A concept of distributed replicated data storages like Cassandra, HBase, MongoDB has been proposed to effectively manage the Big Data sets whose volume, velocity, and variability are difficult to deal with by using the traditional Relational Database Management Systems. Trade-offs between consistency, availability, partition tolerance, and latency are intrinsic to such systems. Although relations between these properties have been previously identified by the well-known CAP theorem in qualitative terms, it is still necessary to quantify how different consistency and timeout settings affect system latency. The paper reports results of Cassandra’s performance evaluation using the YCSB benchmark and experimentally demonstrates how to read latency depends on the consistency settings and the current database workload. These results clearly show that stronger data consistency increases system latency, which is in line with the qualitative implication of the CAP theorem. Moreover, Cassandra latency and its variation considerably depend on the system workload. The distributed nature of such a system does not always guarantee that the client receives a response from the database within a finite time. If this happens, it causes so-called timing failures when the response is received too late or is not received at all. In the paper, we also consider the role of the application timeout which is the fundamental part of all distributed fault tolerance mechanisms working over the Internet and used as the main error detection mechanism here. The role of the application timeout as the main determinant in the interplay between system availability and responsiveness is also examined in the paper. It is quantitatively shown how different timeout settings could affect system availability and the average servicing and waiting time. Although many modern distributed systems including Cassandra use static timeouts it was shown that the most promising approach is to set timeouts dynamically at run time to balance performance, availability and improve the efficiency of the fault-tolerance mechanisms.

Keywords: timeout; NoSQL; distributed databases; replication; performance benchmarking; consistency; availability; latency; trade-off.

Introduction

Distributed data storages have become the standard platform and a major industrial technology for dealing with enormous data growth. They are now widely used in different application domains, including distributed Internet applications, social networks and media, critical infrastructures, business-critical systems, IoT and industrial systems. A new generation of such databases is called NoSQL (Not Only SQL or NO SQL) [1]. They are designed to provide horizontal scalability and employ Internet-scale replication to guaranty high availability, throughput and low latency.

A concept of distributed data storages has been proposed to effectively manage the Big Data sets whose volume, velocity and variability are difficult to deal with by using the traditional Relational Database Management Systems. Most NoSQL databases sacrifice the ACID (atomicity, consistency, isolation and durability) guarantees in favour of the BASE (basically available, soft state, eventually consistent) properties [2], which is the price to pay for distributed data handling and horizontal scalability. They are also subject to the tradeoff between Consistency, Availability, and Partition tolerance (CAP).

The CAP theorem [3], first appeared in 1998-1999, declares that the only two of the three properties can be preserved at once in distributed replicated systems. Gilbert and Lynch [4] consider the CAP theorem as a particular case of a more general trade-off between consistency and availability in unreliable distributed systems propagating updates eventually over time. However, a tradeoff between availability and latency is less studied. There have been a number of studies, e.g. [5 - 8], evaluating and comparing the performance of different NoSQL databases. Most of them use general competitive benchmarks of usual-andcustomary application workloads (e.g. Yahoo! Cloud Serving Benchmark, YCSB). The major focus of those works is to compare and select the best NoSQL databases based on performance measures. However, reported results show that performance of different NoSQL databases significantly depends on the use case scenario, deployment conditions, current workload and...
database settings. Thus, there is no NoSQL database that always outperforms the others. Other recent related works, such as [9 - 11], have investigated measurement-based performance prediction of NoSQL data stores. However, the studies, mentioned above, do not investigate an interdependency between availability and performance and do not study how time-out settings affect database latency.

The aim of this work is to experimentally evaluate a trade-off between availability and latency, which is in the very nature of NoSQL databases, and to study how timeout settings can be used to interplay between them.

1. The role of the application timeout as the main performance and availability factor

Most error recovery and fault-tolerance techniques depend on the time-out setup. In particular, setting appropriate time-outs is key to improving many distributed systems’ performance and dependability. However, researchers have focused mainly on optimizing timeouts used by communication protocols [12, 13]. They haven’t examined how application level timeout settings affect performance and dependability of distributed systems. A replicated fault-tolerant system becomes partitioned when one of its parts does not respond due to arbitrary message loss, delay or replica failure, resulting in a timeout. System availability can be interpreted as a probability that each client request eventually receives a response. In many real systems, however, a response that is too late (i.e. beyond the application timeout) is treated as a failure.

For example, the failure model introduced by Avizienis, et al. in [14] distinguishes between the two main failure domains in distributed systems: (i) timing failures when the duration of the response delivered to the client exceeds the specified waiting time – the application timeout (i.e. the service is delivered too late), and (ii) content failures when the content (value) of the response deviates from implementing the system function.

Failure to receive responses from some of the replicas within the specified timeout causes partitioning of the replicated system. Thus, partitioning can be considered as a bound on the replica’s response time [15]. A slow network connection, a slow-responding replica or the wrong timeout settings can lead to an erroneous decision that the system has become partitioned. When the system detects a partition, it has to decide whether to return a possibly inconsistent response to a client or to send an exception message in reply, which undermines system availability.

Timeout settings are crucially important is distributed replicated systems. If the timeout is lower than the typical response time, a system is likely to enter the partition mode more often. On the other hand, timeout which is too high does not allow timely detect errors and failure and effectively apply fault-tolerance mechanisms. The application timeout can be considered as a bound between system availability and performance (in term of latency or response time) [16, 17]. Thus, system designers should be able to set up timeouts according to the desired system response time, also keeping in mind the choice between consistency and availability.

2. Cassandra Performance Benchmarking

In this paper we put a special focus on quantitative evaluation of one of the fundamental trade-offs between system availability and latency in distributed replicated data storages using the Cassandra NoSQL as a typical example of such system. Various industry trends suggest that Apache Cassandra is one of the top three in use today together with MongoDB and HBase [18].

2.1. Experimental setup

This section describes the performance benchmarking methodology used and reports the experimental results showing how timeout settings affect latency of the read requests for the Cassandra NoSQL database.

As a testbed we have deployed the 3-replicated Cassandra 2.1 cluster in the Amazon EC2 cloud (Fig. 1). Replication factor equal to 3 is the most typical setup for many modern distributed computing systems and Internet services, including Amazon S3, Amazon EMR, Facebook Haystack, DynamoDB, etc.

The cluster was deployed in the AWS US-West-2 (Oregon) region on c3.xlarge instances (vCPUs – 4, RAM – 7.5 GB, SSD – 2x40 GB, OS – Ubuntu Server 16.04 LTS).

2.2. Benchmarking methodology

Our work uses the YCSB (Yahoo! Cloud Serving Benchmark) framework which is considered to be a de-facto standard benchmark to evaluate performance of various NoSQL databases like Cassandra, MongoDB, Redis, HBase and others [5]. YCSB is an open-source Java project. The YCSB framework includes six out-of-the-box workloads [5], each testing different common use case scenarios with a certain mix of reads and writes. In this paper we report experimental results corresponding to the read-only Workload C. All the rest Cassandra and YCSB parameters (e.g. request distribution, testbed database, etc.) were set to their default values. The testbed YCSB database is a table of records. Each record is identified by a primary key and includes F string fields. The values written to these fields are random ASCII strings of length L. By default, F is equal 10 and L is equal 100, which constructs 1000 bytes records. The
YCSB Client is a Java program that generates data to be loaded to the database, and runs the workloads. The client was deployed on a separate VM in the same Amazon region to reduce influence of the unstable Internet delays.

![Cassandra 2.1 Cluster](image)

Fig. 1. Experimental setup: deployment of Cassandra NoSQL cluster

### 2.3. Benchmarking scenario

Some examples of general methodologies for benchmarking Cassandra and other NoSQL databases with YCSB can be found in [18]. However, unlike these and other works (e.g. [5 - 8]) studying and comparing performance of different NoSQL databases we put the focus on analysing the dynamic aspects of the Cassandra performance under different workloads (i.e. number of concurrent requests/threads) and various consistency settings (e.g. ALL, QUORUM, ONE).

Cassandra consistency model defines the number of requested replicas that must acknowledge a read (or write) operation before the most recent result is returned to the client (or the write operation is considered successful). In the paper we consider three different consistency levels:

- **ALL** (the strongest consistency level); all replicas are queried and must respond; the most recent (based on the time stamp) read result is returned to a client;
- **ONE** (the weakest consistency level); only one replica is requested and must respond with the result which is returned to a client; a client can receive stalled data if the most recent updates have not been propagated to that replica;
- **QUORUM** (the moderate consistency level); quorum (e.g. 2-out-of-3) of replicas are queried and must respond; this level provides a compromise between data consistency and system latency.

A series of YCSB read performance tests were performed on the 3-replicated Cassandra cluster with the consistency setting set to ALL, ONE and QUORUM with a number of threads varying from 100 to 1000. The operation count within each thread was set to 1000.

### 3. Data analysis

#### 3.1. Cassandra read performance

In this section we report new experimental results in addition to those discussed in our previous study [19]. Tables 1 - 3 report Cassandra read latency statistics depending on the number of requests executed in parallel (threads) and consistency settings. It is also shown that the average Cassandra latency as well as the maximum response time steadily increase with the increase of the number of threads.

| Threads | Min  | Max  | Average | Std. Dev. | Ops. per second |
|---------|------|------|---------|-----------|-----------------|
| 100     | 3789 | 47818| 17427   | 4494      | 5380            |
| 200     | 6056 | 100394| 29217   | 11208     | 6471            |
| 300     | 4875 | 139900| 41326   | 18638     | 7010            |
| 400     | 2319 | 163312| 52920   | 23231     | 7312            |
| 500     | 7191 | 184161| 65569   | 26339     | 7438            |
| 600     | 1176 | 233869| 77215   | 29799     | 7586            |
| 700     | 4712 | 229903| 84427   | 31298     | 8155            |
| 800     | 6703 | 255587| 92091   | 32050     | 8521            |
| 900     | 2448 | 267868| 107238  | 38731     | 8280            |
| 1000    | 6176 | 407612| 117367  | 44185     | 8398            |

| Threads | Min  | Max  | Average | Std. Dev. | Ops. per second |
|---------|------|------|---------|-----------|-----------------|
| 100     | 1016 | 67819| 18138   | 7273      | 5189            |
| 200     | 4424 | 86830| 26350   | 12764     | 7022            |
| 300     | 4892 | 116258| 35995   | 15503     | 7814            |
| 400     | 5278 | 160904| 48053   | 23762     | 7998            |
| 500     | 1082 | 179521| 59799   | 27485     | 8172            |
| 600     | 1750 | 240746| 72983   | 30551     | 8016            |
| 700     | 939  | 245338| 79918   | 31542     | 8567            |
| 800     | 1225 | 312977| 87444   | 33830     | 9040            |
| 900     | 3047 | 267239| 98086   | 37974     | 9006            |
| 1000    | 1349 | 322059| 110761  | 45804     | 8871            |

| Threads | Min  | Max  | Average | Std. Dev. | Ops. per second |
|---------|------|------|---------|-----------|-----------------|
| 100     | 1340 | 67438| 14268   | 8870      | 6323            |
| 200     | 1152 | 84807| 20153   | 13394     | 9259            |
| 300     | 648  | 115569| 31038   | 19683     | 9324            |
| 400     | 1668 | 173360| 38927   | 22649     | 9660            |
| 500     | 761  | 193154| 49930   | 26879     | 9723            |
| 600     | 1623 | 203336| 56432   | 28424     | 10221           |
| 700     | 2139 | 203004| 69526   | 31119     | 9799            |
| 800     | 1011 | 235942| 74766   | 35047     | 10486           |
| 900     | 1504 | 318241| 89478   | 44925     | 9848            |
| 1000    | 1437 | 347631| 91853   | 44077     | 10707           |

### Table 1

Cassandra read latency (us) for the strong consistency setting ALL

### Table 2

Cassandra read latency (us) for the consistency setting QUORUM

### Table 3

Cassandra read latency (us) for the weak consistency setting ONE
3.2. Interplay between availability and latency

Cassandra uses the following timeout values set by default: 5000 ms for read requests and 2000 ms for write requests (Cassandra is designed to perform write operation faster than read requests).

At the same time in our experiments the maximum read response time never exceeded 500 ms even for the strong consistency level ALL and the maximum number of threads. Thus, the default timeout setup is significantly higher (in 10 times!) than the worst-case execution time. Thus, Cassandra could be slow to respond to possible errors and failures that may occur during operation. At the same time, too short timeout can lead to an erroneous decision that the system has become partitioned. A general approach, widely used in communications protocols, assumes that the doubled average latency or the worst-case execution time can be set as the timeout value. However, Tables 1-3 show that the maximum response time increases with the increase if the database workload.

Moreover, as shown in Fig. 4, probability density series of Cassandra response time considerably expand with increasing database workload. On the one hand, this means that the standard deviation of Cassandra response time increases, and its latency becomes more uncertain [20]. On the other hand, it shows that timeout settings suitable for low workloads could be inadequate when the database experiences the high demand.

Fig. 4 depicts a situation if the timeout is set to 1000 ms (approx. the doubled maximum response time for the threads count 100). Red bars correspond to the situation when Cassandra would have responded after the specified timeouts. This clearly shows that the proposed timeout is too short for heavy workloads. At the same time, short timeout reduces user servicing and waiting time, as discussed in [16]. This is because the average waiting time (for all invocations, including those when a timeout is triggered) is calculated as the sum of the average time of received responses and a product of the timeout value and the probability of timeout.

| Threads | Availability | Timeout=100 ms | Availability | Timeout=150 ms | Availability | Timeout=200 ms |
|---------|--------------|----------------|--------------|----------------|--------------|----------------|
| 100     | 0.99986      | 17428          | 0.99986      | 17428          | 1            | 17428          |
| 200     | 0.99987      | 29213          | 0.99993      | 29218          | 1            | 29218          |
| 300     | 0.97448      | 39598          | 0.99996      | 41326          | 1            | 41326          |
| 400     | 0.94491      | 49232          | 0.99846      | 52762          | 1            | 52921          |
| 500     | 0.88904      | 58806          | 0.99633      | 65240          | 1            | 65569          |
| 600     | 0.80293      | 65908          | 0.98600      | 76055          | 1            | 77207          |
| 700     | 0.75438      | 69944          | 0.97014      | 81843          | 1            | 84084          |
| 800     | 0.66633      | 74857          | 0.94071      | 87262          | 1            | 91391          |
| 900     | 0.50582      | 77891          | 0.85748      | 95656          | 1            | 104426         |
| 1000    | 0.39259      | 77702          | 0.78265      | 99083          | 1            | 112041         |

This clearly shows that the proposed timeout is too short for heavy workloads. At the same time, short timeout reduces user servicing and waiting time, as discussed in [16]. This is because the average waiting time (for all invocations, including those when a timeout is triggered) is calculated as the sum of the average time of received responses and a product of the timeout value and the probability of timeout.
Ultimately, timeout could be considered as a tool to interplay between system availability and latency, as shown in Table 4. Shorter timeout reduces system latency. However, the availability of the system may also be reduced as some responses may arrive after the timeout is triggered.

**Conclusions**

Availability, consistency and performance of distributed database systems are tightly connected. Although these relations have been identified by the CAP theorem in qualitative terms [3, 4], it is still necessary to quantify how different timeout settings affect system latency. Understanding this trade-off is key for the effective usage of distributed databases.

In the paper we report results of Cassandra performance benchmarking and also examine the role of the application timeout as the main determinant in the interplay between system availability and responsiveness. The application timeout can be considered as a bound between system availability and performance (in term of latency or response time). Moreover, application timeout is the fundamental part of all distributed fault tolerance techniques and is used as the main error detection mechanism here. Thus, system designers should be able to set up timeouts according to the desired system response time, also keeping in mind the choice between consistency and availability.

Unfortunately, many modern distributed systems including Cassandra use static timeout settings that are often too long. This can worsen system latency and
causes ineffective failure detection and fault tolerance. Yet the most promising approach is to set timeout dynamically at run time to balance performance, availability and fault-tolerance. Our experiments show that the optimal timeout should be application specific (i.e. set depending on the database structure, volume and the most common read/write queries) and needs to be adjusted dynamically at run-time taking into account various factors, including: current system workload; number of replicas; consistency settings, etc.

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У статті аналізується роль тайм-ауту прикладного рівня, який є фундаментальною частиною всіх розподілених механізмів забезпечення відмовостійкості та використовується в якості основного механізму виявлення відмов при роботі в комунікаційному середовищі Інтернет. Зокрема, тайм-аут розглядається в якості основного фактора, що визначає взаємозв'язок між доступністю системи та її швидкодією. Кількісно показано, як різне налаштування тайм-ауту можуть вплинути на доступність системи, а також на середній час обслуговування й очікування обслуговування. Незважаючи на те, що багато сучасних розподілених систем на прикладному рівні використовують статично-заданий тайм-аут, найбільш перспективним підходом є динамічне визначення максимального часу очікування відповіді від системи для забезпечення балансу між продуктивністю та доступністю, а також для підвищення ефективності механізмів відмовостійкості.

Ключові слова: тайм-аут; розподілені бази даних; NoSQL; реплікація; випробування продуктивності; цілісність; доступність; швидкодія; забезпечення компромісу.

**ІССЛЕДОВАНИЕ ТАЙМ-АУТА КАК ФАКТОРА ВЛИЯНИЯ НА ПРОИЗВОДИТЕЛЬНОСТЬ И ДОСТОПМЕНСТНОСТЬ РАСПРЕДЕЛЕННЫХ РЕПЛИЦИРОВАННЫХ БАЗ ДАННЫХ**

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Концепция распределенных реплицированных хранилищ данных, таких как Cassandra, HBase, MongoDB и др. была предложена для эффективного управления большими данными, объем которых превышает возможности традиционных реляционных систем управления реляционными базами данных по их эффективному хранению и обработке. Такие системы характеризуются наличием компромисса между согласованностью, доступностью, устойчивостью к разделям и временными задержками. Хотя качественные отношения между этими свойствами и были ранее определены в теореме CAP, тем не менее, актуальной остается качественная оценка степени влияния различных настроек согласованности и тайм-аута на производительность та доступности таких систем. В статье представлены результаты измерения производительности нереляционной базы данных Cassandra в помощи набора тестов YCSB и количественно показано, как в какой степени время задержки выполнения запросов чтения информации зависит от настроек согласованности и рабочей нагрузки базы данных. Эти результаты ясно показывают, что более высокая согласованность данных увеличивает временные задержки, что согласуется с качественными выводами теоремы CAP. Более того, показано, как временная задержка и ее вариации в значительной степени зависят от рабочей нагрузки системы. Распределенный характер рассматриваемых систем не гарантирует, что ответ от базы данных будет получен в течение конечного времени ожидания. В этом случае возникает, так называемый временной сбой системы, когда ответ от неё получен слишком поздно или же вообще не получен. В статье анализируется роль тайм-аута прикладного уровня, который является фундаментальной частью всех распределенных механизмов обеспечения отказоустойчивости и используется в качестве основного механизма обнаружения ошибок при работе в коммуникационной среде Интернет. В частности, тайм-аут рассматривается в качестве основного фактора, определяющего взаимодействие между доступностью системы и ее быстродействием. Количественно показано, как различные настройки тайм-аута могут повлиять на доступность системы, а также на среднее время обслуживания и ожидания обслуживания. Несмотря на то, что многие современные распределенные системы на прикладном уровне используют статически-заданный тайм-аут, наиболее перспективным подходом является динамическое определение максимального времени ожидания отклика от системы для обеспечения баланса производительности, доступности и повышения эффективности механизмов отказоустойчивости.

Ключевые слова: тайм-аут; распределенные базы данных; NoSQL; репликация; тестирование производительности; целостность; доступность; быстродействие; обеспечение компромисса.

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