BAR Fault Tolerance for Cooperative Services

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ABSTRACT

This paper describes a general approach to constructing cooperative services that span multiple administrative domains. In such environments, protocols must tolerate both *Byzantine behaviors* when broken, misconfigured, or malicious nodes arbitrarily deviate from their specification and *rational behaviors* when selfish nodes deviate from their specification to increase their local benefit. The paper makes three contributions: (1) It introduces the BAR (Byzantine, Altruistic, Rational) model as a foundation for reasoning about cooperative services; (2) It proposes a general three-level architecture to reduce the complexity of building services under the BAR model; and (3) It describes an implementation of BAR-B, the first cooperative backup service to tolerate both Byzantine users and an unbounded number of rational users. At the core of BAR-B is an asynchronous replicated state machine that provides the customary safety and liveness guarantees despite nodes exhibiting both Byzantine and rational behaviors. Our prototype provides acceptable performance for our application: our BAR-tolerant state machine executes 15 requests per second, and our BAR-B backup service can back up 100 MB of data in under 4 minutes.

Categories and Subject Descriptors

C.2.4 [**COMPUTER-COMMUNICATION NETWORKS**]: Distributed Systems

General Terms

ALGORITHMS, RELIABILITY

Keywords

Game theory, Byzantine fault tolerance, Reliable systems, Peer to Peer

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1. INTRODUCTION

This paper describes a general approach to constructing cooperative services that span multiple administrative domains (MADs). In a cooperative service, nodes collaborate to provide some service that benefits each node, but there is no central authority that controls the nodes' actions. Examples of such services include Internet routing [21, 59], wireless mesh routing [33], file distribution [14], archival storage [38], or cooperative backup [5, 16, 31]. As MAD distributed systems become more commonplace, developing a solid foundation for constructing this class of services becomes increasingly important.

There currently exists no satisfactory way to model MAD services. In these systems, the classical dichotomy between correct and faulty nodes [56] becomes inadequate. Nodes in MAD systems may depart from protocols for two distinct reasons. First, as in traditional systems, nodes may be *broken* and arbitrarily deviate from a protocol because of component failure, misconfiguration, security compromise, or malicious intent. Second, nodes may be *selfish* and alter the protocol in order to increase their utility [1, 27]. Byzantine Fault Tolerance (BFT) [10, 30, 36] handles the first class of deviations well. However, the Byzantine model classifies all deviations as faults and requires a bound on the number of faults in the system; this bound is not tenable in MAD systems where *all* nodes may benefit from selfish behavior and be motivated to deviate from the protocol. Models that only account for selfish behavior [59] handle the second class of deviations, but may be vulnerable to arbitrary disruptions if even a single node is broken and deviates from expected rational behavior.

Given the potential for nodes to develop arbitrarily subtle tactics, it is not sufficient to verify experimentally that a protocol tolerates a collection of attacks identified by the protocol's creator. Instead, just as for authentication systems [8] or Byzantine-tolerant protocols [30], it is necessary to design protocols that *provably* meet their goals, no matter what strategies nodes may concoct within the scope of the adversary model.

To allow construction of such protocols, we define a model that captures the essential aspects of MADs. The Byzantine-Altruistic-Rational (BAR) model accommodates three classes of nodes. *Rational* [59] nodes participate in the system to gain some net benefit and can depart from a proposed program in order to increase their net benefit. *Byzantine* [10, 30, 36] nodes can depart arbitrarily from a proposed program whether it benefits them or not. Finally, BAR accommodates the presence of *altruistic* [46] nodes that execute a proposed program even if the rational choice is to deviate. A protocol is BAR Tolerant (BART) if it provably provides to its non-Byzantine participants a set of desired safety and liveness properties. In this paper, we focus on BART protocols that do not depend on the existence of altruistic nodes in the system: we assume that at most $\frac{n-2}{3}$ of the nodes in the system are Byzantine and that every non-Byzantine node is rational.

A key question is whether useful systems can be built under the BAR model. To answer this question, we develop a general three-level architecture for BART services. The bottom level implements a small set of key abstractions (e.g., state machine replication and terminating reliable broadcast) that simplify implementing and reasoning about BART distributed services. The middle level partitions and assigns work to individual nodes. Finally, the top level implements the application-specific aspects of BART services (e.g., verifying that responses to requests conform to application semantics.)

We use this architecture to construct BAR-B, a BART cooperative backup service. BAR-B is targeted at environments—such as a group of students in a dorm, home machines for researchers in a group, or machines donated to non-profit organizations [32]—that, by supporting a notion of identity that is "expensive" to obtain, avoid the Sybil attack [18]. We do not target open membership peer-to-peer systems.

We find that our architecture makes the design of BAR-B easier to derive, implement, and comprehend. Compared to previous peer to peer backup architectures [15, 16, 31], BAR-B has several advantages: it is unique in tolerating both rational and Byzantine peers, it provides deterministic retrieval guarantees, and it does not require peers to exchange storage symmetrically. Perhaps most importantly, we find that using a layereded architecture simplifies the task of proving safety and liveness properties.

We also show that our approach is practical: our prototype BART state machine executes batches of 15 requests per second and our BAR-B prototype can back up 100 MB of data to 10 nodes in under 4 minutes while guaranteeing data recovery despite the failure of 3 nodes.

In this paper we make three main contributions. First, we formalize a model for reasoning about systems in the presence of both Byzantine and rational behavior. Second, we introduce a general architecture and identify a set of design principles which, together, make it possible to build and reason about BART systems. Third, we describe the implementation of BAR-B, a cooperative backup system within the BAR model. A key component of our system is a BART protocol for state machine replication that relies on synchrony assumptions only for liveness.

The rest of this paper is organized as follows. In Sections 2 and 3 we formally present the BAR model and our system model. In Section 4, we describe our overall 3-level architecture, and the next three sections present our implementation of each of the levels: our asynchronous BART state machine, our techniques for work assignment, and our BAR-B application. Section 8 evaluates the prototype and Section 9 discusses related work.

2. BAR MODEL

To model a MAD environment we must account for three important factors: (a) no node is guaranteed to follow the suggested protocol, (b) the actions of most nodes are guided by self interest [1, 27], and (c) some nodes may be categorically broken [10, 30, 36].

The Byzantine Altruistic Rational (BAR) model addresses these considerations by classifying nodes into three categories.

Altruistic nodes follow the suggested protocol exactly. Altruistic nodes may reflect the existence of Good Samaritans and "seed nodes" in real systems. Intuitively, altruistic nodes correspond to *correct nodes* in the fault-tolerance literature.

Rational nodes are self-interested and seek to maximize their benefit according to a known utility function. Rational nodes will deviate from the suggested protocol if and only if doing so increases their net utility from participating in the system. The utility function must account for a node's costs (e.g., computation cycles, storage, network bandwidth, overhead associated with sending and receiving messages, power consumption, or threat of financial sanctions [31]) and benefits (e.g., access to remote storage [38, 5, 16, 31], network capacity [33], or computational cycles [57]) for participating in a system.

Byzantine nodes may deviate arbitrarily from the suggested protocol for any reason. They may be broken (e.g., misconfigured, compromised, malfunctioning, or misprogrammed) or may just be optimizing for an unknown utility function that differs from the utility function used by rational nodes—for instance, ascribing value to harm inflicted on the system or its users.

Under BAR, the goal is to provide guarantees similar to those from Byzantine fault tolerance to "all rational and altruistic nodes" as opposed to "all correct nodes." We distinguish two classes of protocols that meet this goal.

- Incentive-Compatible Byzantine Fault Tolerant (IC-BFT) protocols: A protocol is IC-BFT if it guarantees the specified set of safety and liveness properties and if it is in the best interest of all rational nodes to follow the protocol exactly.
- Byzantine Altruistic Rational Tolerant (BART) protocols: A protocol is BART if it guarantees the specified set of safety and liveness properties in the presence of all rational deviations from the protocol.

An IC-BFT protocol thus must define the optimal strategy for a rational node. In a BART protocol a rational node may exploit local optimizations not specified in the protocol without endangering the global guarantees. Note that IC-BFT protocols are a subset of the BART protocols.

3. SYSTEM MODEL

Although we seek to develop a general framework for constructing a range of cooperative services, our approach is guided by a specific problem in a specific set of environments. In particular, we are building a cooperative backup system for three user communities: 30 co-workers who cooperatively back up their personal home machines, 500 students in a dormitory who cooperatively back up their personal machines, and 50 nonprofit organizations that receive free or low-cost refurbished PCs [32].

We assume that a trusted authority controls which nodes may enter the system, that each such member has a unique identity corresponding to a cryptographic public key, that each member can determine whether a public key belongs to a specific member, and that no set of nodes has the computational power to subvert the standard cryptographic assumptions associated with public key signatures [51] and secure hashing [47]. These assumptions are reasonable for our target environments—a volunteer distributes a list of keys to coworkers; a university's electronic ID system maps identities to dormitory residents; the refurbisher installs the key information on machines before they are distributed to non-profits—and facilitate the design of BART systems in three ways. First, they provide justification for our assumption that the number of Byzantine nodes in the system can be bounded. Second, they give rational nodes an incentive to consider the long-term consequences of their actions, making it easier to apply internal sanctions (e.g. denial of service or data deletion) against misbehaving nodes. Third, they allow us to tie system identities to real world entities, so that external sanctions (e.g. social disgrace, monetary fines, or contractual penalty) may be applied against the owners of nodes that misbehave. Support for external sanctions increases the flexibility of our protocols, but our protocols do not require the use of external sanctions for safety or liveness.

We have different timing assumptions for BAR-B and for the underlying BART replicated state machine. BAR-B relies on synchrony to guarantee both its liveness and safety properties—data trusted to BAR-B is guaranteed to be retrievable only until the lease associated with it expires. Conversely, the underlying BART state machine is safe even in an asynchronous system, though liveness is only guaranteed during periods of synchrony.

To ensure liveness under the BAR model, we make two additional timing assumptions. First, we give nodes an incentive to stay as synchronized as possible through a "penance" mechanism (discussed in Section 5.1.3) that penalizes untimely nodes. For this mechanism to be acceptable, nodes' clocks must be sufficiently synchronized that these penalties do not outweigh the benefits of participating in the system. Second, we assume that if nodes a and b are non-Byzantine and a sends b a request at time t, b's response will reach a by time $t + max\_response\_time$. This assumption allows us to bound the state that non-Byzantine nodes maintain in order to answer late requests and thereby allows rational nodes to ensure that the benefits of participation outweigh the costs.

In order to complete our model, we must also make specific assumptions on the rational and Byzantine nodes in the system.

Rational nodes. We make four technical assumptions about rational nodes. First, we assume that rational nodes receive a long-term benefit from participating in the protocol. Second, we assume that rational nodes are conservative when computing the impact of Byzantine nodes on their utility. Third, we assume that if a protocol provides a Nash equilibrium, then all rational nodes will follow it [34] [1] .Finally, we assume that rational nodes do not collude—colluding nodes are classified as Byzantine. Relaxing these assumptions is future work.

Rational nodes will only participate in a cooperative system if they receive a net benefit from their participation. In practice, this requires that the long-term benefit (e.g. reliable backup) of participation is sufficient to offset the costs (e.g. storage, bandwidth, computation) of participating in the system; otherwise rational nodes will refuse to participate, compromising liveness.

Rational nodes want to reduce their cost without relinquishing the benefits that come from participating in the protocol. We assume a simple model in which nodes' utilities are affected by the work that must be done but not by the order in which work is performed or by who requests the work. These two variants can be handled by hiding the relevant factors (contents of the request or identity of the sender, respectively) until after nodes commit to executing the request. We assume that rational nodes deviate from the protocol only if they receive a net benefit from doing so—in a tie, they continue to follow the protocol. This assumption appears reasonable, given that deviating from the protocol requires some effort. Furthermore, we assume that rational nodes abide by the *promptness principle*: if they gain no benefit from delaying the sending of a message, they send the message as soon as they have idle cycles and bandwidth available. This assumption recognizes that idle resources are perishable.

Rational nodes are conservative when estimating the potential impact of Byzantine nodes on their utility: we assume that for each rational node, the benefits of the service greatly outweighs the costs, and therefore any increase in the risk of service failure is unacceptable. So, when computing the expected outcome of its actions, a rational node r assumes that the maximum number (f) of Byzantine nodes are present in the system and that they will act in the way that minimizes r's utility.

[1]Because the protocol can be regarded as coming from an external authority, some prefer to regard such an equilibrium as a *correlated equilibrium* [4], which is a generalization of Nash equilibrium. This view would not change our analysis.

Byzantine nodes. We assume a Byzantine fault model for Byzantine nodes [10, 30, 36] and a strong adversary. Byzantine nodes can exhibit arbitrary behavior. For example, they can crash, lose data, alter data, and send incorrect protocol messages. Furthermore, we assume an adversary who can coordinate Byzantine nodes in arbitrary ways. Finally, we assume that at most $\frac{n-2}{3}$ of the nodes in the system are Byzantine.

4. SYSTEM ARCHITECTURE

This section provides an overview of our design. The sections that follow describe each level of our design in more detail.

4.1 3-Level Architecture

We propose a three-level architecture for building BART services (Figure 1). The layered design simplifies the analysis and construction of systems by isolating and addressing classes of misbehavior at appropriate levels of abstraction.

Architecture	Prototype		
Level 3: Application	BAR−B Backup		
Level 2: Work Assignment	Guaranteed Response	Periodic Work	Authoritative Time
Level 1: Primitives	Replicated State Machine		
	Message Queue		

Figure 1: System architecture

Level 1, the *basic primitives* level, provides IC-BFT versions of key abstractions (e.g. Terminating Reliable Broadcast (TRB) [30] and Replicated State Machine (RSM) [10, 29, 55]) for constructing reliable distributed services. The BART RSM gives us the abstraction of a correct (e.g., reliable and altruistic) node.

Level 2, *work assignment*, allows us to build a system in which work can be assigned to specific nodes instead of executed by all replicas in the RSM. The assignment is done through a the *Guaranteed Response* protocol that generates either a verifiable match between a request and the corresponding response or a verifiable proof that a node failed to respond to a request. The assignment protocol enables efficient replication for our backup application, and the protocol itself is optimized to use the RSM as little as possible.

Level 3, the *application* level, implements a desired service using the levels underneath. Our architecture defines a contract between the application and the two lower, application-independent levels. The lower levels provide reliable communication and authoritative request-response bindings, while the application is responsible for providing a net benefit and defining legal request-response pairs.

4.2 Principles of Operation

Accountability lies at the heart of our approach to constructing BART services: if nodes are accountable for their behavior, then rational peers have an incentive to behave correctly. Strong identities and restricted membership make it possible to enforce meaningful internal and external disincentives. But that is only part of the solution. How should a system detect and react to incorrect behavior?

The simplest kind of misbehavior to detect and punish occurs when a set of messages constitute a self-contained cryptographic Proof Of Misbehavior (POM) by a node. For example, if a node first signs a promise to store a file with a particular cryptographic hash and then responds to a request to read the file with a signed message that contains the wrong data, the two messages amount to a signed confession by the node that it is faulty and should be punished. This "aggressively Byzantine" behavior is easy to address, and a number of systems have done so [11, 42].

Two other "passive-aggressive" behaviors are more problematic. First, a node may decline to send a message that it should send. The receiver is in a position to accuse the node of wrongdoing, but it becomes a case of "he said/she said"—it is difficult for any third party to decide whether an accusation of inaction is legitimate or it has been unjustly leveled by a self-interested or faulty node. Second, a node may exploit non-determinism to provide incomplete information or take undesirable steps that interfere with the protocol's operation but are difficult to conclusively prove wrong. For example, in one step of an asynchronous replicated state machine protocol [10], a node normally transmits a signed copy of the request, but for liveness it is permitted to transmit a signed timeout message instead. In such a protocol, self-interested nodes may choose to send the timeout message rather than transmit the request. This choice would inhibit progress, but it would be hard for another node to prove that a timeout message was inappropriate.

The implementation of Level 1 primitives addresses such challenges in three ways. First, nodes *unilaterally deny service* to nodes that fail to send expected messages. This low-level, local tit-for-tat technique provides incentives for cooperation without requiring a third party to judge which node is to blame. Second, the protocol *balances costs* so that when nodes have a choice between two messages, there is no incentive to choose the "wrong" one. Third, nodes can *unilaterally impose extra work* (called *penance*) when they judge that another node's response is not timely. The penance mechanism safeguards liveness by discouraging rational nodes from improperly exploiting timing-based non-determinism.

Addressing the challenges of non-responsiveness and non-determinism in the two higher levels is much simpler. For Level 2 (work assignment), if a node fails to reply to a request issued via the underlying state machine, then a quorum of nodes in the state machine generates a proof of misbehavior against the node. And because applications at Level 3 make use of reliable work assignment, each request is bound to a reply or timeout. As a result of this binding, the application protocol must merely be designed so that requests and responses include sufficient information for any node to judge the validity of a request/response pair.

5. LEVEL 1: BART STATE MACHINE

At the core of fault-tolerant distributed services are a few fundamental primitives. For instance, state machine replication is an essential building block for a range of highly available replicated services [7] and quorum-based replication is the basis for fault-tolerant distributed storage systems [37]. The purpose of the first level of our architecture is to implement fundamental primitives so that they continue to provide their customary guarantees within the BAR model. In this section, we present a BART asynchronous replicated state machine (RSM). Our protocol is based on PBFT [10], with modifications motivated by the BAR model. These modifications are based on four guiding principles.

Ensure long-term benefit to participants. Self-interested nodes must gain long-term utility for participating in the system to be motivated to participate faithfully. Ultimately, these benefits must stem from the higher level service, but as a hook for providing such benefits to all participants our RSM rotates the leadership role to guarantee that every node has the opportunity to submit proposals to the system.

Limit non-determinism. Non-determinism offers nodes the choice of multiple behaviors. Although each of these behaviors is legal under different circumstances, given the specific state of each node one of the behaviors is preferred by the protocol. Self-interested nodes can hide behind non-determinism to shirk work: they can disregard the preferred behavior and adopt a less costly one that other nodes cannot definitively identify as illegal. In our implementation of BAR primitives we carefully limit the choices available to a node. For example, we base our state machine on terminating reliable broadcast (TRB) rather than consensus [24], because the former protocol, by allowing fewer valid outcomes, gives rational nodes fewer options from which to choose when deciding which behavior maximizes their benefit.

Mitigate the effects of residual non-determinism. When non-determinism is unavoidable, two low-level techniques are often useful. First, we employ *cost balancing* when a node has a choice between multiple actions. The costs of the actions are engineered so that the protocol-preferred choice is no more expensive than any other potentially legal choice. For instance, instead of sending a list of nodes that are up-to-date, an IC-BFT protocol would send n bits with entries set to "1" for up-to-date nodes so that the sender saves no network bandwidth by sending incomplete information. Second, *encouraging timeliness* addresses the non-determinism inherent in an asynchronous system by allowing nodes to judge unilaterally whether other nodes' responses are early, on time, or late and to inflict sanctions for untimely messages. Our techniques ensure that (a) nodes have incentives neither to mete out unwarranted sanctions nor to forbear deserved punishments and that (b) the costs imposed by Byzantine nodes through spurious unilateral sanctions are limited.

Enforce predictable communication patterns. We encourage nodes to participate at every step of the protocol instead of just at the steps that bring them a direct benefit. Our protocol requires nodes to have participated in all past steps to be able to propose a command.

5.1 Protocol Description

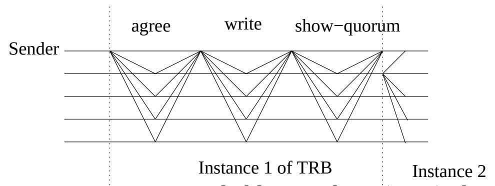

Figure 2: Terminating Reliable Broadcast (TRB) phases.

In this subsection, we first examine the high-level structure of the protocol. We then detail the low-level mechanisms used to enforce periodic communication and limit the effects of non-determinism. Due to space constraints, we limit our discussion to the key differences between our protocol and traditional PBFT implementations. The protocol's detailed pseudo-code can be found in an extended technical report [39]

Our BART replicated state machine protocol is based on PBFT [10]. When a node wants the state machine to execute a command, the node proposes the command in a TRB *instance*. Instances proceed in sequence, with instance i deciding the ith command to be executed by the state machine. We differ from the PBFT protocol in several key ways.

1. We use TRB instead of consensus. This choice is an application of the principle of limiting non-determinism. In TRB, only the initial *sender* may propose a value during a particular instance and an instance can terminate only in two ways:

all non-Byzantine nodes either adopt the value proposed by the sender, or, if the sender is faulty or slow, a default value. Conversely, in consensus a timeout caused by a slow or faulty sender may allow a new leader to propose a different value for that instance. We initially attempted to use a consensus protocol as the engine of our state machine but found the restriction on who can propose in each instance useful for limiting the choices available to rational nodes. Without this restriction, a new leader elected to terminate instance i may prevent progress by selfishly trying to make the state machine adopt its value rather than the sender's [39]. By limiting the possible outcomes of instance i, TRB avoids this conflict of interest.

2. We use a round-robin leader selection policy to ensure that all nodes can benefit from their participation in the state machine. Traditional replicated state machines require a client to send a command to a sender, who proposes the command to the state machine. But, a rational sender would have no incentive to act on a remote client's wishes. So, for each TRB instance we rotate the role of *sender* to the next node in the system. Each participant thus has a periodic opportunity to propose values to the state machine.

3. We require at least $3f+2$ nodes (rather than $3f+1$) to tolerate f Byzantine nodes. The reason is subtle and, once again, has to do with the desire to avoid a conflict of interest involving the sender node in a TRB instance. Suppose the sender s of instance i is slow, and, after sufficiently many nodes time out on s, a new leader is elected to bring instance i to conclusion. Every node but s is interested in a timely conclusion of instance i to ensure *its* turn to propose a value; s, however, is interested in ensuring that i terminates with the adoption of s's original value—rather than the default value—and to this end can take steps that compromise liveness [39]. By using an extra node, we prevent s, after it has proposed its value, from participating in the steps required to complete instance i, eliminating this potential conflict.

Our TRB protocol provides four guarantees in an eventually synchronous BAR environment in which the higher-level service provides net benefits to all participants. *Termination*: every non-Byzantine process eventually delivers exactly one message. *Agreement*: if a non-Byzantine process delivers a message m, then all non-Byzantine processes eventually deliver m. *Integrity*: if a non-Byzantine process delivers m, then the sender sent m. *Non-Triviality*: In periods of synchrony, if the sender is non-Byzantine and sends a message m, then the sender eventually delivers m.

The protocol provides safety (Agreement and Integrity) under an asynchronous model, but guarantees liveness (Termination and Non-Triviality) only during periods of synchrony [24] when there exists a known bound Δ on message delivery time. The requirement that all rational participants realize a net benefit from the service is needed only to achieve liveness; rational nodes that do not benefit from the service will not take any action on behalf of the protocol, but they will not compromise the safety properties.

Figure 2 illustrates an execution of TRB in a period of synchrony when no failures are present. Each TRB *instance* is organized in a series of *turns*. In each turn, some process is designated the *leader*. The *sender* for instance i is the first leader for instance i. In the first turn, the *sender* attempts a three-phase-commit on a proposed value (the phases are labeled agree, write, and show-quorum). If the other nodes receive the messages on time then they accept the value and the broadcast is successful: in this case, the instance consists of a single turn. If, on the other hand, nodes decide the message is late, they send a "set-turn" message to indicate that a new turn should start. Nodes other than the sender are selected round-robin for the leader role.

If a collection of set-turn messages selects a new leader, the newly selected leader first performs a read: it queries all nodes for their observed value and waits for a quorum of responses. If any node reports seeing the *sender*'s proposal, then the new leader attempts to broadcast that value. Otherwise, the new leader broadcasts the null value *senderTO*, indicating that the *sender* is suspected of having failed. Once a value is delivered, the $i+1$st instance starts with the next *sender* in the sequence.

5.1.1 Message queue

Message queues are the low-level mechanism we use to enforce *predictable communication patterns*. All communication takes place through the message queue infrastructure.

Message queues implement a simple local retaliation policy: if node x next expects a message from node y, x will ignore any communication from—and delay any communication to—node y until it receives the expected message. The message queue used by x to regulate its communication with y contains entries for the messages that x intends to send to y, interleaved with "bubbles" corresponding to messages that x expects from y. A bubble must be filled with an appropriate message from y before x can proceed to send the messages in the queue beyond the bubble. To ensure that y sends the appropriate message, a predicate is associated with each bubble: a message from y is allowed to fill a bubble only if it satisfies the corresponding predicate—otherwise, it is discarded. The message queue exports three operations: `send` and `expect`(*predicate*) insert in the queue, respectively, a message and a bubble; `deliver` removes the bubble closest to the head of the queue and returns the corresponding message.

Message queues, combined with quorums of size $n-f-1$, provide the incentive for rational nodes to send all messages expected in the protocol. If a given rational node r chooses not to send a message to some node s, then s will ignore r in the future. In the worst case for r, an additional f Byzantine nodes in the system will not communicate with r, preventing it from gathering a quorum during its next turn as *sender*. This situation would prevent r from gathering the quorum of responses required in a later step of the protocol, stopping r from making progress and effectively excluding it from the state machine. Because we assume that the value of the service greatly exceeds the cost of communication, a rational r prefers to send all expected messages to avoid any risk of losing access to the state machine.

5.1.2 Balanced messages

To apply the principle of *cost balancing* to the state machine protocol, we ensure that whenever the protocol provides a node with the opportunity to choose which message to send next, the intended message is never more expensive to send than the alternatives. For example, after a timeout a node should send either the command issued by the sender for the instance or *senderTO* if no such command was received. We construct the *senderTO* message to always be of the length of the largest possible command so that lying would not allow a node to save bandwidth.

5.1.3 Penance

We implement a "penance" mechanism to encourage timeliness in the state machine. In particular, although the *promptness principle* (Section 3) encourages nodes to promptly send any messages they are deterministically bound to send, we use penances to encourage good behavior when waiting may allow a rational node to avoid sending a specific message. To implement the penance mechanism, each node maintains an *untimely vector* that tracks their perception of other nodes timeliness: a node is considered untimely if any timeout message electing a new leader arrives significantly earlier or later than expected according to the receiver's local clock. When a node x becomes the sender, it includes its untimely vector with the value it proposes. After agreeing on the proposal, all nodes except the sender *expect* a *penance message* from each node indicted in the untimely vector. Because of the way message queues handle expects, the untimely nodes must send the penance message to all non-sender nodes in order to continue using the system.

There are three important considerations to the penance message: (1) the size and form of the penance message are chosen so that the expected benefit of sending late is less than the expected penance cost, (2) the sender is excused from receiving penance messages to prevent the sender from incurring additional costs for truthfully reporting a penance, and (3) the spurious work introduced by Byzantine nodes through the penance mechanism is bounded.

5.1.4 Timeouts and garbage collection

The system makes use of two timeouts for liveness: (1) a "set-turn" timeout to transfer leadership away from a slow leader and (2) a $max\_response\_time$ timeout to garbage collect messages queued for extremely slow nodes.

A sufficient number of set-turn timeout messages transfers leadership of an instance to the node lexicographically after the current turn's leader. The first turn of an instance uses a pre-specified timeout, and this timeout is increased for each subsequent turn of that instance until the instance completes. Note that in every TRB instance only the initial sender (the first leader of the instance) can propose a non-trivial value, so it is important that the initial timeout be significantly larger than common-case network delays. Our prototype uses 10 seconds for its initial set-turn timeout.

The timeout after $max\_response\_time$ bounds local state in the presence of extremely slow nodes. In order to ensure a *predictable communication pattern*, we require all nodes to send all protocol messages. If node a remains silent for an extended period of time, it can force non-Byzantine node b to retain an arbitrarily large set of pending messages to a. If this state becomes too large, the cost of participating in the protocol will exceed the benefit, and rational nodes will withdraw from the system, endangering liveness even in periods of synchrony. The timeout allows a node to bound this state so that its benefits from the system exceed its costs[2].

In particular, if a has been holding pending messages for b for more than $max\_response\_time$, then a (i) records b as faulty by adding b to its $badlist$, (ii) garbage collects all state associated with b, and (iii) refuses further communication with b.

It is undesirable for a non-Byzantine node to declare incorrectly a slow node to be faulty: doing so jeopardizes liveness and thus puts at risk the net utility that nodes expect to gain from participating in the system. Nodes therefore use an extremely long $max\_response\_time$ (e.g., 1 week in our prototype) that significantly exceeds the expected worst-case network disconnection time between any pair of nodes.

[2]An alternative for bounding state that we are exploring as future work is to provide an incentive compatible variation of the garbage collection and checkpoint recovery protocol described by Castro and Liskov [10].

5.1.5 Global punishment

The state machine includes a mechanism to transform local suspicion against other nodes (as recorded in each node's $badlist$) into POMs. The POMs allow nodes to agree that someone misbehaved so that an appropriate global punishment may be applied. This mechanism also enables the use of quorums of smaller size ($\lceil \frac{n+f}{2} \rceil$ rather than $n - f - 1$), improving the availability of the state machine.

When node a is the sender of an instance, it includes its *badlist* as a bit vector with the value it proposes. Nodes monitor the *badlist*s they receive from others: if over time node b appears on at least $f+1$ different senders' *badlist*s, then the receivers of these *badlist*s also begin to consider b faulty: they add b to their own $badlist$, discard the state associated with b, and refuse to communicate with b in the future.

In addition to helping punish misbehaving nodes, the *badlist* mechanism enables us to reduce the size of quorums from $n-f-1$ to $\lceil \frac{n+f}{2} \rceil$. Without *badlist*s, quorums of size $n - f - 1$ are required to provide an incentive for a non-Byzantine node to send all required messages to all recipients that expect the message: by failing to send messages to even one node, the sender jeopardizes its ability to propose new commands to the state machine because the skipped node and f Byzantine nodes could together prevent a quorum from forming. With quorums of size $\lceil \frac{n+f}{2} \rceil$, a sender that skips a node does not risk losing the ability to form quorums for its proposed values; however, the badlist mechanism ensures that the sender faces the equally severe risk of being included on $f + 1$ badlists from the skipped node and f Byzantine nodes.

5.2 Proving IC-BFT

To prove that a protocol is IC-BFT for a given model of rational nodes' utility and beliefs, one must first prove that the protocol provides the desired safety and liveness properties under the assumption that all non-Byzantine nodes follow the protocol. Second, one must prove that it is in the best interest of all rational nodes to follow the protocol.

Our rationality model is described in Section 3. We assume that rational nodes will follow the protocol if they observe that it is a Nash equilibrium, so we must show that no node has a unilateral incentive to deviate. We show this by enumerating all possible deviations.

The simplest deviations are those that do not modify the messages that a node sends. In our state machine protocol, no such deviation increases the utility. We must then examine every message that the node sends and show that there is no incentive to either (i) not send the message, (ii) send the message with different contents, or (iii) send the message earlier or later than required. Also, we must show that nodes have no incentive to (iv) send any additional message.

THEOREM 1. *The TRB protocol satisfies Termination, Agreement, Integrity and Non-Triviality.*

THEOREM 2. *No node has a unilateral incentive to deviate from the protocol. (*Incentive compatibility*)*

The full proofs appear in the extended technical report [39]. To illustrate the methodology, we show some of the lemmas involved in verifying the incentive-compatibility of the sending of the "set-turn" timeout message. The incentive for sending the message at all and not sending it twice are discussed in more general lemmas, not shown here.

LEMMA 1. *No rational node r benefits from delaying sending the "set-turn" message.*

LEMMA 2. *No rational node r benefits from sending the "set-turn" message early.*

The proof for the first lemma relies on the penance protocol described in the previous section. The second lemma deals with early time-outs. This deviation may cause the sender's proposal to be ignored, and *senderTO* to be decided instead. By construction, *senderTO* is at least as large as a resend of the sender's command, so no bandwidth is saved. Nodes other than the sender have no stake in which command is decided because they cannot unilaterally prevent the sender's command from executing—at most, they can delay it. The sender itself could have an interest in manipulating the outcome by sending "set-turn" messages early or late, which is why in our protocol the sender is not allowed to send these messages.

LEMMA 3. *No rational node r benefits from sending a malformed "set-turn" message.*

The "set-turn" message contains no information other than the turn number, so a malformed message reduces to either a nonsensical message, a resend, or an early send.

6. LEVEL 2: PARTITIONING WORK

Our second level partitions work to reduce the replication overhead required by cooperative applications. Even though state machine replication technically suffices to support a backup service directly, the overhead of such an approach would be unreasonable: each replica would have to process each command and maintain a full copy of the program state. In a cooperative backup service with 100 participants, 100 MB of data backed up would consume 10 GB of disk space. Conversely, by assigning work to individual nodes, we can make use of arithmetic codes to provide low-overhead fault-tolerant storage.

We introduce three protocols for work assignment. The *Guaranteed Response* protocol ensures that every request is answered, possibly with a message indicating that the work was not done in in a timely fashion. The *Periodic Work* protocol ensures that clients periodically answer implicit requests required by an application. The *Message Binding* protocol binds messages to an authoritative time.

We first describe these protocols using the abstraction of a trusted altruistic node, which we call the *witness node*. Then we show how the witness node can be implemented on our replicated state machine in an incentive-compatible manner.

For large systems, using a single replicated state machine to implement the witness node becomes impractical. To allow our current system to span more than a few dozen nodes, large systems should be partioned into disjoint state machines of 10-30 nodes each. For applications in which nodes must all be able to work together, these state machines should be able to communicate with each other [2, 50]. There are BAR-specific challenges related to communication between state machines. We believe these challenges are surmountable, but leave them for future work.

6.1 Guaranteed Response

The Guaranteed Response protocol gives rational nodes an incentive to respond to requests. The protocol is necessary because direct communication does not suffice when nodes can behave rationally. Consider an example where some node a sends a request to another node b and gets no answer. Node a may well complain about b, but because a cannot prove that b received and ignored its request, it would be unwise to punish b based on a's complaint. The Guaranteed Response protocol eliminates all ambiguity: in the above situation, it ensures that a lack of response to a can only be the result of uncooperative behavior by b, who can then be safely punished.

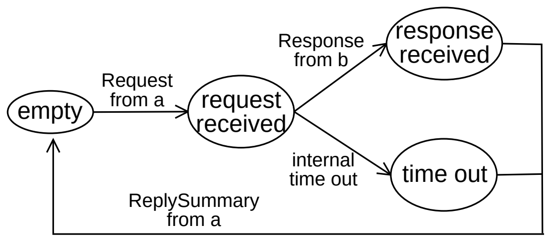

Figure 3: Basic Guaranteed Response protocol

Figure 3 shows the state transition diagram for a correct witness node running the Guaranteed Response protocol. The basic idea is that node a never sends work requests directly to b, but instead goes through the witness node. The witness is then in a position to answer with *NoResponse* if necessary.

More precisely, client a starts by sending *Request* to the witness, who is initially in the *empty* state. *Request* contains the name of the intended recipient, b, as well as the work w that must be performed by it, and causes the witness to transition to state *request received*. The witness stores *Request* and forwards a copy of it to b. If b is correct, it will send a signed *Response* to the witness, causing it to enter state *response received*. *Response* contains the answer to a's request together with a summary of the request to which b is responding. The witness then discards *Request*, forwards *Response* to a, and keeps a copy of *Response* until it receives from a a *ReplySummary* containing a summary of *Response*. If node b does not answer *Request* within a predetermined $max\_response\_time$, then the witness transitions to state *time out* and sends *NoResponse* to a. This message is signed and contains a summary of the request. Again, node a must send *ReplySummary* (this time with a summary of *NoResponse*), returning the witness to the *empty* state.

The state of the witness node includes a copy of the last message sent. This state allows the witness to resend messages that were lost, which in turn allows our protocol to handle nodes that come and go. Nodes cannot stay away for too long, however, because our backup application requires that nodes answer within $max\_response\_time$.

6.1.1 Implementing the witness node

The incentive-compatible replicated state machine allows us to implement the abstraction of a correct witness node on top of a collection of BAR nodes. We must be careful to maintain incentive compatibility: our state machine only provides incentive for communication with members of the state machine, not outsiders, so nodes a and b must be part of the replicated state machine. Therefore communication with the witness node is not by actual message sending: when the Guaranteed Response protocol talks of a node sending to the witness, this translates to the node submitting a command to the RSM. Whenever the protocol talks of the witness sending to a node, no actual sending is necessary: since every node in the RSM has a copy of the witness state, the RSM replica running on the destination node passes the message to the local code that handles it.

The *NoResponse* message is a special case for two reasons. First, the "timeout" decision must be made deterministically. We accomplish this by having the state machine maintain a deterministic RSM time that is a function of recent values of the local clocks of all nodes (see Section 6.4 for details). The RSM replica running on node a is responsible for submitting a "timeout" command to the RSM when the deterministic RSM time indicates that the response is late. Second, the abstraction of a single, signed *NoResponse* message from the witness node to a is actually implemented by having a receive a signed message from $f+1$ RSM replicas. After nodes transition to the *time out* state, these signatures are gathered by replica a, which uses the message queue primitive described in Section 5.1.1 to `expect` a signature from every other replica. The other replicas therefore know, when entering *time out*, that a is ready for their signature message and the message queue mechanism gives them an incentive to send the signature. Once a has enough signatures to form a *NoResponse* message, it passes the message to the local code at a that handles it.

Provided that the application provides sufficient sanctions for nodes that cause a *NoResponse*, the following theorem holds [39].

THEOREM 3. *If the witness node enters the* $request\ received$ *state for some work* w *to rational node* b*, then* b *will execute* w*.*

6.1.2 State limiting

The witness node, naturally, can communicate with more than one node at a time. It runs several instances of the protocol highlighted above, and each instance (which we call a *slot*) is reserved for a particular node.

We limit the overhead associated with Guaranteed Response by limiting the number of slots available to a node. Limiting the number of slots accomplishes three purposes: (1) it applies a limit to the memory overhead of running the Guaranteed Response protocol, (2) it limits the rate at which requests are inserted into the system, and (3) it forces nodes to acknowledge responses to requests.

6.2 Optimization through Credible Threats

The Guaranteed Response protocols allows data to be replicated only where necessary. However, requests and responses are still sent to every node that is part of the replicated state machine and, because backup requests contain the data being backed up, they can be large. We therefore optimize our protocol so that in the common case nodes can communicate directly.

To get the benefits of the Guaranteed Response protocol without requiring all requests and replies to go through the RSM, we leverage the game-theory notion of credible threats [17]. In the game of chicken [12], a credible threat against rational players would be to visibly rip off the steering wheel and throw it out the window [35]. In our case, the credible threat takes a somewhat less spectacular form.

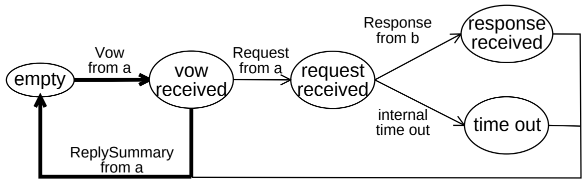

Figure 4: Guaranteed Response protocol with fast path

We optimize the Guaranteed Response protocol by adding a *fast path*. The new protocol is shown in Figure 4 with the fast path in bold. Instead of sending its request to the witness node, node a now only sends it a *Vow* with a summary of its request. The witness supplies the vow to the target (b in our example). Target b sends an ack to node a, and a sends the full request directly to b. Target b then replies to a, who forwards summary of the response to the witness. If the target does not answer then the protocol proceeds as in the unoptimized case, with a sending the full request to the witness.

The threat in this case is the vow: if b does not answer a's request directly, then a will ask b to answer to the witness node, a costlier operation for b. Key to the threat is the fact that it is credible. By sending its vow a has forfeited its right to utilize that slot until it sends the full request or supplies a reply from b that matches the vow. A rational target b knows that if it does not answer a directly, then a *will* send the request through the witness node—and this is enough to motivate b to answer a's direct request.

6.3 The Periodic Work Protocol

Cooperative systems may include maintenance tasks that need to be performed periodically, for example auditing nodes' storage records. However, there may be no incentive for any individual node to initiate such maintenance work. Under the Periodic Work protocol, the witness node checks that this periodic work is done. The existence of this check, in turn, means that rational nodes will perform these tasks.

In the case of the RSM witness, the Periodic Work protocol initializes the system with the expectation that, with a certain frequency, each node will provide the witness with an application-specified response type indicating its completion of a periodic task. If a node does not supply the expected *ReplySummary*, the witness node can either unilaterally deny its services to the offending node or generate a POM to be handled by the application.

6.4 Authoritative Time Service

In applications where time has meaning, authoritatively binding messages to time is a potentially important action. The *Authoritative Time Service* serves two purposes. First, it maintains an authoritative time that is recent, nondecreasing, and identical at all state machine nodes. Second, it binds messages to times according to that time. In particular, our Guaranteed Response protocol relies on this time when generating *NoResponse*s for non-participating nodes, and BAR-B relies on the message-time binding to identify certain classes of misbehavior.

In order to maintain the time, each proposal to the state machine is required to contain a local timestamp generated by the proposer. The authoritative time is computed by taking the maximum of the median of the timestamps of the $f+1$ most recent decisions and the previous authoritative time; when "no decision" is decided, then the time for that decision is defined to be the previous authoritative time. In order to bind a message to a time, node a submits the message to the *Message Binding Protocol* and proposes a *BindingRequest* to the RSM. The nodes in the RSM then send a a signature binding the message to the current authoritative time.

7. LEVEL 3: THE APPLICATION

In our architecture, BART applications must discharge each of the following four responsibilities in order to take advantage of lower-level abstractions.

1. Provide rational nodes with a long-term benefit for participating in the system.
2. Assign work to nodes in a fault tolerant manner.
3. Determine if the contents of a request or response constitute a Proof of Misbehavior (POM) under the application semantics.
4. Sanction nodes that have provably misbehaved.

It is much simpler to design an application under these requirements than under the lower-level concerns discussed in Sections 5 and 6. The replicated state machine of the first level provides the abstraction of a correct node, which is useful in implementing sanctions. Reliable work assignment is taken care of by level two primitives, so the application can focus on defining the legal requests and responses over the system's data. As a result, the reader will notice that the following discussion is considerably simpler than that in earlier sections: it focuses on structuring the messages so that incorrect responses act as proofs of misbehavior and not on encouraging nodes to respond or on balancing costs.

To illustrate how an application addresses these issues, this section examines BAR-B, a MAD cooperative backup system.

7.1 BAR-B Overview

BAR-B is a cooperative backup system in which nodes commit to participating in the system's state machine and contributing an amount of storage to the system in exchange for an equal amount of space on other nodes. Under normal circumstances (see Section 7.2 for recovery), nodes interact with BAR-B through three operations: store, retrieve, and audit. To store a backup file, the owner compresses it, splits it into smaller pieces (chunks), encrypts the chunks, and then sends them to different nodes (storers) for storage on the system. The storers respond with signed receipts. The owner keeps the receipts and the storers keep the StoreInfos (part of the store request) as their record of participation in the system. When the owner needs to retrieve a file, it sends a retrieve request to each node holding a relevant chunk. The retrieve request contains the receipt, so the storer has three options: (i) return the chunk, (ii) show that the chunk's storage lease duration has expired, or (iii) show a more recent StoreInfo for the same chunk. Any other response would indicate that the storer prematurely discarded data entrusted to it and should be punished.

These receipts constitute audit records. Nodes periodically exchange audit records in order to verify that some node is not using more space in the system than its quota allows (both in terms of total storage and number of chunks). BAR-B allows each node to store a limited number of chunks, thereby binding both the state maintained in the system and the cost of performing audits.

7.1.1 Arithmetic coding

To tolerate f faults using less storage than required by full replication, nodes erasure code [52] files with an $x-f$ out of x encoding and store the resulting chunks on different peers. For example, in a 10-node system with $f = 2$, a node must contribute 1.3GB of local storage to back up 1GB of data. Keeping this ratio reasonable is crucial to motivate self-interested nodes to participate.

In practice, many files are small. Since there is both a limit on the number of chunks and some per-chunk overhead, it is beneficial to keep chunks reasonably large. The BAR-B user interface therefore aggregates small files together before uploading the aggregate to BAR-B as a single backup file.

7.1.2 Request-response pattern

The responsibility of Level 2 is to structure messages carefully so that an incorrect response to a request constitutes a POM against the sender of the response. The work assignment primitive in Section 6 provably binds requests either to responses or to NoResponse if the target fails to respond. Every message in the BAR-B protocol is stamped with a unique sequence number and signed by the sender.

Store. A BAR-B store request consists of two components, the chunk being stored and a tuple *(chunkId, owner, storer, hash, size, prevSize, time)* called the *StoreInfo*. The *hash* and *size* fields of the *StoreInfo* correspond to the hash and size, respectively, of the chunk being stored. The *prevSize* field is the size of the file being replaced—the owner's quota is charged for max(*size, prevSize*) until $max\_response\_time$ expires. The *time* is a real-time stamp used to calculate when the storage lease will expire; if it is too far into the future, a storer can generate a POM via the time service described in the previous section. There are three possible responses to a store request: (a) a *Receipt* containing the *StoreInfo* and time-stamped and signed by the storer, (b) a *StoreReject* containing the *StoreInfo* and a *Proof* that is stamped and signed by the storer, and (c) anything else. A *StoreReject* can return proof that the storer is full in the form of a list of *StoreInfo* records, each signed and stamped by its respective sender and holding an active lease, and such that the total size of the *StoreInfo* records plus the request's *StoreInfo* size exceed the node's quota. When the owner issues a *StoreInfo* request or receives a response, the owner adds it to its record of utilization of the system, known as the *OwnList*. Any other response constitutes a POM against the storer—either (a) the response itself is a POM generated by the work allocation level (e.g., NoResponse) or (b) the response is inappropriate for the request and thus a signed confession.

Retrieve. A BAR-B retrieve request consists of the *Receipt* for the chunk to be returned. The three possible responses to a retrieve request are: (a) a *RetrieveConfirm* containing the *Receipt* and the corresponding chunk stamped and signed by the storer, (b) a *RetrieveDeny* containing the *Receipt* and a *Proof* stamped and signed by the storer, and (c) anything else. If the response is a *RetrieveDeny*, then the the *Proof* must show either (a) *Receipt* has expired (b) the *Receipt* has been superseded by a more recent *StoreRequest* from the same $owner$ to the same $chunkId$, or (c) the storer is in the process of recovering its data (see below). Any other response constitutes a POM against the storer—either (a) the response itself is a POM generated by the work allocation level (e.g., NoResponse) or (b) the response is inappropriate for the request and thus a signed confession.

Audit. An audit takes place in three phases. First the auditing node selects a node to audit. The auditing node then requests both the *OwnList* and *StoreList* from the auditee. After retrieving the two lists, the auditing node requests the *OwnList* and *StoreList* for f nodes chosen at random in the system. The collection of lists are cross-checked for inconsistencies; any inconsistencies result in a POM against the offending node. An *OwnList* and *StoreList* are inconsistent if a *Receipt* indicated on one should be present but is not on the other. Audits are potentially expensive operations, and rational nodes would avoid performing them if possible. We avoid this problem by leveraging the Periodic Work protocol described in Section 6.1. The RSM-implemented *witness node* periodically expects the results from a recent audit—either a POM or a complete set of *OwnList*s and *StoreList*s.

7.1.3 Time constraints

The primary purpose of a backup system is to provide retrieval following a catastrophic disk or user failure. The utility of a backup program is greatly reduced if the retrieval guarantee is "eventual recovery" rather than "recovery within time t." In order to guarantee a concrete recovery window, BAR-B assumes that all non-Byzantine nodes will respond to a request within $max\_response\_time$. Any node that fails to do so is considered faulty; a POM against such a node can be acquired by issuing a request through the work allocation primitive.

We utilize leases to bound the duration of store requests on the system. In BAR-B, every *StoreInfo* expires 30 days after the request is issued by the owner. If the owner needs to keep the chunk in the system for more than 30 days, the owner must renew the chunk by sending an additional *StoreRequest* before the current lease expires. Otherwise, the storer is free to discard the data. A lease expires when the *Authoritative Time Service* described in Section 6.4 indicates a date 30 days after the *time* field of a *StoreInfo*.

The introduction of these timing assumptions and lease durations allows BAR-B to (a) provide stronger guarantees with respect to recovery time and (b) limit the amount of "dead" storage in the system. These two factors aid in increasing the overall utility of the system, making it more attractive for rational nodes.

7.1.4 Sanctions

Various components of the BAR-B system, from the primitives in sections 5 and 6 to the mechanisms described earlier in this section, generate POMs against specific nodes. These POMs convict a node of misbehavior and require that the node be punished appropriately; without appropriate punishment, nodes may find it in their interest to misbehave.

We leverage the Periodic Work protocol to force each node to submit periodically to the state machine either a POM it has generated, or a special NoPOM (which, to obey the cost balancing principle, is no cheaper than a POM).

For simplicity, BAR-B handles all POMs in the same fashion: whenever a POM is submitted to the state machine, the POM is distributed to all nodes and each node evicts the guilty party. Note that the POM provides a basis for more sophisticated strategies including suspending a node's store and retrieve rights pending administrative intervention, increasing the storage a node must contribute (without increasing its quota) or releasing the POM to an administrative entity for external disciplinary action.

7.2 Recovery

Since we are dealing with a backup system, nodes that lose their local state must still be able to make use of the system. Our approach (1) allows such a node to assume a new identity to access its old state and (2) restricts this ability to prevent rational nodes from shirking work and to limit damage by Byzantine nodes.

A node only needs a few things to be able to recover: the list of its peers, its membership certificate, and its key pairs. The user saves this information to a safe place when installing the program. Initially we give each node a fixed series of *linked identities*, $i_0 \ldots i_{max}$. A key pair is associated with each identity. After a node using identity i_{j-1} crashes and loses data, it uses a new identity i_j and sends a RECOVER message to every other node. In response, these node send the list of i_j's chunks that they are storing. From this list, the recovering node can then retrieve its backup data as needed.

Any node that receives a message from identity i_j (1) assigns all message queue bubble obligations of any preceding linked identity ($i_k, k < j$) to i_j, (2) grants retrieve rights to i_j for any data with a valid lease by i_k, (3) initiates a fixed grace period during which *RECOVERING* is considered a valid response by i_j to any retrieve request, and (4) evicts i_k from the system. The node also notes that the data it entrusted to i_k is gone, and therefore starts refreshing its backup data. The erasure coding scheme ensures that the full backup is recoverable despite the loss of the chunks stored on i_k.

Two factors prevent a rational node from exploiting linked identities to avoid punishment. First, each node has a small number of identities (e.g., 3 initially plus 1 every two years) and cannot recover its data after all have been used; using a linked identity thus reduces the future utility of the system. Second, a new linked identity is responsible for the messages of previous identities, so nodes cannot avoid work. The first factor also limits the damage that can be done by a series of linked entities under a "persistently Byzantine" node's control. A possible addition to the two factors would be to require identity i_j to contribute 1.1^j times the storage of identity i_0 but give it no corresponding increase in quota; this measure is not strictly necessary, but it would further discourage nodes from needlessly changing identities.

A natural concern in our model is to ensure that nodes respond truthfully to the RECOVER message. A node might send only a subset of the list of chunks it is storing, in the hope of deleting the unlisted chunks to save disk space. This would be against the best interest of a rational node, however, because the recovering node might not have lost all of its receipts. In that case, a signed incomplete answer along with the receipts that should have been listed form a POM against the node.

7.3 Guarantees

The BAR-B system provides the following guarantees under BAR-B's coarse synchrony assumptions. (i) Data stored on BAR-B can be retrieved within the lease period. (ii) No POM can be gathered against a node that does not deviate from the protocol. (iii) No node can store more than its quota on BAR-B without risking being caught. (iv) If a node with at least one unused linked-identity crashes and loses its disk, it is guaranteed a window of time during which it can rejoin the system and recover all data it has stored.

8. EVALUATION

In this section we evaluate our replicated state machine and BAR-B prototype. Our microbenchmarks show that our RSM prototype can perform about 15 operations a second, an adequate level of performance for our application's requirements. We then evaluate the performance of the BAR-B application. We find that our non-optimized BAR-B prototype can back up 100 MB of data to 10 nodes in under 4 minutes and guarantee that the data are recoverable despite the failure of 3 nodes.

8.1 Experimental Setup

Except where noted, experiments run on Pentium-IV machines with 2.4 Ghz processors, 1 GB of memory, and Debian Linux 3.0. These are shared machines, connected through 100 Mbps ethernet. The Emulab [62] experiments were run on Pentium-III machines with 850 Mhz processors, 256 Mb of RAM, and Red Hat Linux 9.

Our prototypes are implemented using Java 1.4. We set the initial TRB network timeout to 10 seconds. The maximum response time and lease duration are set to a week and a month respectively, but our experiments do not rely on these values. Each node is allocated 40 slots in the Guaranteed Response Protocol. Unless otherwise noted, we do not introduce failures in our experiments. We use the BouncyCastle cryptographic library and Onion Networks' FEC library for erasure coding.

8.2 Micro-benchmarks

We use micro-benchmarks to evaluate our replicated state machine prototype. The main questions we try to answer are (a) whether our RSM is practical, (b) whether our RSM scales to a reasonable number of nodes, and (c) whether our RSM handles intentionally slow nodes well.

Figure 5 shows the average speed of TRB operations for systems of 5 to 23 nodes. Each trial measures the average duration over 30 TRB operations with 4 KB proposals. We run each configuration 10 times and show the median value as well as the 10^{th} and 90^{th} percentiles. We run the experiment twice: once with $f = 1$ and once with the maximal f tolerated given the number of nodes. The chart shows that TRB completes in less than 60 ms for 5 nodes

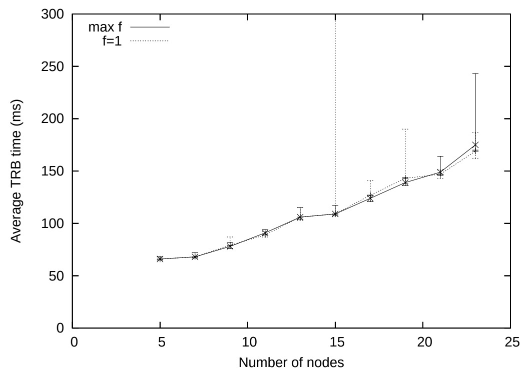

Figure 5: RSM performance as nodes are added

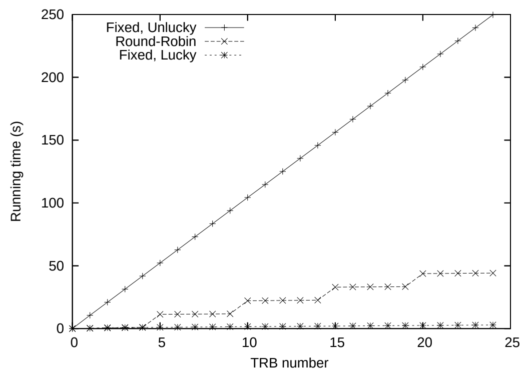

Figure 6: Impact of rotating leadership

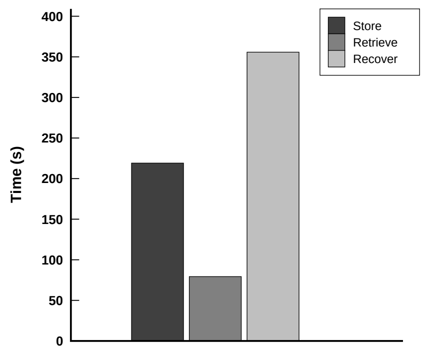

Figure 7: Operation time for 100 MB

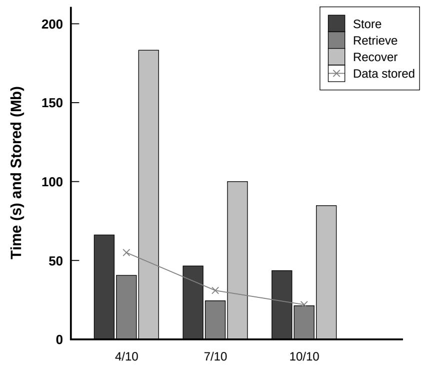

Figure 8: Operation time for 20MB at various encodings

or 175 ms for 23 nodes, a level of performance that is sufficient for our application due to (a) the relatively modest response time demands of backup and (b) the ability to batch multiple application commands in each TRB instance to improve throughput [10]. The graph also shows that performance is hardly affected by the choice of f and is reasonable for the range of sizes we chose. Eventually, however a large cooperative service should be split into multiple state machines as proposed in Section 6.

Our performance is inferior to protocols that are not designed for the BAR model. PBFT [10] requires only 15 ms per consensus on less powerful hardware than ours. Part of the difference is explained by our language choice, but the main factor is the fact that our IC-BFT RSM requires the properties of digital signatures, so we cannot rely on the faster MAC primitives. Note that (just as in PBFT) to maximize application throughput, nodes can submit multiple commands in a batch for each TRB operation.

Figure 6 shows the relative impact of two leader election policies in the presence of failures. Our protocol rotates the role of sender between instances of TRB. A PBFT-like protocol instead rotates the sender only when the current sender is determined to be faulty or untimely. When the sender is timely and non-Byzantine, the state machine proceeds at full speed for either protocol, without timing out (cf. “Fixed, Lucky”). However, a Byzantine sender can proceed slowly—just fast enough to avoid triggering a time-out (cf. “Fixed, Unlucky”). Our sender rotation (cf. “Round-Robin”) limits the worst case damage imposed by a slow node.

8.3 BAR-B

Our BAR-B experiments are designed to determine the following: (a) whether the performance of BAR-B is adequate, (b) the value of the fast path optimization, and (c) the cost of performing system audits.

Figure 7 shows the time required to perform our basic system operations for 100 MB of data on a system with 11 nodes. A node can place data on the system at the rate of 100 MB in 219 seconds, and retrieve it in 90 seconds. Recovery of the data after a local disk failure completes in just under six minutes. Recover is slower than the basic retrieve operation because it performs additional tasks—fetching *StoreList*s from all nodes and reconstructing and storing local BAR-B metadata.

Figure 8 shows the performance of our system under a range of encoding parameters when storing a 20 MB file on a system with 11 nodes. Each group of bars represents a choice of encoding parameters. As the ratio gets closer to one, the total amount of stored data stored on the system (indicated by the line) diminishes and the performance of the system increases. Storing a 20 MB file when encoded at 7 out of 10 (7/10) transmits approximately 31 MB of encoded data at 0.67 MB/s. The corresponding retrieve operation operates at 1.2 MB/s. Overall, the additional cost required for utilizing 7/10 encoding as compared to 10/10 is modest.

Figure 9 shows the effects of loading the system with multiple nodes storing or retrieving at the same time. The experiment itself records the time required when the specified number of nodes each store or retrieve of a single 20 MB file using the 7/10 encoding. When all nodes are active each node sees a modest reduction in throughput (from 0.67 MB/s to 0.54 MB/s) but the aggregate system throughput grows to 5.86 MB/s.

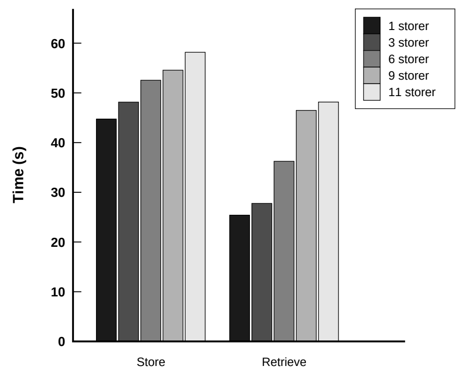

Figure 9: Concurrent operations

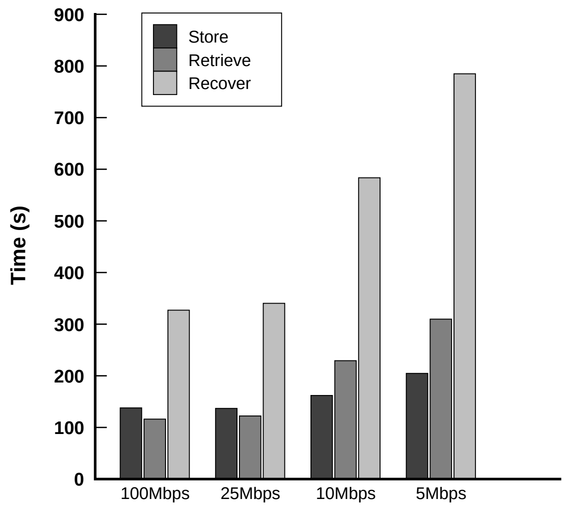

Figure 10: Operation under different network conditions

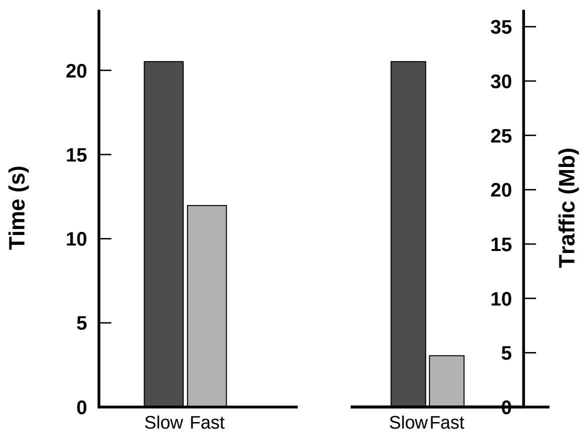

Figure 11: Impact of the fast path optimization

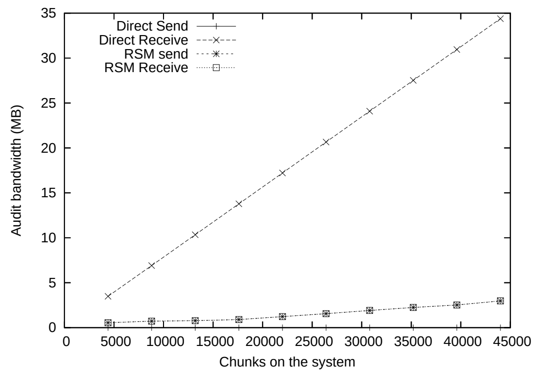

Figure 12: Cost of audit as capacity grows

To this point, we have shown experiments run on a 100 Mbps LAN. Figure 10 shows the time required to store, recover, and retrieve a 20 MB file on Emulab machines with connections of 100 Mbps, 25 Mbps, 10 Mbps, and 5 Mbps, and round-trip latency of 26ms. At bandwidths of 10 Mbps and 5 Mbps, the network becomes a limiting factor and performance falls with network bandwidth. The baseline 100 Mbps store is slower than that found in Figure 8 due to the higher latency and slower machines on the Emulab site.

Figure 11 illustrates the effect of the "fast path" (Section 6.2) optimization on time and bandwidth. In each pair, the first bar shows a measurement of the unoptimized system, and the second bar shows the version with the fast path. For a 2 MB file encoded at 7/10, the fast path cut the duration of the store operation by 40% and reduced the traffic by a factor of five. Larger files would see even greater relative improvement.

Figure 12 shows the bandwidth required to perform an audit of an 11 node system. The bandwidth required is plotted against the number of chunks stored on the system. The "Direct Send/Receive" bandwidth lines correspond to the exchange of *OwnList*s and *StoreList*s. The number and size of requests and replies sent through the RSM is constant, but the RSM bandwidth consumed during an audit increases as the duration of the audit increases because the RSM completes additional (empty) instances. 38 MB of traffic is necessary for audit when the system stores 44000 chunks, which corresponds to up to 40 GB of storage or about 28 GB of backup files encoded at 7/10.

9. RELATED WORK

Our work brings together Byzantine fault-tolerance and game theory.

Byzantine agreement [30] and Byzantine fault tolerant state machine replication have been studied in both theoretical and practical settings [6, 9, 26, 49, 55]. Our work is clearly indebted to recent research [2, 10, 36, 53, 63] that has shown how BFT can be practical in distributed systems that fall under a single administrative domain—indeed, Castro and Liskov's BFT state machine [10] is the starting point for our IC-BFT state machine. Our work addresses the new challenges that arise in MAD distributed systems, where the BFT safety requirement that fewer than one third of the nodes deviate from the assigned protocol can be easily violated.

Game theory [25] has a long history in the economics literature [4, 28, 41] and has recently become of general interest in computer science [3, 20, 22, 23, 45, 48, 61]. Protocol and system designers have used game theoretic concepts to model behaviors in a variety of settings including routing [21, 58, 59], multicast [43], and wireless network [61]. Common across these works is the assumption that *all* nodes behave rationally—the presence of a single Byzantine node may lead to a violation of the guarantees that these system intend to provide.

Shneidman et al. [59, 60] recognize the need for a model that includes both Byzantine and rational nodes, but their protocols address only the latter. Nielson et al [44] identify different rational attacks and discuss high-level strategies that can be used to address them.

To our knowledge, Eliaz's notion of k Fault-Tolerant Nash Equilibrium (k-FTNE) [19] is the only previous attempt to formally model games that include both rational and Byzantine agents. Eliaz's model is more general than the one we assume—for our Nash equilibrium, a rational node that is considering deviating from the protocol assumes that Byzantine nodes will perform the actions that are most damaging to it; to achieve equilibrium, Eliaz requires that rational players have no incentive to deviate *regardless* of the actions of the Byzantine players. Eliaz's problem domain differs from ours: it targets auctions with human participants and provides no example of how k-FTNE may be used to build cooperative computer services with Byzantine and rational nodes.

Rigorous design for incentive compatible systems has largely been restricted to theoretical work. Practical systems for tolerating rational behavior [13, 16] commonly rely on informal reasoning. Bittorrent [13] uses a tit-for-tat strategy to build a Pareto efficient mechanism for content distribution. However Shneidman demonstrates that the algorithm is not actually incentive compatible [60]. Other systems use audits [42] or witnesses [40] to discourage rational nodes from deviating from their assigned task, but they do not specify an incentive compatible or Byzantine tolerant mechanism for implementing audits or witnessing. Using BART state machines to implement a reliable witness from self-interested or Byzantine nodes is one of the contributions of this paper.

Cooperative storage and backup systems have been studied extensively in the literature [2, 5, 15, 16, 31, 50, 54]. The backup systems proposed in [5, 15] rely on the assumption that all non-faulty nodes behave correctly. Samsara [16] and Lillibridge et al. [31] introduce a set of incentives to influence rational nodes, but they do not bound the damage Byzantine nodes can inflict to stored data. An additional limitation of Samsara is its reliance on random spot-checks to verify that a node is storing data it has promised under which if a node o fails such a spot check, the system probabilistically deletes o's data. This increases the likelihood that a node will be unable to retrieve its files precisely when they are needed most. Conversely, we guarantee that a node can recover its data for a period of time, even if it suffers a total disk failure. This property seems useful in a backup system.

10. CONCLUSIONS

This paper describes a general approach to constructing cooperative services spanning MADs in the context of a cooperative backup system. The three primary contributions of this paper are (1) the introduction of the BAR (Byzantine, Altruistic, and Rational) model, (2) a general architecture for building services in the BAR model, and (3) an application of this general architecture to build BAR-B, the first cooperative backup service to tolerate both Byzantine users and an unbounded number of rational users.

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