

Failure Resilient Distributed Commit for Web Services Atomic Transactions

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Abstract—Existing Byzantine fault tolerant distributed commit algorithms are resilient to failures up to the threshold imposed by the Byzantine agreement. A distributed transaction might not commit atomically at correct participants if there are more faults. In this paper, we report mechanisms and their implementations in the context of a Web services atomic transaction framework that significantly increase the probability of atomic commitment of distributed transactions even when the majority of coordinator replicas become faulty. The core mechanisms include a piggybacking mechanism, which limits the way a faulty coordinator replica can do to cause confusion among correct participants, and a voting mechanism, which enables fast agreement on the transaction outcome under fault-free situation, and ensures that the agreement is based on the messages from correct replicas with high probability even if all but one coordinator replica becomes faulty. Our performance study on an implemented prototype system shows only 10% end-to-end runtime overhead under both fault-free and faulty scenarios. This proves the practicality of our mechanisms for use in real-world Web-based transactional systems.

Index Terms—Distributed Transaction, Two Phase Commit, Web Services, Fault Tolerance, Byzantine Agreement, Digital Signature.

I. INTRODUCTION

Any transaction that spans across multiple sites requires a distributed commit protocol to achieve atomic commitment. The two-phase commit (2PC) protocol is the most widely used distributed commit protocol in practical systems. The 2PC protocol is designed with the assumptions that the coordinator and the participants are subject only to crash fault, and the coordinator can be recovered quickly if it fails. Consequently, the 2PC protocol does not work if the coordinator is subject to arbitrary faults (also known as Byzantine faults) because a faulty coordinator might send conflicting decisions to different participants. This problem is first addressed by Mohan et al. in [17] by integrating Byzantine agreement and the 2PC protocol. The basic idea is to replace the second phase of the 2PC protocol with a Byzantine agreement process that involves with the coordinator, all the participants, and enough number of redundant nodes.

Such Byzantine agreement based protocols can tolerate up to f faulty members with $2f+1$ total members in synchronous systems, or $3f+1$ members in asynchronous systems. If there are additional Byzantine faults, either no agreement can be

reached, or a wrong value is agreed upon. Even if the additional faults are crash-only faults, the protocols would block until the faulty members recover. That is, these protocols are not resilient to failures beyond their fault models. However, in practical systems, there is no guarantee that the number of faults will be within the limit that the Byzantine agreement requires. Secondly, all transactions must incur the cost of Byzantine agreement, even when there is no fault. The high overhead perhaps is the main reason why these protocols are not adopted in practical systems.

In this paper, we propose a set of mechanisms that protects the data integrity of all correct participants despite arbitrary fault in the coordinator for distributed transactions. To tolerate the potential crash and Byzantine faults, the coordinator is replicated and a novel voting mechanism is used to select the output from correct replicas. The coordinator also keeps an audit log of the votes from all participants to discourage dishonest participants.

The main novelty of our design is the minimized runtime overhead and the increased failure resiliency of distributed commit under Byzantine faults. This is achieved by a piggybacking mechanism and a failure resilient voting mechanism. According to the piggybacking mechanism, each message disseminated by a coordinator is attached with a unforgeable and verifiable security token that significantly limits the ways a faulty coordinator replica can do to send conflicting information to the participants. Under the fault-free condition (which happens most frequently we believe), the prepare and commit messages carry conclusive information, which enables immediate delivery of these messages without going through a lengthy voting process.

A voting process is needed only for the abort messages that carry inconclusive information. To increase failure resiliency, the voter does not rush to a decision when it has received similar inconclusive abort messages from the majority of the coordinator replicas. Instead, it waits until one of the three conditions are satisfied: (1) a message with conclusive information has arrived; (2) it has received messages from all coordinator replicas; (3) a timer set for the transaction expires. This voting mechanism minimizes the probability of making a wrong decision based on the input from faulty coordinator replicas when they become the majority. As long as the correct coordinator replica sends its decision to all correct participants before the timeout, the transaction is guaranteed to be committed or aborted atomically among correct participants.

The remaining of the paper is organized as follows. Section II describes the system models. Section III presents the core failure resiliency mechanisms. Section IV describes the

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implementation details for the distributed commit framework for Web services. Section VI provides an overview of related work. Section VII summarizes this paper and points out future research directions.

II. SYSTEM MODELS

A. Architecture Model

We consider a Web portal that offers a set of Web services. These Web services are in fact composite Web services that utilize Web services provided by other departments or organizations. We assume that an end user uses the composite Web service through a Web browser or directly invokes the Web service interface through a standalone client application. In response to each request from an end user, a distributed transaction is started to coordinate the interactions with other Web services.

Furthermore, we assume a flat distributed transaction model for simplicity in our discussions. We believe that it is relatively straightforward to extend our mechanisms for a hierarchical transaction model. Each distributed transaction has an initiator (*i.e.*, the composite Web service that the user invokes directly), a coordinator, and one or more other participants. The initiator is regarded as a special participant. In later discussions we do not distinguish the initiator and other participants unless it is necessary to do so.

We assume that the transaction coordinator runs separately from the participants, and it is replicated in several different nodes. In this paper, we assume that the transaction initiator and other participants are not replicated for simplicity. There is no reason why they cannot be replicated for fault tolerance.

B. Fault Model

The coordinator has N replicas and at least one replica remains to be correct. The safety of the two-phase commit is guaranteed only when the number of faulty replicas is less than $N/2$. If the number of faulty replicas exceeds this threshold, the atomicity of a distributed transaction might be violated, but only in very rare cases (we will discuss this further in later sections). The coordinator replicas are subject to arbitrary fault. The same assumption is made for the transaction initiator and other participants, except that they always multicast the same message (including the vote to commit or abort) to all coordinator replicas. This assumption is not as restrictive as it seems to be, *e.g.*, we can easily ensure this property by replicating the transaction initiator and other participants and performs a majority voting at each coordinator replica. Furthermore, most well-known Byzantine fault tolerance frameworks [1], [8], [9], [24] have similar assumption on the clients.

We assume that the coordinator and the transaction participants fail independently. Furthermore, a failed coordinator replica does not collude with any failed participant (including the initiator). We do, however, allow failed coordinator replicas to collude.

All messages between the coordinator and participants are digitally signed. If confidentiality is needed, messages can be further encrypted. We assume that the coordinator replicas and

the participants each has a public/secret key pair. The public key is known to all of them, while the private key is kept secret to its owner. We assume that the adversaries have limited computing power so that they cannot break the encryption and digital signatures.

C. Threat Model

In this section, we enumerate the threats that a compromised coordinator and a participant can impose to the problem of distributed commit.

A Byzantine faulty coordinator can

- Refuse to execute part or the whole distributed commit protocol by not sending or responding with the intention to block the execution of a distributed transaction.
- Choose to abort some transactions despite the fact that it has received a yes-vote from every participant. To do this, the coordinator omits some of the digitally signed yes-vote and pretends that it has timed out those participants. Note that a coordinator cannot fake a commit decision if it does not receive a yes-vote from every participant.
- Send conflicting decisions to different participants. The coordinator can do this only if it has received yes-vote from every participant because it is obliged to piggyback all the yes-votes with a commit decision. To fake an abort decision, it has to omit the vote from some participants. The intention is to corrupt the data integrity of correct participants.
- Execute the distributed commit protocol correctly for some transactions. In this case, the coordinator behaves like a correct coordinator.

A Byzantine faulty participant can

- Refuse to execute part or the whole distributed commit protocol by not sending or responding, this can cause the abort of transactions that it involves.
- Vote abort but internally prepare or commit the transaction.
- Vote commit but internally abort the transaction.

As can be seen, a fault participant cannot disrupt the consistency of correct participants as long as the coordinator is correct. To deter malicious participants, the coordinator keeps an auditing log and records all the votes from all participants. The logged information can be used to hold a faulty participant accountable for lying. For example, if a participant refused to ship a product that it has promised to do, the user and other participants can sue it using the logged vote record from that participant.

III. FAILURE RESILIENT DISTRIBUTED COMMIT

Traditional Byzantine fault tolerant algorithms, if applied to the distributed commit problem, require at least $2f+1$ coordinator replicas to tolerate f faults. If the number of faulty replicas exceeds f , either no agreement can be reached, or a wrong value may be decided. If the majority of coordinator replicas become faulty and they collude together, they can *always* break the safety of the distributed commit by convincing some correct participants to commit and some other to rollback the transaction.

In this section, we introduce failure resiliency mechanisms that can significantly increase the safety of distributed commit even when all but one coordinator replica become faulty. Note that we do not guarantee 100% safety in this situation due to the possible race conditions (to be discussed in detail later). But for all practical purposes, the risk of violating the transaction atomicity among correct participants can be neglected.

A. Piggybacking Mechanism

In the 2PC protocol, the coordinator might send three different messages to the participants: prepare, commit and abort. Each message carries an unforgeable security token to be verified by the receiver, *i.e.*, the participant. If the piggybacked token contains conclusive information that the message must come from a correct replica, the message is delivered immediately without resorting to voting.

This mechanism significantly restricts what a faulty coordinator can do to compromise the atomicity of a distributed transaction. A similar piggybacking idea is first mentioned in [17]. However, it is not being exploited to increase the failure resiliency of distributed commit and a full Byzantine agreement process is still used for each transaction among all coordinator replicas and transaction participants.

Prepare message. The coordinator can send a prepare message to a transaction participant only after the transaction initiator has asked the coordinator to commit the transaction. Each prepare message carries a prepare-token. The token contains the transaction identifier and the original commit request. The token is signed by the transaction initiator, and therefore, is not forgeable by any coordinator replica. The prepare message together with the piggybacked prepare-token are signed by the coordinator replica to prevent alteration of the message during transit, and to ensure the nonrepudiation property.

Upon receiving a prepare message, the mechanism checks if a prepare-token is attached and verifies the token if one is found. The message is discarded if no such token is found or the token is invalid. A prepare message that possesses a valid prepare-token is delivered immediately without voting. A valid prepare-token must pass the following test:

- 1) The signature is valid (it is signed by the initiator).
- 2) The token contains a commit request.
- 3) The transaction identifier in the token must refer to a current transaction.

Note that the coordinator cannot reuse the prepare-token for a different transaction because the transaction identifier would be different.

Commit message. The coordinator can send a commit message only if it has received the yes-vote from all participants. Each vote record consists of a transaction identifier and the vote itself and is signed by the participant that placed the vote. The commit-token is valid if

- 1) It contains the vote records of all participants, including the commit request from the initiator.
- 2) The signature of each vote record is valid.
- 3) All the votes are yes-vote.

- 4) The transaction identifiers in the vote records are identical and match the identifier for the current transaction.
- Again, a commit message with a valid commit-token is delivered right away because the valid commit-token carries conclusive information that it must have been sent by a correct coordinator replica.

Abort message. A correct coordinator may send an abort message in the following two scenarios:

- 1) The transaction initiator decided to abort the transaction.
- 2) The coordinator timed out some participants, or some participants have voted to abort the transaction.

The abort message sent in scenario 1) happens during the first phase of the distributed commit (there will be no 2nd phase in this case). Such an abort message carries an abort-token similar to the prepare-token. The only difference is that it now contains an abort request from the initiator. The abort message sent in scenario 2) happens during the second phase of the distributed commit. The abort-token should contain a set of records similar to those in the commit-token, one for each participant that has responded to the prepare request, including the initiator. In fact, the abort-token in both scenarios takes the same form: A set of signed vote records from the participants.

The token verification process contains the following steps:

- 1) Check if the signature of each vote record is valid.
- 2) Match the transaction identifiers in each vote record with the identifier for the current transaction.
- 3) Check if the token contains at least one no-vote, or there is at least one missing vote from some participant because a correct coordinator is obliged to commit a transaction if it has collected yes-vote from every participant. It is possible that the abort-token carries no vote record at all, for example, if the transaction initiator fails before it sends a commit/abort request to the coordinator.

Unlike the tokens in the prepare and commit messages, a valid abort-token in an abort message might not carry conclusive information, in which case, immediate delivery of the abort message will not be possible. A valid conclusive abort-token is one that contains at least one no-vote. Note that a faulty coordinator replica can abort a transaction only by omitting votes from some participants if in fact all participants have voted to commit the transaction.

The immediate benefit of using this mechanism is fast distributed commit because the voting process is avoided in most cases. However, the piggybacking mechanism by itself does not increase the failure resiliency. The failure resiliency is taken care of by a voting mechanism, which will be elaborated below.

B. Voting Mechanism

The piggybacking mechanism prevents a faulty coordinator from sending conflicting decision messages to different participants without being detected, if some participants voted to abort the transaction, or indeed has failed (no response). This is because a commit decision message must carry a token with a complete set of yes-vote and there is no way a faulty coordinator replica can fabricate a yes-vote without knowing

the private key of the corresponding participant. This is true as long as the faulty coordinator does not collude with any participant, which is our assumption.

Therefore, a faulty coordinator replica can possibly disseminate conflicting decisions to the participants (without being caught) only when all participants have voted to commit a transaction. There are only two “legitimate” ways to do so:

- 1) The faulty replica sends a commit decision to some participants, but an abort decision to some other by falsely claiming that it did not receive the vote from one or more participants. In fact, the faulty replica could send the abort decision to a subset of participants as soon as the distributed commit starts without going through the first phase.
- 2) The faulty replica sends a commit decision to some participants, but nothing at all to some other participants, hoping that the subset of participants that does not receive a decision to indefinitely hold valuable resources for the transaction, or the participants to unilaterally abort the transaction due to a timeout.

Note that the abort decision message sent by a correct coordinator replica due to the timeout of a participant should come much later than the beginning of the first phase of the distributed commit. If a participant indeed has failed, the voting process (on the decision message) at other participants will inevitably take a long time because no decision messages carry a conclusive token and consequently, no fast delivery can be made if all coordinator replicas are correct.

However, if the majority of the replicas become faulty, they could attack the mechanisms that rely on a simple majority voting algorithm by sending false abort messages to some participants as soon as these participants have responded with a yes-vote in the first phase of the distributed commit, as mentioned in case 1). If the simple majority voting algorithm were to be used, such an attack would succeed in causing a nonatomic commitment of the distributed transaction. Consequently, the simple majority voting algorithm must be abandoned to achieve better failure resiliency. In the following, we describe a more robust voting algorithm that can counter such attacks.

Let T be the timeout parameter for a coordinator to timeout a participant, and T_{voting} be timeout parameter used by each participant for the voting process. The voting timer T_{voting} is set to at least $3 * T$ to allow unpredictable network and processing delays so that the commit message, if any, from a slow but correct coordinator replica has a reasonable chance to reach the participant by the timeout of the voting process. (The delay can also be caused by a slow participant.) A participant starts a voting timer when it receives the first legitimate abort message that carries an inconclusive vote token. (The timer is not started if a participant receives a valid abort or commit message that carries a conclusive vote token, because the message can be delivered right away without going through the voting process.) If the participant receives a decision message containing a conclusive token, it cancels the timers and commit or abort the transaction according to the conclusive decision message. If the participant has collected the decision messages from all coordinator replicas before the voting timer expires

(apparently all these decision messages contain inconclusive information), it cancels the timer and abort the transaction (recall that any valid commit message must carry a complete yes-vote set, which will be delivered immediately without voting). When the voting timer expires, the participant stops collecting decision messages and aborts the transaction.

This novel voting algorithm virtually eliminates the possibility of nonatomic distributed commit with a reasonable large voting timeout. However, due to the asynchrony of the distributed computing environment, some rare race condition could happen. For example, the commit message from a slow coordinator replica reaches some participants *before* the voting timer expires, but reaches other participants *after* the timer expires.

IV. IMPLEMENTATION

We have implemented the failure resiliency mechanisms and integrated them into a distributed commit framework for Web services in the Java programming language. The architecture of the failure resilient distributed commit framework is shown in Figure 1. The framework is based on a number of Apache Web services projects, including Kandula (an implementation of the Web Services Atomic Transaction Specification) [4], WSS4J (an implementation of the Web Services Security Specification) [5], and Apache Axis (SOAP Engine) [3]. Most of the failure resiliency mechanisms are implemented in terms of Axis handlers that can be plugged into the framework without affecting other components. Some of the Kandula code is modified to enable the control of its internal state and to enable voting. The failure resiliency mechanisms consist of approximately 4000 lines of code.

In this section, we first introduce the architecture and the normal operations of the distributed commit framework as implemented in the Apache Kandula Project. This will provide the necessary background information for further discussions. Next, we describe the main components that implement the failure resiliency mechanisms. Finally, we discuss a number of important system-level issues related to integrating the failure resiliency mechanisms into the distributed commit framework, including reliable multicast, replica non-determinism control, and the recovery of coordinator replicas.

A. Distributed Commit Framework for Web Services

The distributed commit framework provides a coordination service for atomic distributed transactions in the Web services paradigm, and implements the completion protocol and the two-phase commit protocol defined in the Web Services Atomic Transaction Specification (WS-AT) [6]. As defined in WS-AT, the coordination service consists of several coordinator-side services and a couple of participant-side services. In the following, we provide a brief summary of these services.

The coordinator side consists of the following services:

- *Activation Service*: This service is invoked at the beginning of a distributed transaction by the initiator. The activation service creates a coordination context for each transaction and returns the coordination context to the initiator. The coordination context contains a unique

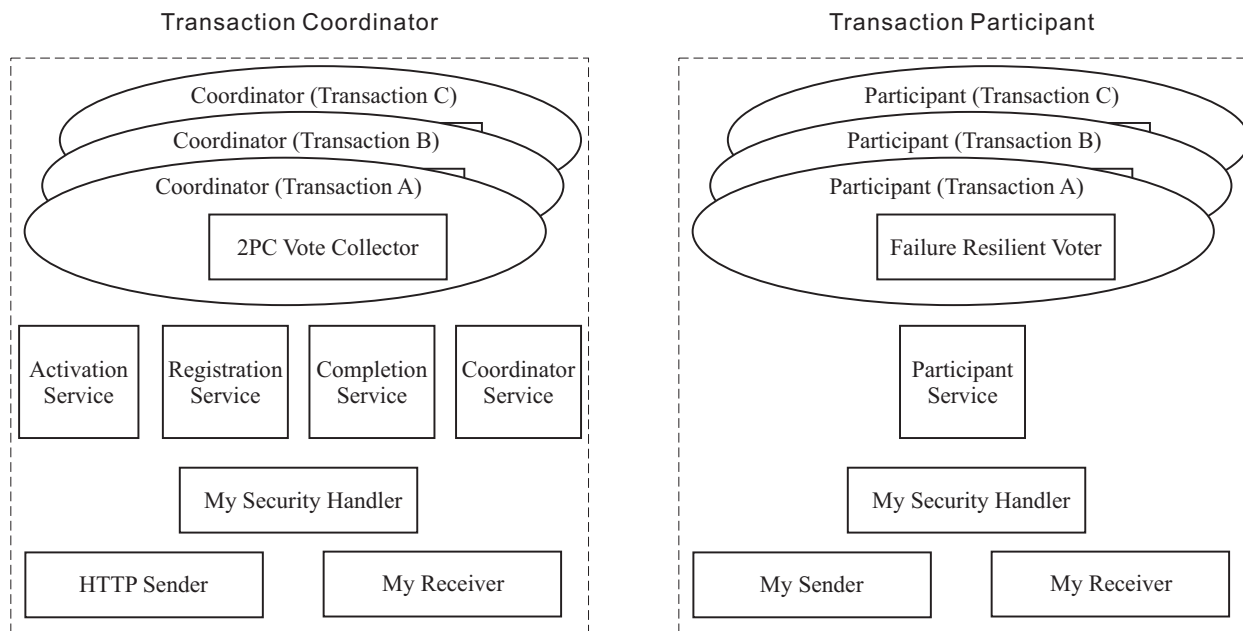


Fig. 1. Architecture of the failure resilient distributed commit framework.

transaction identifier and an endpoint reference¹ for the Registration Service (to be introduced next). This coordination context is included in all request messages sent within the transaction boundary. Furthermore, a coordinator object is created for the transaction.

- *Registration Service*: This service is provided to the transaction participants (including the transaction initiator) to register their endpoint references for the associated participant-side services. These endpoint references are used by the coordinator to contact the participants during the two-phase commit of the transaction.
- *Coordinator Service*: This service is invoked by transaction participants (excluding the initiator) to place their votes in response to a prepare request, and to send their acknowledgement in response to a commit/abort request. The participants obtain the endpoint reference of the Coordinator Service during the registration step.
- *Completion Service*: This service is used by the transaction initiator to signal the start of a distributed commit or abort. The Completion service, together with the CompletionInitiator service on the participant side, implement the WS-AT completion protocol. The endpoint reference of the Completion Service is returned to the initiator during the registration step.

The set of coordinator services run in the same address space. For each transaction, all but the Activation Service are provided by a (distinct) coordinator object. Consequently, we refer these services collectively as the coordinator in later text for convenience. These services are replicated for fault

¹The term endpoint reference is defined in [14]. An endpoint reference typically contains a URL to a service and an identifier used by the service to locate the specific handler object (it is referred to as a callback reference in the Apache Kandula Project). It may also include identifier information regarding a particular user of the endpoint reference. The endpoint reference resembles the object reference in CORBA.

tolerance.

The participant-side services include:

- *CompletionInitiator Service*: This service is provided by the transaction initiator so that the coordinator can inform it the final outcome of the transaction, as part of the completion protocol.
- *Participant Service*: This service is invoked by the coordinator to solicit votes from, and to send the transaction outcome to the participants according to the two-phase commit protocol.

To get a better idea how the distributed commit framework works, consider the banking example (adapted from the Kandula project and used in our performance evaluation) shown in Figure 2. In this example, a bank provides an online banking Web service that a customer can access through a Web browser, or a stand alone application. Assuming that the customer has two accounts with the bank. The two accounts are managed by different database management systems running in distinct locations. Web services are used as the middleware platform for all communications between different systems in the bank (*i.e.*, each system exposes a set of well-defined Web services that others can invoke). Figure 2 shows the detailed steps for a single Web service call from the customer on the bank to transfer some amount of money from one account to the other. Upon receiving the call from the customer, the bank application initiates a new distributed transaction, invokes a debit operation on one account, and a credit operation on the other, all through Web services.

To start a new distributed transaction, the initiator (*i.e.*, the bank application) invokes the Activation Service. A unique coordination context is created for the new transaction (or transaction context in short) and is returned to the caller (steps 2 and 3). The initiator subsequently registers a CompletionInitiator reference with the Registration Service so that the coordinator can inform the outcome of the transaction at the

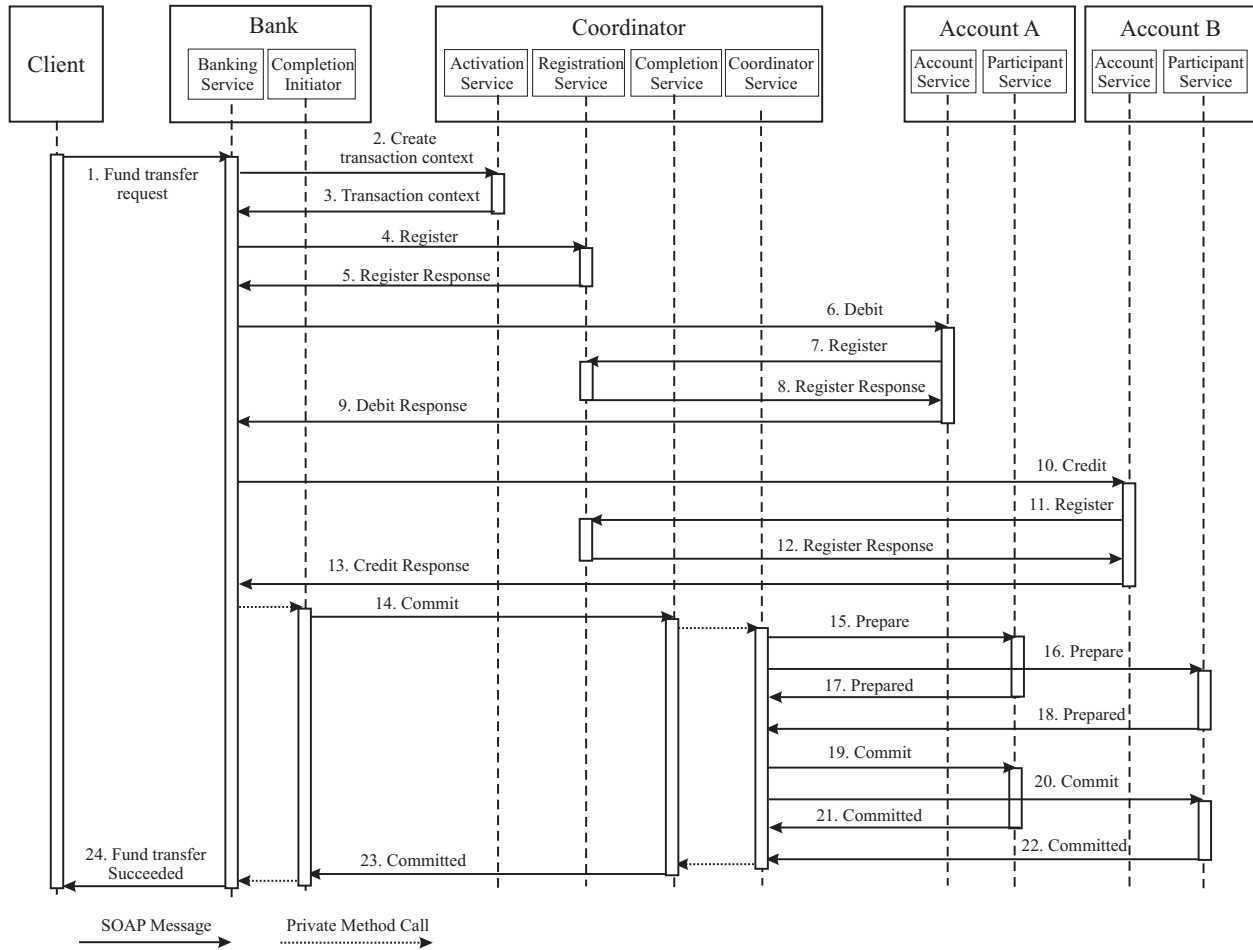


Fig. 2. The sequence diagram showing the detailed steps for a banking example using WS-AT (replication is not shown).

end of the distributed commit process asynchronously (steps 4 and 5)². The bank then invokes the debit operation on the Web service provided by account A (steps 6 and 9). The account A then registers a participant reference with the coordinator (steps 7 and 8) for distributed commit. The steps for the credit operation on account B is similar (steps 10-13). The two-phase commit starts when the initiator asks the Completion Service to commit the transaction (step 14). During the first phase, the prepare requests are sent to the two participants (steps 15 and 16). When the two participants responded with yes votes (steps 17 and 18), the coordinator decides to commit the transaction and notify both participants and eventually the initiator as well (steps 19-23). Finally, the bank application replies back to the customer (step 24).

In this paper, we regard the transaction initiator as a special participant because it also involves with the two-phase commit process in a way (even though the interaction between the initiator and the coordinator follows the WS-AT completion protocol). The initiator's commit request can be considered as a yes vote in response to an omitted prepare request. The notification message (step 23) to the initiator is equivalent to the decision message in the second phase of the distributed

commit. Therefore, the vote from the initiator is included in the signed vote collection. The signed vote collection is piggybacked with the decision messages to both the participants and the initiator.

B. Implementation of Failure Resiliency Mechanisms

The core failure resiliency mechanisms are implemented collectively by the following components, as shown in Figure 1:

- *2PC Vote Collector*. One vote collector object is created for each coordinator object. The lifespan of the collector object is identical to that of the coordinator object. The collector object stores the digitally signed vote messages sent by participants.
- *Failure Resilient Voter*. There is one voter object for each participant. The voter object and the participant are colocated in the same process. On receiving a message from a coordinator replica, the message is first passed to the voter for verification according to the criteria listed in Section III-A. Only messages that have passed the test are delivered to the participant.
- *My Security Handler*. This handler is invoked transparently according to the Apache Axis deployment descriptor for message signing and verification. A message that cannot be verified is discarded without further processing.

²The registration step is actually carried out at the commit time. We show the step here because it fits the logical order more naturally.

- *My Receiver*. This is implemented as an Axis handler to process the incoming messages and to suppress duplicate messages. This handler replaces the default Axis RPC handler. Upon receiving a message, the handler first checks if the message is a duplicate or if it is an out-of-order message. The message is discarded if it is a duplicate, and is queued for future delivery if it has arrived out-of-order (to be discussed further in Section IV-C). Further actions depend on the type of the message:
 - Vote messages (prepared/aborted messages from participants, and commit/abort³ messages from the initiator). They are passed to the 2PC Vote Collector for logging before they are delivered.
 - Transaction decision messages (commit/abort messages from the coordinator to participants, or the committed/aborted messages from the coordinator to the initiator). They are first passed to the voter object before delivery. A message is delivered only if the voter indicates it is time to do so.
 - Other messages arriving at the participant side, including the response messages to the activation and registration requests. They are delivered only if they can pass a verification test. The verification test can determine with certainty if the message is sent by a correct service, *i.e.*, if the message can pass the test, it must be sent by a correct replica and all correct replicas for the service are guaranteed to return a response with the same information. An invalid message is discarded. This is different from failure resilient voting on the transaction decision messages, in which case a message may be labeled as uncertain. The simplicity of the verification test is made possible by our deterministic identifier generation mechanism, to be discussed in detail in Section IV-D.
 - Other messages arriving at the coordinator side. They are delivered immediately (they must pass the signature verification check done by the security handler).
- *My Sender*. It is implemented as an Axis handler to replace the default HTTP Sender handler. This handler performs source ordered reliable multicast based on static membership information (to be discussed further in Section IV-C). For the transaction decision messages, this handler also piggybacks the vote set logged by the 2PC Vote Collector.

C. Application-Assisted Ordered Reliable Multicast

To ensure the replica consistency of a stateful service, all incoming requests to the service must be totally ordered in general. This would require the use of a totally ordered reliable multicast system. We see two problems in applying this strategy to Web Services replication. First, such a multicast system often dominates the overall performance cost of the

fault tolerance infrastructure [27]. This is especially true for totally ordered reliable multicast under the Byzantine fault model. Second, the use of a totally ordered multicast system strongly couples the participants and the replicated coordinator services (the multicast system would introduce many shared state and dependencies among its members). This seems to contradict the design principles of Web Services.

Therefore, we designed and implemented a reliable multicast system that provides minimum ordering guarantee for low runtime overhead and for loose coupling. This is made possible by exploiting the application semantics. In this case, the “application” is the two-phase commit framework. Recall that only the coordinator-side services are replicated. The activation service, which would create a coordinator object for each distributed transaction, is stateless. Therefore, there is no need to order the activation requests. The rest of the services are stateful only within the boundary of a distributed transaction. Because a unique coordinator object is created for each transaction, only the requests to the same coordinator should be ordered, *i.e.*, requests to different coordinators are unrelated and should not be ordered to reduce the runtime overhead. Furthermore, we recognize that as long as the requests to the same coordinator are causally ordered, the coordinator replicas would remain consistent. Hence, our framework includes only a causally ordered reliable multicast system.

The runtime overhead for a causally ordered reliable multicast system can still be significant if we were to use a traditional approach such as the vector-timestamp based method. To reduce the runtime cost, and also to minimize the complexity of the multicast system, we choose to use an application-assisted approach to control the ordering of incoming requests to each coordinator replica. Our multicast system requires the application (*i.e.*, the coordinator) to help determine if it is time to deliver a request through a plugin interface. Upon receiving a request, the multicast system asks the corresponding coordinator replica if it is time to deliver the message. If the response is no, the message is queued. Otherwise, the message is delivered. Periodically, the queue is examined and the coordinator is consulted to see if a queued message can be delivered in the right order.

We believe that the application can implement such a service without much hassle because it can easily determine the causal order of different requests based on the application logic. For example, a coordinator would inform the multicast system to defer the delivery of a “prepared” message if it has not issued the corresponding “prepare” request to the transaction participant.

By delegating the ordering task to the application, it is sufficient to implement a source ordered reliable multicast system. We decide to carry out the multicast using multiple point-to-point messages on top of the SOAP protocol for maximum interoperability. On the sending side, a thread pool is used to concurrently send the multicast messages to their destinations to achieve good performance. In fact, we need only a partially source ordered reliable multicast, *i.e.*, only the messages sent to the same coordinator are source ordered. If two participants from the same process send messages to different coordinators (for different transactions), the messages

³In the Web Services AtomicTransaction Specification [6], the abort message is referred to as rollback message. We use the term abort here for consistency with other part of the paper.

from each participant are ordered separately.

For simplicity, our implementation of the reliable multicast assumes static membership provided by a configuration file.

D. Replica Nondeterminism Control

a) Identifier Generation: In the WS-AT framework, each distributed transaction is assigned a unique transaction identifier. The identifier is generated when the transaction initiator invokes the activation service for a new distributed transaction. This identifier is included in all messages exchanged between the coordinator and the participants of a transaction. In the Apache Kandula implementation, the identifier is generated as a Universally Unique Identifier (UUID) according to the algorithm defined by the Open Group [21]. Obviously, we must replace the default algorithm by a deterministic identifier generation mechanism so that all replicas generate the same identifier for the same transaction, and the identifier must be unique with respect to those for other transactions. Otherwise, the state of the coordinator replicas would diverge and distributed commit could not be carried correctly.

We choose to follow a pragmatism approach for deterministic generation of the transaction identifiers. A transaction identifier is constructed by applying a secure hash function on the following items concatenated together:

- A UUID generated by the transaction initiator.
- The timestamp of the activation request message (assigned by mechanism at the transaction initiator).

The initiator-generated UUID is used as the basis for the transaction identifier. To enhance the uniqueness and the freshness of the identifier, the second item is needed. Even if the initiator is faulty and tries to supply a used UUID, the timestamp will still guarantee the transaction identifier to be different. Upon receiving an activation request, the coordinator compares the timestamp of the request with the current clock value. The message is discarded if the timestamp differs from the coordinator's clock by more than a predefined threshold. This requires that the clocks at the coordinator and the initiator nodes are approximately synchronized. With the pervasiveness of the NTP service, it is not an unrealistic assumption. Alternatively, we could replace the timestamp with a monotonically increasing sequence number. However, doing so would introduce additional state that spans across difference transactions (the activation service would have to remember what is the next expected sequence number). This would increase the complexity of recovery mechanisms for coordinator replicas and make it harder to perform server-side load balancing.

Ideally, the activation service should make contribution to the identifier as well so that no one can unilaterally decide on the transaction identifier for maximum robustness. We did not do so because it is not clear to us how to devise a method to deterministically generate some information without imposing additional assumptions on the activation service. For example, if we can assume that the replicated activation service has a pair of group keys, we could include the private group key (or a key derived from the private key deterministically) in the transaction identifier generation. Even without the contribution

from the activation service, the man-in-the-middle attack cannot happen as long as the private key of the transaction initiator is not compromised because all messages are protected by digital signatures.

We should note that the deterministic identifier generation mechanism does not work flawlessly in all circumstances. For example, if the transaction initiator is faulty, it could potentially send different timestamp and UUID with the activation request message to different coordinator replicas. This would have negative impact on the voting mechanism at each participant regarding the outcome of the transaction. If a participant has accepted one of the transaction identifiers for the current transaction, it would discard all messages (including the transaction outcome messages) that carry other transaction identifiers. This in effect reduces the voting set (potentially to a single coordinator replica), and therefore, increases the risk of nonatomic distributed commit. This problem can be resolved by executing a Byzantine agreement protocol among the coordinator replicas for the activation request message. If no agreement can be reached, the activation message is ignored.

In response to the registration request, the registration service returns an endpoint reference for the coordinator service (for 2PC participants), or an endpoint reference for the completion service (typically for the transaction initiator). In addition to the transaction identifier and the identifier for the handler object for the corresponding service, each endpoint reference contains a callback reference identifier assigned to the caller. This identifier is to be used by the caller to identify itself when it invokes the coordinator service and the completion service, respectively. In the original Apache Kandula implementation, a new UUID is generated and used as the callback reference identifier. To ensure deterministic response from the replicated registration service, we rewrote the related code and implemented a mechanism similar to that for transaction identifier generation, *i.e.*, the caller designates the identifier to be used as the callback reference identifier. This also makes it possible for the callers (participants and initiator) to verify the correctness of the registration responses.

b) Time Related Nondeterminism: The 2PC protocol uses a number of timeout during its execution. Naturally, there is a risk of getting into some race conditions that might lead to nonatomic completion of a distributed transaction. This situation may arise if some participants' yes-votes arrive very closely to the timeout set by the coordinator for the first phase of the 2PC protocol. Some coordinator replica might accept the votes and commit the transaction, while some other replicas might time out these participants.

However, we decide not to control the time-related operations, for a number of reasons. First, it is extremely expensive to ensure consistent clock readings by different replicas under the Byzantine fault model. (It is very expensive even when the crash-only model is used, as our previous work has shown [25].) The coordinator replicas access local clocks very often during the distributed commit process. For each clock operation, a Byzantine agreement must be reached among the replicas. Resorting to this type of control would render our framework impractical. Second, our voting mechanism is

designed to prevent inconsistent commitment of distributed transactions. As long as each participant receives a commit decision message (with a valid commit-token), possibly sent by different correct coordinator replicas, the atomicity is guaranteed.

Note that all practical distributed transaction processing systems use timeout as a way to avoid lengthy delay in case of the coordinator failures, *i.e.*, a transaction is aborted when a predetermined timeout occurs, even if the transaction is prepared. This practice has intrinsic risk of nonatomic commitment of distributed transactions when the race condition happens. We believe that our framework for distributed commit do not incur noticeable higher risk than their nonreplicated counterpart under this circumstance. For all practical purposes, our failure resilient distributed commit is sufficiently robust.

E. Coordinator Replica Recovery

Replicas may fail over time, due to intrusion attacks, or hardware/software failures. It is important to be able to introduce new replicas, and recover repaired replicas into the system to maintain the degree of replication. Due to our semi-stateless design, a coordinator replica (new, or repaired) can be introduced into the system at any time without the complexity of Byzantine fault tolerant state transfer from existing replicas. To understand this, consider a message that arrives at the new replica. If it is not the activation request message, which would cause the creation of a new transaction context and a new coordinator object, the message would simply be discarded because no target coordinator object is found in the replica. If it is an activation request message, the replica processes the request properly and join other replicas for this new transaction.

V. PERFORMANCE EVALUATION

We have conducted extensive performance evaluation of our prototype implementation. Our focus is to compare the runtime overhead of the failure resiliency mechanisms during both fault-free and various faulty scenarios. Our experiment is carried out on a testbed consisting of 8 Dell SC1420 servers connected by a 100Mbps Ethernet. Each server is equipped with two Intel Xeon 2.8GHz processors and 1GB memory running SuSE 10.0 Linux. The framework and the mechanisms are implemented using the Java programming language. The failure resiliency mechanisms consist of approximately 4000 lines of code.

The test application is the banking Web service example that we have shown in Figure 2. The coordinator-side services are replicated on up to 3 computers. The transaction initiator and other participants are not replicated. The client for the banking Web service, the transaction initiator and all other participants run on distinct computers. The same client is used for all tests, where it invokes a fund transfer operation on the banking Web service within a loop without any “think” time in between two consecutive calls. In each run, 10000 samples are obtained. The end-to-end latency for the fund transfer operation is measured at the client. In addition, the latency for the two-phase commit is measured at the replicated coordinator. The

latency information for each call is temporarily stored in memory and is flushed into a file at the end of each run.

A. Fault-Free Runtime Overhead

To evaluate the runtime overhead of our failure resiliency mechanisms, we compare the performance of the original WS-AT implementation and the modified one that contains our failure resiliency mechanisms with various replication degrees. The results for different configurations are shown as bar charts in Figure 3. The end-to-end latency result is shown in the left hand side of figure (Figure 3(a)), and the two-phase commit latency result is displayed in the right hand side.

The end-to-end latency for the original WS-AT implementation without message signing ranges from 180-280 milliseconds for 2-4 participants. When the framework is configured to use digital signature for all messages transmitted over the network, which should be a basic requirement for secure communication over the Internet, the latency increases dramatically to the range of 600-890 milliseconds. We believe it is fair to use this configuration as the reference to compare with the performance of our failure resilient framework (termed as “Secure 2PC” in Figure 3). As shown in Figure 3(a), the end-to-end latency increases only modestly to the range of 640-990 milliseconds when our failure resilient distributed commit framework is used. This amounts to approximately 10% overhead, which is very reasonable from the end users’ point of view. Furthermore, the increase of the replication degree from 1 to 3 does not introduce noticeable higher overhead.

The latency results for the two-phase commit illustrated in Figure 3(b) exhibit a similar trend. Comparing with the message-signing-only configuration, our failure resilient framework incurs about 20% overhead, which is higher than that for the end-to-end latency. This is not surprising because our major effort is to harden the two-phase commit protocol.

B. Performance Under Faulty Scenarios

We instrumented the coordinator code to simulate coordinator fault. We do not study the impact of faulty participants for two reasons. First if a participant has a benign crash fault, the transaction is guaranteed to be aborted because no coordinator can fabricate a vote from this faulty participant due to our strong cryptography assumption. Second, if a malicious faulty participant sends different vote to different coordinator replicas, it requires a full scale Byzantine agreement process among all participants and all coordinator replicas to ensure the atomicity of a transaction, therefore, it may be too expensive to use in practical systems, especially for Web services applications.

We simulate the first scenario described in Section III-B because it is the most effective way that a faulty coordinator replica can use to cause nonatomic transaction commit. We do not consider coordinator crash fault because it is masked by replication in a trivial manner. The fault is injected when all participants have voted to commit a transaction. A (simulated) faulty coordinator replica requests some participants to commit and directs some others to abort the transaction by omitting

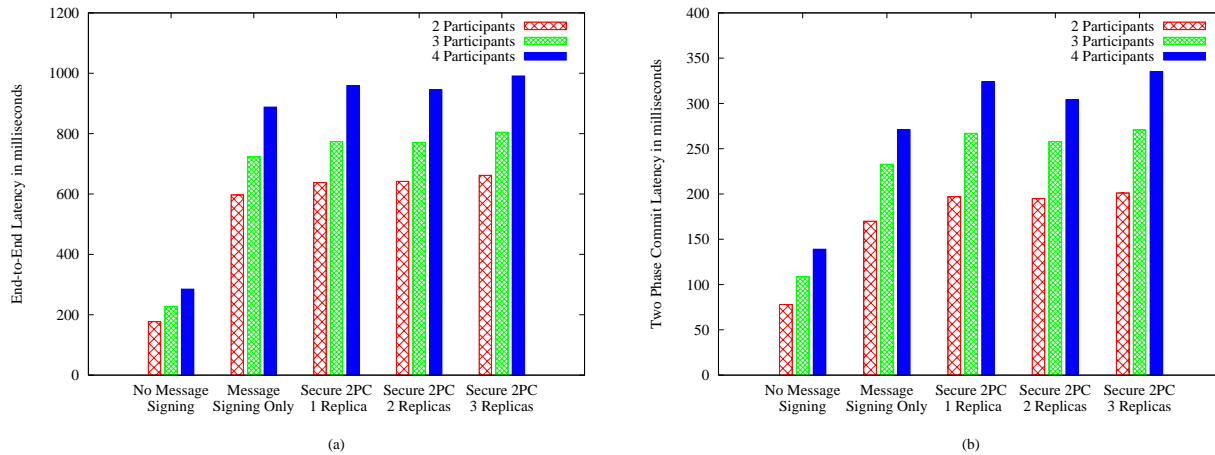


Fig. 3. The measurements of the end-to-end latency (a) and the two-phase commit latency (b) under different fault-free scenarios.

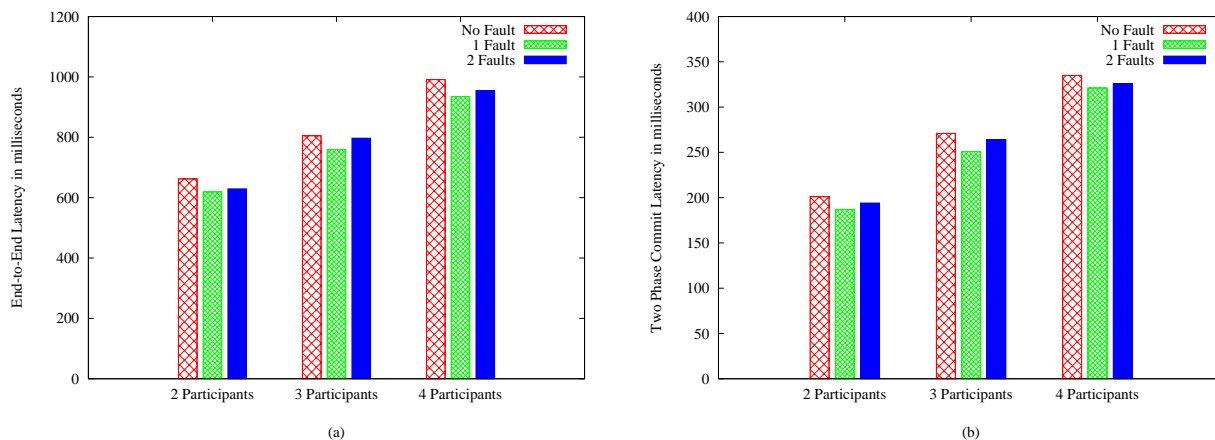


Fig. 4. The measurements of the end-to-end latency (a) and the two-phase commit latency (b) under different number of coordinator fault for 2-4 participants. The no-fault performance result is included as a reference.

some yes-votes. With 3 coordinator replicas, we simulate up to 2 faults.

Figure 4 shows the end-to-end latency measured by the client and the two-phase commit latency measured by a correct coordinator replica, when there are 2-4 participants (including the transaction initiator) and 0-2 faulty coordinator replicas. It may be counter-intuitive to see that the latency is actually smaller when there are faults. This is in fact caused by the lower computation cost on signature verification for the abort messages sent by faulty coordinator replicas (recall that the faulty replica did this by omitting some vote records).

We performed numerous runs in the faulty scenarios, each run contains 10000 transactions. All transactions are committed successfully on all participants, even when two out of three coordinator replicas are faulty. This shows the robustness of our failure resiliency mechanisms for distributed commit.

VI. RELATED WORK

This work is inspired by [23]. Even though [23] is about sensor networks and the failure resiliency mechanisms in [23] are completely different from those discussed in this paper,

the very idea of restricting the impact of compromised node is the same. In [23], the security keys for sensor nodes are based on the nodes' locations. Therefore, a compromised node cannot fabricate false report about events in other regions. In this paper, we resort to a piggybacking mechanism to limit the behavior of a compromised coordinator for distributed commit. Consequently, a faulty coordinator cannot fabricate a participant's vote without being detected. Furthermore, we invented a novel voting mechanism that significantly increases the resiliency of distributed commit when the majority coordinator replicas become faulty.

Byzantine agreement and Byzantine fault tolerance in distributed systems have been studied over the past several decades. The Byzantine agreement problem was first formulated by Lamport [16]. Since then, many different algorithms have been proposed and many Byzantine fault tolerance systems have been proposed. In particular, the recent progress in practical Byzantine fault tolerance made by Castro *et al.* [8], [9] has triggered widespread interest in this topic. Yin *et al.* [24] proposed a method to reduce the number of replicas used to achieve Byzantine fault tolerance by separating agreement

and execution. Adya *et al.* [2] applied the Byzantine fault tolerance technique to Internet based storage systems. However, all these approaches require that the number of faulty nodes does not exceed a threshold (*i.e.*, $(n-1)/3$, or $(n-1)/2$ with separate agreement nodes, for n number of replicas). If the number of fault exceeds this threshold, either no Byzantine agreement can be reached, or a wrong agreement is decided. Therefore, they are resilient to failures only up to that threshold. A very interesting exception is the BAR system proposed by Aiyer *et al.* [1], which considers fault tolerance in the presence of additional selfish nodes beyond the Byzantine agreement threshold. They resorted to game-theory based mechanisms to counter the threats from the selfish nodes.

The subject of Byzantine fault tolerant distributed commit can be viewed as an application of general Byzantine fault tolerance to the domain of distributed transactions [10], [12], [17]. There are methods proposed shortly after the introduction of the two-phase commit protocol [13] and the Byzantine agreement problem [16]. The first comprehensive proposal for Byzantine fault tolerant distributed commit is due to Mohan *et al.* [17]. It uses possibly two rounds of Byzantine agreement to ensure the atomicity of distributed commit. Even though this method can cope with both coordinator and participants failure, it will stop working if the number of fault exceeds the Byzantine agreement threshold, as mentioned before. Furthermore, the high runtime overhead makes it impossible to be used in practical systems. Rothermel *et al.* [22] addressed the challenges of ensuring atomic distributed commit in open systems where participants (may also serve as subordinate coordinators) may be compromised. However, [22] assumes that the root coordinator is trusted. Therefore, [22] does not address the main concern of this work.

The latest investigation on fault tolerant distributed commit is reported in [12]. In [12], Gray and Lamport proposed a novel algorithm, termed as Paxos commit algorithm, to achieve fault tolerant commitment of distributed transactions. The Paxos commit algorithm is an application of the Paxos algorithm, which is a well-known distributed consensus algorithm, to the distributed commit problem. The Paxos commit algorithm does not tolerate Byzantine faults, so it is not directly comparable with our protocol.

Our piggybacking mechanism is very similar to that mentioned in [17]. In both mechanisms, the commit message carries the vote records collected during the prepare phase. However, there are subtle differences. In [17], both the coordinator and the participants, and other nodes that are present in the cluster (serves as the coordinator replicas) participate a Byzantine agreement protocol to decide on the outcome of a transaction. If a participant detects a discrepancy between its vote and the one included in the commit message, it starts a second Byzantine agreement process. In our approach, only a single voting step is used at each participant instead of a full scale Byzantine agreement. Furthermore, we recognize that the piggybacked vote records in the commit message may provide conclusive information, in which case, the participant can safely commit the transaction immediately without waiting for the commit messages from other coordinator replicas.

A similar piggybacking mechanism is used in [22] to

prevent a Byzantine faulty subordinate coordinator from lying about its participants' votes. However, [22] assumes that the root coordinator is trusted, *i.e.*, it is only subject to non-malicious fault and it can recover quickly from fault. This assumption negates the necessity to replicate the coordinator for fault tolerance, and also avoids running any Byzantine agreement process to achieve atomic commitment. However, this assumption might not be realistic for Web services applications.

Both [17] and [22] supports transactions with hierarchical participants, *i.e.*, some participants may serve as subordinate coordinators, while our current work assumes a flat transaction. However, it is straightforward to extend our mechanisms to cope with hierarchical structured transactions.

We are not aware of any work directly related to our failure resilient voting mechanism. Majority voting has been known for many years and used widely in many applications. A distributed majority voting mechanism has been proposed in [15] as an alternative to the two-phase commit in distributed systems. However, the majority voting is not resilient to failures if the majority of the voting members become faulty.

Last, but not least, we have yet to see system-level work on Byzantine fault tolerant distributed commit frameworks. So far, the related work on distributed commit cited above has mostly focused on the algorithmic aspect. To put a fault tolerant distributed commit algorithm into practical use, one must consider many complexities in real transactional systems, such as the ones we discussed in Section IV. There are a number of system-level work on fault tolerant distributed commit, such as [11], [19], [26]. However, they all use a benign fault model. Such systems do not work if the coordinator is subject to intrusion attacks.

VII. CONCLUSION

In this paper, we described two core mechanisms, namely, the piggybacking mechanism and the voting mechanism, to achieve failure resilient atomic commit for distributed transactions. Unlike other Byzantine fault tolerant distributed commit algorithms, our mechanisms ensure successful atomic commit of transactions with high probability, even if the majority of the coordinator replicas are compromised, as long as at least one replica remains to operate correctly.

Furthermore, we implemented the failure resiliency mechanisms in a distributed commit framework for Web services atomic transactions. We addressed many system-level issues in incorporating the mechanisms into the framework, such as replica non-determinism control and efficient reliable message multicast with minimum required ordering guarantees.

We verified the correctness of our mechanisms design and their efficiency with a suite of tests, both under fault-free and simulated fault scenarios. Our measurement shows only 10% runtime overhead as seen by an end user under all circumstances that we have tested. It is our hope that both researchers and practitioners will find our mechanisms interesting and useful.

We believe that the failure resiliency mechanisms introduced in the context of distributed commit can be extended to other

application domains. In addition, we are looking into the possibility of building a higher-level abstraction on failure resiliency mechanisms so that they can be applied to many other applications in a systematic manner.

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