Theoretical study of cache systems

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Abstract

The aim of this paper is a theoretical study of a cache system in order to optimize proxy cache systems and to modernize construction principles including prefetching schemes. Two types of correlations, Zipf-like distribution and normalizing conditions, play a role of the fundamental laws. A corresponding system of equations allows to describe the basic effects like ratio between construction parts, steady-state performance, optimal size, long-term prefetching, etc. A modification of the fundamental laws leads to the description of new effects of documents’ renewal in the global network. An internet traffic caching system based on Zipf-like distribution (ZBS) is invented. The additional module to the cache construction gives an effective prefetching by lifetime.

Key words: Zipf-like distribution, cache optimization, principles of cache construction, renewal of Web documents, long-term prefetching

1 Introduction

Rapid development of computer technologies in the end of the last millennium leads to appearance of a virtual world with its own laws. Unfortunately, in this period too few attention was given to studying of fundamental principles of virtual life.

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The main constructions of the virtual world base on the concrete algorithms intended for providing vital functions. The easiest and obvious principles were used for constructing and modernizing of these algorithms. During their implementation weren’t any time for studying and optimization. Often their low performance was compensated with growing power of computers. The main thing was that the new constructions of the virtual world allowed to manage the raising problems.

Now days we can afford some respite and part of forces should be transferred to studying of fundamental laws and to optimization of vital systems on a base of recent knowledge. Frankly speaking, any research area may be considered as scientific field if and only if its basic principles are enveloped in a mathematical form and new rules may be predicted on a base of known facts.

The aim of this paper is a theoretical study of a cache system in order to find a way for optimization of proxy systems and to modernize construction principles. Principles that should be used for a model is discussing as well. A universal model can be easy generalized to any applications based on Zipf-like distribution like prefetching schemes, Content distribution Networks (CDN) [7], peer-to-peer systems [12,13], Internet search engine, etc.

The rest of the paper is organized as follows. Section 2 provides some background information about model parameters. Section 3 presents the analytical laws and the special points of theoretical model. Section 4 describes the main elements of cache construction. In Section 5 we examine steady-state or limiting performance of static caching schemes when Web documents were not changing and new documents were not being generated. Section 6 discusses the ways of optimization of cache systems. New principles of cache construction are formulated in Section 7. Section 8 discusses the mathematical description of renewal of Web documents. The benefit of web prefetching is the contest of Section 9.

2 Model parameters

In this section definitions of variables are given and basic approaches and terminus has been analyzed.

In todays common web configurations, the proxy server exists between clients and web servers. Clients send all requests to a global network as it is shown on the Fig. 1. Some documents are requested several times and therefore they should be held in a cache system.

As it was reported in Refs. [2,3,10] the relative frequency of requests to Web
pages follows Zipf-like distribution [16]. This distribution states that the relative probability of a request for the $i$’th most popular page is

\[ p_i = \frac{A}{i^\alpha}, \]  

(1)

where $A = p_1$ is the probability of the most popular item and $\alpha$ is positive exponential value less then unity.

Let the users ask for $K$ documents during time $t$:

\[ K(\nu_{out}, t) = C\nu_{out}t. \]  

(2)

This result depends on aggregated bandwidth $\nu_{out}$, on time $t$ and a constant $C$. The constant $C$ from Eq. (2) is an inverse proportion of a mean size $E(C)$ of documents received from the global network:

\[ C = \frac{1}{E(C)} \]  

(3)

In Ref. [15] a number of received documents $K$ is defined by request stream from a population of $N$ users

\[ K(\lambda, N, t) = \lambda Nt, \]  

(4)

where $\lambda$ is average client request rate.

Let $p$ documents be unique and $M$ be equal to quantity of documents that can be requested from the cache system as it has shown on the Fig. 2. Then an efficiency of the system or a hit ratio can be defined as

\[ H = \frac{k - p}{K} = \int_1^M \frac{A}{x^\alpha}dx \]  

(5)
the ratio of non-unique cacheable documents \( k - p = k \int_1^M \frac{A}{x^\alpha} dx \) to their total number \( K \).

Wolman et al. [15] examined steady-state or limiting performance of caching schemes. Their model of steady-state performance assumes that a cache can store all cacheable documents in the Web and there isn’t any capacity misses in workload. The probability that a requested document is cacheable is \( p_c \), \((k = p_cK)\). With this assumptions the maximal rates of \( H \) is identical with \( p_c \), i.e. the ideal hit rate for cacheable documents \( H_i = H/p_c \) would approach 100%.

A key difference between the models presented by Breslau et al [3] and by Wolman et al [15] is that document rate of change has been incorporated into the model rather than assuming that documents are static. In order to describe this effect an additional multiplier has been included to a integral from Eq. (5):

\[
\lambda N p_i / (\lambda N p_i + \mu),
\]

where \( \mu \) is an exponential parameter of interarrival times for object requests and updates, \( p_i \) is proportional to \( 1/i^\alpha \). This multiplier throws off one effective query of any document from cache during its lifetime \( T_{ch} = 1/\mu \), that is the interval between two consecutive modifications of object. Such an updating request must be redirected to the global network to get the renewed Web page.

3 The analytical laws and the special points

An analytical model is constructed with a goal to predict behaviour of the investigated systems on the base of the analytical laws written in a mathematical form and to find ways for optimization. Mathematical constructions of computer models remind laws of the thermodynamics and the molecular
physics in many respects. There are two directions of modeling: macroscopic and microscopic approaches.

In the first case the corresponding laws are formulated for parameters describing cache systems as an indivisible object. The following values should be considered as macroscopic parameters: hit ratio $H$, Zipf exponent $\alpha$, the number of unique documents $p$, $M$, etc.

The microscopic description assumes an analysis on a level of transmitting IP packets, of requests to the global network, i.e. huge number of the events. In this case investigators have to apply the theory of stochastic processes such as Poisson’s distribution or Markov’s chain. The main problem of this approach is a right interpretation of analytical results and their generalization, i.e in a limit passage from microscopic values to macrolaws.

Usually the macroscopic dependencies operate with values that are measured directly. Unfortunately, corresponding laws are not yet found for the main part of the virtual world therefore a particular attention should be given to their search. Proxy cache is a pleasant exception to the general rule.

Two types of correlations pretend to a role of fundamental laws described cache systems [5]:

- A Zipf-like distribution, see Eq. (1)
- Normalizing conditions or a sum of the probability to request the universe of $1 \leq n \leq k$ objects.

Mentioned laws could be applied to the special points of Zipf distribution. As it is shown on the Fig. 2 there are a few special points but only two of them, $M$ and $p$, are used for construction of the theory. Then the Zipf-like distribution leads to

$$\frac{Ak}{M^\alpha} = 2,$$

$$\frac{Ak}{p^\alpha} = 1.$$  

Normalizing conditions for the first $M$ and $p$ documents from a cache are

$$\int_1^M \frac{A}{x^\alpha} dx = H_i,$$  

$$\int_1^p \frac{A}{x^\alpha} dx = 1.$$
Here $H_i$ is an ideal (steady-state) performance that assumes unlimited capacity. For a real system the Eq. (9) has been transformed to

$$H = p_c \int_1^{S_k} \frac{A}{x^\alpha} dx,$$

where $S_k$ is a number of cache objects requested repeatedly, i.e. $\vartheta_i \geq 2$ ($\vartheta_i = p_i k$) for $i \leq S_k$.

Five Eqs. (7-11) allow to describe the basic effects, to predict parameters value, ways of optimization, etc. Modification of this system of five equations would lead to describing of new effects.

### 4 Elements of cache construction

This section discusses which elements are compulsory for cache system. Also possible ratios between these elements should be investigated.

Three main parts are distinguished in any cache system:

- A kernel $S_k$ that contains popular documents with $\vartheta_i \geq 2$.
- An accessory part $S_u$ that keeps unpopular documents requested from the Internet once, i.e. $\vartheta_i = 1$.
- A managing part $S_m$ that contains statistics of requests and rules for replacement of cache objects.

A system of the Eqs. (7-11) determines mathematical correlations between cache elements $S_k, S_u, S_m$.

First of all it is necessary to write the expressions for experimental search of $\alpha$ With help of the Eqs. (7,8)

$$p = 2^{1/\alpha_1} M.$$  \hspace{1cm} (12)

The correlation between $p$ and $k$ from system of Eqs. (8,10) gives

$$k = \frac{p}{1 - \alpha_2}.$$  \hspace{1cm} (13)

Another useful relation is a solution of a system of Eqs. (7,9) concerning
variable $M$:

$$M = \frac{(1 - \alpha_3)H}{2} K. \quad (14)$$

This means that only each 15th document should be stored in the cache among all documents requested from the global network (for typical values $\alpha \geq 0.7, H \geq 35\%$).

It should be noted that three Eqs. (12-14) give the different values of $\alpha$

$$\alpha_1 < \alpha_2 < \alpha_3. \quad (15)$$

These differences $\alpha_3 - \alpha_2, \alpha_2 - \alpha_1$ are of order $0.04 \div 0.05$ and may be graphically explained, see Fig. (3). As a rule the value $\alpha_3$ from Eq. (14) is found from experimental data and it is used for the further calculations.

Analyzing log files of proxy cache a mean lifetime $t_u$ can be calculated for those documents, which popularity is $\vartheta_i = 1$. Such a statistic determines also lifetime $T_{eff}$ of cache objects with a citing index $\vartheta_i = 2$, i.e. those items that have been stored in proxy cache, requested one time from a proxy and have been deleted subsequently.

It is easy to see that a number of documents in a cache kernel $S_k$ is a value $M(T_{eff})$ corresponding to the time $T_{eff}$, and $S_u$ depends on $p, M, t_u$:

$$S_k = M(T_{eff}), \quad (16)$$
$$S_u = p(t_u) - M(t_u), \quad (17)$$

The following ratio between the part $S_k, S_u$ has been found with help of Eqs. (2), (12):

$$\frac{S_k}{S_u} = \frac{T_{eff}}{(2^{1/\alpha} - 1)t_u} \quad (18)$$
The Eq. (18) gives a criteria for optimal using of a storage capacity. This criteria allows to plane an experiment: how does efficiently of cache replacement algorithm depend on correlation of the proxy parts? It should be noted this result as well as the experiment plan was the consequence of the theoretical study.

The analysis of log files from Samara State Aerospace University proxy [6] leads to the facts that variables \( t_u \) and \( T_{eff} \) are directly proportional to the cache size \( S_{eff}/\nu_{int} \) and can be considered as coincided values:

\[
T_{eff} \simeq t_u. \tag{19}
\]

In other words the kernel and accessory parts are approximately correlated as 1:2 or less then 40% of storage capacity has been used for the basic goal to store the repeatedly requested documents.

5 Steady-state performance (static Web)

In this section we examine steady-state or limiting performance of static caching schemes when Web documents were not changing and new documents were not being generated. Wolman et al model [15] of steady-state performance assumes that a cache can store all cacheable documents in the Web and there aren’t any capacity misses in the workload. With this assumption, they conceive that in the long term the hit rate \( H_i \) for cacheable documents would approach 100%. However, considerable part of cacheable documents \( p - M \) is requested from the global network only one time as it is shown on Fig. 2 that illustrate Zipf-like distribution.

More accurate expression for ideal hit ratio \( H_i \) may be written with help of Eqs.(12,13,14) to in consecutive order \( k, p, M \)

\[
H_i \leq 2^{(\alpha - 1)/\alpha}, \tag{20}
\]

that gives 75% for \( \alpha = 0.7 \).

The alternative expression for ideal hit ratio \( H_i \) follows from Fig. 2:

\[
H_i \leq 1 - \frac{p - M}{k} \tag{21}
\]

that gives 80% [6].
The hit rate $H$ of web cache is considered to grow in a log-like fashion as a function of cache size [1,3,4]. Wolman’s work [15] shows that there is no benefit in additional cache size beyond a certain size. However such an statements are impeccable only for an extremely huge sizes.

The cache administrators believe that a production cache should store about 2-3 days of traffic. Such an recommendation can be found on the cite of the Measurement Factory Inc., that tested well-known cache products [11].

From analyzes of the Eq. (11) for cache performance the following dependence appears

$$
\frac{H_1}{H_2} = \left(\frac{S_1}{S_2}\right)^{1-\alpha},
$$

(22)

that allows to talk about power fashion [6] in size’s area of a few days traffic. This fact has been confirmed by experimental research [6].

6 Optimization of cache systems

A fine tuning of cache that increases hit ratios by only several percentage points would be equivalent to a several-fold increase in cache size. In order to determine an optimal cache size Kelly and Reeves [9] are guided on economical methods like monetary cost of memory and bandwidth.

The aim of our theoretical investigation is a search of dependencies between cache size $S = S_k + S_u$ and other macroscopic parameters like internal bandwidth $\nu_{int}$, maximum hit ratio $H_i$, Zipf’s exponent $\alpha$, etc.

As it is shown in Ref. [5] a ratio of effective size of cache system $S_{eff}$ to aggregated bandwidth of external links $\nu_{int}$ can be considered as a constant:

$$
\frac{S_{eff}}{\nu_{int}} = \tau.
$$

(23)

Our goal is to calculate a lower limit $\tau(\mu, \alpha)$ when the performance mounts to the 35% level ($H_{eff} \geq 35\%$) of well working system.

Eqs.(20,21) give the following estimation for a real system with $\alpha \geq 0.7$, $p_c = 0.6$:

$$
\frac{p_c H_i}{\sqrt{2}} \geq H_{eff} \geq 35\%
$$

(24)
Eqs. (9,11) allow to calculate the correlation between documents number in a real cache kernel $S_k$ and a number $M_{max}$ corresponding to limiting performance $H_i$:

$$S_k = 2^{1/(2(\alpha-1)))} M_{max}$$

(25)

where

$$M_{max} = \frac{(1 - \alpha)p_c H_i}{2 \nu_{out} T_{ch}}$$

(26)

Parameter $T_{ch} = 1/\mu_u = 186$ days is the time between renewal of unpopular documents [15]. If $H_{eff} = 0.35$, then

$$\tau(\mu_u, \alpha) = 2^{1/(2(\alpha-1)))} \frac{1 - \alpha}{2.61 \mu_u}.$$  

(27)

It is easy to calculate $\tau = 6,0$ days for $\alpha = 0.8$.

7 New principles of cache construction

The main result of any research of cache system should be finding a way for increasing hit ratio. We see the two basic directions for achievement that goal. The first conjecture is that the hit rate $H$ increases with growth of $S_k/S_u$. The second one is based on the general feature of the existing cache algorithms that the only documents requested two times and more during the time $t_u$ are included in the kernel $S_k$. Therefore we conclude that caching algorithm based on the rigid tie of the main cache parameters to the time $t_u$ is low effectiveness. Our approach is to separate the management block based on the requests’ statistics from the time $t_u$.

The current situation can be resolved with the new construction principles for cache systems. The most important feature is that fixed ratio between cache parts must be guaranteed. The statistics of requests must be kept long time for all cacheable documents including delayed ones. An inseparable part of the new construction is a replacement algorithm with a metric function based on Zipf law.

The basic principles of system of internet traffic caching based on a Zipf-like distribution (ZBS) could be formulated as follows:

(1) Three main construction parts are distinguished in ZBS-system:
Fig. 4. The illustration of variables included in metric function

- A kernel $S_k$ that contains popular documents with $\vartheta_i \geq 2$.
- An accessory part $S_u$ keeps unpopular documents requested from the Internet once, i.e. with $\vartheta_i = 1$. Size of the accessory part $S_u$ must not exceed 10% from the full size of the ZBS cache $S_{eff}$.
- A managing part $S_m$ contains statistics of requests as a base for a replacement policy. The control information including statistics are kept in $S_m$ for a long time interval $t_s \geq 10(S_{eff}/\nu_{int})$, where $\nu_{int}$ is an aggregated bandwidth of the external links. The value $t_s$ must exceed one month, the maximal time interval is restricted by a half of an year. A document popularity $\vartheta_i$ takes into account all requests that made by users during the time $t_s$.

(2) An additional necessity to request a cached document from the global network is caused by document modification. The newly received document item is stored in the kernel $S_k$ and the corresponding frequency parameter assumes to be equals unity $\vartheta_i = 1$.

(3) An replicate metric $C_i = T_{iz}^{\nu_i}/\vartheta_i$ is calculated for each document stored in the kernel $S_k$, where $T_{iz}^{\nu_i}$ is a time period spent from the last modification of the document and $\vartheta_i$ is the corresponding request’s frequency. The Fig. 4 contains a graphical explanation of these variables. A document with the biggest $C_i$ is deleted when the kernel $S_k$ is overfilled.

(4) A metric $C_i = \frac{T_{iz}^{\nu_i}}{\nu_i E_i}$ is applied for increasing byte hit ratio. Here $E_i$ is the size of the corresponding document.

(5) The document from the accessory part $S_u$ is deleted
  - when it is placed to the kernel $S_k$ after the second request,
  - accordingly recently-based policies, e.g. FIFO, when the accessory part $S_u$ is overfilled.
The described cache scheme improves the hit ratio by a few percent according to Eq. (22) because of the kernel size $S_k$ increases twice from 40% to 90% when other things being equal. For the huge cache size the profit consists of in an economy of the half of disk storage.

8 Renewal of Web documents

In the previous section our analysis has been based on the model presented by Breslay et al [3] and extended by Wolman et al. [15] to incorporate document rate of change. The Wolman model yields formulas to predict steady-state properties of Web caching systems parameterized by population size $N$, population request rates $\lambda$, document rate of change $\mu$, size of object universe $n$ and a popularity distribution for objects.

The key formulas from Wolman et al.

\[
C_N = \int_1^n \frac{1}{C x^\alpha} \left( \frac{1}{1 + \frac{\mu C x^\alpha}{\lambda N}} \right) dx
\]

\[
C = \int_1^n \frac{1}{x^\alpha} dx
\]

yield $C_N$, the aggregate object hit ratio considering only cacheable objects. Document rates of change $\mu$ were considered to take two different values, one for popular documents $\mu_p$ and another for unpopular documents $\mu_u$. An additional multiplier from Eq. (28) throws off one effective query to any document from cache during time $T_{ch} = 1/\mu$ between its changes. Such an request updates the existing objects when it has been modified.

In present paper we assume that the document rate of change $\mu(i)$ depends on its popularity $i$. Mathematical equivalent of this assertion is that the steady-state process of demand cache is again described by Zipf distribution with a small $\alpha_R$ as it is shown on Fig. 5.

The difference between an ideal performance of a cache system and its real value has been conditioned by the renewal of documents in the global network

\[
\Delta H = \left( \sum_{i=1}^M \vartheta_i - H K \right) / K
\]

The ideal Zipf-like distribution corresponds to the upper line on the Fig. 5 but
the real hit ratio $H$ determines $\alpha_R$ as

$$\alpha_R = 1 - \frac{2M}{HK}$$  \hspace{1cm} (31)

Now it is easy to find $\mu_i$

$$\mu(i) = \frac{\varphi_{id}^i - \varphi_{id}^R}{T_{st}} = \frac{(p/i)^\alpha - (p/i)^{\alpha_R}}{T_{st}}$$  \hspace{1cm} (32)

It should be noted again that the experiment’s plan is the consequence of the theoretical study. The corresponding results have been calculated from the proxy’ trace of Samara State Aerospace University [6] and has been assembled in the Table 1.

Finally, the system of Eqs. (7-11) must be modernized by change of variables $\alpha$ on $\alpha_R$.

### 9 Long-term Prefetching

One way to further increase the cache hit ratio is to anticipate future requests and prefetch these objects into a local cache. The benefit of web prefetching is to provide low retrieval latency for users, which can be explained as high hit ratio.

This section examines the costs and potential benefits of long-term prefetching for content distribution. In traditional short-term prefetching, caches use
recent access history to predict and prefetch objects likely to be referenced in the near future. In contrast, long-term prefetching uses long-term steady-state object access rates and update frequencies to identify objects to replicate to content distribution locations.

Using analytic models and trace-based simulations, Venkataramani at al. [14], Jiang at al. [8] examine algorithms for selecting objects for long-term prefetching. They use threshold-based algorithms and fetch those objects with values that exceed the threshold. The object selection criterion of prefetching determines which object to replicate in advance. They have several options of criteria such as object popularity and lifetime.

An algorithm of prefetching by good-fetch was proposed by Venkataramani at al. [14]. As for object \( i \), assume the objects lifetime \( l_i \), its probability of being accessed \( p_i \), and user request arrival rate denoting how many requests arrive per second is \( a \). Then the probability of object \( i \) to be accessed before it dies is

\[
P_{\text{goodFetch}} = 1 - (1 - p_i)^{a \times l_i}
\]  

(33)

where \( a \times l_i \) is the number of requests arriving during the lifetime of object \( i \).

Jiang at al. [8] has proposed an algorithm using the \( ap_i l_i \) value to select objects. Objects with the highest value of \( ap_i l_i \) will be included in the prefetching set, meaning those objects with most possible requests will be prefetched in caches.

The analytical model derived in [14] allows to express the hit ratio of threshold-based algorithms. In order to describe this effect an additional multiplier has been included to a integral from Eq. (5). Such an fraction

\[
f f(i) = \frac{ap_i l_i}{ap_i l_i + 1}
\]  

(34)

is identical to Wolman multiplier from Eq. (6). The fraction (34) represents the hit ratio among accesses to the object \( i \). Stated otherwise, this denotes the probability of object \( i \) being fresh when it is being accessed. It is called a freshness factor of object \( i \) denoted as \( f f(i) \) in [14].

The approach developed in the Section 8 allows to calculate freshness factor \( f f(i) \) as coefficient between hit ratios of demand cache and of ideal performance, see Fig. 5. Taking into account the Eq. (13) and the data from the Table 1 it is easy to see

\[
f f(i) = \frac{k_R}{k_i} = \frac{(1 - \alpha_R)}{(1 - \alpha_i)} = 0.93.
\]  

(35)

For threshold-based algorithms, an object \( i \) is always kept fresh by prefetching
it whenever there is any change, if its corresponding metric is above its threshold value \( T_p \). Then we will always have a hit on object \( i \), while the hit ratio for other objects remains same as \( ff(i) \). In other words the prefetching algorithms allow to reach highest hit ratio corresponding to upper line on Fig. 5 to use an additional bandwidth. This additional value has been estimated [14]

\[
\Delta BW = (1 - ff(i))\nu_{int}
\]

(36)
as 7% to the mean magnitude of aggregated bandwidth of external links from Eq. (23).

On our opinion the additional module to the cache construction described in Section 7 can give an effective prefetching by lifetime:

- An additional mark \( N^i \) is introduced for each cache item. It equals the number of document modification for the time \( T_{ins} \) from installation of cache system.
- The threshold value is \( T_{ip}^i = T_{ins}/N^i \).
- If the time from a last modification of the document \( T_{iz}^i \) exceeds corresponding threshold \( T_{ip}^i \) then the cache fetches this object.

Mathematical basis of this module is uniform distribution of modification moments inside \( T_{ins} \).

10 Conclusions

The aim of this paper is a theoretical study of a cache system in order to optimize proxy cache systems and to modernize construction principles including prefetching schemes. Two types of correlations, Zipf-like distribution and normalizing conditions, play a role of the fundamental laws. A corresponding system of equations allows to describe the basic effects like ratio between construction parts, steady-state performance, optimal size, long-term prefetching, etc. A modification of the fundamental laws leads to the description of new effects of documents’ renewal in the global network.

The main result of any research of cache systems is finding a way for increasing hit ratio. Our theoretical study leads to the criteria for an optimal using of storage capacity. This criteria allows to plane several experiment on the base of the mathematical analysis.

The current situation can be resolved with the new construction principles for cache systems. An internet traffic caching system based on Zipf-like distribution (ZBS) is invented. The new system construction consists of the three
parts: a kernel for storing popular documents, an accessory part for unpopular documents and a management part for keeping requests’ statistic. Documents’ replacement algorithm based on a metric function that uses Zipf-like distribution is a part of the new ZBS system. The additional module to the cache construction described in Section 7 gives an effective prefetching by lifetime.

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