2PC*: a distributed transaction concurrency control protocol of multi-microservice based on cloud computing platform

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Abstract

The two-phase commit (2PC) protocol is a key technique for achieving distributed transactions in storage systems such as relational databases and distributed databases. 2PC is a strongly consistent and centralized atomic commit protocol that ensures the serialization of the transaction execution order. However, it does not scale well to large and high-throughput systems, especially for applications with many transactional conflicts, such as microservices and cloud computing. Therefore, 2PC has a performance bottleneck for distributed transaction control across multiple microservices. In this paper, we propose 2PC*, a novel concurrency control protocol for distributed transactions that outperforms 2PC, allowing greater concurrency across multiple microservices. 2PC* can greatly reduce overhead because locks are held throughout the transaction process. Moreover, we improve the fault-tolerance mechanism of 2PC* using transaction compensation. We also implement a middleware solution for transactions in microservice support using 2PC*. We compare 2PC* to 2PC by applying both to Ctrip MSECP, and 2PC* outperforms 2PC in workloads with varying degrees of contention. When the contention becomes high, the experimental results show that 2PC* achieves at most a 3.3x improvement in throughput and a 67% reduction in latency, which proves that our scheme can easily support distributed transactions with multi-microservice modules. Finally, we embed our middleware scheme in the PaaS cloud platform and demonstrate its strong applicability to cloud computing through long-term analysis of the monitoring results in the cloud platform.

Keywords: 2PC, Distributed transactions, Microservices, Protocol optimization, Cloud computing, PaaS platform

Introduction

With the rapid and iterative development of Internet products, the traditional monolithic-service architecture is not suitable for the current large-scale data business scenarios. Therefore, microservice architecture has gradually replaced the traditional approach and has become an important topic in industrial and academic circles. Microservice architecture [1] is widely used in large-scale cloud computing platforms and application development. The key to microservice architecture is to provide flexibility for program development and the reuse of fine-grained services.

Microservices can be developed by different-domain teams to support business applications, and they can be implemented in various languages and access multiple underlying databases. In a distributed system, we usually deploy various microservice modules, which are homogeneous or heterogeneous systems composed of service clusters. Meanwhile, most microservices are used in cross-service and cross-resource scenarios. In other words, they need to access multiple databases in different environments when processing business. When an application invokes multiple microservices, distributed transactions are needed to support the consistent updating of these underlying databases and to ensure data consistency throughout the system. In recent years, academia and industry have carried out...
Considerable amounts of research on the data consistency of certain distributed databases, such as Spanner [2] and OceanBase (https://oceanbase.alipay.com/). Fortunately, microservices are closely related to these distributed databases in transactions, although supporting data-consistent distributed transactions across multi-microservice modules is even more challenging research [3].

The traditional technique is to implement a distributed transaction using the two-phase commit (2PC) protocol [4]. Unfortunately, this does not work well in large-scale and high-throughput systems, especially for applications with a large number of transaction conflicts [5]. The reason is that locks are held throughout the 2PC process. However, the number of modules across microservices is large, and it is necessary to support users with extremely high numbers of concurrent requests. For this reason, due to the limitations of the 2PC protocol, the performance of the original business will be seriously reduced, possibly rendering it unusable. Other approaches include persistent message queue patterns for loosely coupled distributed transactions [6, 7], which require additional application logic to compensate for failed transaction steps, thus increasing the cost of the system and possibly affecting the experience of users. In many business scenarios, such as e-commerce and e-finance, to ensure that the entire system always has strong data consistency, it must be controlled with the strictest consistency protocols, e.g., 2PC. Although systems such as YugaByte [8] and FoundationDB [9] can support distributed transactions for a single database, this is not yet scalable in distributed systems with multi-microservice modules.

In view of the above problems, we aim to find a solution suitable for consistently distributed transactions in the micro-service architecture. On the one hand, it is strictly required to meet the basic principles of data consistency in the heterogeneous distributed system of the microservice architecture. On the other hand, the solution must achieve the same level of throughput as the original microservice business. In other words, it is expected to obtain a high processing performance under the scenario of an extremely high number of concurrent user requests.

In the paper, we propose 2PC*, which is a novel distributed transaction control protocol that can extract more concurrent processing capabilities under high-intensity competitive workloads than previous approaches for a multi-microservice. 2PC* is an optimized protocol based on the traditional 2PC. It utilizes a two-level asynchronous lock to reduce the overhead of synchronous blocking caused by a surge in the number of transactions, thereby avoiding deadlocks. To achieve this, we propose a novel optimistic lock, i.e., the SAOL. Additionally, 2PC* uses a runtime protocol for transaction concurrency control to reduce the probability of conflicts between transactions.

In a distributed system environment where microservices are located, especially in cloud computing platforms, there are uncontrollable factors in service, e.g., service loss and network delays. Moreover, microservices are often called remotely through a gateway, such as XML-RPC or SOAP (simple object access protocol), which increases the probability of these conditions occurring. Therefore, we improve the transaction compensation mechanism to achieve the ultimate consistency of distributed transactions across microservices.

Finally, we implement a middleware solution for transactions distributed across microservices based on 2PC* and deploy it on a specific PaaS cloud platform. Specifically, we use the Netty framework [10] to complete RPCs (remote procedure calls) [11] between transaction roles. Netty is based on Java NIO (non-blocking input and output), so its I/O operation is asynchronous and non-blocking. Therefore, the throughput and stability of RPCs can be greatly improved. We adapt our middleware to two popular microservice frameworks, Spring Cloud and Dubbo [12, 13]. We implement 2PC* and evaluate its performance using a case of the MSECP platform. 2PC* outperforms the original 2PC in workloads with varying degrees of contention. When the contention is high, 2PC*'s throughput is nearly 10 times that of 2PC. As the system scales across microservices and contention increases, the throughput of 2PC* continues to grow, while the 2PC throughput drops to almost zero with no capacity to scale.

The rest of this paper is organized as follows. Section “Overview” elaborates on the overview of our scheme and the classic approach. In Section “Design”, we introduce the design details of the 2PC*, including the design of SAOL and a runtime protocol. The implementation of the middleware solution based on 2PC* will be introduced in Section “Implementation”. In Section “Evaluation”, we will give the experimental data of the middleware solution implemented with 2PC* and compare it with 2PC. Section “Related Work” discusses some related work. Finally, Section “Conclusion” concludes this paper.

Overview

Low performance traditional approaches

2PC and OCC

In consistent transactional processing for traditional distributed databases, developers prefer the transaction’s strongest isolation level, such as serializability [14], to simplify the correctness criteria for concurrent transactions. Therefore, to ensure strict serializability, traditional distributed storage systems usually run standard transactional concurrency control schemes, such as the
OCC (optimistic concurrency control) [15] combines with 2PC. Unfortunately, 2PC and OCC perform poorly under com-petitive workloads in large-scale conflict transactions. We introduce a case that simulates the process of a customer buying two items from a store (Table 1). The process contains two fragments, $F_1$ and $F_2$, each of which reduces the stock quantity of different items. Each fragment can be executed atomically on the server where it is located. However, in the entire distributed system, an additional distributed transac-tion control protocol is needed to prevent fragmented transac-tions across servers from being non-serializable and interla-ced. For example, suppose the store keeps the stock quantities of item$_1$ and item$_2$ unchanged and always sells the two items in a bundle. In the absence of a distributed transac-tion control protocol, the user can purchase item$_1$ but not item$_2$, while another user can purchase item$_2$ but not item$_1$.

We evaluate the performance of 2PC combined with OCC with two transactions, $T_1$ and $T_2$. Both purchase the same item$_1$ and item$_2$ stored on different services. When OCC detection is performed during the execution of 2PC, any interleaving of $T_1$ and $T_2$ will cause the process to abort. For example, if $T_2$ reads the stock number after $T_1$ reads it but before $T_1$ commits its update to item$_1$, $T_2$ will not be able to verify the process and abort later. We introduce another example where both $T_1$ and $T_2$ are aborted during 2PC because their corresponding 2PC precommit instructions are proc-essed by the service in different orders.

However, the performance of 2PC combined with OCC under high-intensity workloads is far from satisfactory, especially across high-concurrency microservices. 2PC acqui-res keys on data access for each transaction. When threads perform a conflicting operation, they serialize the transac-tions’ execution order. In the example described above, once $T_1$ modifies the stock quantity of item$_1$, $T_2$ must be blocked until $T_1$ completes its entire process and commits successfully. In addition to blocking, 2PC also prevents deadlock by pass-ive thread abort [2]. However, as the number of competing threads increases, so does the probability of deadlocks. In addition, effective deadlock prevention mechanisms [16] (e.g., wound-wait) have many false positives. As a result, even without a real deadlock, most threads will still be abort-ed unexpectedly.

### New distributed Transaction’s characteristics in microservice architecture

ACID [17] is a design concept for transactions in traditional databases to ensure the correctness of data and avoid errors such as Read-Committed and Repeatable-Read. However, in distributed systems, especially at the application level, it is more important to meet business requirements than to pursue strict system characteristics. According to the CAP principle, strong consistency (C), availability (A), and partition tolera-nce (P) [18] cannot be met simultaneously. However, BASE theory adopts a completely different design idea than ACID. BASE sacrifices strong consistency for high availability and eventual consistency [19], which can be achieved through appropriate methods and is consistent with the characteristics of distributed systems in reality. On this basis, distributed transactions are mostly focused on the application layer for microservices. Therefore, it is necessary to not only ensure the data’s eventual consistency but also obtain high availab-ility in the system.

#### 2PC* optimize lock in two-phase commit

According to the details described below, our optimized transmission control protocol 2PC* avoids lock-blocking du-ring the two-phase commit between transactions, es-pecially under scenarios with high-level contention.

2PC* optimizes the inefficient synchronization-blocking lock in 2PC and replaces it with a novel sec-ondary asyn-chronous optimistic lock (SAOL). Bor-rowing from the design of the MVCC (multi-version concurrency control) [20], the SAOL allocates an ever-growing sequence of ver-sions to each transac-tion step, which is similar to the snapshot. The fine granularity of locks can be broken down into two levels of optimistic locks, borrowing from OCC (optimistic concurrency control) [15]. The SAOL allows multiple transactions to perform updates to the same transaction frag-ment concurrently, with two specific snapshots controlling the order in which transactions are executed, i.e., begin-Version and commitVersion.

Meanwhile, the SAOL adopts a two-level optimistic lock (i.e., one composed of a firstLock and second-Lock) to control the transaction commit. Using the

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**Table 1**: A fragment of new-order transaction containing two pieces

| transaction | new_order_fragment |
|-------------|---------------------|
| **input**:  | item$_1$ and item$_2$ |
BASE mechanism, the firstLock is responsible for controlling the resources in the main process between multiple transactions; thus, the secondLock can separate from it and compensate for the unfinished process in the firstLock.

2PC* simplifies conflicts to commit
2PC* is able to change and optimize the order of execution for transactions because it uses two phases of indicators to commit. In the beginning phase, when microservice modules participate in the same distributed transaction, 2PC* does not immediately execute the subsequent process but instead adds the order relations (i.e., conflicts) between trans-actions to the neighbourList of the directed graph, which can be denoted as $\text{GraphNode}$. We conduct a preliminary merge and de-duplication of conflicts for the neighbourList. In the commit phase, $\text{GraphNode}$ then combines all the conflict information and distributes it to all the microservices. 2PC* then further simplifies the transaction conflicts for the neighbourList so that it performs better under high-competition transaction scenarios, such as those involving microservice architecture.

A middleware based on cloud platform for distributed transaction control with 2PC*
Based on 2PC*, we implement a middleware scheme that supports consistent distributed transactions for microservices. Our prototype contains over 23,000 lines of Java code, 17000 of which are for transaction concurrency control, and is based on the Spring-Boot framework. In particular, we adopt the Netty framework to complete the underlying communication between transaction roles. We deploy it in a specific PaaS cloud platform. Experimental data prove that our scheme has very good performance for multi-microservice scenarios with high concurrent requests from users, including higher throughput and lower latency.

Design
The design of the 2PC* protocol includes a novel optimistic lock mechanism (i.e., the SAOL), a concurrency control protocol for transactions and a compensation measure.

In this section, we first explain the design of the SAOL. Then, we introduce a concurrency control protocol in 2PC*, an optimizing strategy, and a verification of its correctness. Finally, we provide a fault-tolerant mechanism.

Secondary asynchronous optimistic-lock
The novel 2PC*’s SAOL replaces the synchronous blocking lock with a high-performance secondary asynchronous lock. The process in each transaction fragment is identified by a unique version number, i.e., snapshot. We adopt Twitter’s distributed identification number generation algorithm Snowflake [21], which contains a timestamp to identify the execution order of the transaction fragment. The specific design of the SAOL is described below.

Transaction property initialization
In the SAOL, we first define four key attribute fields in the transaction object, which are represented as follows.

- **value**: This indicates the current actual value of the transaction object.
- **beginVersion**: That is the version sequence number at the beginning of the process.
- **commitVersion**: That is the version at the time the transaction was committed.
- **lock**: This is responsible for locking up the resources of uncommitted transactions. The lock is divided into two different levels, namely the firstLock and the secondLock, which represent the two phases of lock respectively. And we specify that in the secondLock, it needs to contain firstLock information.

Begin transaction process
First, we need obtain the beginVersion in the transaction object $T_1$, denoted $b_v$, and then determine whether there is a lock in $T_1$. If no lock exists, we try to obtain the latest committed transaction object directly from the version number interval $[0, b_v]$ and obtain the current latest value through its beginVersion. Otherwise, the subsequent process is executed according to the following three branches.

- **Case 1.** If there is another transaction object $T_2$ committing a transaction, then the value of $T_2$ is locked. At this point, we need to wait for $T_2$ to finish committing transactions, then poll and retry to obtain the current latest value.
- **Case 2.** In case 1, if the waiting time of $T_1$ has passed a certain threshold, denoted WAIT_TIME_OUT, but $T_2$’s value is still locked, it can be determined that $T_2$ is facing some unexpected exceptions, e.g., a network delay or downtime. We can simply assume that $T_2$ has been interrupted and it can release lock directly.
- **Case 3.** $T_2$’s lock may have been remained because it has not been released properly. In this case, $T_2$’s transaction was committed and its firstLock released successfully, but some unforeseen exceptions occurred in the secondLock, so the transaction could not be committed, thus causing the lock to remain.
**Transaction pre-commit process**

At this point, $T_1$ has completely obtained its latest value, so we can perform the $T_1$ first-phase commit, denoted preCommit. This process can be divided into three branches as follows.

- **Case 1.** For any two transaction objects $T_1$ and $T_2$, in the version sequence interval $(b_{\gamma T}, + \infty)$ corresponding to their values, we determine whether another transaction object $T_x$ is updating the data. If this condition matches, it means that $T_x$ might have changed the value. At this point, both $T_1$ and $T_2$ need to roll back their transactions directly, and then we can complete the process.

- **Case 2.** Determine whether a lock exists in both $T_1$ and $T_2$, that is, whether their transaction resources are locked. If so, $T_1$ and $T_2$ need to directly roll back transactions and we can terminate the process directly.

- **Case 3.** If neither of the above two cases matches, we set the firstLock of $T_1$ and $T_2$ to locked, write the latest data to value at this time and commit the transaction.

**Transaction second-commit process**

First, we determine whether the firstLock of $T_1$ or $T_2$ is locked; if so, we commit the transaction directly. The secondLock that belongs to $T_1$ and $T_2$, it can be completely separated from the main process, and we can then use an asynchronous mode of the thread to release the secondLock and commit transactions in the second phase. Therefore, even if an exception has been occurred throughout $T_1$ or $T_2$, as the subsequent transaction object, denoted $T_{next}$, it observes that the firstLock belonging to $T_1$ or $T_2$ has been released, but the secondLock still unexpectedly remains, thus $T_{next}$ will automatically release the lock in their secondLocks and commit the transactions.

**Concurrency control protocol**

Under the microservice architecture, business modules are often deployed on multiple machines in a distributed cluster to achieve scalability and high availability. When multiple microservices act as participants and concurrently execute the same group of distributed transactions, conflicts are inevitable, and they greatly affect the performance between concurrent transactions. To reduce the probability of conflict between concurrent transactions, a novel concurrency control protocol is proposed based on the 2PC in this subsection. Our scheme is able to avoid the additional performance overhead caused by conflicts between frequent transactions.

Similar to 2PC, the design of the basic protocol is divided into two phases, i.e., the begin phase and the commit phase, which are summarized below.

**Begin phase**

When the distributed transaction process officially begins, the TCM (transaction coordination manager) generates a globally unique transaction number TID for the transaction group. Then, this transaction group does not immediately perform the subsequent process but instead caches it in a temporary area (such as Redis). Finally, we determine whether the transaction group matches a specific condition (which will be described in detail later); if so, the next step is performed. The key to the protocol is to maintain a graph data structure in the appropriate microservice module MS, which is used to record all conflict dependencies from the transaction group and is denoted as GraphNode. Its implementation code is shown in Table 2, in which data is the generic Java type corresponding to vertex E in the Graph, and it records the key information for transaction object $T$, including the status of the transaction, which can be summarized as the three kinds of situations below.

- **BEGUN.** This indicates that the transaction has started execution.
- **COMMITTING.** This indicates that the transaction is performing the committing process.
- **FINISHED.** This indicates that the workflow of each transaction has been determined.

The execution order of these statuses needs to be strictly guaranteed to be serial. Thus, we restrict BEGUN to be earlier than COMMITTING and COMMITTING to be earlier than FINISHED; i.e., BEGUN < COMMITTING < FINISHED.

The field visited of GraphNode is set to the Boolean type, and it indicates whether transaction object $T$ is finished with the corresponding MS. It is TRUE if done, FALSE otherwise.

The neighbourList of GraphNode corresponds to the subset of V\*V in the direct graph, denoted $E$, which is represented by the ArrayList type in Java. The sequence of all concurrent transactions in the neighbourList is recorded. For example, the MS may receive a transaction request initially from transaction $T_1$ and then accept another request from $T_2$. Therefore, $T_1$ and $T_2$ are prevented from participating in the same group; they conflict and need to be added to the neighbourList.

Finally, when $T$ prepares to participate in the transaction, MS does not immediately perform subsequent logical operations but first enumerates all other transaction objects $T'$ that collide in parallel with $T$ and adds them to the neighbourList. The neighbourList is...
then loaded into the TCM to perform initial processing of these conflicting transactions, including aggregation and deduplication (Table 3). Finally, we save the neighbourList to the corresponding GraphNode.

**Commit phase**

After the begin phase, the conflicts of all transaction objects have been saved in the TCM and recorded in the corresponding GraphNode. The vertex data and the edge neighbourList belonging to the GraphNode have executed preliminary data aggregation processing. The TCM further aggregates the status of all transaction objects to preserve the latest version. As shown in the pseudo-code (Table 4), we first determine whether the status of the local T is BEGUN. If so, the status can be updated to COMMITTING and synchronized to the local GraphNode.

We now describe the judgement condition mentioned in the begin phase, that is, whether the transaction object T needs to be reordered. We first calculate the ancestor T_root of T, and then wait for the status of T_root to be set to COMMITTING or FINISHED. This is summarized in the following two situations:

- **T_root** is in the MS where T is located. The MS will eventually receive the transaction request of T_root through the TCM, and no additional operations are required to wait for the request.

- **T_root** is not in the MS where T is located. At this point, the MS needs to initiate an inquiry request to the MS’ where T_root is located. When the MS’ observes that the status of T’ is COMMITTING or FINISHED, it responds to MS and returns the GraphNode to the MS.

The while operation is performed in both cases until all ancestors’ statuses of the transaction object T in the MS are set to COMMITTING or FINISHED to jump out of the loop. We calculate the MS's strongly connected component (SCC) through the GraphNode. According to the definition of the SCC, in a directed graph GraphNode, for each pair of vertices V_i and V_j (V_i and V_j do not belong to the same vertex), it is guaranteed that there are paths from V_i to V_j and V_j to V_i.

We utilize the classic Tarjan algorithm [22] to calculate the SCC of the GraphNode. The core design is to maintain the graph based on the depth-first search (DFS) algorithm, and each SCC is a subtree in the search-tree. The nodes belonging to the DFS that are not traversed are added to a stack. When backtracking, we determine whether the top-to-middle node is a strongly connected component. In the best case, only the vertices of the SCC belonging to the GraphNode are traversed, thus the time complexity is no more than O(V). In the worst case, all the vertices and edges in the GraphNode need to be traversed in turn, with time complexity is O(V + E).

**Table 2** GraphNode data structure

| Algorithm 1  | GraphNode< T > |
|--------------|----------------|
| class GraphNode< T > | { |
| T data; | |
| List<GraphNode< T >> neighbourList; | |
| Boolean visited; | |
| } | |

**Table 3** Algorithm implementation of Begin phase

```plaintext
Algorithm 2 Begin
1: function Microservice MS: begin (t, GraphNode):
   # t stands for a transaction object.
2:   MS. GraphNode[t.group].status = BEGUN
3:   for t’ received by MS
4:     if t’ conflicts with t then
5:       add { t’.group → t.group } to MS. GraphNode
6:       merge and de-duplication in MS. GraphNode
7:     end if
8:   end for
9: return (MS. GraphNode, output )
```
The SCC of $T$ is simply referred to as $T_{SCC}$. If there are no conflicts with the MS, the $T_{SCC}$ contains only $T$ individual nodes. Otherwise, the following three conditions must be met.

- The MS sets the status update in all transaction objects belonging to $T_{SCC}$ to FINISHED.
- The MS waits for the status of other ancestors in GraphNode to be FINISHED.
- The MS waits for the visited in its associated ancestor $T_{root}$ to be TRUE.

When all of the above conditions are met, the MS determines the eventual order based on the global transaction number TID in each $T$.

The MS sets the field visited in each $T$ belonging to $T_{SCC}$ to TRUE; this is executed sequentially in the order in which they are arranged. Finally, the output is sent to the TCM, and the TCM then notifies the transaction initiators of the final execution result. We can determine the time complexity of algorithm 3 as $O(n*(V + E))$ in the worst case and $O(n*V)$ in the best case (where $n$ stands for the number of MSs).

### Table 4: Algorithm implementation of Commit phase

```
Algorithm 3  Commit
1: function Microservice MS: commit (t, GraphNode):
# t stands for a transaction object, t' stands for another
# transaction object, MS' represents the microservice that
# initiates the request to MS.
2: for t' received by MS
3:   if MS. GraphNode[t.group].status == BEGIN then
4:     MS. GraphNode[t.group].status = COMMITTING
5:   if t' is not belong to MS then
6:     MS request MS'
7:   end if
8:   if (MS'. GraphNode[t'.group].status == COMMITTING
9:     || MS'.GraphNode[t'.group].status == FINISHED) then
10:    MS' response to MS
11: end if
12: # The SCC was obtained through Tarjan, denoted t_info
13: t_info = getSscByTarjan (t)
14: if t_info conflict with MS. otherScc then
15:   if ( MS. otherScc.status == FINISHED &&
16:     MS. GraphNode[t. ancestor].status == FINISHED
17:     && t'.visited == TRUE ) then
18:   MS decide execution order on t in cache
19:   t.visited = TRUE
20: end if
21: end if
22: end if
23: return ( MS. GraphNode , output )
```

### Table 5: Algorithm implementation of SimplifyConflicts

```
Algorithm 4  SimplifyConflicts
1: function simplifyConflicts (t, GraphNode):
# t stands for a transaction object, t'->t is a LRCD.
2: for {t'->t} to GraphNode
3:   if GraphNode contains ( {t' => t} ).length >
   ( {t'->t} ).length then
4:     remove { t'->t} from GraphNode
5:   end if
6: end for

```
more rigorous version of the TLA+ language is available at [24].

**Constant**
We set the two invariants in the transaction to constants, i.e., the data of all transaction participants, denoted as value, and the participant transaction object, denoted as RM.

**Variable**
We represent all transaction status in RM as the variable rm_status. The current version sequence number is represented by the variable rm_v, which includes a collection of all the states of the transaction, i.e., “beginning”, “preparing”, “precommit”, “committed”, “cancel”). We define the global version sequence ascend_v, which is a snapshot and is always increasing. The information about two locks in RM that control the version, firstLock and secondLock, is represented by the variable rm_lock.

**Begin**
At this point, the transaction status rm_status is at “beginning” and its next state is expected to be “preparing”. The data rm_value in the transaction object is obtained by the getVal method.

**Loading**
At this stage, rm_status is in the “preparing” state and its next state is bound to be “precommit”. We determine whether the condition of resetting lock is met. If so, we then perform the resetLock process. Otherwise, the next state of rm_status is set to “cancel”.

**PreCommit**
We present the TLA+ language for the pre-commit phase of the transaction. At this point, rm_status is “precommit”, and we determine whether the second-commit of the transaction is performed, if so, ascend_v needs to be incremented, and next state of rm_v is restricted to be the latest value of ascend_v, and rm_status's next state is limited to “committing”. Otherwise, we need determine whether these transaction's values are all locked, if so, we perform the allLock method to lock all values. Otherwise, we set rm_status to “cancel”.

**SecondCommit**
Finally, we present the TLA+ language for the second-commit of the transaction. We determine whether the first value of the transaction can be committed, i.e., isCommitFirstVal, if so, we can commit the transaction and then set rm_status to “committed”. Otherwise, the transaction aborts and we set rm_status to “cancel”.

**Next**
The entire validation process follows the four steps above.

**Consistent**
Finally, we present the consistency constraint for the transaction. These two constraints are met: the version sequence number committed_v for all committed transactions satisfies the ascending ordering rule, and the lock of first_v in RM can be released when the transaction committed successfully.

We run the complete TLA+ language in the TLC [25] tool and analyze the result as shown in Fig. 1. It generates 1296 states, of which 324 is distinct. More importantly, based on the results, i.e., “No error has been found”, which can prove that the 2PC* protocol will not occur deadlock and ensure the strict serialization during the transaction process.

**Simplifying NeighborList of GraphNode**
As the number of transaction participant increases, the amount of data stored in the GraphNode becomes increasingly cumbersome, which significantly affects the subsequent workflow and potentially makes it unavailable. For example, the Trajan algorithm is used to calculate the SCC steps. However, much useless information
has been recorded in the Graph-Node, mainly related to the concurrent conflict dependencies of transaction objects, i.e., the neighbourList, which is irrelevant for the subsequent process. Moreover, it is unnecessary to transfer the entire GraphNode between micro-services. To solve these problems, we optimize the runtime protocol further.

LRCD design
To simplify the neighbourList belonging to the Graph-Node, only the least recent conflict dependence (LRCD) between transactions needs to be recorded Table 5. The LRCD is defined as follows: for any conflicting relationship path \( T' \rightarrow T \) in GraphNode, if the path \( T' \Rightarrow T \) does not exist in GraphNode, the number of paths \( T' \Rightarrow T \) is not less than two, and \( T' \rightarrow T \) is called an LRCD in GraphNode. According to the explanation in Fig. 2 below, \( T1 \rightarrow T2, T2 \rightarrow T3 \) is an LRCD, while \( T1 \Rightarrow T3 \) is not an LRCD; thus, \( T1 \Rightarrow T3 \) can be removed. The location of Table 5 Algorithm implementation of SimplifyConflicts

In the original protocol, the following three locations need to be simplified in the neighbourList and saved only as LRCDs:

- In the begin phase, the TCM received a response from the MS and then simplified the neighbourList that belonged to the response message.
- During the commit phase, the MS received a request from the TSM. The MS simplified the neighbourList in the request body with its local value.
- During the commit phase, the MS received an inquiry response from the other MS'. The MS' simplified the neighbourList in the request body with its local value.

Simplify MS swaps with GraphNode steps
For the MS and TCM corresponding to \( T \), we only need to obtain the GraphNode of \( T \). Therefore, the MS and TCM only need to obtain the SCC whose status is FINISHED and whose GraphNode contains all transaction objects.

Similarly, when the MS receives the query request from MS', the MS first detects the status of the GraphNode under the local environment. If the status is not FINISHED, we calculate the SCC for all the transactions contained in GraphNode belonging to the MS. Otherwise, if status becomes FINISHED, this means that \( T \) and its SCC have been obtained by the MS and its response is returned directly to MS'. The process is shown in pseudo-code in Table 6 below.

Fault tolerance
To achieve fault tolerance, we persisted the transaction logs in each coordination and transaction participant service to the disk. Moreover, we used the Paxos-based
replication protocol [26] to synchronize the log data across multiple machines.

First, we execute a scheduled thread-pool task, denoted as STPT. STPT polls the logs in the disk at intervals. It filters out the key information in the failed transactions, including the TID that identifies the transaction, and the list of participating transactions. Then, we push the information into a circle message queue (CMQ). Finally, the CMQ repeats the request to the corresponding business method through the asynchronous polling until the response returns successfully.

The CMQ design is shown above (Fig. 3), it is a circular message queue with a high latency and has 2000 slots. Each transaction compensation can be regarded as a task that is added to the Set without repetition, i.e., Set<Task>. We then push the Set<Task> into the tail of the CMQ. There are two key pieces of information stored in Set, i.e., layer_num and Function < Task>. The layer_num represents the number of CMQ layers in which the task resides, and the Function < Task > indicates the target function of the task. The CMQ uses a pointer to specify the index of the currently running task, denoted cur_index.

Reliability and idempotency

We use a local message table to record the relevant data of the transaction compensation task, which includes the TID for the transaction, and the current state of execution (i.e., status). To ensure reliability, The TCM returns the result of the asynchronous message with the field status record and sets it to TRUE if successful and FALSE if not. Then, the failed transaction steps need to be pushed to the next task queue until it is compensated for successfully. To ensure idempotency, the TCM determines whether the message is duplicated by the TID. If the TID already exists and its status is TRUE, this step is skipped. Moreover, the TCM provides a remote message record query interface, thus the transaction participant can invoke this interface to determine whether the current message has been consumed. If so, this compensation process is skipped.

Implementation

We implemented a middleware solution with transactional in distributed microservices support using 2PC*. We design the annotation @TxTransactional to inject distributed transactional functionality into specified microservices business with spring’s AOP (aspect oriented programming), which achieves decoupling from the original business module. Obviously, our prototype consists of three functional modules, i.e., transaction initiator, transaction actor, and transaction coordinator. In particular, their network communication is implemented through high-performance Netty framework.

![Fig. 3 The design of CMQ](image-url)
Transaction initiator
The role of the transaction initiator is an active part of the process. In addition to creating transaction group information and executing the local transaction, it also notifies the coordinator to perform commit or rollback operations on the transaction group (Fig. 4). The implementation process can be summarized as follows.

1) Generating the transaction group identifier TX_ID through the snowflake algorithm to ensure that it is unique in the entire distributed system, and then creating a new transaction group. If this step is successful, we can execute step 2. Otherwise, we just throw the runtime-exception and end the process.

2) We determine the transaction propagation mechanism type of the initiator. If it is PROPAGATION_NEVER, which means that there is no transaction requirement from the initiator. If it succeeds, we perform step 3. Otherwise, end the process. If the type of propagation is PROPAGATIONQUIRES_NEW, it means that the new transaction was initiated. We similarly execute the transaction group’s pre-commit process, and if successful, we perform step 4, otherwise, jump to step 5.

3) Following step 2 above, there is no transaction request in this initiator, and after performing the pre-commit, the coordinator is asynchronously notified to complete the second-commit. We adopt the CompletableFuture interface [27] provided by the JDK1.8. When these multiple threads attempt to complete or cancel it at the same time, only one thread is guaranteed to succeed. In practice, we use the runAsync, a method without a return value, to construct the initiator and coordinator as Netty transmission object in the asynchronous mode, then complete the second-commit’s notification step between the initiator and coordinator.

4) Similar to step 3, we also use the CompletableFuture to asynchronously notify the coordinator to execute the second-commit after the transaction group pre-commit succeeds. Because the transactional requirement of the initiator is newly opened, it must first commit the local transaction, thus we can adopt the PlatformTransactionManager (PTM) interface [28] provided by Spring to execute it.

5) In this situation, the transaction group failed during the pre-commit phase and the initiator’s transaction is newly opened. Then, we perform the local transaction rollback, executing the PTM’s rollback function and closing the process.

6) If some unexpected exceptions occurred in steps 4 or 5, as shown in the dotted box of Fig. 4. First, we use the PTM’s rollback function to complete the local transaction rollback. The coordinator is then asynchronously notified by CompletableFuture to complete the rollback of the transaction group.

Transaction actor
The transaction actor is a passive role in distributed transaction processing. Its main functions include adding the micro-service’s business module to the distributed...
transaction group and completing local transactions through the coordinator’s instruction (Fig. 5). The process of the transaction actor can be summarized as follows.

1) The actor joins the corresponding transaction group according to TX_ID. If the execution fails, the local transaction needs to rollback and then the process should be terminated. Otherwise, it initiates an add-to-transaction request to the coordinator. It’s similar to the initiator, the communication between actors and coordinators is also based on Netty.

2) At this point, the initiator’s thread is blocked. We use the interface provided in JDK called ReentrantLock to lock the main thread and wake it up in combination with Condition’s signal method. The initiator then waits for the coordinator’s response within the specified time threshold, denoted WAIT_TIME_OUT. If the response time is no more than WAIT_TIME_OUT, step 3 is executed directly. Otherwise, we need to perform step 6.

3) We then create a scheduled task to wake up the main thread at specified intervals within the time threshold denoted TASK_TIME_OUT. If this process is successful, the task can be closed and step 4 is executed. Otherwise, we need to skip to step 5.

4) Following step 3, the subsequent process is based on the coordinator’s response, which is obtained from the thread’s asynchronous callback function. If the response is second-commit, we first commit the local transaction, and then the output is asynchronously notified to the coordinator via Netty. Otherwise, the local transaction needs to rollback, and then also asynchronously notify the coordinator of the result through Netty.

5) Continuing with step 3, we repeat the scheduling task for the specified time TASK_TIME_OUT until it succeeds. Otherwise, a timeout occurs and the process can be terminated.

6) Next, following step 2, the coordinator’s response is timed out. The initiator needs to proactively obtain the transaction group’s status through Netty. If the status is either pre-commit or second-commit, the transaction group has successfully committed and then the actor sends the commit notification asynchronously to the coordinator. Otherwise, there are some exceptions have occurred in the execution, and actor can asynchronously send the timeout exception notification to the coordinator. Finally, we need to wake up the main thread that is blocked by the Condition’s signal.

7) If some exceptions occurred to the initiator during the process of the local transaction’s commit, as shown in the dotted box in Fig. 5, we should rollback this transaction and notify the coordinator asynchronously through Netty.

**Transaction coordinator**

The transaction coordinator is at the core of the hub in the distributed transaction processing. On the one hand, it deals with the corresponding business according to the notification requested by the initiator and the actor. On the other hand, it sends the instruction response to the
The process can be divided into the following steps.

1) With the `updateItemStatus` method of TMS, we update the current transaction’s status to COMMIT.
2) Through the `listByGroupIds` method in TMS, we obtain the list of all transaction objects under the current transaction group number TX_ID, denoted `items`. Determine whether the `items` are empty. If so, it can terminate the process. Otherwise, we execute the next step.
3) Following the above steps, we now perform specific preliminary filtering of `items`. The filtering principle is that we remove the transaction objects that have been committed by the initiator from the `items`, that is, avoiding duplicate the communication between these transactions. By the filter function, we divide `items` into a list of transactions under the local domain environment, denoted `currentItems`, and another list under other domains, denoted `elseItems`.
4) Detecting whether Netty’s channels of `currentItems` are activated. If so, we run the `executeCommit` method to commit the transaction, otherwise, run the specific `executeRollBack` method to complete the transaction rollback. The `executeCommit` and `executeRollBack` will be described later.

**ExcuteCommit**

This method applies to the distributed transaction’s commit process that is divided into the following steps.

1) First, we iterate through the list of local transaction groups to be committed, i.e., `currentItems`.
2) Then, we build Netty’s `ChannelBean` object and load it in the `HeartBeat`, and set the transaction status to COMMIT.
3) Determining if the channel in the `ChannelBean` object is empty. If so, we record the transaction object’s TX_ID in the Error log. Otherwise, pushing the `HeartBeat` to `Queue` and refresh it.
4) Finally, we execute the remote request method with the `elseItems` and set the transaction status to COMMIT. Because these coordinators are clustered, thus the channels in `elseItems`’ transaction objects may be connected to different coordinators. There are two functions in the remote request method. On the one hand, we observe the status of the transaction coordinator channel under the local domain and notify it to perform the transaction commit. On the other hand, we connect to the clusters of transaction coordinators under other remote domains and similarly notify them of committing transactions.

**ExcuteRollback**

It is responsible for the rollback process of distributed transactions, which can be roughly divided into the following steps.

1) First, we determine whether the `currentItems` are empty. If it matches, we just skip to the last step. We then load the list of transaction groups into the specified `ThreadPool`, i.e., `CompletableFuture`, which asynchronously performs the tasks of the subsequent multi-transaction groups. To achieve this, we then execute the asynchronous method in the `CompletableFuture`, i.e., `runAsync`. Meanwhile, we build the Netty’s `ChannelBean` object, load it into a `HeartBeat`, and set status to ROLLBACK.
2) Determining if the channel exists in the `ChannelBean`. If not, we just skip this step, otherwise, execute the `writeAndFlush` method for `ChannelBean’s` channel. Finally, we can push the `HeartBeat` object to `Queue` and refresh it.
3) Until all transaction objects have been loaded into Netty’s channel and have been executed asynchronously through `CompletableFuture`. At this point, we execute the `allOf` method, which can acquire the execution result of all transaction objects.
4) Finally, the approach is roughly similar to the last step in ExecuteCommit. The only difference is that we set the transaction status to ROLLBACK and perform the transaction rollback.

Evaluation
Experimental setup
In order to minimize the extra impact of CPU’s performance bottlenecks on the experiment, we chose higher performance machines to build service clusters. Each machine has an eight-core 2.7 GHz Intel Core i7 with 8GB RAM and 500GB SSD. Therefore, we have achieved much higher throughput when running on a local testbed with faster CPUs.

Experimental case
We applied our middleware solution based on 2PC* to the microservice case, that is, the online e-commerce transaction platform MSECP of an Internet company. In this paper’s experimental case, we primarily consider three microservices, i.e., the OrderMicroservice (COMS), the StockMicroservice (CSMS), and the AccountMicroservice (AMS). The distributed transaction process between the microservices can be summarized as follows (Fig. 6): A user initiates an order creation request from COMS, which then invokes CSMS and AMS through an RPC to complete the business of item out-bound and account deduction, respectively. Only when the business of these three microservice modules is successfully executed can we return a successful response to the user and commit transactions in the respective microservice modules. Otherwise, if exceptions occurred in one of these micro-services, the user is notified that the purchase failed; thus, the transactions of the respective microservices need to be rolled back immediately.

We adapted the middleware solution to two popular micro-services frameworks, i.e., Spring Cloud and Dubbo. In this section, we only present the experimental case of Dubbo, whose overall architecture is shown in Fig. 7. We adopted Dubbo to implement the three microservice modules, i.e., COMS, CSMS and AMS, which deployed three physical machine clusters for each module. They completed the service registry on the Zookeeper [30] and used the Nginx [31] server to complete the service’s reverse proxy. To ensure the high availability of the coordination service (denoted as CS), we adopted Eureka [32] to achieve service registry and service renewal and transferred the transaction entities to the cluster-ed Redis database. In particular, the network communication between the CS and multi-microservice modules is based on Netty’s persistent connection.

Functional experiment
In this subsection, we design a specific test case with high randomness and a wide range to prove the functional reliability of our middleware solution with distributed transactions in the multi-microservice modules, which can be described as follows.

- In COMS, the unit-price of item is randomly generated between $100 and $10,000, and the order number is set to be randomly generated between 1 and 1000, and the quantity purchased by the user is randomly generated between 1 and 100. We initialize the account balance in AMS to be $0, and the amount of stocks in CSMS to be 0.
- In COMS, CSMS, and AMS, we embed a runtime exception to abort the transaction process in the business code for order numbers 100, 200 and 500, respectively.
- Then, we continuously invoked the createOrder API interface, making a total of approximately 50,000 calls.

Fig. 6 A case of Ctrip MSECP
Finally, we determined that the data-consistent distributed transaction in this case should meet the following two conditions: the sum of the order amount and the account balance should be 0, and the sum of the order quantity and stock quantity should be 0.

According to the five groups of experimental results shown in Table 7 above, the createOrder interface was called approximately 5000 times, and its orders were successfully created approximately 2,450,000 to 3,180,000 times. More importantly, all experimental data met the above two conditions, i.e., Order amount + Account balance = 0; Order number + Stock number = 0. Therefore, our scheme is able to achieve consistent distributed transactions for multiple applications involving microservices.

Performance experiment

In this section, the evaluation of our scheme explores three key questions:

1) How does the throughput and latency of the optimized 2PC* compare with the traditional 2PC approach at varying levels of contention across microservices?
2) Can 2PC* guarantee its commit rate under the scenario of high-level contention?
3) Can our optimization scheme compensate for failed transaction steps?

Throughput

In this experimental case, we evaluated the throughput performance of our scheme through the indicators of TPS (transactions per second). We compare the TPS of the optimized protocol 2PC* and 2PC and adopt the number of local transactions of the database (i.e., Mysql) as a reference. We ran 10, 20, 50, 100, 200, 300, and 500 concurrent threads to call COMS's CreateOrder interface, and each thread executed 10 comparison experiments. Finally, we calculated and recorded the TPS averages.

Table 7: Data consistency experiment results

| No. | Call times | Order amount   | Account balance | Order number | Stock number |
|-----|------------|----------------|-----------------|-------------|-------------|
| 1   | 50,142     | 24,842,305,224 | −24,842,305,224 | 2,850,098   | −2,850,098  |
| 2   | 51,203     | 27,514,201,548 | −27,514,201,548 | 3,183,214   | −3,183,214  |
| 3   | 50,893     | 22,870,237,842 | −22,870,237,842 | 2,581,249   | −2,581,249  |
| 4   | 50,071     | 24,847,024,109 | −24,847,024,109 | 2,708,291   | −2,708,291  |
| 5   | 50,019     | 23,787,312,291 | −23,787,312,291 | 2,457,219   | −2,457,219  |
Through the experimental data shown below (Fig. 8), when the number of concurrent threads is between 20 and 50, the distributed transactions are under low-level contention. Compared with 2PC, the 2PC* protocol has no significant advantage in terms of the TPS metric. However, when the number of concurrent requests increases from 50 to 100, the contention of the distributed transactions increases from low to moderate, and the performance gap between 2PC* and 2PC gradually widens. At this point, when the number of concurrent threads is between 100 and 200, the TPS of 2PC* can still be maintained at a relatively optimistic level, i.e., 670.3 and 552.8 new transactions/s, respectively, while 2PC’s TPS is reduced to 391.6 and 324.5, respectively. Compared to transactions from the local database, 2PC*’s TPS drops by ~32.7% when the number of concurrent requests is 200, while 2PC’s drops by ~60.5%; the throughput of 2PC* improved by ~70.4% compared to the original approach under moderate contention.

In the scenario with high-level contention, i.e., when the number of concurrent requests is from 300 to 500, 2PC* shows significant advantages. Under the scenarios with 300 concurrent requests, 2PC*’s TPS reduces to 401.5 new transactions/s, which is still half the performance of the local transactions, while 2PC’s TPS reduces to only 92.6. In particular, when the number of concurrent requests peaked at 500, the throughput of 2PC reached a performance bottleneck, while our scheme could still scale out. As the experimental data show, the transaction throughput performance of 2PC* is still quite high compared to that of 2PC; the TPS values are 304.6 new transactions/s and 12.7 new transactions/s, respectively. We abandoned the low-performance synchronous blocking lock in the control of transaction resources and replaced it with a novel second-level asynchronous lock, i.e., the SAOL, which can greatly reduce the blocking caused by the surging number of transactions; this is the key factor in the obvious advantage of the TPS performance of 2PC*.

In summary, our scheme has a significant improvement of throughput compared to the traditional approach, especially in scenarios of high-level contention. In other words, when the number of concurrent requests from users reaches a peak, the throughput of 2PC* can still maintain excellent performance, and it can be applied to highly concurrent requests for microservices with distributed transactions.

**Latency**

Transaction latency is another key indicator in our evaluation. We adopt the service’s RT (response time) parameter to evaluate the latency performance of 2PC*. Similar to the experimental case in the “Throughput” sub-section, we ran 10, 20, 50, 100, 200, 300, and 500 concurrent threads to call COMS’s CreateOrder interface, performed 10 comparison experiments for each thread and calculated their RT averages. Through the analysis of the experimental results (Fig. 9), when the transactions are under low-level contention, i.e., the number of concurrent requests is between 20 and 50, 2PC*’s RT has no obvious advantage compared with that of 2PC; for example, when the number of requests reaches 50, our scheme only reaches 18.3% improvement. The RT of 2PC is more sensitive to the increase in contention. When the number of concurrent requests grew to 200, the transactions reached moderate-level contention, and the latency of 2PC* achieved a significant performance advantage. In detail, when the number of concurrent requests reaches 100, the RT of 2PC* is only half that of 2PC. Compared to the original businesses’ RT value, our scheme drops by ~39.6%. The latency superiority of 2PC* under high
contention becomes more obvious. When the number of concurrent requests reaches 300, the RT of 2PC is 823.7 ms, which is 2.89 times that for the original business, while our scheme only increases to 401.5 ms. In particular, when the contention reaches its peak, 2PC is no longer suitable for the distributed transaction across microservices because its RT surpasses one second; it is 1352.7 ms. 2PC* is less sensitive to the increase in contention; the RT drops by ~33.4% with the original business and the latency is reduced by more than half compared with that of 2PC.

Similar to TPS, the factors affecting RT performance are closely related to the blocking rates between transactions. In the runtime protocol, 2PC* adopts an optimization algorithm based on a directed graph to aggregate and reorder the dependencies between transactions, which is able to reduce the conflict probability and avoid deadlocks and aborts between transactions. Additionally, the specific implementation utilizes the persistent connection network communication mode of the Netty framework, and we choose asynchronous threads in the coding; these are the key factors that show the obvious advantages of our proposed scheme in the experimental results of latency.

In summary, 2PC* demonstrates a better latency performance with high-level contention than the traditional approach. Moreover, under the high-concurrency business scenario of microservices, our scheme can create less overhead due to latency.

Committing rate
In the three cases of low, moderate, and high contention, we evaluate the transactions’ commit rate under our scheme. As shown in Fig. 10, 2PC* guarantees that the transactions are committed successfully even when the number of concurrent requests reaches a peak, while 2PC cannot be extended. When the transactions reached high contention, 2PC’s commit rate dropped to almost zero—from 0.31 to 0.03.

Under the scenario with 500 concurrent requests, we count the instances of each of the three states of the transaction, i.e., RUNNABLE, WAITING and BLOCKED. We then calculate their blocking rates. According to Fig. 11, the blocking rates of 2PC* and 2PC both peaked at 450 ms and were 31% and 97%, respectively; thus, 2PC* is more than 3 times better than 2PC in terms of the committing rate. At this point, almost all threads in 2PC were blocked, which is the key reason for its commit rate almost reaching zero. 2PC* is also affected by the increase to high-level contention, although it is less sensitive than 2PC because it avoids aborting and retrying transactions. Compared with the traditional approach, 2PC* improves the performance of transaction committing by 3 to 4.5 times.

Transaction compensation
We continuously request the CreateOrder interface in the weak network environment with 100 concurrent threads, for which the running time is 30 s. As shown in the experimental data (Fig. 12), the transactions under 2PC* and 2PC occurred with 23,853.6 and 21,976.1 exceptions, respectively. We then recover the network environment and perform the transaction compensation process.

Our scheme can continuously compensate for exceptional transactions, which takes less than 3 s in total. 2PC* can be maintained at approximately 4831.4 groups per second, while 2PC has little ability to compensate. Based on BASE theory, 2PC* uses the CMQ asynchronously to compensate for these failed transaction steps. In other words, it improves the fault tolerance of the system, which is also essential in large distributed systems, such as microservices.
Deployment and operations in cloud platform

Finally, we deployed our middleware solution in Ctrip’s intelligent PaaS (Platform as a Service) cloud platform [33], called CPaaS Fig. 13. Its core includes three basic modules, namely, the big data platform, microservice application platform and application integration platform. The microservice business is deployed in the microservice application platform. Meanwhile, application performance monitoring is responsible for managing the monitoring of the service interfaces. More importantly, our transactional middleware is deployed in the application integration platform, which is responsible for the distributed transaction control of microservices deployed in the CPaaS platform.

Through the monitoring system of the CPAAS cloud platform, we obtained the performance data of our scheme over 3 months. The results are shown in Table 8 below. TPS can be maintained at ~700 new transactions/s with an RT of no more than 96 ms. Most importantly, the transaction commit rate is always 100%, and transaction compensation can be successfully completed. Therefore, the long-term monitoring results prove that our scheme is stable and has universal applicability in cloud computing.

Related work

In academia and industry, much of the recent work is still focused on transaction concurrency control using 2PC combined with OCC in distributed databases, such as H-Store [32], VoltDB [34] by Michael and Samuel et al. In both H-Store and VoltDB, where data is assigned to different partitions according to specific rules, one of the great contributions of H-Store is that most transactions can be performed in a single partition, thus greatly reducing the additional overhead of concurrency control. For example, H-Store can avoid the overhead of concurrent protocols with single-thread model for absolute single-partition transaction. It can supplement a few cross-partition transactions with the lightweight concurrency protocol [35] to ensure possibility of serializability. However, as we have mentioned in this paper, these distributed databases can only be applied to the single database and cannot be extended across...
multiple microservices, while 2PC* improved this function.

The multi-data-center consistency (MDCC) proposed by Tim Kraska et al. [36] used a commit method based on optimistic control, which was frequently used for storage across data centers. Therefore, MDCC does not require a global master node or a static data partitioning approach, and provides additional overhead similar to the design of eventual consistency. MDCC is based on Generalized Paxos [37] design, combined with Commutative Operations support. Therefore, MDCC performs better than any synchronous commit method. The reason is that it requires only single message to commit most transactional requests between multiple data centers.

Google’s proposed Percolator [2] adopts OCC to support Snapshot Isolation [38]. Percolator compensates for the lack of batch processing of document updates in systems such as MapReduce [39]. It supports incremental document processing and has been deployed by Google in its internal web search system. To improve throughput, Percolator allows multiple clients to fetch documents simultaneously, and to provide isolation between different clients, it uses 2PC combined with MVCC for transaction support. Percolator has improved the timeliness of Google web search results by 50% since Google deployed it. The SAOL locking mechanism in 2PC* is also borrowed from the Percolator’s design. SAOL uses the snapshot to breaking down locks in transactions into multiple levels of optimistic control, thereby reducing the blocking overhead of synchronous locks in a transaction.

In the Sinfonia [40] system built by Marcos K Aguilera et al., the concept of Min Transaction was innovatively
proposed, and its transaction implementation was also based on the 2PC protocol. Min Transaction is performed by locking the access object in the first phase of the Transaction and then committing it in the second phase. Sinfonia perfected the 2PC mechanism and came up with the concept of 1PC so that a single message exchange could commit the entire transaction for the coordinator. Unfortunately, the 1PC protocol of the Sinfonia is not able to be scaled for multiple microservices, as microservices often exist in the form of cross-projects and cross-resources, which is the reason that 2PC* is still based on the two-phase commit protocol. Andrei Furda et al. migrated microservices into the cloud computing environment and addressed several key issues in the process, one of which was data consistency [41]. That is, the challenges encountered in migrating legacy code runs can be summarized as operating decentralized data repositories from a centralized data repository to the microservices. Guy Pardon et al. studied the BAC theorem (backup, availability, and/or consistency) [42], which is an effective solution for the consistent disaster recovery for microservices, and is inspired by the CAP theorem. We also improved the fault tolerance of the 2PC* protocol, which is similar to the even-tual consistency they proposed, except that we borrowed from the BASE theory.

Zhang et al. proposed GRIT’s distributed transaction model across microservices [3], which utilizes deterministic database technology and OCC to process data consistently. During the execution phase, transactions are optimally executed by capturing their read and write operations. Then, at commit time, this method performs a conflict check and makes a global commit decision. Logically committed transactions are first transferred to the log and then executed asynchronously to carry out the database business. GRIT works at the procedural language level of the different databases, and 2PC* also adopts OCC’s optimistic control, but we focus on transaction concurrency optimization and data consistency constraints.

Conclusion
This paper proposed 2PC*, a novel concurrency control protocol for distributed transactions in microservice modules. For this purpose, we designed a novel secondary asynchronous optimistic lock, which can avoid the locks that are held in the transaction process. 2PC* utilizes a novel transaction concurrency control protocol, which is able to reduce the probability of concurrent conflicts among multiple transactions. Compared to the original 2PC, 2PC* can extract greater concurrency across multiple microservices. Finally, we implemented a middleware prototype based on 2PC* and applied it to a case of Ctrip MSECP deployed in the CPaaS cloud platform. The experimental results demonstrate that in high-level contention scenarios, our scheme has a higher throughput and lower latency than 2PC. Additionally, through long-term application performance monitoring by the CPaaS cloud platform, our scheme effectively supports distributed transaction concurrency control in a multi-microservice system.

In addition, we intend to continue some of our research in future work. We will adapt our scheme to some microservice frameworks in addition to Spring Cloud and Dubbo, which were discussed in this paper. As cloud computing becomes more popular, we can deploy it in DevOps [43, 44] in the PaaS [33, 45] cloud platform. In the IoT (Internet of Things) [27, 29], where cloud computing takes place, our scheme can also be extended. We also need to improve the QoS (quality of service) [29, 46] of microservices under various scenarios for mobile social networks [47] and hybrid networks [48] in the future.

Table 8 Data consistency experiment data

| No. | Date    | TPS (new-transactions/s) | RT (ms) | Commit Rate | Compensation |
|-----|---------|--------------------------|---------|-------------|--------------|
| 1   | August  | 680.5                    | 95.8    | 100%        | 984          |
| 2   | September | 701.3                   | 89.3    | 100%        | 879          |
| 3   | October | 692.7                    | 98.5    | 100%        | 1034         |

Abbreviations
- 2PC: Two-phase commit; OCC: Optimistic concurrency control; MVCC: Multi-version concurrency control; TCM: Transaction coordination manager; RPC: Remote procedure call

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Authors’ contributions
Pan Fan designed and developed the proposed protocol as well as implemented the middleware solution based on cloud computing platform. Jing Liu directed working research and paper writing, and gave the experimental scheme. Wei Yin and Hui Wang provided experimental environments and designed use cases. Xiaohong Chen and Haiying Sun gave guidance on the grammar and abstract of this paper. The authors read and approved the final manuscript.

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Availability of data and materials
The full experimental data and the description of the experiment setup are provided in this manuscript in section Evaluation and our github, https://github.com/Leofan93/2pc-star.

Competing interests
The authors declare that they have no competing interests.

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