequencies in all cases.

TABLE I

Calculated slopes of spectral density.

Case	Disk speed [rpm]	Buffer size [MB]	Calculated slope β for $S(f)$	
			All frequencies	10% of highest frequencies
1	5400	8	–0.07627	0.0137
2	5400	8	–0.00086	–0.00274
3	7200	16	–0.17563	–1.0578
4	7200	16	–0.26477	–0.55858
5	7200	32	–0.43503	–0.54025
6	7200	32	–0.02346	–0.10875
7	5400	8	–0.33687	–0.65793
8	7200	16	–0.56283	–0.37724
9	5400	8	–0.00133	0.00091
10	5400	8	–0.0066	–0.02087
11	5400	8	–0.28022	–0.45371
12	5400	8	0.00024	0.00044
13	5400	8	–0.0023	–0.00066
14	5400	8	–0.02859	–0.12241
15	7200	16	–0.15531	–0.46179
16	5400	8	–0.42315	–0.50885
17	7200	16	–0.00385	–0.01148
18	5400	8	–0.00019	–0.00089
19	7200	16	–0.02183	–0.78275
20	7200	32	–0.36495	–1.18864
21	7200	16	–0.00747	–0.03247
22	5400	8	–0.0058	–0.01738
23	7200	16	–0.57962	–0.64764
24	5400	8	–0.00021	–0.00032

TABLE I cont.

Calculated slopes of spectral density.

Case	Disk speed [rpm]	Buffer size [MB]	Calculated slope β for $S(f)$	
			All frequencies	10% of highest frequencies
25	5400	8	–0.45031	–0.74498
26	5400	8	–0.542	–0.85298
27	7200	16	–0.31112	–0.68812
28	5400	16	–0.42911	–0.58429
29	5400	8	0	0.00013
30	7200	16	–0.34103	–0.83873
31	7200	32	–0.44767	–1.38106
32	5400	8	–0.0055	0.00937
33	7200	16	–0.00494	–0.02137
34	5400	8	–0.00177	–0.00721
35	5400	8	–0.02263	–0.06535
36	5400	8	–0.00112	–0.00087
37	5400	8	–0.0066	–0.02087
38	5400	8	–0.49419	–0.58536
39	5400	8	–0.00196	–0.00838
40	7200	8	–0.00054	–0.02018
41	7200	16	–0.00367	–0.01245
42	5400	8	–0.25389	–0.28183
43	5400	8	–0.4213	–0.69575
44	5400	8	–0.00039	–0.00034
45	5400	16	–0.00103	–0.00273
46	7200	8	–0.77021	–0.53584
47	5400	8	–0.05952	–0.00467
48	5400	8	–0.62135	–0.85881
49	5400	8	–0.03002	–0.15463
50	10400	32	–0.78682	–0.81125
51	5400	8	–0.00253	–0.01505
52	5400	8	–0.33916	–0.85001
53	5400	8	–0.00023	–0.00222
54	5400	8	–0.11221	–0.43254
55	5400	8	–0.44593	–0.7709
56	5400	8	0.00017	–0.0003
57	5400	8	–0.23869	–0.54908
58	7200	16	–0.00403	–0.01404
59	7200	8	–0.38934	–0.60901
60	7200	16	–0.06229	–0.35809

In next section we refer to the explanation of noted situation in terms of influence of long-term processes on hard drive performance.

5. Influence of long term processes on hard disk performance

Because chosen counter includes time of disk serving and time of queuing in our analysis we try to show the levels of both of these phenomena but focusing on long-term time dependences in obtained time series according to results presented in Table I. The existence of long-range term dependences in time series is usually related to pioneer works of Hurst [10], Mandelbrot and Van Ness [11] who showed that this can be one of the most important features of time series that are not random but with long memory effects. As it is known this fact is usually described by the theory of self-similar processes in time and spatial domain. We will focus only on time domain and according to descriptions presented in [12] we would like to calculate d parameter as a measure of long-term dependences. There are several statistical methods [12] but in this paper we focus only on one, namely, periodogram. As it is known for stationary processes there is a possibility to do their analysis in frequency domain. One of the available methods is the usage of the Fourier transform to obtain spectral density $S(f)$ for analyzed time series and its analysis on a log–log plot, i.e. $S(f)$ vs. f. Spectral density method can be used for calculations of long-term d dependences remembering that $S(f) \propto 1/f^{\beta}$ and $\beta = -2d$.

In our proposed model the following assumptions will be done:

(i) Hard disk is considered as a service point modeled in queuing theory as a $G/G/m$ queue where $m = 1$ (one hard disk) according to Kendall's notation [13]. In this case we have a very general model with arrivals and service probability distributions defined as arbitrary ones. This is an expansion of typically assumed queueing model for hard disks proposed for example by Harrison and Patel in [14] described as $M/G/1$;

(ii) The arrival process to a $G/G/1$ queue is a renewal process; each new request is served immediately after arriving or waits in the queue until hard disk is free to serve. The service time required by each request is an independent and identically distributed (i.i.d.) random variable, the length of queue is unlimited and hard disk uses a strategy first come first served [15];

(iii) The total response time R of the hard drive is given as a sum of service time (S_T) and waiting time (W_T) in the queue;

- [(iv)] Distributions G (for arrivals and service) can have in particular case power-like behavior. In such a case as a result our renewal process has fractal properties (fractal renewal process) [16].

Taking into account the above noted assumptions, a main idea of the McWorther model [17] proposed for explanation of the existence of $1/f^{\beta}$ noise in MOS transistors and remembering that the fractional renewal processes and the superposition of such processes can lead to the existence of $1/f$ noise [18] we propose the approach in which disk response time R (in frequency domain) is divided into two components: service time (S_T) — related to white noise in $S(f)$ — and waiting time (W_T) — related to excess $1/f^{\beta}$ noise in $S(f)$ — see Fig. 3 (a similar model was proposed in [19]).

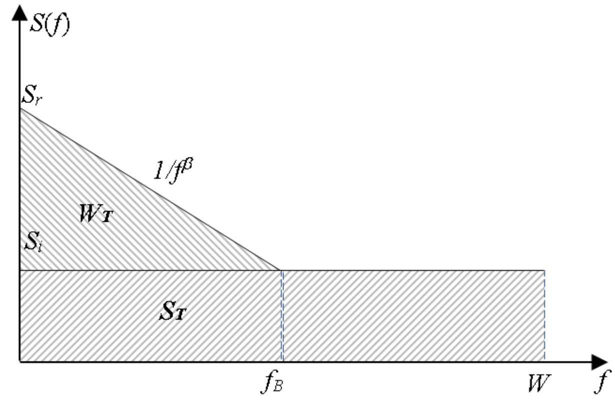

Fig. 3. Model of spectral density with reference to service S_T and waiting time W_T of system in frequency domain. Both axes in log scale.

Proposed approach leads to a general model of service point performance expressed in terms of energy dissipation during task serving. Let $\overline{E}_i$ stand for the average energy dissipation in our ideal system during processing of each request in order to serve it, $S(f)$ denotes the power spectral density of this process, W is the bandwidth of our system analyzed in frequency domain, f_{B} is the borderline frequency between short term and long term dependences (i.e., between the excess $1/f^{\beta}$ noise and white noise, $f_{\mathrm{B}} < W$, $W = nf_{\mathrm{B}}$, $n > 1$), $\overline{R}_i$ is the mean value of response time (including only service time S_T) of our hard disk if it works with queuing caused by short term dependences (ideal, non-disturbed case). One can write that

$$\overline{E}_i = S_i \int_0^W \mathrm{d}f \overline{R}_i = S_i W \overline{R}_i. \tag{1}$$

If one takes into account the real system in which long-range dependent queueing appears (i.e., the excess noise appears as a consequence of long-term processes) the average energy dissipation $\overline{E}_{\mathrm{r}}$ during requests serving will be given as follows:

$$\overline{E}_{\mathrm{r}} = S_i \overline{R}_{\mathrm{r}} \int_{f_{\mathrm{B}}}^W \mathrm{d}f + S_{\mathrm{r}} \overline{R}_{\mathrm{r}} \int_0^{f_{\mathrm{B}}} \frac{1}{f_{\mathrm{B}}} \mathrm{d}f$$
$$= S_i \overline{R}_{\mathrm{r}} (W - f_{\mathrm{B}}) + S_{\mathrm{r}} \overline{R}_{\mathrm{r}} \frac{f_{\mathrm{B}}^{1+2d}}{1+2d}. \tag{2}$$

where $\beta \neq 1$, $\overline{R}_{\mathrm{r}}$ stands for mean disk response time for each served request including service time S_T and waiting time W_T and the slope $\beta = -2d$ as it is described in [12]. This is a simplified model because it is assumed that our analyzed processes belong to the Gaussian domain of attraction, but even this is not the truth (one can check this by the detailed analysis of probability distributions for counter records, but this is not the aim of this paper) we can use proposed model, because it is believed that for non-Gaussian processes the relation $\beta = -2d$ also holds [12].

Let us note that waiting time W_T can be related to the amount of energy that is wasted during request. In order to guarantee that $\overline{E}_i = \overline{E}_\mathrm{r}$ (this means that we would like to dissipate the same amount of energy in both cases) we need to compare Eq. (1) and Eq. (2). If we take a look at Fig. 3 we will see that the value of $\log(S_\mathrm{r}) = \log(S_i)+\log(f_\mathrm{B})^{-\beta}$. The plot from Fig. 3 is done on a log–log scale; it can be assumed for simplicity (when $S_i \ll S_\mathrm{r}$) that $S_\mathrm{r} = MS_i$ where $M > 1$, $M = (f_\mathrm{B})^{-\beta} = (f_\mathrm{B})^{2d}$. Having this assumption we can compute

$$\overline{R}_\mathrm{r} = \overline{R}_i \frac{W}{W - f_\mathrm{B} + \frac{f_\mathrm{B}^{1+4d}}{1+2d}} = \overline{R}_i\gamma. \quad (3)$$

In other words, to ensure the dissipation of the same amount of energy, $\overline{R}_\mathrm{r}$ should be shortened (see Fig. 4) by a factor γ calculated from the right side of Eq. (3). As a consequence, in disturbed case, where W_T is caused by queuing, we need to have shorter service time S_T, i.e. faster service point.

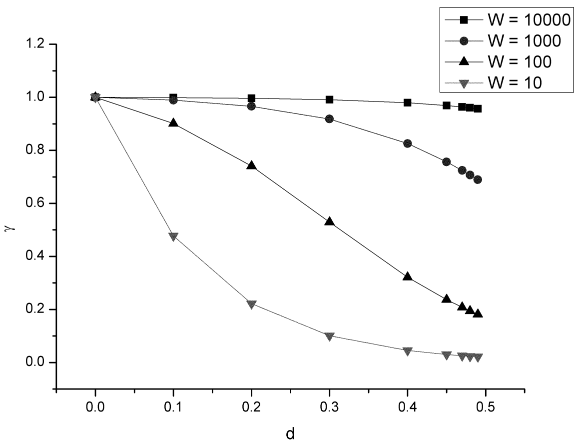

Fig. 4. Dependence of γ parameter on long-term dependences d assuming that the system bandwith W is constant and $f_\mathrm{B} = 10$. It was assumed that $M = (f_\mathrm{B})^{-\beta}$.

If we assume that for our service point in both cases S_T is always the same (we have the same device, i.e., hard disk), $R_i = S_T$ and $R_\mathrm{r} = S_T + W_T$, the additional amount of energy that is dissipated in queueing process is proportional to $E_\mathrm{r} - E_i$ and is given by

$$E_\mathrm{r} - E_i = S_i R_\mathrm{r}(W - f_\mathrm{B}) + S_i R_i \frac{f_\mathrm{B}^{1+4d}}{1+2d} - S_i W R_i$$
$$= S_i \left[W_T \left(W - f_\mathrm{B} + \frac{f_\mathrm{B}^{1+4d}}{1+2d} \right) + S_T \left(\frac{f_\mathrm{B}^{1+4d}}{1+2d} - f_\mathrm{B} \right) \right]$$
$$= S_i \left[W_T W + R_\mathrm{r} \left(\frac{f_\mathrm{B}^{1+4d}}{1+2d} - f_\mathrm{B} \right) \right]. \quad (4)$$

If waiting time of queue service point $W_T \to 0$ (there are no long-term queueing effects in the system and excess $1/f^\beta$ noise does not exist) the degree of long-range dependences $d \to 0$ and the difference in Eq. (5) approaches 0.

If we reverse our way of thinking in order to show how $\overline{R}_i$ should be enlarged to obtain the same response time like in disturbed system, we can see how long-term dependences d influence $\overline{R}_\mathrm{r}$ assuming that $W = \mathrm{const}$ — this is simply an inverse of Eq. (3):

$$\frac{\overline{R}_\mathrm{r}}{\overline{R}_i} = \frac{W - f_\mathrm{B} + \frac{f_\mathrm{B}^{1+4d}}{1+2d}}{W}. \quad (5)$$

This approach allows for preparation of graph presented in Fig. 5 and explains why the long-term dependences decrease the system performance.

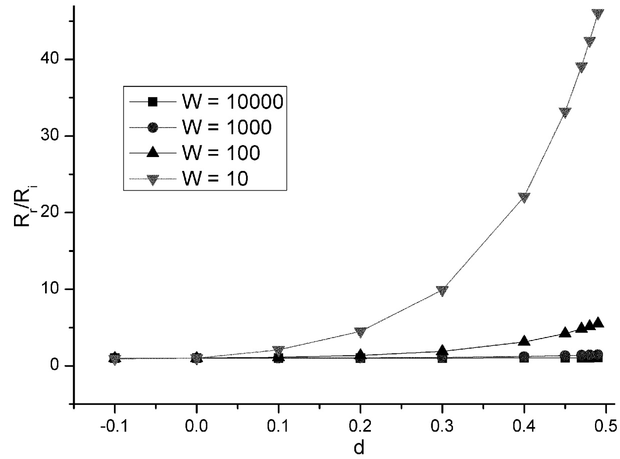

Fig. 5. Influence of long-term processes measured by d parameter on system response time R_r when the system bandwith W is constant and $f_\mathrm{B} = 10$. It was assumed that $M = (f_\mathrm{B})^{-\beta}$.

From Eq. (5) it is seen that the existence of long-range dependences lead to the need of spending more time (dissipate more energy) in service point than in ideal case. This shows the direct impact of long-term dependences on disk performance especially in terms of dissipated energy and longer time of queuing during processing. Figure 5 shows that if f_B is close to W, the impact of these dependences is significant.

In Table I one can also find additional information about disk parameters, such as disk speed in rpm and buffer size. Having this it is possible to calculate the linear correlation coefficient between obtained values of spectral density slope β and, as it seems, the most important physical parameters of disks. In both cases we obtain negative values: for correlation between disk speed measured in rpm this is –0.34 while for correlation between buffer size measured in MB this is –0.276. In other words: despite the fact that we use disk with faster rotation speed and with higher buffers the degree of long term dependences is still growing. This is a little surprising fact, because one might expect that the *faster* hard drives can quickly serve more tasks and the impact of task queueing can be neglected. On the other hand Windows 7 operating system uses a memory management strategy in which available resources are used by cluster paging. If the amount of RAM memory is not sufficient, a system of virtual memory (that is usually located on hard drive) is used. This leads to the increase of requests directed to hard drive. Typical user expects that fast computer is able to process more tasks, but in turn these beliefs can lead to deepening dependences. However, these suppositions need future research.

6. Conclusions

In paper we show that the existence of long-term processes is an immanent feature of processing in nowadays personal computer systems. These processes influence computer system performance and this was especially well-visible in the case of hard drive behavior. Basic counter that measures the hard drive performance indicates the existence of excess $1/f$ noise and as a consequence high values of d parameter. As it was shown, this influences the queueing time and the amount of dissipated energy during processing in computer systems. Because computers are machines that are physical systems there is a need of detailed studies how processing is done in terms of energy transformation and entropy production. Our further work should focus on more detailed study of probability distributions, more accurate calculations of statistical self-similarity (including the study about multifractal properties) in order to develop a new approach for modelling physics of computations.

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