Modeling modern DNS caches

Nicaise Choungmo Fofack, Sara Alouf

Modeling modern DNS caches*

Nicaise Choungmo Fofack[a,b]
[a]University of Nice Sophia Antipolis
28 Avenue Valrose
06100 Nice, France
nicaise.choungmo_fofack@inria.fr

Sara Alouf[b]
[b]Inria
2004 Route des Lucioles, B.P. 93
06902 Sophia Antipolis Cedex, France
sara.alouf@inria.fr

Abstract

Caching is undoubtedly one of the most popular solution that easily scales up with a world-wide deployment of resources. Records in Domain Name System (DNS) caches are kept for a pre-set duration (time-to-live or TTL) to avoid becoming outdated. *Modern* caches are those that set locally the TTL regardless of what authoritative servers say. In this paper, we introduce analytic models to study the modern DNS cache behavior based on renewal arguments. For tree cache networks, we derive the cache performance metrics, characterize at each cache the miss process and the aggregate request process. We address the problem of the optimal caching duration and find that constant TTL is the best only if if inter-request times have a concave CDF. We validate our theoretical findings using real DNS traces (single cache case) and via event-driven simulations (network case). Our models are very robust as the relative error between empirical and analytic values stays within 1% in the former case and less than 5% in the latter case.

1 Introduction

In-network caching is a widely adopted technique to provide an efficient access to data or resources on a world-wide deployed system while ensuring scalability and availability. For instance, caches are integral components of the Domain Name System, the World Wide Web, Content Distribution Networks, or the recently proposed Information-Centric Network (ICN) architectures. Many of these systems are hierarchical. The content being cached is managed through the use of expiration-based policies using a time-to-live (TTL) or replacement algorithms such the Least Recently Used, First-In First-Out, Random, etc.

In this paper, we focus on hierarchical systems that rely on expiration-based policies to manage their caches. These policies have the advantage of being fully configurable and provide parameters (i.e. timers) to optimize/control the network of caches. Each cache in the system maintains for each item a timer that indicates its duration of validity. This timer can be initially set by an external actor or by the cache itself.

The Domain Name System (DNS) is a valid application case. In short, the DNS maintains in a distributed database the mappings, called *resource records*, between names and addresses in the Internet. Servers in charge of managing a mapping are said to be *authoritative*. Caches—used to avoid generating traffic up in the DNS hierarchy—are found in both servers and clients (devices of end users). Caching is however limited in duration to avoid having stale records which may break the domains involved.

DNS cache updates are strongly related with how the DNS hierarchy works. When a requested resource record R is not found at the client's cache, the client issues a request to a bottom level DNS server (usually that of the Internet server provider). If R cannot be resolved locally and is not found in the cache, the latter server forwards the request to a server higher in the hierarchy. The process repeats itself until R is fetched at a cache or ultimately from the disk of an authoritative server. The server providing R is called the *answerer*. The record R is sent back to the client through the reverse path between the answerer and the client, and a copy of R is left at each cache on this path.

According to RFC 6195, all copies of R are marked by the answerer with a time-to-live (TTL) which indicates to caches the number of seconds that their copy of R may be cached. Consequently, all copies of a record along a path would be cached mainly for the same duration. This RFC specification is called the *TTL rule* in the literature. Caches compliant with it are referred to as *traditional DNS caches*. Those overriding the advocated TTL with a locally chosen value (cf. [16, 2]) are called *modern DNS caches* [3].

In a tree of traditional DNS caches a request occurring anywhere just after the content expired in the local cache yields cache misses at all caches along the path to an authoritative server. Such a *miss synchronization effect* [11] is avoided with modern caches. Other differences between traditional and modern DNS caches can be found in the companion technical report [15].

The objective of this paper is to assess the performance of tree of caches. Our contributions are: (i) we are the first

*This is an author version of the 10-page paper that has appeared in the Proceedings of ValueTools'13, December 10 – 12 2013, Turin, Italy.

to provide analytic models to study both a single (modern) DNS cache and a tree of caches with general caching durations; (*ii*) we characterize the distribution of the DNS traffic flowing upstream in the DNS hierarchy besides deriving the usual cache performance metrics; (*iii*) for the case of a single cache we identify when is the deterministic caching duration the optimal policy and discuss the optimal deterministic value when this is the case; (*iv*) for the case of a network of caches with diagonal matrix-exponential distributions, we compute the distribution of the request and miss processes anywhere in the network in closed-form; (*v*) we check the robustness of our single cache model over DNS traces collected at Inria and (*vi*) the robustness of our network of caches model through event-driven simulations.

The rest of the paper is organized as follows. Section 2 reviews the works most relevant to this paper. Section 3 presents the scenario considered and some introductory material. Our single cache model is analyzed in Sect. 4 and the case of a tree of caches in Sect. 5. We validate our models in Sect. 6 and show some numerical results. Section 7 summarizes our findings.

2 Related Works

Since the recent observation of the modern behavior of DNS caches [3, 16], only few results of the state of the art are applicable to modern DNS caches. Hou *et al.* consider in [10] a tree of traditional DNS caches fed by Poisson traffic. The performance metrics derived in [10] cannot characterize modern caches as these do not cause a miss synchronization effect—like traditional caches do—which is extensively used in their model.

Jung, Berger and Balakrishnan study in [12] a single traditional DNS cache fed by a renewal process. Their model assumes that each content is cached for a deterministic duration which would be either the value marked by an authoritative server or the maximum among all values received from intermediate caches. The hit/miss probabilities derived are approximate in traditional DNS caches receiving different TTLs from higher-level caches and exact in traditional DNS caches getting always their responses from authoritative servers. It is interesting to note that the model of [12] is valid for a single modern DNS cache that overrides the given TTL with a fixed caching duration. Characterizing the traffic not served by the cache (the miss process), considering distributions of caching durations other than the deterministic one, and most challenging extending to the case of a network of caches are issues yet to be addressed.

The closest paper to our work, methodologically speaking, is [5]. Choungmo *et al.* analyze both a single cache and a network of caches in which each content remains in cache for a random period. The essential difference with our work is that caching durations are regenerated from the same distribution at each cache hit. As such, the model of [5] applies to modern DNS caches only if caching durations are exponentially distributed, thanks to the memoryless property of the exponential distribution. Observe that the context targeted in [5] is that of ICN achitectures.

It has been reported in [3, 13, 16]—and we have observed it in our collected DNS traces—that the sequence of TTLs received relatively to a given resource record exhibits some randomness. We believe it is crucial to consider this randomness when modeling a modern DNS cache. Another key issue concerns the optimal distribution for the caching durations. Callahan, Allman and Rabinovich mention in [3] that no model or experiment characterizes the optimal (deterministic) TTL choice. We will address a more general problem in this paper, namely, finding the best distribution.

3 Definitions and Assumptions

3.1 Considered Scenario

In this paper, caches are assumed to consist of infinite size buffers. This assumption derives naturally from the fact that the cached entities—the DNS records—have a negligible size when compared to the storage capacity available at a DNS server [12]. A nice consequence is that the management of different records can safely be decoupled, simplifying thereby the modeling of caches. Our analysis will focus on a *single* content/record, characterizing the processes relevant to it, keeping in mind that the *same* can be *repeated* for every single content requested by users.

Without loss of generality, consider that a *cache miss* occurred at time $m_0 = t_0 = 0$. In other words, the content was not in cache at a request arrival at time t_0. We will neglect the request/record processing time at each server/client and the request/record travel time between servers, as these times are typically insignificant in comparison with the request inter-arrival time. Consequently the content requested is cached and made available to the requester also at time t_0. More precisely, upstream requests and downstream responses are instantaneous.

A cache miss makes the content available in the respective cache for a duration T. Each cache samples this duration from its respective distribution. Caches along the path between the server/client receiving the original request and the server where the content was found all initiate a new duration T at the same time, but the durations initiated being different they will expire at different instants. Consequently, caches become asynchronous, something that would not occur should the caches follow the so-called TTL rule.

Any request arriving during T will find the content in the cache. This is a *cache hit*. The first request arriving after T has expired is a *cache miss* as depicted in Fig. 1. It initiates a new duration during which the content will be cached.

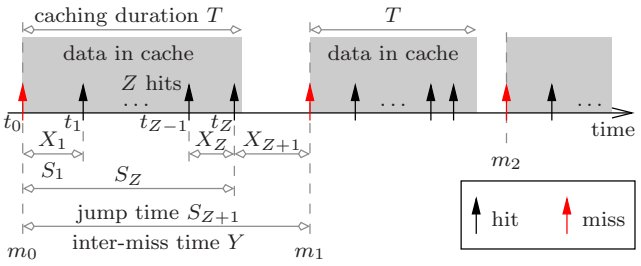


Figure 1: Requests, caching durations and inter-miss times.

3.2 Metrics and Properties of a Cache

The performance of a cache policy can be assessed through the computation of several metrics. The *hit probability* h_P captures the chances that a request has to be served by the cache. The *miss probability* m_P is simply the complementary probability. The *hit/miss rate* (h_R/m_R) represents the rate at which cache hits/misses occur. The *occupancy* π is the percentage of time during which the content is cached. We say "a cache policy is *efficient*" if its miss probability is low. This is relevant as long as cached contents are up-to-date.

In fact, by setting timers (or violating the TTL rule in the case of modern DNS), a server/client takes a risk by caching a content for a longer period than it should, as the content may well have changed by the time the locally chosen duration T expires. The cache would then be providing an outdated content. Observe that the content in cache is updated only upon a cache miss. But it is only when the update originates from the authoritative server that one can absolutely be certain that the given update is correct. Therefore, a relevant performance metric is the *correctness* probability of a cache. Another property of a cache is its *freshness*. It defines how fast a change in a record can propagate until this cache. High freshness is desirable with dynamic authoritative servers.

3.3 Processes at Hand

To fully analyze a cache one needs to consider:

- *The arrival process:* it may result from the superposition of multiple independent requests arrival processes. Let $X_k = t_k - t_{k-1}$ be the k-th inter-request time ($k > 0$). It is useful to define the kth jump time $S_k = X_1 + X_2 + \ldots + X_k$ with its cumulative distribution function (CDF) $F_{(k)}(t) = \mathbb{P}(S_k < t)$ and its probability density function (PDF) $f_{(k)}(t) = \frac{dF_{(k)}(t)}{dt}$. Let $N(t) = \sup\{k : S_k \leq t\} = \sum_{k>0} \mathbb{1}\{S_k \leq t\}$. The arrival counting process is then $\{N(t), t > 0\}$.
- *The caching duration:* a cache draws the duration T from the same distribution, such that $\mu = 1/\mathbb{E}[T]$. The scenario analyzed here considers memoryless caches, i.e. all caching durations set by the same cache are independent and identically distributed. With a slight abuse of notation, let $T(t)$ be the CDF of the random variable (rv) T.
- *The outgoing miss process:* cache misses form a stochastic process whose inter-miss time is denoted by $Y_k = m_k - m_{k-1}$ for $k > 0$.
- *The number of hits between consecutive misses:* these hits occur within a single caching duration. Their number is a rv denoted by Z.

In the case of a tree of caches, a subscript referring to the cache label will be added to the rvs for disambiguation. Besides the "instantaneous transmission/processing" assumption that holds throughout this paper, the following holds:

Assumption 1 (renewal arrivals)**.** *Inter-request ti-mes are independent and identically distributed rvs.*

Let X be the generic inter-request time, $F(t)$ be its CDF, $f(t) = \frac{dF(t)}{dt}$ be its PDF, and $\lambda = 1/\mathbb{E}[X]$.

Assumption 2 (independence)**.** *At any cache, inter-request times and caching durations are independent.*

Assumption 3 (independent arrivals)**.** *Multiple arrivals at any high-level cache are independent.*

Assumption 4 (independent caches)**.** *Caching durations from any two different caches are independent.*

Assumption 1 is in agreement with the analysis in [12] and [8]. Feldmann and Whitt show in [8] that heavy-tailed processes can be well approximated by a renewal process with a hyper-exponential inter-arrival distribution. Jung, Berger and Balakrishnan show in [12] that the request process arriving at a DNS server's cache is heavy-tailed. Renewal processes with either Weibull or Pareto inter-event distributions are used to fit the collected inter-request times. Assumptions 2 and 4 hold at modern DNS servers [16, 3] and Web browsers [2] as these use their own caching durations independently of the requests and other servers/browsers. Assumption 3 holds if exogenous arrivals are independent, as long as requests for a given content "see" a *polytree* network (that is a directed graph without any undirected cycles).

It is worth noting that the scenario and the set of assumptions considered here fit the case of a *single traditional* DNS server if the distribution of its caching durations fits the values marking the responses. Observe also that the popularity of a content is proportional to its request rate λ. Therefore, it should be clear that our models account for a content's popularity (which can be Zipfian, Uniform, Geometric, etc.) through the per-content request rate λ.

A word on the notation: for any function $\chi(t)$, its Laplace-Stieltjes Transform (LST) is $\chi^*(s) = \int_0^\infty e^{-st} d\chi(t)$ ($s \geq 0$). Observe that the LST of a function is the Laplace transform of its derivative. The complementary cumulative distribution function (CCDF) of a CDF $\chi(t)$ is $\bar{\chi}(t) = 1 - \chi(t)$. Table 1 summarizes the main notation used in the paper.

4 Analysis of a Single Cache

We are ready now to analyze a cache taken in isolation. The results found here will be used in Sect. 5 when studying multiple caches in a tree network.

Table 1: Glossary of Main Notation

h_P	hit probability
h_R	hit rate
m_P	miss probability
m_R	miss rate
π	occupancy
T	caching duration (random variable)
$T(t)$	CDF of T
$1/\mu$	expectation of T
X	inter-request time (random variable)
$F(t)$	CDF of X
$f(t)$	PDF of X
λ	arrival rate ($1/\mathbb{E}[X]$)
S_k	kth jump time (random variable)
$N(t)$	requests during t (random variable)
$M(t)$	renewal function
$m(t)$	renewal density function
Y	inter-miss time (random variable)
$G(t)$	CDF of Y
Z	hits during T (random variable)
$\chi^*(s)$	LST of a function $\chi(t)$
$L(t)$	expected number of hits until t within T
$H(t)$	CDF of inter-request time at higher-level cache

4.1 The Model and its Analysis

Our first goal is to characterize the miss process which is the same as the process going out from a server towards the higher-level server. The request process and the caching durations are as assumed in Sect. 3, i.e. $\{N(t), t > 0\}$ is a renewal process. The renewal function and the renewal density function associated to $\{N(t), t > 0\}$ are, respectively, $M(t) = \mathbb{E}[N(t)] = \sum_{k>0} F_{(k)}(t)$ and $m(t) = \frac{dM(t)}{dt} = \sum_{k>0} f_{(k)}(t)$. It is well-known that the renewal function satisfies the so-called renewal equation [6]

$$M(t) = F(t) + \int_0^t F(t-x)dM(x). \tag{1}$$

Since T is a rv and $N(t)$ the counting variable, $N(T)$ is a rv which represents the number of requests during a caching duration T. As all requests arriving during this period are necessarily hits, then following the definition of Sect. 3 we have that $Z = N(T)$ and its expectation is $\mathbb{E}[Z] = \mathbb{E}[N(T)] = \mathbb{E}\left[\mathbb{E}[N(T)|T]\right] = \mathbb{E}[M(T)]$ (M is a function).

Proposition 1 (Miss process)**.** *Under Assumptions 1 and 2 the miss process of a single cache is a renewal process.*

Proof. Without loss of generality, we assume that the first request arrives at time $t_0 = 0$ while the content is not cached. This cache miss triggers a new caching period. Consequently, miss instants are regeneration points of the state of the cache, implying that these form a renewal process. □

According to Proposition 1 inter-miss times $\{Y_k\}_{k>0}$ are independent and identically distributed. Let Y be the generic inter-miss time and $G(t)$ be its CDF. Deriving $G(t)$ completes the characterization of the miss process. To this end we consider first the number of hits occurring in a renewal interval Y until time t, and more specifically its expectation $L(t)$. We can readily write for $t \geq 0$

$$L(t) = \sum_{k>0} \mathbb{P}(S_k < t, T > S_k) = \int_0^t \bar{T}(x)dM(x). \tag{2}$$

Observe that $L(\infty)$ is nothing but the expected number of hits in a renewal interval and is equal to $\mathbb{E}[Z]$.

Proposition 2 (Inter-miss times)**.** *The CDF $G(t)$ of the generic inter-miss time Y and its LST are given by*

$$G(t) = F(t) - \int_0^t (1 - F(t-x))dL(x) \tag{3}$$

$$G^*(s) = 1 - (1 - F^*(s))(1 + L^*(s)). \tag{4}$$

Proof. Let $m_0 = 0$ be the first miss time. The CDF $G(t)$ of the inter-miss time Y can be derived by noticing that $Y = S_{Z+1}$ where Z is the number of hits in a renewal interval ($Z \in \mathbb{N}$). As such, the $(Z+1)$st request occurs after T expires and it will initiate a new renewal interval. By considering the possible values of Z, we can write

$$\begin{aligned} G(t) &= P(S_{Z+1} < t) = \sum_{k\geq 0} P(S_{Z+1} < t, Z = k) \\ &= \sum_{k\geq 0} P(S_k + X_{k+1} < t, S_k < T < S_k + X_{k+1}). \end{aligned}$$

By conditioning first on S_k and then on X_{k+1}, we get

$$\begin{aligned} G(t) &= \sum_{k\geq 0} \int_0^t \int_0^{t-u} (T(u+x) - T(u)) f(x)dx \; f_{(k)}(u)du \\ &= \sum_{k\geq 0} \int_0^t \int_0^v (T(v) - T(u)) f(v-u) f_{(k)}(u)\, du\, dv \end{aligned}$$

The last equality is obtained after letting $v = u + x$ in the inner integral and then exchanging the integrals. Observe now that, under Assumption 1, the density $f_{(k)}(t)$ of the jump time S_k is the k-fold convolution of $f(t)$ (the density of X). Also, the convolution of $f_{(k)}$ and f is nothing but $f_{(k+1)}$. Note that $S_0 = 0$ and $f_{(0)}(t) = \mathbb{1}\{t = 0\}$. A straightforward calculation yields

$$\begin{aligned} G(t) &= \sum_{k>0} \int_0^t (1 - F(t-x))T(x) f_{(k)}(x)dx \\ &= \int_0^t (1 - F(t-x))(1 - \bar{T}(x))dM(x) \\ &= F(t) - \int_0^t (1 - F(t-x))\bar{T}(x)dM(x) \end{aligned} \tag{5}$$

where we have used (1) to write (5). By differentiating (2) and using $dL(x)$ in (5), we find (3). It suffices to differentiate (3) then apply the Laplace transform to get the LST given in (4). The proof is complete. □

Proposition 2 states that one needs to know the CDFs of the arrival process and the caching duration to derive the CDF of the miss process, or equivalently, the outgoing process. This proposition will be repeatedly used in Sect. 5 when analyzing networks of caches.

4.2 Performance Metrics

Our next goal is to derive the performance metrics defined in Sect. 3 at a single cache. Note that these metrics have been defined with respect to a single content. Similar metrics for the a set of contents can also be defined as long as the contents popularity is known. The following proposition provides the cache performance metrics.

Proposition 3 (Cache performance)**.** *Under Assumption 1, the stationary hit probability h_P, the stationary miss probability m_P, the occupancy π, the stationary hit rate h_R, and the stationary miss rate m_R are respectively given by*

$$h_P = \frac{\mathbb{E}[Z]}{1+\mathbb{E}[Z]}\ ; \qquad m_P = \frac{1}{1+\mathbb{E}[Z]}\ ; \qquad \pi = \frac{\lambda/\mu}{1+\mathbb{E}[Z]}\ ;$$
$$h_R = \frac{\lambda\mathbb{E}[Z]}{1+\mathbb{E}[Z]}\ ; \qquad m_R = \frac{\lambda}{1+\mathbb{E}[Z]}.$$

Proof. In the stationary regime, $\mathbb{E}[Z]$ is the expected number of hits within a renewal interval and $\mathbb{E}[Z]+1$ is the expected number of requests (including the single miss) in a renewal interval. Their ratio naturally gives the hit probability. We can readily find $m_P = 1 - h_P$, $h_R = \lambda h_P$ and $m_R = \lambda m_P$ since λ is the requests arrival rate. As Y is the inter-miss time, we have $\mathbb{E}[Y] = 1/m_R$. Last, regarding the occupancy or the stationary probability that the content data is in cache, we know that a content is cached for a duration T in a renewal interval Y. Then by renewal theory the occupancy π is the ratio $\mathbb{E}[T]/\mathbb{E}[Y] = \mu^{-1}m_R$ which completes the proof. □

Proposition 3 states that it is enough to compute $\mathbb{E}[Z]$ and estimate the request rate λ at a cache to derive all its metrics of interest (μ is locally known). It is worth noting that the hit probability h_P and the occupancy π are different in general and in particular under renewal arrival processes. The equality $h_P = \pi$ holds only if the arrival process is a Poisson process thanks to the PASTA (Poisson Arrivals See Time Average) property.

A cached content may be refreshed only after T expires, upon a cache miss. Hence the refresh rate is nothing but the miss rate in the case of a cache directly connected to the authoritative server. In the presence of intermediate caches, the refresh rate of a cache is its miss rate times the product of miss probabilities at all intermediate caches. The correctness probability of a server is the probability that a request gets the correct content, whether it was cached or not. When a cache is directly connected to the authoritative server, a cache miss ensures that the delivered content is correct whereas a cache hit may or may not provide a correct content. This will depend on the distribution of the interchange time at the authoritative server. A thorough analysis of this metric is left for future work.

4.3 Special TTL Distributions

We will consider three particular cases for the distribution of the caching duration and derive the corresponding results.

4.3.1 Deterministic Distribution

We first look at the case when the caching duration is deterministic and equal to the constant D. This setup (single cache, deterministic TTL) is identical to the one in [12].

Result 1 (deterministic TTL)**.** *The expected number of hits in a renewal interval is $\mathbb{E}[Z] = M(D)$.*

Combining Result 1 with Proposition 3 yields the performance metrics. These are exactly the ones found in [12, Thm 1]. The CDF $G(t)$ of inter-miss times, on the other hand, is a new result. Using $T(t) = \mathbb{1}\{t > D\}$, (3) becomes

$$G(t) = \mathbb{1}\{t > D\}\left(F(t) - \int_0^D (1 - F(t-x))dM(x)\right). \quad (6)$$

4.3.2 Exponential Distribution

If caching durations follow an exponential distribution with rate μ, then $T(t) = 1 - e^{-\mu t}$ and the following holds.

Result 2 (exponential TTL)**.** *The expected number of hits in a renewal interval is $\mathbb{E}[Z] = \frac{F^*(\mu)}{1-F^*(\mu)}$, and (4) giving the LST of $G(t)$ becomes*

$$G^*(s) = \frac{F^*(s) - F^*(s+\mu)}{1 - F^*(s+\mu)}. \quad (7)$$

The result above is identical to Propositions 3.1 and 3.2 in [5]. The system considered in [5] consists of caches using expiration-based policies whose caching durations are reset at every cache hit. The DNS scenario considered in this paper pre-sets the caching duration at each cache miss. However, when durations are drawn from an exponential distribution, both systems coincide thanks to the memoryless property of the exponential distribution.

4.3.3 Diagonal Matrix-Exponential Distribution

The third particular case considered here is the one of a family of distributions, the so-called *diagonal matrix exponential* distribution (diag.ME for short). The CDF of an ME distribution can be written as $1 - \alpha\exp(\mathbf{S}t)\mathbf{u}$, where α and $\mathbf{u}$

are dimension-n vectors and $\mathbf{S}$ is an $n \times n$ matrix; the ME distribution is said to be of order n. If $\mathbf{S}$ is diagonalizable,[1] then a diag.ME is obtained. The LST of its CDF is rational.

Our interest in the diag.ME is threefold. First, it covers a large set of distributions including the acyclic phase-type distributions like the generalized coxian distribution, the exponential distribution, the hypo-exponential distribution or generalized Erlang, the hyper-exponential distribution or mixture of exponentials. Second, as reported in [8], a general point process can be well fitted by a renewal process having a "phase-type distribution" such as the "mixture of exponentials". Third (and most attractively) it is analytically tractable as will become clear in Sect. 5. In brief, if inter-request times of exogenous arrivals and caching durations all follow this distribution, then any inter-miss time and any overall inter-request time in a network of caches will also follow this distribution (with other parameters), as long as an additional assumption is enforced.

The CDF of a caching duration following a diag.ME of order K can be written

$$T(t) = 1 - \sum_{k=1}^{K} b_k e^{-\mu_k t} \ , \quad \text{with} \quad \sum_{k=1}^{K} b_k = 1. \tag{8}$$

There is no restrictions on $\{\mu_k\}_{1 \le k \le K}$ except that $T(t)$ must be a CDF. The following then holds.

Result 3 (diag.ME TTL)**.** *The expected caching duration and the expected number of hits are, respectively,*

$$\mu^{-1} = \sum_{k=1}^{K} b_k \mu_k^{-1}; \qquad \mathbb{E}[Z] = \sum_{k=1}^{K} \frac{b_k F^*(\mu_k)}{1 - F^*(\mu_k)}, \tag{9}$$

and the LST of $G(t)$ given in (4) *can be rewritten*

$$G^*(s) = 1 - \sum_{k=1}^{K} b_k \frac{1 - F^*(s)}{1 - F^*(s + \mu_k)}. \tag{10}$$

Using (9) in Proposition 3 yields the performance metrics.

4.4 Optimal TTL Distribution per content

This section addresses the following challenging question: which distribution optimizes the performance of a content caching policy and under which conditions? A partial answer will be provided in the following.

There are conflicting objectives when optimizing a caching policy. Caching has been introduced to limit wide-area DNS traffic and to speed up DNS lookups at clients. An efficient cache is then one that has a small miss rate, a high hit probability and yet a small occupancy (data is in cache only when needed). The counter effect is an increase in the probability for the user to obtain an outdated content. Indeed, as explained in Sect. 3, contents are refreshed only upon a cache miss. Having then a high miss rate is desirable when the content is likely to change often.

In this section, we will order distributions according to the achieved performance metrics, namely the miss rate m_R, the hit probability h_P and the occupancy π. Consider two different policies. In one policy, a content is cached for a deterministic duration D; in the other, the caching duration T has a CDF $T(t)$ such that $\mathbb{E}[T] = D$. The performance metrics vary with the distribution, the rv is then explicitely appended to the notation, e.g. $\pi(T)$.

Proposition 4 (optimal policy)**.** *If inter-arrival requests at a cache have a concave CDF then the deterministic caching duration yields the most efficient caching, i.e.*

$$m_R(D) \le m_R(T) \ , \quad h_P(D) \ge h_P(T) \ , \quad \pi(D) \le \pi(T).$$

Proof. Define $\phi(t) = 1 + M(t)$. We therefore have (use $\mathbb{E}[Z] = \mathbb{E}[M(T)]$ in Proposition 3)

$$m_R(T) = \frac{\lambda}{\mathbb{E}[\phi(T)]}, \ h_P(T) = 1 - \frac{1}{\mathbb{E}[\phi(T)]}, \ \pi(T) = \frac{\lambda D}{\mathbb{E}[\phi(T)]}.$$

We will now prove that ϕ is concave. Recall that $M(t)$ is the renewal function. Differentiating twice (1) yields

$$\phi''(t) = m'(t) = f'(t) + \int_0^t m(t-x) f'(x) dx. \tag{11}$$

Since $m(t)$ is a positive function, it follows that $\phi(t)$ is a concave function if $F(t)$ is concave (i.e. if $f'(t) < 0$). Using now Jensen's inequality yields $\mathbb{E}[\phi(T)] \ge \phi(\mathbb{E}[T]) = \phi(D) = \mathbb{E}[\phi(D)]$ which completes the proof. □

As F is a CDF, it may not be convex and the corollary of Proposition 4 never applies. Finding the optimal policy when F is not concave is an open problem. The simulations discussed in Sect. 6.2 suggest however that, in this latter case, the higher the coefficient of variation, the better.

The concavity of the CDF $F(t)$ of the inter-request times is not a strong condition. Jung, Berger and Balakrishnan use in [12] Pareto and Weibull (with shape less than 1) distributions to fit collected inter-request times (cf. discussion around Assumption 1 in Sect. 3). These distributions have concave CDFs. Also, it is known that long-tailed distributions having a decreasing failure rate can be well approximated by a mixture of exponentials [8], whose CDF is concave. Last, a conceptual model often used in the analysis of caches (e.g. [7, 18, 19]) is the so-called *independent reference model* (IRM). This model is equivalent to assuming that requests for a single content form a Poisson process [9]. The CDF of the (exponential) inter-arrival times is then concave.

Proposition 4 states that deterministic caching durations are the optimal when F is concave (Assumption 1 must hold). *This does not mean that all contents should use the same constant TTL value but rather to have a fixed value per content.* For each content which receives its own deterministic timer, the hit probability is maximized and yet the

[1] There exist then an $n \times n$ matrix $\mathbf{P}$ and an $n \times n$ diagonal matrix $\mathbf{A}$ such that $\mathbf{S} = \mathbf{P}\mathbf{A}\mathbf{P}^{-1}$.

occupancy is minimized, suugesting that *the content is found in the cache mainly when needed, i.e. at requests arrivals.* The next obvious question is: which deterministic value is the optimal one? This question, already posed in [3], will be addressed now.

Since the deterministic policy is optimal only for concave F, we will only consider this case in the discussion. Ideally, the optimal deterministic value, $D^\star$, should maximize the hit probability and minimize the occupancy. For concave F, the renewal function $M(D)$ is also concave (and increasing) (cf. (11)). By combining Result 1 and Proposition 3, it becomes clear that the hit probability $h_P(D)$ is concave increasing (and the miss rate $m_R(D)$ convex decreasing).

Introduce now the function $g(D) = 1 + M(D) - Dm(D)$. The derivative of $\pi(D)$ w.r.t. D yields $\pi'(D) = \frac{\lambda\, g(D)}{(1+M(D))^2}$. Given that $g(0) = 1$ and $g'(D) = -Dm'(D) \geq 0$ for any $D \geq 0$ (recall that $m'(D) < 0$ for concave F), the function g is thus always positive and so is π'. Hence, the occupancy is an increasing function of the caching duration. It is therefore not possible to maximize $h_P(D)$ while minimizing $\pi(D)$, as both increase with the caching duration D.

We believe that having a high hit probability supersedes the desire of having a low occupancy. However, the miss rate should not be minimized (its minimum is 0 when $D \to \infty$) as it directly relates to the correctness of the cached content. Cache misses must occur in order to update the content.

The proper thing to do in such a case is to solve a constrained optimization problem, looking for instance to maximize the hit probability subject to a maximal occupancy $\pi_{\max}$ (for cache size issues) and/or a minimal miss rate $m_{R,\min}$ (for correctness issues). Given the monotonicity of h_P, m_R and π (for concave F), the solution is readily found as

$$D^\star = \min\{\arg \pi_{\max}, \arg m_{R,\min}\}.$$

The maximal occupancy $\pi_{\max}$ for a given content can be for instance the fraction of the cache size that is proportional to the content's popularity.

4.5 Applicability to a Traditional DNS Cache

The modern DNS cache analyzed in Sect. 4 holds the content for a locally chosen duration. Instead, in a traditional DNS cache, the caching duration is the one advocated by the answerer. What matters in the analysis of a single cache is the distribution of the caching durations and not whether the distribution is set locally or it is imposed. Therefore, the findings of Sect. 4 apply in the case of a single traditional DNS cache, as long as Assumptions 1-2 hold. Note that the model developed in [12] provides *approximate* results for a single traditional DNS cache everytime the answerer is not an authoritative server, because the authors consider a deterministic caching duration (set to the maximum value among all those observed in the responses). Instead our model yields *exact* results for both traditional *and* modern caches, regardless of the distribution chosen for the whole range of caching durations.

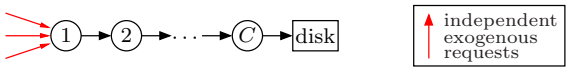


Figure 2: A linear network with C caches.

5 Analysis of a Cache Network

Section 4 focused on results for a single cache. In this section, we will extend these results for the case where we have caches at multiple nodes (e.g. client, ADSL modem, Internet server provider's DNS server, authoritative server). We say that we have a *network of caches*. To analyze it, one additionally needs to consider the network topology. The notation relative to cache c will have an extra subscript c. Assumptions 1-4 are enforced throughout this section. Requests for a given content may only flow over a tree network and exogenous arrivals are independent so that Assumption 3 holds. In the following we consider the particular case of linear networks for which exact results can be derived (cf. Sect. 5.1). We will move next to the general tree network case for which approximate results can be derived by enforcing an additional assumption (cf. Sect. 5.2). Last, we focus on the particular case where caching durations and exogenous inter-request times follow a diag.ME distribution (cf. Sect. 5.3). Results for this last case are interesting as the diag.ME distribution will be preserved inside the network.

5.1 Linear Networks: Exact Results

Consider the linear network depicted in Fig. 2. There are C caches and the disk of the authoritative server (the rightmost cache is the one of the authoritative server). By Assumption 1, the overall request process at cache 1 is a renewal process. By Proposition 2, the miss process at cache 1 (which is nothing but the request process at cache 2) is also a renewal process. Hence, all processes in this linear network of caches are renewal processes. The performance metrics at each cache are derived using Proposition 3.

5.2 Tree Networks: a Recursive Procedure

The aggregation of several renewal processes in *not* a renewal process. However, it is mandatory to have a renewal process for Proposition 1 to hold at any high-level cache inside the network. Similarly to [5], we overtake this limitation by proceeding as if we do have a renewal process, and then assess the robustness of the model against situations where this is not the case. The approximate results obtained are strikingly accurate as will be seen later in Sect. 6.2. In the rest of the paper, the following assumption will be enforced.

Assumption 5 (aggregation)**.** *The overall request arrival process at each cache is a renewal process.*

A direct consequence of Assumption 5 is that the miss process at each cache is a renewal process thanks to Proposition 1. Propositions 2 and 3 are also valid at any cache. For the case of a single cache, the CDF of the inter-miss time at a cache, namely $G(t)$, is expressed as a function of the CDF of the inter-request time, namely $F(t)$; see (3).

In the case of a network, one needs to consider at a cache c the inter-request time of the *aggregate* process arriving at cache c. Let $H_c(t)$ be its CDF. Equation (3) provides the CDF of the inter-miss time at cache c, denoted by $G_c(t)$, after replacing $F(t)$ with $H_c(t)$ and by using the renewal function associated with the aggregate request process, say $M_c(t)$, in (2). To explicitly write this equation for the case of a network of caches, additional notation is needed.

The set of children of cache c is $\mathcal{C}(c)$ with $C = |\mathcal{C}(c)|$. The rate of *exogenous* requests (if any) at cache c is λ_c; the CDF of inter-exogenous request times is $F_c(t)$. There are $C+1$ request processes at cache c. Their aggregation has a rate

$$\Lambda_c = \lambda_c + \sum_{i \in \mathcal{C}(c)} m_{R,i}. \tag{12}$$

The C miss processes at the children of c and the exogenous request process at cache c are all independent. Thereby, the result derived by Lawrance in [14, Eq. (4.1)] applies. By Assumption 5, the aggregate request process at cache c is a renewal process and the CCDF of the inter-request time is

$$\begin{aligned}\bar{H}_c(t) \;=\; & \frac{\lambda_c}{\Lambda_c}\bar{F}_c(t) \prod_{i \in \mathcal{C}(c)} m_{R,i} \int_t^\infty \bar{G}_i(u)du \qquad (13)\\ & + \sum_{i \in \mathcal{C}(c)} \frac{m_{R,i}}{\Lambda_c}\bar{G}_i(t)\lambda_c \int_t^\infty \bar{F}_c(u)du \prod_{\substack{j \in \mathcal{C}(c)\\ j \neq i}} m_{R,j} \int_t^\infty \bar{G}_j(u)du.\end{aligned}$$

Equation (5) becomes

$$G_c(t) = H_c(t) - \int_0^t (1 - H_c(t-x))\bar{T}_c(x)dM_c(x) \tag{14}$$

with $\bar{T}_c(t)$ the CCDF of the caching duration at cache c and $M_c(t)$ the renewal function associated with the aggregate request process at the same cache. Equations (13)-(14) provide a recursive procedure for calculating the CDFs $H_c(t)$ and $G_c(t)$ at each cache c of a tree network. Numerical procedures such as Romberg's method or other techniques for computing (13)-(14) recursively can be found in [20]. We consider next a special case in which closed-form expressions for $H_c(t)$ and $G_c(t)$ can be found.

5.3 Closed-Form Results with diag.ME RVs

In this section, we consider a tree network where caching durations at any cache follow a diag.ME distribution. Also, we will consider that the *exogenous* request process at any cache is a renewal process whose inter-request time follows a diag.ME distribution. More precisely, at a cache c we have

$$F_c(t) = 1 - \sum_{j=1}^{J_c} a_{c,j} e^{-\lambda_{c,j}t},\ \bar{T}_c(t) = \sum_{k=1}^{K_c} b_{c,k} e^{-\mu_{c,k}t}, \tag{15}$$

for $t > 0$. J_c and K_c are the respective orders of the diag.ME distributions. We are now in position to prove an interesting property that is another main contribution of this work. This property is the self-preservation of the diag.ME distribution across a tree network as stated in what follows.

Proposition 5 (diag.ME preservation)**.** *Under Assumptions 1-5 and as long as* (15) *is verified at each cache c of a tree network, miss processes and aggregate requests are all renewal processes whose inter-event time follows a diag.ME distribution (parameters are in the proof).*

Proof. The proof rests on three arguments: (i) the miss process at each of the lowest-level caches checks Proposition 5; (ii) the aggregate request process and (iii) the miss process at each of the next higher-level caches verify Proposition 5. Arguments (ii) and (iii) will be used repeatedly until all caches in the network are covered. By Proposition 1 and Assumption 5, the processes at hand are renewal processes. We focus then on the distribution of the inter-event time.

Argument (i): the miss process at a lowest-level cache. Let c be such a lowest-level cache, it corresponds to a leave in a tree. The CDF of the inter-request time is given by (15). The renewal equation (1) can be written as follows

$$M_c(t) = F_c(t) + \int_0^t \sum_{j=1}^{J_c} a_{c,j}\lambda_{c,j} e^{-\lambda_{c,j}(t-x)} M_c(x)dx. \tag{16}$$

The solution of (16) is given in [17, Sect. 2.2.1.19] which we can differentiate to find

$$dM_c(t) \;=\; \sum_{j=1}^{J_c} \gamma_{c,j} e^{-\theta_{c,j}t}dt \tag{17}$$

where $(\theta_{c,j})_{1 \le j \le J_c}$ are the J_c roots of the algebraic equation

$$0 = 1 - \sum_{j=1}^{J_c} \frac{a_{c,j}\lambda_{c,j}}{\lambda_{c,j} - z}, \tag{18}$$

and $(\gamma_{c,j})_{1 \le j \le J_c}$ are the solution of the linear system

$$\Big\{ 0 = 1 + \sum_{j=1}^{J_c} \frac{\gamma_{c,j}}{\theta_{c,j} - \lambda_{c,n}}, \qquad 1 \le n \le J_c. \tag{19}$$

Combining now (15) and (17), we can apply Proposition 2 to rewrite (5) as follows

$$\begin{aligned}G_c(t) = 1 &- \sum_{j=1}^{J_c} a_{c,j} \left(1 + \sum_{k=1}^{K_c}\sum_{i=1}^{J_c} \frac{b_{c,k}\gamma_{c,i}}{\theta_{c,i} + \mu_{c,k} - \lambda_{c,j}}\right) e^{-\lambda_{c,j}t}\\ &- \sum_{k=1}^{K_c}\sum_{i=1}^{J_c} \left(\sum_{j=1}^{J_c} \frac{(-a_{c,j})b_{c,k}\gamma_i}{\theta_{c,i} + \mu_{c,k} - \lambda_{c,j}}\right) e^{-(\theta_{c,i}+\mu_{c,k})t}. \qquad (20)\end{aligned}$$

Clearly, the inter-miss time at a lowest-level cache follows a diag.ME distribution, whose order is $J_c(K_c+1)$ which is the number of exponentials in (20).

Argument (ii): the aggregate request process at a next higher-level cache. The CCDF of the inter-request time at this intermediate cache c is given in (13), where $F_c(t)$ is relative to the exogenous request process and $G_i(t)$ is relative to the ith cache in $\mathcal{C}(c)$, the set of children of cache c. Recall that $C = |\mathcal{C}(c)|$. To ease the derivation of $H_c(t)$, we rewrite $F_c(t)$ (15) and (20) with a new/modified notation ($t > 0$)

$$F_c(t) = 1 - \sum_{l_0=1}^{\mathcal{L}_0} a_{0,l_0} e^{-\lambda_{0,l_0} t}, \quad G_i(t) = 1 - \sum_{l_i=1}^{\mathcal{L}_i} a_{i,l_i} e^{-\lambda_{i,l_i} t}.$$

The exogenous request rate is denoted $r_0 = \sum_{l_0=1}^{\mathcal{L}_0} a_{0,l_0}\lambda_{0,l_0}$. The miss rate at the ith cache in $\mathcal{C}(c)$ is denoted r_i. The overall request rate at cache c becomes $\Lambda_c = \sum_{i=0}^{C} r_i$ (see (12)). After tedious calculations, (13) can be rewritten

$$\begin{aligned} \bar{H}_c(t) \quad = \quad & \frac{\prod_{i=0}^{C} r_i}{\Lambda_c} \sum_{l_0=1}^{\mathcal{L}_0} \sum_{l_1=1}^{\mathcal{L}_1} \cdots \sum_{l_C=1}^{\mathcal{L}_C} \sum_{i=0}^{C} \lambda_{i,l_i} \times \\ & \times \left(\prod_{j=0}^{C} \frac{a_{j,l_j}}{\lambda_{j,l_j}} \right) \exp\left(- \left(\sum_{j=0}^{C} \lambda_{j,l_j} \right) t \right). \end{aligned} \tag{21}$$

The inter-request time at the intermediate cache c follows a diag.ME distribution of order $\prod_{i=0}^{C} \mathcal{L}_i$.

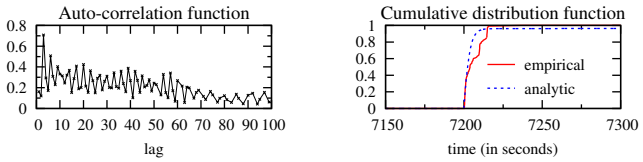
Argument (iii): the miss process at a next higher-level cache. Argument (i) can be repeated here by carefully replacing the exogenous request process with the aggregate request process discussed in Argument (ii). We can conclude that it is enough to have the caching duration at a cache and the inter-request time at the same cache follow a diag.ME distribution for the inter-miss process at this cache to follow a diag.ME distribution. This completes the proof. □

The performance metrics can be found at each cache by using Result 3 and Proposition 3. It is important to start the computation with the lowest-level caches as their miss rates will be used to derive $H_c(t)$ at a higher-level cache. It is also $H_c^*(s)$ that should be used instead of $F^*(s)$ in Result 3 at each higher-level cache.

Sections 5.2 and 5.3 provide approximate results as Assumption 5 is not true. The robustness of our model is tested in Sect. 6.2.

6 Validation, Numerical Results

The objective of this section is to test the robustness of our models against violations of the main assumptions. We first address the case of a single cache by comparing the analytic results of Sect. 4 to results derived from a real DNS cache trace. The case of a network of caches is addressed next, where the objective is to validate Assumption 5.



(a) correlated requests (b) inter-miss times

Figure 3: (a) Correlation; (b) miss process prediction.

6.1 Using a Real Trace (Single Cache)

In this section, we use traces collected from a real DNS cache to assess the robustness of our analysis. Our home institution Inria at Sophia Antipolis manages two DNS servers in parallel to ensure a good load balancing. The DNS traffic at one of these servers has been collected from 21 June to 1 July 2013. The trace contains information about 2313984 resource records requested by a total of 2147 users. Processing the trace provides, for each resource record (or content): (1) the requests instants (from users to Inria's DNS server); (2) the cache miss instants (coinciding with the instants of requests from Inria's DNS server to Internet); (3) the responses instants (from Internet to Inria's DNS server); (4) the final responses instants (from Inria's DNS server to users); (5) the TTL values (in response packets).

A careful analysis of this trace reveals the following. First, requests instants and final responses instants do not differ much, thereby justifying our instantaneous transmission/processing assumption. Second, requests are time-varying (week day/week-end, day/night) and clearly dependent as illustrated in Fig. 3a for one of the contents (cf. lags 3 and 6). Therefore, Assumption 1 (renewal request process) is not met. *Testing our model using this trace will give insights on its robustness* since the main assumptions used in the single cache analysis are not met in this trace. Third, based on the TTLs recorded, Inria's DNS server respects the TTL rule. We are therefore in the case of a single traditional DNS cache. The TTLs found in the final response packets vary from 1 to the initial TTL advocated by authoritative servers; this emphasizes the pertinence of our models as caches at the user side are given non-deterministic TTLs.

Our aim is to predict the cache performance metrics and most importantly the cache miss process as it represents the traffic that flows upstream in the DNS hierarchy (also needed for network analysis). We picked one resource record out of the most requested among users. The caching duration of the chosen content (ranked 6th) turns out to be deterministic and equal to 2 hours (value provided directly by five authoritative servers). We used the KPC-Toolbox [4] to find the Markovian Arrival Process (MAP) that best fits the inter-request times X of the aggregated arrival process (generated by 145 different users). This tool matches with priority higher-order correlations and can convert any MAP into a renewal process having inter-arrival times identically

Table 2: Performance Metrics and Relative Errors (Rank 6)

Metric	Trace	Model	Rel. err. (%)
miss rate	0.00013876	0.00013749	0.920
hit probability	0.99943	0.99941	0.002
occupancy	0.99914	0.98995	0.920

distributed as arrivals in the MAP. The number of states of the fitted MAP is 128. The moments of the empirical inter-request time (as computed by the tool) are: mean = 4.1614, variance = 4476.9, skewness 83.8809, kurtosis 7973.3.

Taking as input the fitted distribution and the TTL value, we use the findings of Sect. 4.3.1 to obtain the performance metrics of the cache relative to the content ranked 6th (cf. Table 2) and the CDF of the inter-miss times (cf. Fig. 3b). To determine the CDF (6), we use a naive Riemann's sum for the integral computation. Two parameters must be set: (i) the upper bound of the integral τ, and (ii) the step length Δ. Clearly, the larger τ and the smaller Δ, the smaller the numerical error but also the larger the computational cost. We set $\tau = 720000$ (100 times the maximum between the mean inter-request time and the TTL) and $\Delta = 0.1$.

The analytic results are compared to those computed from the trace. Table 2 reports *negligible values of the relative errors on the performance metrics. Proposition 3 appears to be applicable even if Assumption 1 is not met.* In fact, we believe that it is enough to have *stationary and ergodic* point processes as requests for Proposition 3 to apply; cf. [1, Eq. (1.3.2), p. 21]. Lawrence's theorem [14, Eq. (4.1)] can then be replaced with [1, Eq. (1.4.6), p. 35].

As for the miss process, Fig. 3b is clear: *our model accurately estimates the CDF of the inter-miss time. Proposition 2 appears to be applicable even if Assumption 1 is not met.* This section suggests that *our single cache model is robust.*

6.2 Validating Assumption 5

We now proceed to evaluating the robustness of our model of a network of caches. To this end, we resort to performing event-driven simulations. It is worth recalling that with exponentially distributed caching durations our model coincides with the one developed in [5] to study caches that reset the caching durations at each hit. In [5], Assumption 5 is also used; the authors evaluate the robustness of their model by comparing the approximate results it yields to exact analytic results that can be found when the conceptual IRM is used for requests. An excellent match is found which legitimates the use of Assumption 5. The same applies to our model when caching durations are exponentially distributed.

We consider a tree consisting of 7 caches as shown in Fig. 4. This tree represents well the hierarchy found in DNS: cache 7 is that of the authoritative server, caches 5 and 6 are typically those of ISP's DNS servers, and caches 1-4 are found at the client side (ADSL modem, laptop, etc.).

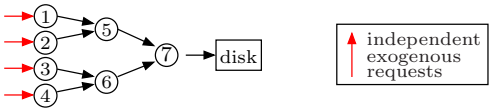


Figure 4: A binary tree with 7 caches.

To capture the fact that users have interleaving activity and inactivity periods, requests for all contents are assumed to form a Markov-Modulated Poisson Process (MMPP). In other words, requests for a single content form an Interrupted Poisson Process (IPP). As a consequence, Assumption 5 is not satisfied at caches 5, 6 and 7 since each component (miss process) of their overall request process is not a Poisson process.

In each performed simulation, we consider a single content whose requests at each bottom-level cache form an IPP. The request rate at cache i is $\lambda_i \in [0.5, 20]$ for $i \in \{1, 2, 3, 4\}$. The caching durations at all caches follow the same distribution, with expectation in $[0.5, 1.5]$. Four distributions have been considered in the simulations: deterministic, hypo-exponential, exponential and hyper-exponential. Their respective coefficients of variation are 0, < 1, 1, and > 1.

The "exact" values of the performance metrics are those obtained after running long enough simulations. Our criterion for a long simulation is one that yields a relative incertitude on each metric less than 10^{-4}. For instance, the hit probability at cache i obtained through simulation is $h^S_{P,i}$ (the superscript S stands for "simulation"). We calculated the 99% confidence interval $[h^S_{P,i} - \epsilon, h^S_{P,i} + \epsilon]$, the relative incertitude on $h_{P,i}$ is then $2\epsilon / h^S_{P,i}$. At the end of a simulation run, the latter was at most 0.6×10^{-4}.

The approximate values of the performance metrics are those predicted by our model and are obtained by following the recursive procedure explained in Sect. 5.2. We have implemented a MATLAB numerical solver that determines the CDFs in the network (using (13)-(14)) and then the metrics of interest at each cache (using Proposition 3 where $\mathbb{E}[Z_c] = L_c(\infty)$). The numerical error comes from the integral computation used in (13)-(14) (e.g., the integrals over infinite ranges). Again, we use Riemann's sum and, for simplicty, unique values for τ and Δ for all computations relative to a single simulation run. Consider all inter-request times and all caching durations within the network of caches. We set τ to one hundred-fold the *maximum* expectation among all these rvs, and Δ to one thousandth of the *minimum* expectation among the same rvs.

We have computed the relative error between the exact results obtained from simulations and the approximate results predicted by our model. The average relative error across all simulations on the miss rate, the hit probability and the occupancy at caches from different hierarchical levels are reported in Table 3 (columns 4, 6, 8, and 10). Our model is extremely accurate in predicting the performance metrics when caching durations are not deterministic as the relative

Table 3: Analytic Performance Metrics and their Relative Errors (in Percentage) at Representative Caches ($\lambda_1 = 1.57$ requests/s, $\lambda_2 = 0.87$ requests/s, $\lambda_3 = 1.37$ requests/s, $\lambda_4 = 0.68$ requests/s)

Cache	Performance metric	Distribution of caching durations								Trend
		deterministic		hypo-exponential		exponential		hyper-exponential		
		value	rel. err.	value	rel. err.	value	rel. err.	value	rel. err.	
1	miss rate	**0.49479**	0.00921	0.49906	0.00649	0.50039	0.08715	0.50235	0.07702	↗
	hit probability	**0.43275**	0.03832	0.42785	0.02724	0.42632	0.00660	0.42408	0.00065	↘
	occupancy	**0.35786**	0.04466	0.36094	0.04712	0.36191	0.03360	0.36333	0.02360	↗
5	miss rate	0.56708	1.1214	0.52673	0.08478	0.51681	0.10264	**0.51073**	0.00132	↘
	hit probability	0.41611	1.4561	0.46389	0.18679	0.47589	0.1514	**0.48412**	0.10321	↗
	occupancy	0.58169	1.146	0.54023	0.04850	0.53005	0.06307	**0.52379**	0.04179	↘
7	miss rate	0.52928	5.0614	0.48234	0.23668	0.46971	0.06873	**0.46045**	0.00650	↘
	hit probability	0.51789	4.536	0.52049	0.25253	0.52361	0.1067	**0.52731**	0.07069	↗
	occupancy	0.67667	5.0986	0.61667	0.19648	0.60051	0.02771	**0.58866**	0.03662	↘

error does not exceed 0.3%. For deterministic caching durations, an excellent prediction is available at bottom-level caches. The relative error increases as we consider caches at higher hierarchical levels, it reaches roughly 5% at the third level, which is nevertheless an affordable value. We conclude that *using Assumption 5 is not a limitation* and that *our model is very robust* to violations of this Assumption.

6.3 Optimal Caching Policy in a Network

According to Sect. 4.4, if the CDF of inter-request times at a cache is concave, then the best caching policy is to cache a content for a deterministic duration. If exogenous request processes satisfy this condition, it will not be the case of the aggregate request process reaching a higher-level cache.

Consider again the simulations presented in Sect. 6.2. Table 3 reports in columns 3, 5, 7, and 9 the analytic values of the performance metrics obtained at caches 1, 5 and 7 (one cache at each level) of the synthetic network of Fig. 4. The trend observed on these metrics as the distribution changes from the least variable (i.e., the deterministic) to the most variable (i.e., the hyper-exponential) is shown in column 11.

The optimal values of the performance metrics are in bold fonts in Table 3. The best distribution at bottom-level caches (e.g., cache 1) is the deterministic one. This is predicted by Proposition 4 which applies here as the inter-request time of an IPP has a concave CDF. The trend on each of the metrics is inverted at higher-level caches. The deterministic policy achieves then the worst performance. The more variable a distribution, the better the performance metrics. The inter-request time at higher-level caches no longer has a concave CDF. Recall that these observations are for each content individually. The parameters of a given distribution will vary from a content to another according to the popularity.

The above trends are observed when all the caches in a tree use the same distribution. Since we have established that for concave CDF (the case of IPP requests) the deterministic distribution is the best, we repeated the simulations described earlier with the exception of having deterministic TTLs at all bottom-level caches. We observed the same trends for the same values of λ_i for $i \in \{1, 2, 3, 4\}$ as in Table 3 and for another set of values that is $\lambda_1 = 0.052$ requests/s, $\lambda_2 = 0.061$ requests/s, $\lambda_3 = 0.091$ requests/s, $\lambda_4 = 0.078$ requests/s.

Our study suggests that for better performance, *deterministic caching durations should be used only at bottom-level caches*, i.e., at the client side. *Caches at servers should store contents for durations as variable as possible (large coefficient of variation).*

7 Conclusions

The analytic models introduced in this paper proved to be very useful to study the modern DNS cache hierarchy. Our single cache model has been tested on real DNS traces that do not meet the renewal assumption. It predicts the performance metrics and the CDF of the miss process remarkably well. The main approximation used in our network of caches model has been validated through simulations. We have addressed the problem of the optimal caching duration and found that if inter-request times have a concave CDF, then the deterministic policy is the best. For non-concave CDF, our numerical analysis suggests that more variable distributions are better. We plan to pursue the validation of our model using the real traces collected.

8 Acknowledgments

The authors would like to thank Francis Montagnac (IT staff at Inria, Sophia Antipolis) for collecting the DNS traces. The authors are deeply grateful to Fabrice Huet for his help in processing the large amount of data collected.

References

[1] F. Baccelli and P. Brémaud. *Elements of Queueing Theory, Palm Martingale calculus and Stochastic recurrences*. Springer, Berlin, 2nd edition, 2003.

[2] R. J. Bayardo, R. Agrawal, D. Gruhl, and A. Somani. YouServ: a web-hosting and content sharing tool for the masses. In *Proc. ACM WWW'02*, pages 345–354, New York, USA, 2002.

[3] T. Callahan, M. Allman, and M. Rabinovich. On modern DNS behavior and properties. *ACM SIGCOMM Comp. Comm. Rev.*, 43(3):7–15, 2013.

[4] G. Casale, E. Zhang, and E. Smirni. KPC-Toolbox: Simple yet effective trace fitting using Markovian Arrival Processes. In *Proc. 5th Intl. Conf. on the Quantitative Evaluation of SysTems (QEST'08)*, 2008.

[5] N. Choungmo Fofack, P. Nain, G. Neglia, and D. Towsley. Analysis of TTL-based cache networks. In *Proc. ACM ValueTools'12*, Cargèse, France, Oct. 2012.

[6] D. R. Cox. *Théorie du Renouvellement*. Monographies DUNOD, Paris, 1966.

[7] A. Dan and D. Towsley. An approximate analysis of the LRU and FIFO buffer replacement schemes. In *Proc. ACM SIGMETRICS'90*, pages 143–152, Boulder, CO, USA, May 1990.

[8] A. Feldmann and W. Whitt. Fitting mixtures of exponentials to long-tail distributions to analyze network performance models. In *Proc. IEEE INFOCOM'97*, Kobe, Japan, Apr. 1997.

[9] J. A. Fill and L. Holst. On the distribution of search cost for the move-to-front rule. *Random Structures Algorithms*, 8(3):179–186, 1996.

[10] Y. T. Hou, J. Pan, B. Li, and S. Panwar. On expiration-based hierarchical caching systems. *IEEE J. on Selected Areas in Communications*, 22(1), 2004.

[11] Y. T. Hou, J. Pan, K. Sohraby, and S. X. Shen. Coping miss synchronization in hierarchical caching systems with nonlinear TTL functions. In *Proc. IEEE ICC'04*, pages 2194–2198, 2004.

[12] J. Jung, A. W. Berger, and H. Balakrishnan. Modeling TTL-based Internet caches. In *Proc. IEEE INFOCOM'03*, San Francisco, CA, USA, Mar. 2003.

[13] J. Jung, E. Sit, H. Balakrishnan, and R. Morris. DNS performance and the effectiveness of caching. In *Proc. ACM SIGCOMM Workshop on Internet Measurement (IMW '01)*, New York, NY, USA, Nov. 2001.

[14] A. T. Lawrance. Dependency of intervals between events in superposition processes. *J. of the Royal Statistical Society, Series B (Methodological)*, 35(2):306–315, 1973.

[15] N. Choungmo Fofack and Sara Alouf. Non-renewal TTL-based cache replacement policy and applications: Case of modern dns hierarchy. Technical Report RR-0003, Inria, Sophia Antipolis, France, Nov. 2013.

[16] J. Pang, A. Akella, A. Shaikh, B. Krishnamurthy, and S. Seshan. On the responsiveness of DNS-based network control. In *Proc. IMC*, Taormina, Italy, 2004.

[17] A. D. Polyanin and A. V. Manzhirov. *Handbook of Integral Equations*. CRC Press, 1st edition, 1998.

[18] E. J. Rosensweig, J. Kurose, and D. Towsley. Approximate models for general cache networks. In *Proc. IEEE INFOCOM'10*, San Diego, USA, 2010.

[19] A. Simonian, M. Gallo, B. Kauffmann, L. Muscariello, and C. Tanguy. Performance of the random replacement policy for networks of caches. In *Proc. ACM SIGMETRICS/PERFORMANCE'12*, pages 395–396, London, England, UK, June 2012.

[20] M. Tortorella. Numerical solutions of renewal-type integral equations. *INFORMS J. on Computing*, 17:73–96, 2005.