Peer-to-Peer Data Trading to Preserve Information

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Data archiving systems rely on replication to preserve information. This paper discusses how a network of autonomous archiving sites can trade data to achieve the most reliable replication. A series of binary trades among sites produces a peer-to-peer archiving network. Two trading algorithms are examined, one based on trading collections (even if they are different sizes) and another based on trading equal sized blocks of space (which can then store collections). The concept of *deeds* is introduced; deeds track the blocks of space owned by one site at another. Policies for tuning these algorithms to provide the highest reliability, for example by changing the order in which sites are contacted and offered trades, are discussed. Finally, simulation results are presented that reveal which policies are best. The experiments indicate that a digital archive can achieve the best reliability by trading blocks of space (deeds), and that following certain policies will allow that site to maximize its reliability.

Categories and Subject Descriptors: H.3.7 [**Information storage and retrieval**]: Digital libraries—*systems issues*; E.5 [**Files**]: Backup/recovery

General Terms: Design, Reliability

Additional Key Words and Phrases: Data replication, digital archiving, digital library, fault tolerance, resource negotiation

1. INTRODUCTION

Digital information is best preserved by replicating it at multiple archives run by *autonomous organizations*. For instance, if a single publisher stores a collection of journals (even with backup tapes), there is a danger that the publisher might go out of business and the information may become inaccessible. It is much safer for several publishers or libraries to jointly archive the journals. Similarly, it is best if the copies are managed by different software, so that a common error, say in one brand of file system, does not corrupt all copies. This is the way today's libraries work with paper copies, and several projects [Goldberg

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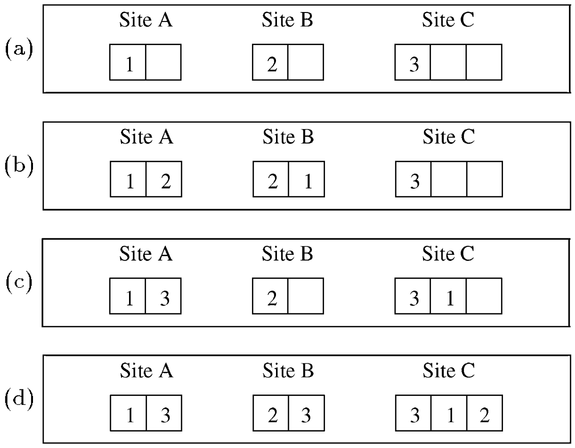

Fig. 1. Data trading example.

and Yianilos 1998; Cooper et al. 2000; Rosenthal and Reich 2000; Kubiatowicz et al. 2000] have been extending this preservation approach to digital data.

To achieve data preservation in a network of cooperating archives, we propose the concept of *data trading*: sites replicate their data by contacting other sites and proposing trades. Thus, technical reports owned by site A may be replicated at site B. In return, a copy of a collection of software documentation owned by site B is stored at site A. In such a network, each site makes local decisions about which other sites to contact and offer trades as well as whether to accept trades offered by other sites. The result is a global peer-to-peer archiving network, built up from a series of trading agreements concluded between pairs of sites.

To illustrate such a data trading mechanism, consider the example shown in Figure 1. Figure 1(a) shows sites A and B, each of which have two gigabytes of space, and site C, which has three gigabytes of space. (A gigabyte is represented in the figure as a box.) Site A owns a collection of data labeled "1," site B owns collection "2," and site C owns collection "3." (A collection is an application unit, e.g., a set of technical reports, or a set of census files.) Each collection requires one gigabyte of space. Sites A and B can trade their collections, resulting in the configuration of Figure 1(b). Collections 1 and 2 are now stored more reliably, because if one site goes out of business, goes on strike or burns down, another copy is available. However, now site C cannot trade with either A or B since neither site has free space for collection 3. Thus, collection 3 is not stored reliably.

A different trading order can result in a more desirable scenario. For example, say that from the initial configuration, site A first contacts C and offers a trade. The result is shown in Figure 1(c). Now there is still enough space to make another trade, this time between sites B and C. The resulting situation, in Figure 1(d), has all three collections reliably stored with two copies. A trading scheme should be effective enough so that sites can make local decisions about which sites to trade with, while still allowing other sites to replicate their collections. At the same time, trading must be flexible enough to deal with the

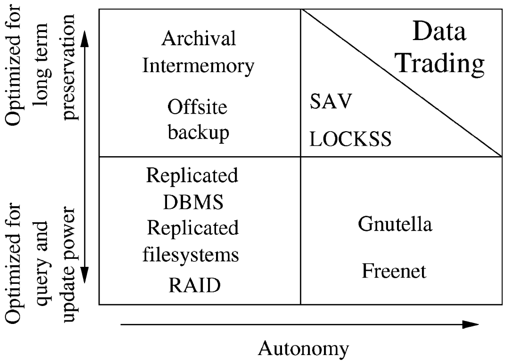

Fig. 2. Classification of data management schemes.

appearance of new sites, new collections, and even new free storage added at an existing site.

There are a number of interesting variations for trading, that lead to different reliabilities and implementation costs. In particular, sites can trade collections or blocks of space. With collection trading, complete collections are exchanged, as in our previous example. With blocks of storage, the "buckets" that hold data are traded, but they do not have to be filled in immediately. We use the term *deed* to refer to an empty block; it represents the right to use a certain amount of space at a given site. Deeds can be combined to obtain larger blocks of space, and they can be traded with third parties.

Collection trading is simple to implement and manage; however, it may not be fair because the traded collections may be of different sizes. When trading blocks of space, a site can ask for a large enough block to contain a collection it wants to replicate, and can then give an equal sized block in return. Trading blocks of space requires more bookkeeping, to record blocks that have been traded but not yet used.

In this paper we study these two trading strategies, and the design decisions that must be made to implement them. For example, in what order does a site look for trading partners? How much free space does a site "advertise" when making trades? When and how are deeds traded? We also study the impact of key parameters, such as the number of participating sites and the amount of free space available, on the achievable reliability. We evaluate designs and scenarios with a detailed trading simulator. The simulator lets us mimic large numbers of trading sessions to find expected reliabilities.

1.1 Related Work

Our work draws upon concepts developed in related systems. Figure 2 shows a schematic classification of data management schemes, including our work and some other sample systems. This classification divides schemes based on the amount of autonomy given to participating sites (horizontal axis) and whether the system is optimized for query and update performance, or for long term preservation (vertical axis).

For example, the lower left box of Figure 2 contains traditional data management schemes, such as replicated DBMS's [Bastani and Yen 1987; Gray et al. 1996; Taaffe et al. 1990], replicated filesystems [Liskov et al. 1991] and RAID disk arrays [Patterson et al. 1988]. Such schemes utilize replication to protect against failures in the short term. However, they do not provide a high level of autonomy to the nodes participating in the replication network, relying instead on a central controller to determine data placement or manage free-space tables. We do not believe that autonomous sites will, or should, surrender such decision making. Also, we are concerned with "fairness": a site that provides a higher amount of free space per collection should expect a correspondingly higher level of reliability. Fairness and autonomy are much less important for disk arrays and file systems, since typically all disks are owned by the same organization. Another difference is that traditional solutions are concerned with load distribution, query time and update performance, as well as reliability [Du and Maryanski 1988; Sandhu and Zhou 1992; Wolfson et al. 1997; Hindel 1990]. Here, we are primarily concerned about preservation (given the constraint of preserving site autonomy). Thus we are willing to trade some access performance for increased reliability and site independence. In contrast, traditional replicated databases tend to trade some reliability for increased performance [Lee and Thekkath 1996].

Similarly, replicated filesystem schemes such as Coda [Kistler and Satyanarayanan 1992] or Andrew [Morris et al. 1986] use caching to improve availability. Data is replicated so that it can be read despite temporary site failures or network partitions. This is a different goal than long term reliability (preserving data despite permanent site failures or data corruption.) Andrew and Coda treat replicates as cached copies that are created on demand and ejected from the cache when necessary. Data trading places data in response to reliability needs, and we assume that replicates are not ejected once placed.

The lower right box of Figure 2 shows existing peer-to-peer trading systems such as Freenet [fre 2000] or Gnutella [gnu 2001]. Such systems are focused on finding resources within a dynamic, ever-changing collection, and not on reliability. While popular items may become widely replicated, less popular or frequently accessed items are deleted. Thus, systems like Gnutella provide searching but do not guarantee preservation. A searching and resource discovery mechanism could be built on top of our data trading system; however, our primary focus is surviving failures over the long term.

Systems such as the Archival Intermemory [Goldberg and Yianilos 1998; Chen et al. 1999] (in the upper left box of Figure 2) are very good at preserving digital objects. High replication is achieved at the cost of site autonomy, as sites do not have control over where their collections are replicated or which remotely-owned collections they store. For example, under our mechanism, the MIT library can tell its funders that they are hosting ACM journals and Berkeley reports, as opposed to saying that they are hosting some ever-changing set of files. Moreover, the MIT library can refuse to store information that it deems improper or illegal.

Another possibility is for archives to contract for an offsite backup, in which another organization agrees to store a copy of the data, usually for a fee. Such a scheme provides reliability, but the backup lacks autonomy, because the offsite backup must store the data given to it by the archive site. Offsite backups may be quite expensive, and offer no guarantee of preservation if the archive goes bankrupt and no longer pays its bills. Under a data trading scheme, an archive achieves the high reliability of having multiple offsite backups, while only having to buy extra local data storage. This is especially important for libraries and other organizations that are on a limited budget, and require a data preservation scheme that can utilize their existing resources. Libraries that already provide digital access to their collections will not have to buy additional infrastructure (beyond disk storage) but can augment the systems they already have with the data trading mechanisms we describe here.

Another difference between data trading and many of the existing systems mentioned above is that it is often very desirable to keep collections contiguous and immovable. It is much easier to manage and index a collection if each of its copies is at a single site, rather than fragmented and scattered around the network. Similarly, management is simpler if a collection rarely moves. We expect collections to be large, so the cost of movement across geographically distributed sites would be high. Therefore, in this paper we only study algorithms that keep collections together and that do not move the collections once they have been copied. (Collections can grow over time; see Section 3.) This is the reason that in the example in Figure 1, we did not consider "undoing" site A's mistake (trading first with site B) by moving previously traded collections. Many of the systems in Figure 2 do allow collections or files to be fragmented and moved. For example, in a RAID system, files are often fragmented to improve read/write times.

The upper right box of Figure 2 shows systems such as SAV [Cooper et al. 2000] and LOCKSS [Rosenthal and Reich 2000], which are good at both preserving site autonomy and ensuring long term data archiving by utilizing a community-based approach to preservation. A member of the community benefits if the system is able to preserve information, because then the member's own information is protected. Thus, if one site experiences a failure (temporary or permanent), then the remaining sites are motivated to preserve the data owned by the failed site. Moreover, organizations such as libraries have a commitment to preserving information, even if it is "owned" by other sites. This is an additional incentive to protect the data. Motivations such as these have led over 40 libraries and 30 publishers to participate in LOCKSS [loc 2001]. Other systems that utilize community-based preservation include Intermemory [Goldberg and Yianilos 1998] and OceanStore [Kubiatowicz et al. 2000]. A community preservation approach could utilize the data trading mechanism we describe here to achieve a highly reliable data distribution. Currently these systems either require administrators to manually configure data replication (in the case of SAV), distribute data based on accesses while potentially failing to preserve rarer materials or collections of specialized interest (such as with LOCKSS), or simply distribute data randomly (as with Intermemory/OceanStore).

The problem of optimally allocating data objects, given space constraints, is well known in computer science. Distributed bin packing problems [Martello and Toth 1990] and the file allocation problem [Chu 1969] are known to be NP-hard. This is one reason we have not sought to find an optimal placement for data collections. Moreover, these problems are even harder when the number of sites and number and sizes of collections are not known in advance.

Digital library researchers have examined the archiving problem from many different angles [Garrett and Waters 1996]. Some projects have focused on maintaining collection metadata [Rajasekar et al. 2000], or on dealing with the data formats [Rothenberg 1995; Maria et al. 1998; Heminger and Robertson 1998]. Others have focused on policy issues surrounding information archiving [Beagrie 1998]. All of these issues are important, and complement the basic bit-level reliability we seek to provide here.

1.2 Overview

In this paper we describe how data trading among autonomous sites can be used to achieve high reliability. Specifically, we make the following contributions:

—We define two algorithms, COLLECTION_TRADING and DEED_TRADING, for automatically conducting trades between autonomous data archiving sites. We also propose the concept of *deeds* as a mechanism to facilitate trading blocks of space.

—We identify ways to tune the operation of both the COLLECTION_TRADING and DEED_TRADING algorithms; for example, by changing the order in which sites should be contacted and offered trades.

—We present results of simulation experiments that show the impact on reliability of each alternative policy. This allows us to choose the most reliable policies and thus effectively tune the trading algorithm.

In order to build a reliable archiving system, we must both design an effective mechanism and implement that mechanism in a real system. Our goal in this paper is the design phase: to examine various algorithms and policies that provide the best reliability. In ongoing work we are implementing these mechanisms in a prototype archival repository. Also, our focus here is on protecting the "bits" of the data. Other aspects of preservation, such as metadata, translating formats or protecting intellectual property rights can be dealt with by layers operating on top of the mechanism we describe here.

This paper is organized as follows. In Section 2, we discuss our model, and in Section 3 we present the COLLECTION_TRADING and DEED_TRADING algorithms, as well as the tunable policies for each. Section 4 describes our simulator, and Section 5 presents results and discusses tradeoffs. In Section 6 we review our conclusions.

2. DATA PRESERVATION OVERVIEW

Redundancy is the primary mechanism for achieving preservation. Making several copies of important data is critical to ensure that the data can survive

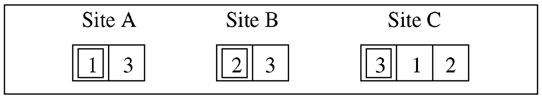

Fig. 3. Reliability example.

multiple failures. Our model of a preservation system based on redundancy contains the following components:

—A network of *archiving sites*. Sites are autonomous units, managed by different organizations, and thus are not under any centralized control. New sites can be created at any time.

—Each site has a quantity of *archival storage*: storage that is devoted to storing archived data, including copies of data that originated at other sites. The site provides *online access* to this archival storage. New archival storage may be added to a site at any time.

—The basic unit of archived data is the *data collection*: a set of related data—for example a group of files, a database table, a set of documents, and so on. Collections may contain any number of data items, and different collections may be different sizes. Collections may also grow over time, as new data is added.

—Archiving sites have *clients*: users or applications that connect to the site to utilize archiving services. A client archives data by depositing a collection at a site; the site is then said to *own* the collection and takes primary responsibility for preserving it. A client can deposit a new collection at any time. Clients can also read archived data.

Once a digital collection has been replicated, a client can retrieve data from the collection, either from the owning site or from any site that holds a copy. This requires a mechanism that allows the clients to determine where collections are stored in the trading network. In previous work [Cooper et al. 2000], we have described how sites can keep a directory of the remote sites holding copies of its collections. There could also be a mechanism for searching for collections within the network, for example using keywords. Implementing distributed indexing in our peer-to-peer trading network for this purpose is a topic of our ongoing work.

We also need a method for determining *reliability*. The goal of an archiving system is to reliably protect data, despite the potential for site failures. Thus, we use the following concepts:

site reliability. The probability that a site will not fail.

local data reliability. The probability that the collections owned by a particular site will not be lost.

global data reliability. The probability that no collection owned by any site will be lost.

Figure 3 can be used to illustrate these reliability concepts. Each of the three sites (A, B and C) could fail independently. If we assume (for example) a 0.1

probability of site failure, then the *site reliability*, or probability of no failure, is 0.9 for each site. We can then calculate the *local reliability* for each site. In Figure 3, the collections owned by a particular site are shown double boxed; thus site A owns collection 1, and so on. Collection 1 will be lost if both site A and site C fail, but will not be lost if either site survives. The probability of both sites failing is $0.1 \times 0.1 = 0.01$, so the probability of one or both sites surviving is $1 - 0.01 = 0.99$. This is the probability that collection 1 will not be lost. Because this is the only collection owned by site A, the *local reliability* of site A is 0.99. Similarly, the local reliability of site B is 0.99, since collection 2 will be lost only if both site B and site C fail. However, the local reliability of site C is 0.999. For collection 3 to be lost, all three sites must fail, and this event has a probability of $0.1^3 = 0.001$. As a result, the probability that at least one site survives is $1 - 0.001 = 0.999$.

We calculate *global reliability* by determining the probability that any collection is lost, regardless of which site owns it. In the example of Figure 3, all collections will survive if site C survives. This event has a probability of 0.9. If site C fails, an event with probability 0.1, then the collections will survive only if both site A and site B survive. The probability of both sites avoiding failure is $0.9 \times 0.9 = 0.81$. The global probability is then

$$\begin{aligned} &P(\text{C lives}) \times P(\text{All data survives given C lives}) \\ &\quad + P(\text{C fails}) \times P(\text{All data survives given C fails}) \\ &\quad = 0.9 \times 1 + 0.1 \times 0.81 = 0.981 \end{aligned}$$

Thus, even though each local site reliability is ≥ 0.99, the global reliability is only 0.981. Each site can justify its expenditure of resources by noting that it has achieved very high reliability for its collections, e.g. ≥ 0.99. The designer of a trading mechanism would consider the global reliability of 0.981 to evaluate design choices.

In this paper, we assume for simplicity that all site reliabilities are equal. We have conducted experiments where site reliabilities differ, and the trends are the same as those reported here. We have also generalized our algorithms to take into account the possibly different reliabilities of sites when making trades; those results are reported elsewhere [Cooper and Garcia-Molina 2001] and summarized in Section 5.8. We also assume that there is some mechanism to protect the security of the data, for example using encryption to ensure the privacy of sensitive material that is replicated to other sites.

3. DATA TRADING

In our data trading scheme, a site that wishes to make a copy of a data collection contacts another site and proposes a trade. We refer to the *local site* as the site that actively makes a connection to another site and proposes a trade. The site contacted by the local site is called the *remote site*; the remote site can accept or refuse the trade proposal. If the trade succeeds, each site devotes a portion of its archival storage to storing the other site's data.

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I. The local site $L$ repeats the following until the replication goal <G> for
   collection $C_L$ is met, or until all sites have been contacted and offered trades:
   (1) Select a remote site $R$ according to the trading strategy <S>.
   (2) Contact $R$, and request that $R$ advertise its free space. The amount of
       free space $A_R$ advertised by $R$ is determined by $R$'s advertising policy
       $<\mathrm{A}>_R$.
   (3) If $R$ cannot store $C_L$ (because $A_R < size(C_L)$), then the trade cannot be
       completed. $L$ returns to step I.
   (4) $L$ advertises its own free space $A_L$ to $R$ according to $L$'s advertising
       policy $<\mathrm{A}>_L$.
   (5) $R$ selects a collection $C_R$ that it owns, where $A_L \geq size(C_R)$, according
       to the collection copy policy <C>.
       — If no collection exists that meets the condition $A_L \geq size(C_R)$, the
         trade cannot be completed. $L$ returns to step I.
   (6) The trade is executed, with $L$ storing a copy of $C_R$ and $R$ storing a copy
       of $C_L$.
II. If the goal <G> is not met for collection $C_L$, $L$ may decide to try again in
    the future, according to the retry policy <R>.
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Fig. 4. Algorithm COLLECTION_TRADING.

One possibility is that sites trade *collections*. For example, site A may agree to store a copy of site B's collection of technical reports, and in return, site B stores a copy of site A's image collection. Under this approach, the traded collections may be different sizes.

We assume here that collections have a set size, although different collections may have different sizes. The scenario where collections grow can be handled by assigning a fixed size to the collection that is larger than its actual size; this provides extra space for growth. If this space is exhausted, then a new collection is created to contain the new data, and a new round of trading is conducted to replicate this new collection. We also assume that all collections are equally important, and equally difficult to preserve. (If necessary, a site could choose to make more copies of especially important or fragile collections than of other collections.) Finally, we assume in this paper that collections, once traded, are not moved (see Section 1).

The first algorithm, COLLECTION_TRADING, is shown in Figure 4. It is conducted separately by each local site wishing to make a trade. The algorithm starts when a client contacts the local site L and deposits a collection C_L to be archived. COLLECTION_TRADING can be tuned using several policies, each of which cause the algorithm to behave differently: <G>, <S>, <A>, <C>, and <R>.

<G>: The *replication goal* of the local site. In this paper we assume that the replication goal is that each site wants to make N copies of a collection. The generalization of our algorithm to other replication goals is straightforward.

<S>: The *trading strategy* of the local site. The trading strategy determines the order in which remote sites are contacted and offered trades. We describe the strategies in Section 3.1.

<A>: The storage space *advertising policy* followed by a site. A site may advertise all of its free storage space, or may advertise only a fraction of the space and reserve the rest for future trades. This issue is discussed in more detail in Section 3.2.

<C>: The *collection copy* policy. When a remote site is offered a trade, it must select one of its collections to copy to the local site. For example, it may decide to replicate only collections that have not met the replication goal <G>. In this paper, we assume that the remote site always selects the rarest collections to copy first, even if these collections have enough copies to meet the goal <G>.

<R>: The *retry* policy followed by a site. A site may use *active retries*, in which it initiates COLLECTION_TRADING again at some future time for collections that do not meet the replication goal <G>. The site would maintain a list of collections that had not met the goal, and retry these collections in response to a trigger (e.g., every week). In contrast, a site may limit itself to *passive retries*: after running COLLECTION_TRADING once for a collection, a site waits to be contacted by other sites to make further copies.

COLLECTION_TRADING can be illustrated by the following example. At first, there is one archiving site, site A, with 12 GB of space. A client contacts site A, and deposits collection 1, which requires 1 GB of space. Site A stores collection 1, and now has 11 GB of free space. However, in the absence of any other sites, site A cannot replicate the collection. Now, a second archiving site is created, site B, with 6 GB of space. A client contacts site B and deposits collection 2, which requires 2 GB of space. Site B now has 4 GB free, and contacts site A to propose a trade. Site A agrees to store collection 2, and in return, site B will store a copy of collection 1. Now, there are two copies of both collections 1 and 2, as each is stored at both sites 1 and 2. This process continues with more collections and more sites being created at any time.

The alternative to collection trading is to trade blocks of space. These blocks of space will be used to store collections, although the sites may decide not to exchange data immediately. For example, a local site may acquire a block of space at a remote site; in trade, the local site reserves a block of its own space for use by the remote site. The local site may use a portion of the block at the remote site to make a copy of an existing collection, but save the rest for future collections. The local site may also decide not to use any of the space it has just acquired, but to save all of it for the future. This flexibility results in added complexity compared to collection trading, and a bookkeeping mechanism is required to manage this complexity.

The mechanism we propose is called *deeds*, an analogy to property deeds. A deed is a right to use a block of space at a particular site. This deed may be used, in whole or in part, at any time by the site holding the deed. If site A holds a deed for 500 MB of site B's space, site A may exercise a portion of the deed now to store a copy of 100 MB of images, and reserve the remaining 400 MB. Deeds may also be transferred, in whole or in part, to other sites. Thus, site A may *split* its deed for site B into two deeds, one of size 200 MB and another of size 300 MB. Site A can then transfer the 200 megabyte deed to site C, which can then use the deed to store its own collections.

The algorithm for trading blocks of space utilizes deeds; DEED_TRADING is shown in Figure 5. This algorithm is similar in some respects to COLLECTION_TRADING, and in particular can be tuned with policies <G>, <S>, <A> and <R>. However, there are additional parameters for DEED_TRADING: <D>, <U>, <T>, and <S$_T$>.

<D>: This is the *deed size policy*, and represents the amount of space each site will request from the other. The simplest policy is that L selects a deed size (D_L) equal to the size of collection C_L minus the size of any deeds L already has for R, and R picks an identical size (D_R). This is the policy we assume in this paper. However, the algorithm could be generalized to the case where $D_L \neq D_R$. This might occur for example if one site was more reliable than the other, and thus the less reliable site may have to give more space to compensate.

<U>: This is the *deed use policy*, which determines when a site will use a deed it has acquired. A local site running DEED_TRADING will use the deeds it acquires to immediately replicate the collection C_L. However, the remote site R will acquire a deed that it may use immediately or at some future time. Clearly, if R has rare collections it should use the deed to propagate them. However, if R does not have rare collections, it must decide what to do. If R is aggressive, it might use the deed immediately to replicate collections, even if they are not rare. In contrast, R might decide to save the deed for use with new collections that it acquires in the future.

<T>: This is the *deed transfer policy*. This policy either allows deeds to be transferred among sites, or requires that the original holder of a deed be the one that uses it. If <T> allows deeds to be transferred, a site running DEED_TRADING may decide to propose trades to acquire deeds held by other sites at any time. However, a site should only acquire deeds held by other sites if it facilitates data replication; see Section 3.3.

<S$_T$>: The is the *third party trading strategy*. If the remote site R does not have enough undeeded free space, the local site may decide to collect deeds for R currently held by other sites. The local site chooses an order to contact *third party* sites which hold deeds for the remote site. That order is determined by the third party trading strategy. Here, for simplicity, we assume that the local site uses the same strategy used to select remote sites, that is, <S$_T$> = <S>. It is straightforward to extend our mechanism to allow sites to choose a different strategy for contacting third party sites; in other words <S$_T$> ≠ <S>. Several strategies are described in Section 3.1.

We can illustrate DEED_TRADING by extending the example above. Site A (12 GB of storage) is given collection 1 (requiring one gigabyte of space) and stores it, but cannot make trades until new sites are created. Site B is created with 6 GB of space, and is given collection 2 (requiring two gigabytes). Site B stores collection 2, and then contacts site A, proposing a trade for deeds worth two gigabytes. Site A agrees to this trade, and reserves two gigabytes of its space for site B, while site B likewise reserves two gigabytes of its space for site A. Site B uses its deed to store collection 2 at site A; the deed is now used up. Site A uses its deed to store collection 1 at site B, but afterwards still has

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I. The local site $L$ repeats the following until the replication goal <G> for collection $C_L$ is met, or until all sites have been contacted and offered trades:
   (1) Select a proposed deed size $D_L$, according to $L$'s deed size policy $<\mathrm{D}>_L$.
   (2) Select a remote site $R$ according to the trading strategy <S>.
   (3) If $L$ has a deed for $R$ then:
       (a) If the existing deed is $\geq$ $size(C_L)$ then:
           i. Use the existing deed to store a copy of $C_L$. Return to step I.
       (b) If the existing deed is $\leq$ $size(C_L)$ then:
           i. Set $D_L = D_L - size$(existing deed).
   (4) Contact $R$, and request that $R$ advertise its free space. The amount of free space $A_R$ advertised by $R$ is determined by $R$'s advertising policy $<\mathrm{A}>_R$.
   (5) If $A_R < D_L$ then:
       (a) If the transfer policy <T> allows deeds to be transferred from one site to another:
           i. $L$ may contact a *third-party site* $T$ (that is, a site other than $R$) and trade some of $L$'s storage space for $T$'s deed for $R$. $L$ may have to conduct several such trades to acquire enough deeds; if so, it contacts them according to the third party trading strategy $<\mathrm{S}_T>$.
           ii. If the total of the deeds acquired through third-party trades, plus the deed $L$ already had for $R$, plus the free space $A_R$, is enough to store collection $C_L$, the trade can be completed. Otherwise, the trade cannot be completed and $L$ returns to step I.
           iii. $L$ adjusts $D_L$ downward such that $A_R \geq D_L$, subject to the constraint that the total of the deeds held by $L$ for $R$ plus $D_L$ is still greater than or equal to $size(C_L)$.
       (b) If <T> does not allow transfers, the trade cannot be completed and $L$ returns to step I.
   (6) $L$ advertises its own free space $A_L$ to $R$ according to $L$'s advertising policy $<\mathrm{A}>_L$.
   (7) $R$ selects a proposed deed size $D_R$, according to $R$'s deed size policy $<\mathrm{D}>_R$.
   (8) If $A_L < D_R$ then the trade cannot be completed. $L$ returns to step I.
   (9) The trade is executed, with $L$ acquiring a deed of size $D_L$ for $R$'s space, and $R$ acquiring a deed of size $D_R$ for $L$'s space.
   (10) $L$ uses its deeds for site $R$ to store a copy of $C_L$.
II. If the goal <G> is not met for collection $C_L$, $L$ may decide to try again in the future, according to the retry policy <R>.
III. At any time site $L$ may use a deed that it posesses to replicate one of its collections. A decision to use a deed is based on the deed use policy <U>.
```

Fig. 5. Algorithm DEED_TRADING.

Table I. Trading Strategies (<S>)

Strategy	Description
Random	Trade with sites in random order
First fit	Trade with sites according to a globally defined order
Neighbors	Trade with sites according to a locally defined order
Clustering	Trade preferentially with sites that we have traded with before
Best deed	Trade first with sites for which we have the smallest deed
Worst deed	Trade first with sites for which we have the largest deed
Best fit	Trade first with sites that have the least free space
Worst fit	Trade first with sites that have the most free space
Neediest	Trade first with sites that have the rarest collections

a deed worth one gigabyte for site B. Now, a client contacts site A and deposits collection 3, of size three gigabytes. Site A, which has 9 GB of space remaining, uses three of those gigabytes to store collection 3. Site A contacts site B and proposes a trade, but only requests a two gigabyte deed, since A still holds a deed for site B worth one gigabyte. Site B, which has two gigabytes of free space remaining, agrees. Site B's space is now used up, and site B holds a two gigabyte deed for site A. This process continues, although B will not be able to store new collections or make new trades unless it acquires more local space.

Clearly, DEED_TRADING is more complex than COLLECTION_TRADING. Moreover, deeds may introduce more fragmentation, as supposedly "free" space is rendered unusable by virtue of being reserved under a deed. On the other hand, DEED_TRADING seems more "fair," since equal amounts of space are always traded, and judicious use of deed transfer could reduce the fragmentation problem. We have evaluated both algorithms in terms of reliability. We have also evaluated various choices for the tuning parameters (<S>, <A> and so on). Section 4 describes our evaluation methodology, and Section 5 discusses our results.

3.1 <S>: Trading Strategies

The order in which a local site contacts remote sites can have a significant impact on the reliability achieved. We have designed several strategies for selecting trading partners; they are listed in Table I. Although some of the strategies are drawn from previous work in memory allocation (e.g. best fit), we are applying them in a new, distributed, negotiation based context. Moreover, others, such as the neediest strategy, have no analog in memory allocation. In this section, we describe these strategies. In Section 5.4, we evaluate them in terms of reliability.

The strategies we have examined fall into two categories. The *random*, *first fit*, *neighbors*, *clustering*, *best deed* and *worst deed* strategies allow a site to make decisions using only local information. Local information includes a record of sites previously traded with, and a knowledge of deeds held for other sites. In contrast, the *best fit*, *worst fit*, and *neediest* strategies require up-to-date information about the global state of the system, such as how much free storage each site has and how many copies have been made of each collection. Of course, all strategies require information about which sites have been created.

We assume that a newly created site announces its existence in some way, and that knowledge about which sites exist is stored locally at each site.

For the strategies that require global information, there must be some way of acquiring an up-to-date picture of the global state. One way of doing this is to contact all sites and request the needed information. Another possibility is to maintain a central information repository that is updated by a site when its state changes. Then, any site could contact the repository and obtain a snapshot of the global state. A third possibility is that sites could broadcast state information to other sites, for example whenever there is a local change. We are not concerned here with the actual mechanism for obtaining global information. Instead, we assume that the global state can be examined by a site wishing to make a trade, and our concern is how best to use this information. The strategies which require global state may run counter to the distributed, autonomous nature of the system, especially if they require a centralized information repository. We have examined them here to understand whether trading can be truly distributed or if some global state maintenance mechanism must be used to achieve the best reliability.

A site using the *random* strategy randomly selects sites to trade with. The order of sites contacted varies from collection to collection.

In the *first fit* strategy, sites are always tried in the same order, and this order is global. For example, sites could be contacted in order by IP address or domain name.

The *neighbors* strategy is like first fit except that each site contacts other sites according to a local ordering. Each site can choose its own local order of remote sites to contact, and follows this order for each trade. The first fit strategy will cause a few sites to be tried first for every trade, and those sites will likely be overloaded. The neighbors strategy attempts to avoid this phenomenon.

The placement of copies can be important in addition to the number of copies. The *clustering* strategy attempts to take advantage of this fact. For example, imagine that there are four sites, sites A–D, which are each given one collection, collections 1–4. There are many ways to distribute copies of these collections, including:

	Site A	Site B	Site C	Site D
I.	1 2	1 2	3 4	3 4
II.	1 2	2 3	3 4	4 1

Configuration I is more reliable with a global reliability of 0.98, as compared to 0.96 for configuration II. This difference is due to the fact that after a site failure in configuration II, a failure at either of the "neighboring" sites will cause data loss, while in configuration I, a second failure must come at one specific site to cause loss.[1] This argument suggests that clustering copies of collections, along

[1] Configuration I is equivalent to a mirrored disk architecture [Borr 1981], while configuration II is known as chained declustering [Hsiao and DeWitt 1990]. Lee and Thekkath [1996] note that database systems tend to use chained declustering (configuration II) since it provides better throughput after a failure, even though it is less reliable.

the lines of configuration I, is important. For example, if a cluster of collections 1 and 2 occurs at one site, it is beneficial to make a cluster of 1 and 2 at other sites. Under *clustering*, a site trades preferentially with the same sites it has concluded trades with before, in an attempt to keep its collections clustered. If there are ties (e.g. two sites could be chosen to achieve clustering), the local site can use any strategy to break the ties. Moreover, if no clusters exist yet, some strategy must be used to select new partners to trade with. We assume here for simplicity that the *random* strategy is used to break ties and to select new partners.

In the *best deed* and *worst deed* strategies, a site examines the deeds it is already holding before deciding which site to trade with. These strategies are only applicable if DEED_TRADING is being used. Under *best deed*, a site uses the smallest deed first, while under *worst deed* a site uses the largest deed first. Note that in both cases, the held deed may be large enough for the collection being replicated, and the deed may be then used without requring any actual trading. However, if the deed is smaller than the collection size, the local site will have to trade with the remote site to make up the difference. We assume here that for both best deed and worst deed, the random strategy is used if there are no deeds, and that ties are broken randomly.

The *best fit* and *worst fit* strategies require global state information about the free space available at remote sites. The *best fit* strategy attempts to find the site whose free space best fits the collection to be replicated. Specifically, if a site wishes to replicate a collection of size N units, then all sites with at least N units of free space are selected and then sorted in order of increasing free space. In contrast, a site using the *worst fit* strategies will contact sites with the most free space first, and contact other sites in order of decreasing free space. We assume here that for both best fit and worst fit, ties are broken using the random strategy. Also, if DEED_TRADING is being used and deed transfer (<T>) is allowed, then a local site includes the size of unused deeds in the best fit or worst fit calculations. This space is effectively free since the local site can trade with the deed holders to acquire the deeds, if necessary.

Finally, in the *neediest* strategy, a site contacts the neediest site first. The neediest site is defined as the site with the rarest collection—the collection with the fewest copies. The local site must use global state information to determine which sites are needier than others. Again, we assume that ties are broken randomly.

3.2 Space Advertising

A site must decide how much of its local space should be offered for use by other sites. In the ideal situation, a site always has enough space to store collections deposited by local clients, while simultaneously offering the optimum amount of space to remote sites. A simple solution would be to advertise the total amount of free local space. However, if this space becomes used up, the site will no longer be able to store collections deposited by local clients, and thus will fail to provide archiving to its users.

Therefore, a better solution would be to partition the site's total space (called T) into a *local* portion L_{total} (for use by local clients) and a *public* portion P_{total} (to store collections owned by remote sites). When trading, the local site advertises all or part of its public space. A good partition may be hard to find. If L_{total} is too small, the local portion can become used up, preventing local clients from depositing collections. If L_{total} is too large, the public portion can become used up, preventing the site from making trades. Ideally, L_{total} is no larger than the total size of collections that will be deposited locally, although this value may be hard to predict.

Even if the local space is "ideally" partitioned, the local site will be unable to make trades if the public portion becomes filled up. Thus, a local site should slowly release the public space for use by others. Instead of advertising all of the available public portion all of the time, the local site would advertise only a fraction initially, and increase the amount advertised as more trades were made.

There are two different ways to advertise the public portion so that space is released over time. One way, which we call the *space-fractional* policy, advertises a fixed fraction of the amount of free public space. Then, if the unused part of the public space is P_{free}, sites would advertise:

$$x \times P_{free} \text{ where } (0 \leq x \leq 1)$$

If a site chooses $x < 1$, then a fraction of the public space is released while the rest is kept in reserve for the future. If a site chooses $x = 1$, then it always advertises all of its free public space.

The second way to advertise public space is called the *data-proportional* policy. In this policy, a site releases public space to reflect the amount of locally owned data. The motivation behind this policy is that by releasing new public space to correspond with newly deposited collections, a site ensures that it has some public space to trade away to replicate those collections. If the portion of L_{total} and P_{total} that has been used is L_{used} and P_{used} respectively, then a site advertises:

$$MIN(y \times L_{used} - P_{used}, P_{free})$$

A site chooses a factor y, for example $y = 2$, and releases y times the amount of locally owned data. As more data is archived locally, the amount of released space increases. Some of this released space is used to store collections owned by remote sites, so the value advertised is $y \times L_{used} - P_{used}$. The site can never advertise more public space than it has; hence, the advertised amount should not exceed P_{free}.

3.3 Deed Transfer

The DEED_TRADING algorithm allows sites great flexibility in using the deeds they have acquired. This flexibility includes the ability to transfer a deed to another site that needs it. For example, site A may wish to trade with site B, but finds that most of site B's space is reserved under deeds held by other sites. Site A can then contact these sites and try to acquire deeds for site B, and site A can then use these deeds to store its collection. Step 5 of Figure 5 describes how a site would acquire deeds from third parties. There may be other reasons why a site transfers deeds; for example, a site may wish to trade away deeds it holds instead of giving away precious local space. We do not consider these situations in this paper.

Note that deed transfer is only useful if the local site can acquire enough deeds to meet its needs. Trading is a parallel, distributed process, with each local site executing DEED_TRADING concurrently and independently. Thus, even if enough deeds exist to meet a local site's needs, the site must be able to acquire them all by making separate, binary trades with each of the third party sites. If another site in a similar situation acquires some of the deeds before the local site can, then the local site may be unable to accumulate enough deeds to replicate its collection at the remote site. There are a number of mechanisms that could be used to deal with this situation. The local site could contact each third party site and reserve the deeds before trading for any of them. Then, if the local site is unable to reserve enough deeds, it can release all of the reservations. This prevents a site from acquiring some deeds and finding them to be useless since the rest are unexpectedly taken by another site. Another possibility is to have a central deed registry, where a local site can both find out which deeds are available and atomically acquire all of them.[2] A third possibility is to simply make as many trades as possible, and hope that enough deeds can be acquired to meet the local site's needs. We are not concerned here with the specific mechanism used to reserve deeds, but instead with the reliability that could be achieved if deeds were effectively acquired by sites that need them.

4. TRADING SIMULATION

In order to evaluate the different variations of data trading, we have developed a simulation system. This system generates a trading scenario, and then conducts a series of simulated trades using a given set of trading policies. The global and local reliabilities of the resulting collection distribution are then calculated. Table II lists the key variables in the simulation and the initial base values we used; these variables are described below.

The simulation works as follows. The simulator generates a *trading scenario*, which contains a set of sites, each of which has a quantity of archival storage space as well as a number of collections "owned" by the site. The number of sites, S, is specified as an input to the simulation. For most of our experiments we use $S = 15$, but in Section 5.7 we consider other values and their impact on system reliability. The number of collections assigned to a site is randomly chosen between $CperS_{MIN}$ and $CperS_{MAX}$, and the collections assigned to a site all have different, randomly chosen sizes between $Csize_{MIN}$ and $Csize_{MAX}$. The sum of the sizes of all of the collections assigned to a site is the *total data size Ctotal* of that site, and ranges from $Ctotal_{MIN}$ to $Ctotal_{MAX}$. The values we chose for $CperS_{MIN}$, $CperS_{MAX}$, $Csize_{MIN}$, $Csize_{MAX}$ and $Ctotal$ represent a highly diverse trading network with small and large collections and sites with small or large amounts of data. Thus, it is not the absolute values but instead

[2] As noted above, the idea of a central registry runs counter to the distributed, autonomous nature of sites. We mention it here for completeness, but a more distributed solution may be desired.

Table II. Simulation Variables

Variable	Description	Base values
S	The number of sites	2 to 15
F_G	The global free space factor	2 to 7
F_L	The local free space factor	2 to 7
P	Site reliability	0.9
$CperS_{MIN}$, $CperS_{MAX}$	Min and max collections per site	$CperS_{MIN} = 4$, $CperS_{MAX} = 10$
$Csize_{MIN}$, $Csize_{MAX}$	Min and max collection size	$Csize_{MIN} = 50$ GB, $Csize_{MAX} = 1000$ GB
$Ctotal_{MIN}$, $Ctotal_{MAX}$	Min and max data at a site	$Ctotal_{MIN} = 200$ GB, $Ctotal_{MAX} = 10,000$ GB
<G>	Replication goal	3 copies
<S>	Trading strategy	9 strategies tried
<A>	Advertising policy	fixed or increasing
<R>	Retry policy	active and passive, or passive only
<D>	Deed size policy	$size(C_L)$, C_L = local site's collection
<U>	Deed use policy	aggressive or non-aggressive
<T>	Deed transfer policy	transfer allowed or not allowed

the range of values that are important. The archival storage space assigned to the site is some multiple F_L of *Ctotal* at the site.[3] The ratio of the global storage space to the global total amount of data is F_G. In some experiments, we set $F_L \approx F_G$ such that every site has roughly the same ratio of space to data. In other experiments, we vary F_L widely while keeping F_G fixed; for example $F_G = 4$ and $2 \leq F_L \leq 6$. Unless explicitly indicated otherwise, experiments reflect the case where $F_G \approx F_L$.

The scenario also contains a random order in which collections are created and archived. The simulation considers each collection in this order, and the "owning" site replicates the collection. A site is considered "born" when the first of its collections is archived, and thus all of the sites begin trading at different times. A site does not have advance knowledge about the creation of other sites or collections. Our results represent 100 different scenarios for each experiment. For each scenario, the simulator runs simulated trading sessions for each policy setting. Here, all sites use the same policies. In ongoing work we are examining the impact of different sites using different policies, including so-called "rogue sites" that pursue local benefit to the detriment of the global system.

We model site failures by specifying a value P: the probability that a site will not fail. This value reflects not only the reliability of the hardware that stores data, but also other factors such as bankruptcy, viruses, hackers, users who accidentally delete data, and so on. History has shown that any of these factors can cause data loss, and may be more likely than a simple disk failure. In this paper, $P = 0.9$. We have conducted experiments with scenarios that may have different values of P for different sites as well as strategies that may take these differing values into account. Results are reported in Cooper and Garcia-Molina [2001].

In this paper we assume that the replication goal <G> of a site is to make three copies of its collections. As the example of Figure 3 shows, a collection

[3] The amount of archival storage may be influenced by other factors besides data size, such as cost.

that has three copies is stored very reliably with only a 0.001 probability of data loss.

5. RESULTS

We have evaluated the COLLECTION_TRADING and DEED_TRADING algorithms, as well as the policies used to tune the algorithms, using our simulator. Our evaluation is primarily concerned with reliability. We report results for both global and local reliability. Since we are concerned here with designing a trading mechanism to provide the best reliability for all sites, we tend to focus on global reliability. Moreover, for experiments where local reliability is not reported, the trends observed were not different between local and global reliability, although the magnitude of the reliability values differed. We report more results involving local reliability in Cooper and Garcia-Molina [2001]. Other factors, such as the complexity of implementing the trading algorithms, are not considered here.

In the following sections, we evaluate each design choice presented in Section 3, and then summarize the recommended policies for each algorithm.

5.1 COLLECTION_TRADING versus DEED_TRADING

We start by studying our basic trading algorithms, COLLECTION_TRADING and DEED_TRADING, in a particular scenario with 15 sites:

—<S>: Each site uses the *random* strategy to select trading partners.

—<A>: Each site uses the space-fractional advertising policy, with $x = 1$.

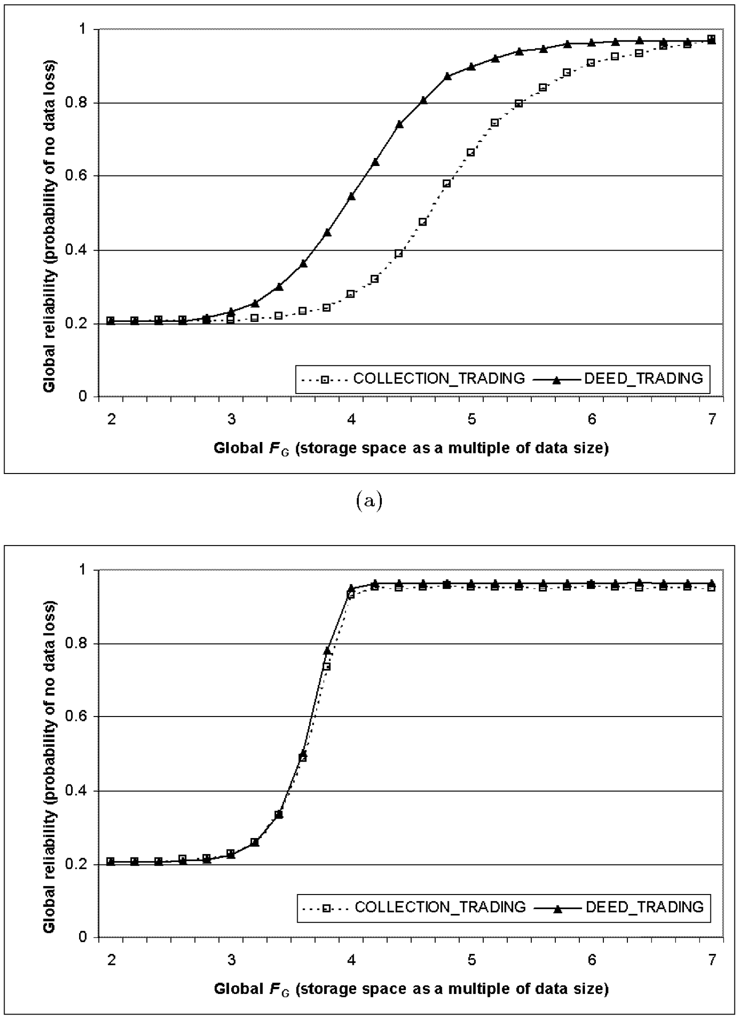
—<R>: A site restricts itself to passive retries only.

—<U>: A site uses its deeds to replicate as many collections as possible (*aggressive* deed use).

—<T>: Sites can transfer deeds if needed.

Figure 6(a) shows the global reliability as a function of the space factor F_G. As expected, the system achieves higher reliability as the amount of storage space increases, and sites are able to make more copies of their collections. Although both algorithms achieve very high global reliability ($\approx$0.99), DEED_TRADING is able to achieve high reliability ($\approx$0.9) at $F_G = 5$, while COLLECTION_TRADING requires more space, as much as $F_G = 6$, to achieve equivalent reliability. Thus, DEED_TRADING appears to be the more desirable algorithm because it provides higher global reliability using less space.

Note that the difference in reliability shown in Figure 6(a) is quite significant; even smaller reliability differences can have a large impact. Consider the difference between 0.99 and 0.98 global reliability, a difference of one percent. We can interpret these values as the probability that data will not be lost over the course of some interval, for example, one year. Then, we can calculate the mean time to failure (MTTF) of the system by computing the expected number of years before data is lost. A global reliability increase from 0.98 to 0.99 increases the MTTF from 50 years to 100 years. Thus, when evaluating the



(a)

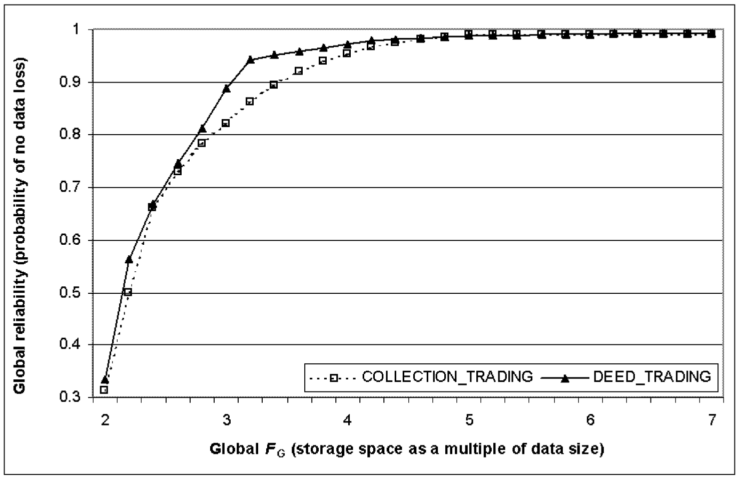
(b)

Fig. 6. COLLECTION_TRADING versus DEED_TRADING algorithms, with (a) the space-fractional advertising policy, and (b) the data proportional advertising policy.

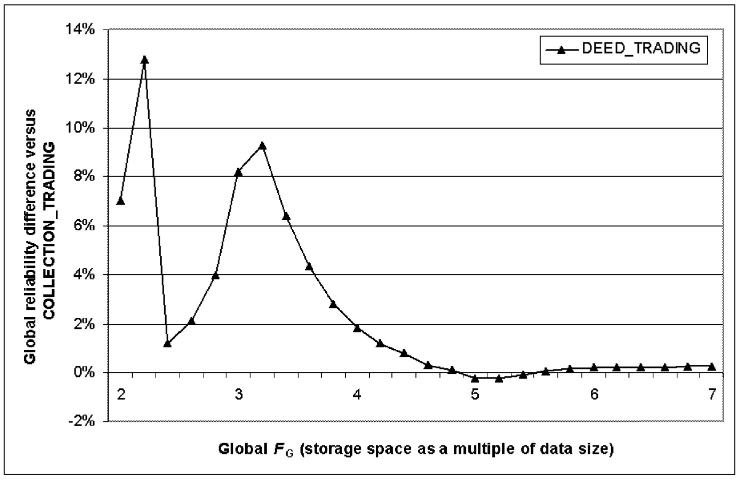
results we present, remember that an increase in reliability even as small as 0.01 can be very important.

The experimental results depend greatly on the policies used. For example, Figure 6(b) shows the same results as Figure 6(a), except that the advertising policy <A> has been changed to one that keeps some space in reserve and releases the space over time. (Specifically, this is the *data-proportional* policy with $y = 3$; see Section 3.2.)

Since results depend heavily on the policies used with each algorithm, we have found it useful to graph the "potential maximum" reliability of an algorithm if it were tuned using the best policies. For example, in



(a)



(b)

Fig. 7. Potential maximum reliability of COLLECTION_TRADING and DEED_TRADING algorithms.

Figure 7(a), we show the maximum reliability of COLLECTION_TRADING and DEED_TRADING as a function of F_G. To generate each point, we simulated both algorithms with every possible combination of the policies <A>, <S>, <R>, and so on, and selected the highest reliability achieved by each algorithm. For example, when $F_G = 3.2$, the best reliability is obtained using the clustering strategy for DEED_TRADING and best fit for COLLECTION_TRADING. In contrast, the points at $F_G = 6$ represent the neighbors strategy for both DEED_TRADING and COLLECTION_TRADING. Thus, Figure 7(a) shows an "upper bound" on the reliability achievable with each algorithm, assuming that the best policies are used. Another way to view these results is in Figure 7(b), which shows the differences between the two algorithms by showing the percent difference of DEED_TRADING versus COLLECTION_TRADING. For example, the peak at $F_G = 3.2$ in Figure 7(b) corresponds to the points at $F_G = 3.2$ in Figure 7(a), where DEED_TRADING produces 0.94 global reliability, a nine percent improvement over the COLLECTION_TRADING result of 0.86 global reliability. In this figure, it is clear that DEED_TRADING produces better reliability until $F_G = 4.8$, at which point the reliability of the two algorithms becomes roughly equivalent.

Figure 7(b) shows a dip in the relative reliability at $F_G = 2.4$, which is caused by the uneven increase in global reliability for DEED_TRADING as F_G increases. There are two inflection points in the DEED_TRADING curve in Figure 7(a), such that the rate of increase decreases when $F_G > 2$ and again when $F_G > 3$. Simulation results indicate that at $F_G = 2$ two copies can be made of every collection, while at $F_G = 3$ three copies can be made. At the inflection points, increasing space becomes less important; two copies is significantly better than one, three copies is somewhat better than two, but four copies is only slightly better than three. Consequently, "knees" appear in the reliability curve. Such inflection points do not occur for COLLECTION_TRADING because even when $F_G = 3$, sites have difficulty making three copies of every collection. Thus reaching $F_G = 3$ is not such a significant improvement over say $F_G = 2.8$, and the COLLECTION_TRADING curve is more even. The uneven shape of the DEED_TRADING curve, combined with the even shape of the COLLECTION_TRADING curve, produces the dip shown in Figure 7(b).

Our results indicate that DEED_TRADING is the most appropriate algorithm, although if F_G is large, both algorithms are roughly equal. When space is relatively tight (e.g. $F_G = 3$), sites using COLLECTION_TRADING have trouble making three copies of collections. In a trade, the local site must be able to store one of the remote site's collections, but often cannot, if space is tight. Thus, no trade can be made, even if the remote site has enough space. Under DEED_TRADING, a trade can always be concluded if the remote site has enough space. If the remote site's collections do not fit in the proposed deed, then the remote site keeps its deed instead of using it. Under DEED_TRADING, the local site can make more trades and almost always makes at least three copies, improving global reliability. As space increases, the impediment to trades under COLLECTION_TRADING disappears, and the algorithm begins to perform as well as DEED_TRADING.

Figure 7 deals with expected reliabilities. (Each value shown is averaged over 100 simulation runs.) So it could be that even though DEED_TRADING has better average performance, it could also have higher variance. This would mean that DEED_TRADING is "riskier" to use, as there could be a few real-life situations where it would provide very poor reliability. To address this issue, Figure 8 plots the worst reliabilities found in the 100 simulation runs. This graph gives a sense of the variability observed over the different runs, even if we tune the algorithms to provide the best average reliability. The graph shows not only that DEED_TRADING has better average performance, but it is "less risky" than COLLECTION_TRADING. Therefore, DEED_TRADING is the superior algorithm in terms of global reliability.

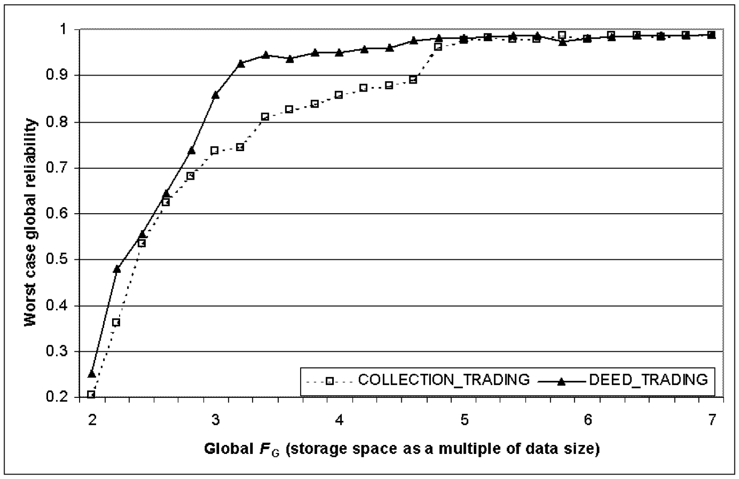


Fig. 8. The worst case global reliability for trading algorithms.

The results we have reported so far assume that all sites have approximately the same space factor. It is possible, and even likely, that different sites will have varying values of F_L. We have examined this situation with an experiment where the local space factors varied in the range $2 \leq F_L \leq 6$, with $F_G = 4$. Thus, in one simulation run, one site might have $F_L = 3.2$ while another might have $F_L = 5.1$. The result is that DEED_TRADING still provides higher reliability, with a global reliability of 0.92, versus 0.88 for COLLECTION_TRADING. Using this same experiment, we have also attempted to measure the "fairness" of each algorithm. If an algorithm were "fair," we would expect the local reliability of the site to increase as the site's F_L increased; thus, sites that contribute more space get correspondingly higher reliability. The results are shown in Figure 9. The figure shows that for both algorithms, sites that have more space experience increased local reliability. Although the local reliability versus F_L curve is not smooth for either algorithm, the general trend fits our expectations. Sites with less space (e.g. $F_L < 2.5$) seem to benefit more under COLLECTION_TRADING. The largest increase is for sites with $F_L = 2.3$, which experience a 1.7 percent improvement in local reliability over DEED_TRADING. Other sites, such as those with $F_L > 2.6$, experience a 0.9 percent decrease in local reliability versus DEED_TRADING. DEED_TRADING then seems to be slightly fairer by not helping sites with less space while penalizing those with more space. However, neither algorithm is clearly superior in terms of "fairness."

Because the DEED_TRADING algorithm allows us to optimize global reliability while preserving fairness, we only report results for DEED_TRADING for the rest of the paper.

5.2 <A>: The Storage Space Advertising Policy

Each site must advertise its free space. A site wishing to make copies of a collection uses these advertisements to determine which sites have enough free space

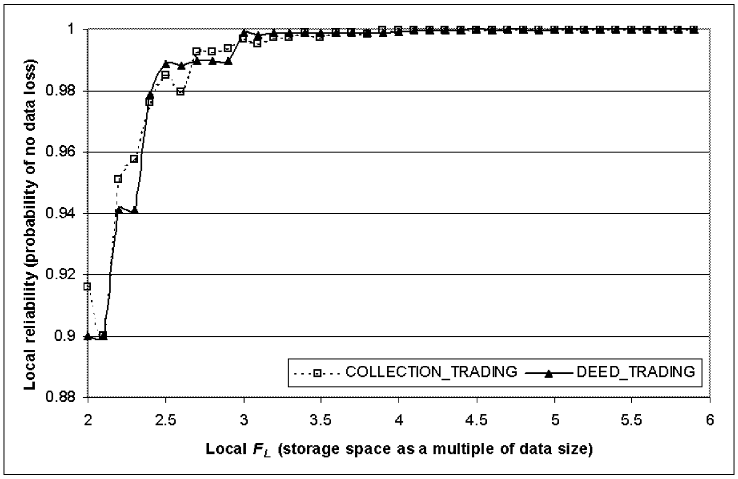


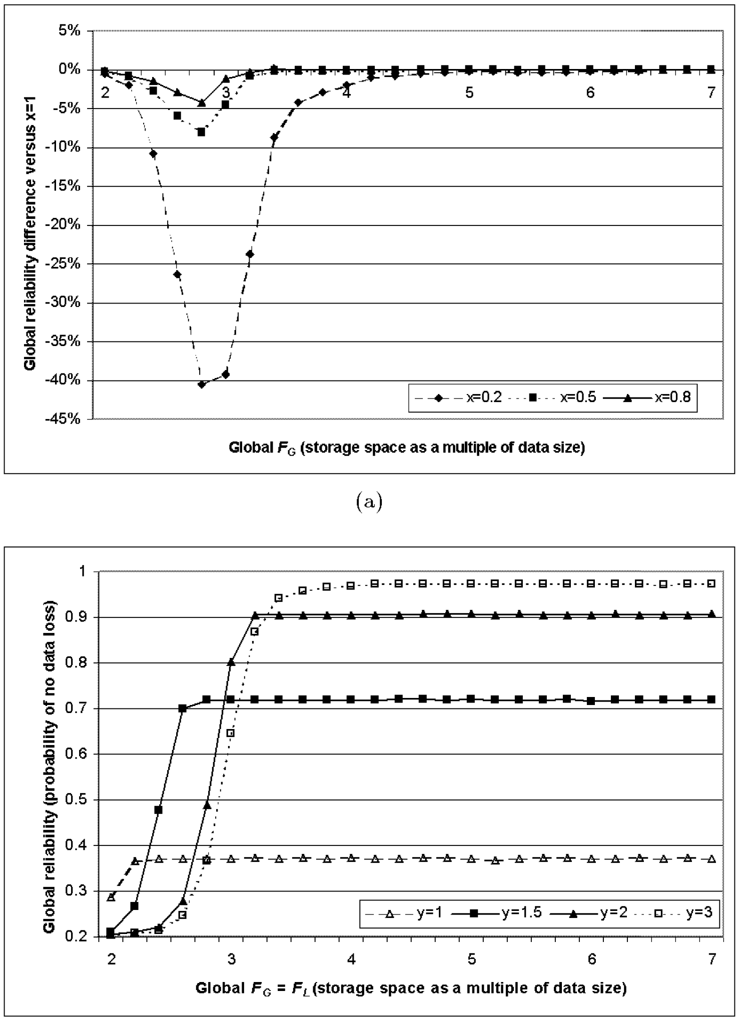
Fig. 9. The trading algorithms in terms of potential maximum local reliability.

to store a copy. Some of the trading strategies described in Section 3.1 also take the advertised free space into account. Section 3.2 describes the *space-fractional* and *data-proportional* advertising policies. In this section we evaluate these policies.

For simplicity, we have not investigated the process of determining a good partition between local space L_{total} and public space P_{total}. Such a partition must be done carefully, and is related to external factors such as the expected amount of data that will be deposited locally. A site knows the total storage space T it owns locally, and must estimate what ratio F_L of total storage to locally owned collections is needed. We can call this estimate F'_L. Then, $L_{total} = T/F'_L$, and $P_{total} = T - L_{total}$. In our simulation, we have assumed that a good partition has been chosen such that F'_L does indeed represent the final ratio between total storage and locally owned data collections (e.g. $F'_L = F_L$).

The potential maximum reliabilities for the space-fractional policy are shown in Figure 10(a), where $S = 15$ sites, the global space factor F_G varies in the range $2 \leq F_G \leq 7$, and $F_L \approx F_G$ for each site. The figure shows several versions of the space-fractional policy, where $x = 0.8, 0.5$ and 0.2, versus a baseline of $x = 1$. As Figure 10(a) shows, it is much better to advertise all free space (e.g. $x = 1$) if the space-fractional policy is used. Whatever the value of x, all of the public space will eventually be advertised. Therefore, setting $x < 1$ does not adequately reserve space for future use by the local site. On the other hand, if $x < 1$, then remote sites that need to use the public space at the local site may not be able to do so, because the full extent of the free space is not available. As x gets smaller, less space is available at the time of a trade (when the remote sites need the space most). Consequently, the reliability of remote sites suffers, and the global reliability correspondingly decreases.

Figure 10(b) shows potential maximum reliabilities for the data-proportional policy where $y = 1, 1.5, 2$ and 3. (Again, $S = 15$ and $2 \leq F_G \leq 7$.) Each policy peaks when $y = F_L - 1$ and then levels off. This trend continues with $y > 3$,



(a)

(b)

Fig. 10. The potential maximum reliabilities for the (a) space-fractional and (b) data-proportional policies.

though with diminishing reliability increases. If $y = F_L - 1$, a site will eventually advertise all of its public portion, but only when $L_{used} = L_{total}$ (e.g. when the local partition is also used up). If $y < F_L - 1$, some of the public component is never advertised, while if $y > F_L - 1$ then all of the public component is advertised (and possibly used up) before all local collections have been deposited. Thus, if $y = F_L - 1$, a site uses its public space very efficiently, and always has some space to trade away when new collections are deposited. We simulated the data-proportional policy with $y = F'_L - 1$, and this provided the best global reliability. In order to use this policy, a site must know F'_L, but does not need to know the global F_G. Our experiments indicate that the best global

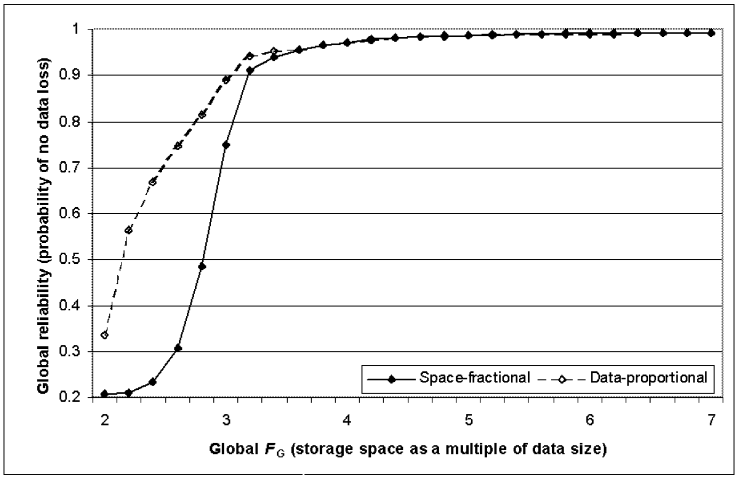


Fig. 11. Advertising policies (potential maximum reliabilities).

and local reliability occurs when each site advertises $y = F'_L - 1$ even when F_L varies widely from site to site.

In Figure 11 we compare the space-fractional policy (with $x = 1$) and the data-proportional policy (with $y = F'_L - 1$) directly. Clearly, the data-proportional policy is the best choice. Under the space-fractional policy, a site's public storage can become used up, preventing future trades. Reserved space is released as a result of newly stored, remotely owned, collections, but there is no guarantee that space will be available for trades. In contrast, with the data-proportional policy, reserved space is released in response to new locally owned collections. Consequently, a site looking to make copies of a new collection has new space to trade.

Once again, we have looked at the worst case reliability, the global reliability when F_L varies from site to site, and the impact on local reliabilities. Each of these experiments indicate that data-proportional is the best policy; we do not show the results here.

5.3 <R>: Active versus Passive Retries

Sites may fail to meet the replication goal when trading data. This failure may be due to the small number of sites that have entered the trading, or to a global shortage of free space. In either case, as time progresses, the condition that prevented trading may disappear, either because new sites have been born or because new space has been added to existing sites. Thus, a site may "retry" to replicate its rare collections. This is called *active retries*. As we noted in Section 3, each site would maintain a queue of rare collections, and would try again to trade them in response to some trigger.

We have simulated both allowing and disallowing active retries. For simplicity, our simulation has replaced the individual site retry queues with a global queue containing all collections to retry. After each new collection is traded, each collection in the retry queue is "retried"—the site owning the collection

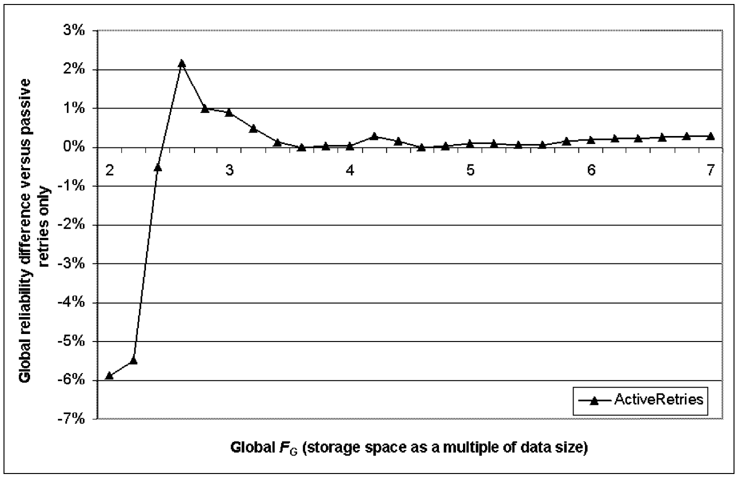


Fig. 12. The effect of active retries (potential maximum reliabilities).

tries again to propagate it. In the real world, every site would locally decide to retry at a particular time, and trades for both retries and new collections would run in parallel. However, our simulation serializes the trading process, thus intermixing all of the local queues into a global retry queue simulates this concurrency to some extent.

Note that a collection in the retry queue may be replicated during normal trading due to *passive retries*. For example, site A may only make two copies of collection 1, and the collection is placed in the retry queue. However, before collection 1 is retried, site A may be contacted by site B and offered a trade. If at this time site A copies collection 1 to site B, then collection 1 has been copied enough to meet the replication goal. The collection is then removed from the retry queue.

If the retry policy <R> does not allow active retries, then a collection not meeting the replication goal cannot actively try again. Then, the site owning the collection must wait for a passive retry to make more copies. The simulation models this situation simply by disabling the retry queue, and only running the trading algorithm for new collections.

We have compared the benefits of allowing versus prohibiting active retries. Figure 12 shows simulation results for $S = 15$ sites and F_G from 2 to 7; this graph shows the benefit or detriment of active retries over a baseline of only passive retries. (As with previous results, these results represent the upper bound on reliability.) As the figure shows, active retries are significantly detrimental when space is tight (e.g. $F_G < 2.4$). Active retries can prematurely propagate collections that will be propagated later under passive retries, and the effect is that excessive space is used for one collection to the detriment of others. The impact can be significant, with up to a six percent decrease in reliability.

However, active retries are beneficial (up to two percent increased reliability) in the region $F_G \geq 2.4$. The reason for this effect is that the negative impact of active retries is lessened by deed transfer. If a site prematurely makes trades, then it still may have future opportunities to trade due to passive retries. These future trades may cause the site to accumulate unnecessary deeds, but if necessary, these deeds can be transferred to another site that needs them.

The risk of a large decrease in reliability (up to seven percent) may not justify using active retries to achieve a potential two percent increase unless the free space factor F_G can accurately be calculated to be at least 2.4. However, if F_G is known to be greater than 2.4, then the benefits of active retries are clear. We also compared the worst case reliabilities represented by the averages in Figure 12, and the lower bound for both policies was roughly equal.

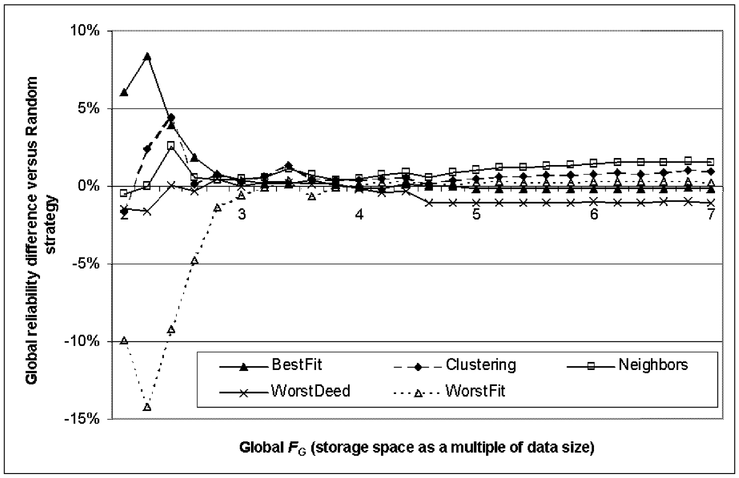
Once again, we have evaluated global reliability and fairness if sites have different F_L, such that $2 \leq F_L \leq 6$ and $F_G = 4$. Our results indicate that if F_L varies widely from site to site, active retries have a slight advantage, with a global reliability 0.923 versus 0.917 for passive retries only. We evaluated fairness by examining local reliability versus F_L; both allowing and disallowing active retries produced roughly equivalent results, such that sites with higher F_L achieved higher local reliability.

5.4 <S>: Trading Strategy

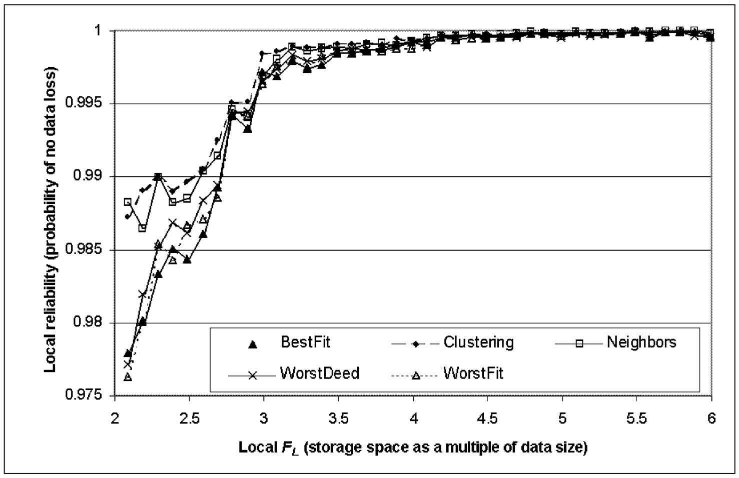
We have implemented the various trading strategies described in Section 3.1 in order to evaluate them. The implementation of most of the strategies was straightforward. For the *neighbors* strategy, each site must choose a local order in which to contact other sites. For our simulation, each site calculates its local order as the older, then younger sites. Thus, the site born third would first contact the site born second, then the site born first, then the site born fourth, and so on.

As shown in Figure 13(a), the strategy that proves to be best differs depending on the free space factor F_G. This figure shows the difference between each strategy versus a baseline of the random strategy, and again, the potential maximum reliability is reported. For clarity, not all strategies are shown; the omitted strategies are bounded by those in the figure. We also looked at the worst case resulting from each strategy; the results were similar to those shown in Figure 13(b) in that the same strategies provided the best reliability.

When space is tight ($F_G \leq 2.8$), best fit provides the highest reliability. In the region $2.8 \leq F_G \leq 4$, the clustering strategy does the best, but for higher values of F_G, neighbors is the best strategy. Clustering is not significantly better than neighbors when $2.8 \leq F_G \leq 4$; however, when $F_G > 4$, neighbors is somewhat better than clustering. Thus it is sufficient (and simplest) to choose neighbors as the strategy when $F_G \geq 2.8$. Switching to best fit when space is extremely tight is likely to provide significant benefit. This is because best fit does a good job of matching collections to available space, and minimizing external fragmentation of public storage space. Such fragmentation can be a problem when space is at a premium. Best fit requires global information about the amount of space available at remote sites. Thus, when space is tight, some mechanism of disseminating this information is required, such as through broadcast. As noted earlier, this may contradict the goal of a truly distributed mechanism which preserves site autonomy.



(a)



(b)

Fig. 13. Trading strategies: (a) potential maximum global reliabilities, (b) potential maximum local reliabilities.

However, as the amount of space increases, fragmentation becomes less of a problem, and sites can make better decisions about clustering their collections together for maximum reliability. Although the "clustering" strategy is designed to achieve clustering, the results suggest that neighbors actually does a better job. Since each site trades preferentially with a locally determined set of neighbors, collections are easily clustered. The "clustering" strategy, on the other hand, must randomly select partners to form clusters with. Such random selection is less successful at forming collection clusters.

If F_L varies from site to site, then neighbors is still the best strategy. The results from simulations (not shown) with $2 \leq F_L \leq 6$ and $F_G = 4$ show that the neighbors strategy produces a global reliability of 0.923 versus a global reliability of 0.92 for clustering and 0.89 or less for other strategies.

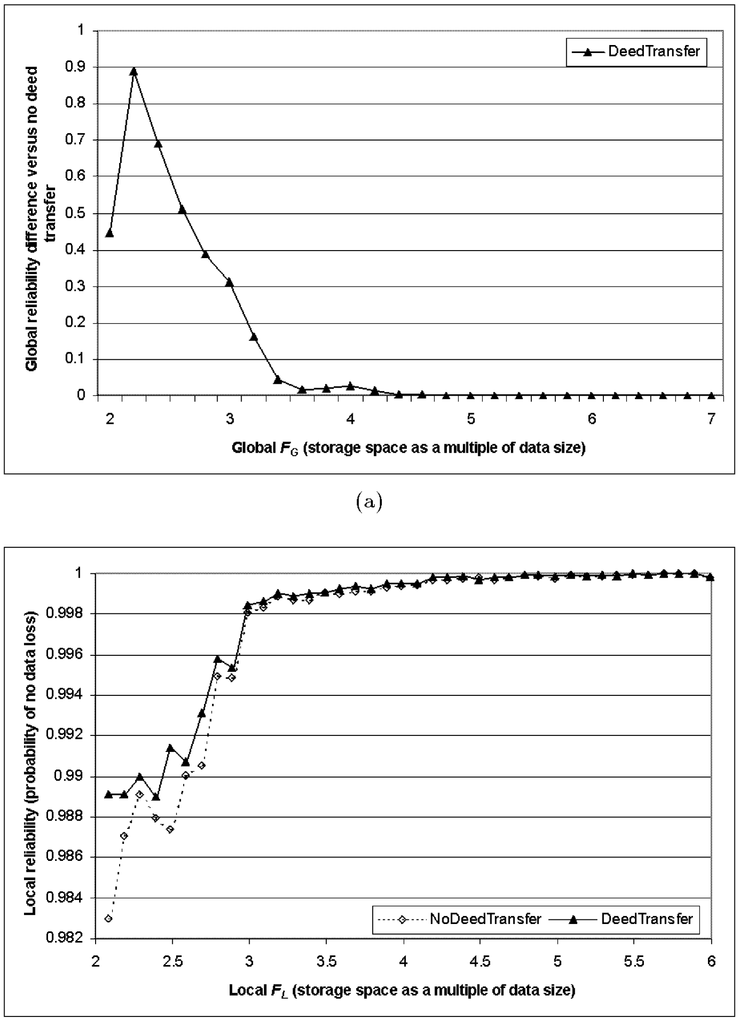
Figure 13(b) shows local reliability versus F_L. We would expect that under a "fair" strategy, sites with more local space experience correspondingly higher reliability. All strategies provide more local reliability for sites with large F_L, although neighbors and clustering provide higher reliability for sites with very little space (e.g. $F_L = 2$). Note that the differences shown in Figure 13(b) may appear to be small but are still significant. For example, the difference between best fit and neighbors when $F_L = 2$ is about 0.01, much larger than the standard deviation in the measurements, which is on the order of 0.002. Moreover, recall from the discussion in Section 5.1 that even a difference on the order of 0.01 can affect the mean time to failure of the system by several decades. As indicated in Figure 13(a), neighbors is the strategy that provides the best global reliability for large values of the global F_G. When F_G is small (e.g. $F_G = 2$), then best fit is better for global reliability, as shown in Figure 13(a). However, best fit provides the worst local reliability, even for sites with a small local F_L. Therefore, if local reliability is more important than global reliability, sites should use the neighbors strategy.

5.5 <T>: Deed Transfer

A site may acquire deeds for other sites that it is unable to use. A site may also have a large amount of effectively free space that is fragmented among several deeds held by other sites. An obvious way to deal with these problems is to allow a site to transfer its deeds to another site. Then, a site wishing to replicate a collection can gather several deeds together into one large enough to hold the collection. For example, if site A wishes to trade with site B, site A may contact other sites that hold deeds for site B. Site A would then trade a deed for its own local space in return for a deed for site B's space.

For simplicity, our simulation assumes that a site will only trade for other existing deeds when the contacted remote site does not have enough undeeded free space remaining. The simulator models a central deed registry, as described in Section 3.3, which allows a site to atomically acquire as many deeds as it needs. As noted earlier, truly autonomous sites may not wish to use such a central registry, and thus our results represent the best reliability that can be achieved, though at the cost of losing some autonomy.

Our results are in Figure 14(a), which shows the potential maximum reliability of deed transfer versus a baseline of no transfer. For example, when $F_G = 3$, allowing deed transfer results in 0.89 global reliability, a 31 percent improvement over the no deed transfer policy (0.68 global reliability). As shown in the figure, the reliability benefit of deed transfer is quite large (up to 90 percent improvement) when storage space is tight, but makes no difference if the free space factor $F_G > 4$. Although the benefit of deed transfer is most pronounced for very low values of F_G, the benefits are still significant when $F_G = 3$: allowing deed transfers results in an absolute global reliability of 0.89 versus 0.68 for no deed transfer. The large benefit clearly suggests that the added complexity of allowing deed transfers is worthwhile.



(a)

(b)

Fig. 14. The deed transfer policy versus no transfer policy: (a) potential maximum global reliability, (b) potential maximum local reliability.

For very large F_G, there is enough space globally so that transfers are not necessary, but allowing them anyway avoids the risk of losing reliability if F_G decreases.

We have also evaluated the situation where each site's F_L differs, such that $2 \leq F_L \leq 6$ and $F_G = 4$. Deed transfer results in a 0.92 global reliability, versus 0.87 for no deed transfer. The local reliability versus the F_L is shown in Figure 14(b). As the figure shows, deed transfer provides higher local reliability for sites with less space (e.g. $F_L = 2$) without harming the local reliability of sites with more space. (Again, the seemingly small differences indicated by the figure can have significant consequences.) This indicates that deed transfer is a good policy, because sites that cannot afford much storage benefit without hurting sites that have a lot of storage.

DEED_TRADING with deed transfer is more complicated to implement than DEED_TRADING without transfer, because a site must have a mechanism to contact third party sites, reserve their deeds, and then acquire their deeds in return for local space. Figure 14(b) indicates that the local reliability of sites with a lot of space does not increase due to deed transfer, thus sites may try to avoid the complexity of transfer by simply purchasing more disk space. However, unless the global F_G is large, other sites will lose reliability. That is, site A may buy more disk space, but if other sites do not buy extra storage, then the global reliability will be harmed if site A refuses to conduct deed transfers. Our experiments show a 6 percent decrease in global reliability in this situation. As indicated in Figure 14(b), it is the sites with less space that will lose reliability. Thus, a site can avoid the complexity of deed transfer but only by harming the reliability of its trading partners.

5.6 <U>: Deed Use Policy

When a site acquires a deed as part of a trade that it did not initiate, that site may have several candidate collections that could be replicated. The site must decide which to replicate first since all candidates may not fit in the deed. We assume that sites will prefer to replicate their rarest collections first (e.g. the collection with the fewest copies). However, the rarest collection may still have enough copies to have met the replication goal. A site must decide how aggressive to be in replicating collections beyond the replication goal.

We have evaluated two possible deed use policies. A site using the first policy, *aggressive deed use*, uses deeds as soon as possible to replicate as many collections as possible. This includes collections that are not “rare” (e.g. for which three copies already exist). The second policy, *non-aggressive deed use*, specifies that a site will use deeds only to replicate rare collections. Otherwise, the site will save the deed for future use.

Figure 15 shows the results (potential maximum reliability) of the simulation. The figure indicates that when $F_G \leq 3.6$, the non-aggressive policy is significantly better, with up to nine percent more reliability over using the aggressive policy. This is because when space is tight, sites have difficulty making the minimum number of copies of collections, and aggressive deed use worsens the situation. In contrast, Figure 15 shows that when space is plentiful, the aggressive policy does slightly better because it is the only policy able to make extra copies (e.g., more than three), while both policies are able to do an equal job of making the minimum number of copies. The results are similar if we look at the worst case represented by the averages in Figure 15. Aggressive deed use can cause a worst case that is up to 23 percent less reliable than the worst case for non-aggressive deed use. Sites should choose a level of aggressiveness based on the amount of free space available. If one policy must be chosen (or if F_G is not easy to calculate), it is safer to follow the non-aggressive deed use policy and avoid the risk that F_G is small and the aggressive policy causes significant negative impact.

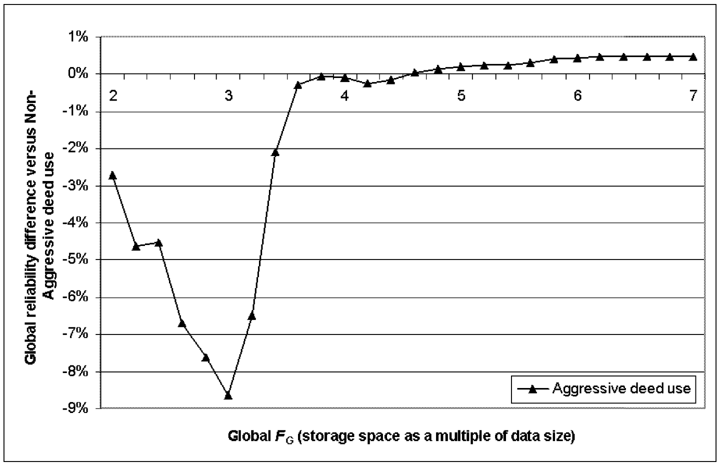


Fig. 15. Aggressive versus non-aggressive deed use (potential maximum reliability).

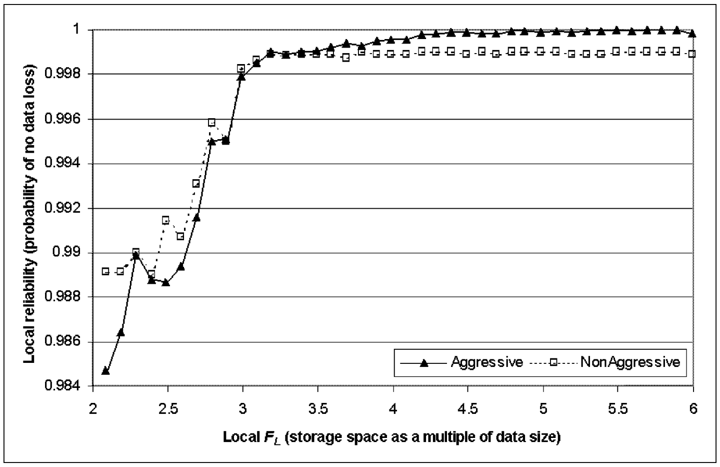


Fig. 16. Deed use policy in terms of potential maximum local reliability.

If sites' local F_L varies in the range $2 \leq F_L \leq 6$, with $F_G = 4$, then the non-aggressive deed use policy is better, with a global reliability of 0.92 versus 0.91 for aggressive deed use. Interestingly, the non-aggressive deed use policy seems to be less fair than the aggressive deed use policy. The local reliability versus F_L is shown in Figure 16. Although sites with low F_L (e.g. $F_L = 2$) benefit more under non-aggressive deed use, sites with a large amount of space (e.g. $F_L > 3.5$) would have better local reliability under aggressive deed use. Thus, if fairness is a concern, the aggressive deed use policy may be preferred.

5.7 The Impact of the Site Count

The reliability that can be achieved with data trading varies with the amount of free space available globally as well as the number of sites that are trading.

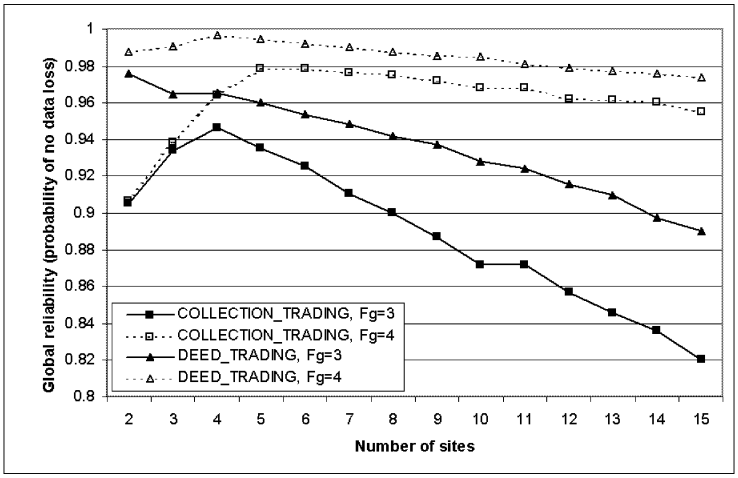


Fig. 17. Potential maximum reliability versus the number of sites.

In previous sections we have presented results with F_G, the free space factor, as the independent variable. In this section we discuss the impact of varying S, the number of sites that are trading. The results for both COLLECTION_TRADING and DEED_TRADING, with $F_G = 3$ and $F_G = 4$, are shown in Figure 17. The values shown represent the maximum reliability possible under each algorithm and value of F_G; the strategies and policies used for each data point may differ in practice. As the figure shows, for both algorithms reliability peaks at a relatively small number of sites, and then decreases as more sites enter trading. The value of S at which reliability peaks varies depending on the algorithm as well as the value of F_G. However, it is clear that the best reliability can be achieved when $2 \leq S \leq 9$, and that if more than nine sites enter the trading, then reliability suffers.

Global reliability suffers when there are too few sites because sites are unable to make sufficient trades. When there are only two sites, for example, one site may have a large data collection but be unable to replicate it at all if the second site has insufficient storage. As more sites enter trading, the chance of finding a site with enough space to store a copy of a collection increases.

However, global reliability peaks and then decreases with increasing site count. As more sites enter the trading network, there are more collections competing for space. Although the global aggregate amount of space increases with increasing site count, the space available at local sites remains fixed, as a function of the local site factor F_L. Consequently, as more collections compete for space, it is more likely that one or more sites will find their local public storage filled up. These sites cannot conduct trades, and the decrease in their local reliability drags down the global reliability. When the number of sites is small, this effect lessens, and higher global reliability results.

This result indicates that it is best to form partnerships of a few sites and to trade within these partnerships rather than trying to include all archiving sites in the same trading network. In fact, this is a positive result; it shows

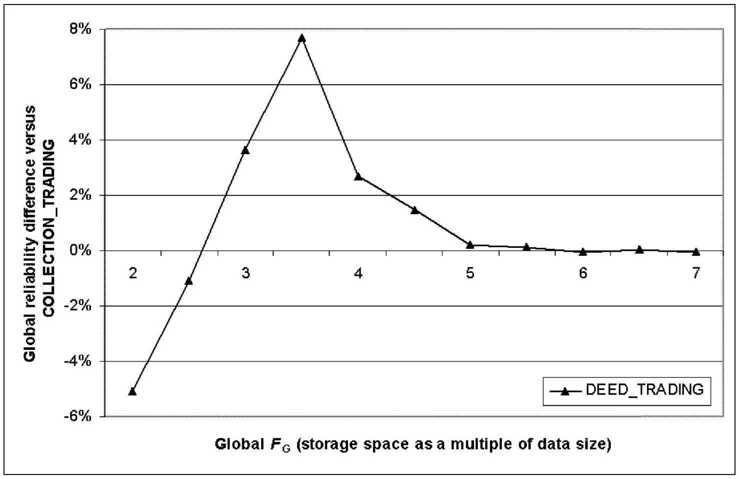


Fig. 18. COLLECTION_TRADING versus DEED_TRADING algorithms when $S = 6$, potential maximum reliability.

that a very large number of sites is not needed to achieve reliability, and that a small confederation of archives can trade among themselves to achieve high reliability. Moreover, it indicates that we can scale data trading to a very large number of sites and attain high reliability simply by dividing the sites into small groups.

Because the number of sites has a significant impact, we have simulated trading scenarios where there are fewer sites (e.g. $S = 6$). In this case, the conclusions we have reached in previous sections about which policies are best remain valid, with the following exceptions:

—*Algorithm:* When space is extremely tight ($F_G < 2.5$), COLLECTION_TRADING produces up to five percent higher global reliability than DEED_TRADING. This result is shown in Figure 18.

—<R>: There is no significant benefit to active retries, even as F_G grows.

—<S>: The best strategy for DEED_TRADING is still best fit when F_G is small or neighbors when F_G is large. However, if COLLECTION_TRADING is being used (e.g. because F_G is small), then the best strategy is neediest, with up to 2 percent improvement over the random strategy.

—The margin of improvement for several policies has changed, although the policy that is the “best” remains the same. For example, deed transfer is still beneficial when $F_G < 5$, although the improvement is up to 8 percent, as compared to 80 percent when $S = 15$. Other changes are less dramatic, such as with deed use, where the detriment to an aggressive policy has increased to 12 percent (versus 9 percent for $S = 15$).

5.8 Summary

Our experiments indicate that the most appropriate trading mechanism has the characteristics shown in Table III. This figure divides the policies into the

Table III. Summary of the Most Reliable Policies

Space is tight, there are few sites	Algorithm: Use COLLECTION_TRADING <A>: Use the data proportional policy, with $y = F'_L - 1$ <R>: Active retries should be disallowed <S>: Use neediest
Space is tight, there are many sites	Algorithm: Use DEED_TRADING <A>: Use the data proportional policy, with $y = F'_L - 1$ <R>: Active retries should be disallowed <S>: Use best fit <T>: Deed transfer is significantly beneficial <U>: Non-aggressive deed use is best
Space is adequate, there are any number of sites	Algorithm: Use DEED_TRADING <A>: Use the data proportional policy, with $y = F'_L - 1$ <R>: Active retries should be allowed <S>: Use neighbors <T>: Deed transfer is somewhat beneficial <U>: Non-aggressive deed use is best
Space is plentiful, there are any number of sites	Algorithm: Use DEED_TRADING <A>: Use the data proportional policy, with $y = F'_L - 1$ <R>: Active retries should be allowed <S>: Use neighbors <T>: Deed transfer is does not help or hurt <U>: Aggressive deed use is best

situations where space is tight (e.g. $F_G = 2$), space is adequate (e.g. $F_G = 3$), and space is plentiful (e.g. $F_G = 5$). The figure also illustrates that different policies are best if the number of sites is small (e.g. $S = 6$) and space is tight (e.g. $F_G = 2$).

We have also conducted experiments where the reliability varied from site to site. Our results show that the policies in Table III still apply, with two exceptions. First, highly reliable sites do better by offering trades to other highly reliable sites, but less reliable sites should still try to trade with all sites, regardless of reliability. Second, highly reliable sites can benefit by asking for larger deeds from less reliable sites, with a corresponding detrimental effect for the less reliable sites. These results are presented in Cooper and Garcia-Molina [2001].

6. CONCLUSIONS

We have proposed a new way to distribute copies of data collections among cooperating data storage sites. By trading in a peer-to-peer manner, sites can make multiple copies of their collections despite a highly dynamic, distributed environment. In this way, archives can ensure that their data is reliably preserved. We have defined basic algorithms for data trading, and identified policies that can be used to tune these algorithms. We have also proposed several alternative choices that could be made for each of these policies.

Using our simulator, we have evaluated these alternative choices. For some decisions, a clear policy should always be followed; for example, a site should always use the data-proportional policy when advertising its free space to other sites. For other decisions, the best policy depends on the amount of free space available in the system. Usually, the policy that appears to be the best under a criterion of global reliability is also best from the perspective of local reliability, although the deed use policy is an exception. Moreover, we have determined that the best reliability is achieved when just a few sites (e.g. less than 10) trade together. These conclusions can be used to design a peer-to-peer data trading protocol among any collection of storage sites interested primarily in reliability.

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