A Case for Continuous Data Protection at Block Level in Disk Array Storages

Weijun Xiao, Jin Ren, and Qing Yang

Abstract— This paper presents a study of data storages for continuous data protection (CDP). After analyzing the existing data protection technologies, we propose a new disk array architecture that provides Timely Recovery to Any Point-in-time, referred to as TRAP-Array. TRAP-Array stores not only the data stripe upon a write to the array, but also the time-stamped Exclusive-ORs of successive writes to each data block. By leveraging the Exclusive-OR operations that are performed upon each block write in today's RAID4/5 controllers, TRAP does not incur noticeable performance overhead. More importantly, TRAP is able to recover data very quickly to any point-in-time upon data damage by tracing back the sequence and history of Exclusive-ORs resulting from writes. What is interesting is that TRAP architecture is very space-efficient. We have implemented a prototype TRAP architecture using software at block level and carried out extensive performance measurements using TPC-C benchmarks running on Oracle and Postgress databases, TPC-W running on MySQL database, and file system benchmarks running on Linux and Windows systems. Our experiments demonstrated that TRAP is not only able to recover data to any point-in-time very quickly upon a failure but it is also space efficient. Compared to the state-of-the-art continuous data protection technologies, TRAP saves disk storage space by one to two orders of magnitude with a simple and a fast encoding algorithm. In addition, TRAP can provide two-way data recovery with the availability of only one reference image in contrast to the one-way recovery of snapshot and incremental backup technologies.

Index Terms: Disk Array, Disk I/O, Data Storage, Data Protection and Recovery, Data Backup

1. INTRODUCTION

RAID architecture [1] has been the most prominent architecture advance in disk I/O systems for the past two decades. RAID1 provides 2xN data redundancy to protect data while RAID3 through RAID5 store data in parity stripes across multiple disks to improve space efficiency and performance over RAID1. The parity of a stripe is the Exclusive-OR (XOR) of all data chunks in the stripe. If a disk failed at time t_0, and the system found such a failure at time t_1, the data in the failed disk can be recovered by doing the XOR among the good disks, which may finish at t_2. The recovered data is exactly the same image of the data as it was at time t_0. There are recent research results that are able to recover data from more than one disk failures [2,3,4,5], improving the data reliability further.

The question to be asked is "can we recover data at time t_2 to the data image of t_0 after we found out at time t_1 that data was damaged by human errors, software defects, virus attacks, power failures, or site failures?"

With the rapid advances in networked information services coupled with the maturity of disk technology, data damage and data loss caused by human errors, software defects, virus attacks, power failures, or site failures have become more dominant, accounting for 60% [6] to 80% [7] of data losses. Recent research [8,9] has shown that data loss or data unavailability can cost up to millions of dollars per hour in many businesses. Current RAID architecture cannot protect data from these kinds of failures because damaged data are not confined to one or two disks.

Traditional techniques protecting data from the above failures are mainly periodical (daily or weekly) backups and snapshots [10,11,12]. These techniques usually take a long time to recover data [13]. In addition, data between backups are vulnerable to data loss. More importantly, recent research study has shown that 67% of backup data cannot be recovered in the real world [14]. While this fact is well known, there has been no research study on why this is the case. Therefore, it remains unclear and an open question why such high percentage of data recovery failed.

This paper presents an analytical study on snapshot and backup technologies from the block level storage point of view. Our investigation uncovered the limitations of the existing data protection technologies and provided theoretical explanations as to why so many data recoveries (over 67% recoveries) failed using these existing technologies. We show mathematically the data recovery capabilities and limitations of the existing technologies.

Based on our theoretical results, we propose a new storage architecture that overcomes the limitations of existing technologies. We provide mathematical proof of the correctness of the new data protection technique. Besides being able to recover data damaged by various type of failures, our new architecture provides **T**imely **R**ecovery to **A**ny **P**oint-in-time, hence named *TRAP* architecture. *TRAP* architecture has the optimal space and performance characteristics [15]. The idea of the new *TRAP* architecture is very simple. Instead of providing full redundancy of data in time dimension, i.e. keeping a log of all previous versions of changed data blocks in time sequence [13, 16, 17], we compute XORs among changed data blocks along the time

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Weijun Xiao, Jin Ren, and Qing Yang are with the Department of Electrical and Computer Engineering, University of Rhode Island, Kingston, RI 02881. E-mail: {wjxiao,rjin,qyang}@ele.uri.edu.

dimension to improve performance and space efficiency. With a simple and fast encoding scheme, the new *TRAP* architecture presents great space savings because of *content locality* that exists in real world applications.

We have implemented a prototype of the new *TRAP* architecture at block device level using standard iSCSI protocol. The prototype is a software module inside an iSCSI target mountable by any iSCSI compatible initiator. We install the *TRAP* prototype on PC-based storage servers as a block level device driver and carry out experimental performance evaluation as compared to traditional data recovery techniques. Linux and Windows systems and three types of databases: Oracle, Postgres, and MySQL, are installed on our *TRAP* prototype implementation. Real world benchmarks such as TPC-C, TPC-W, and file system benchmarks are used as workloads driving the *TRAP* implementation under the databases and file systems. Our measurement results show up to 2 orders of magnitude improvements of the new *TRAP* architecture over existing technologies in terms of storage space efficiency. Such orders of magnitude improvements are practically important given the exponential growth of data [18]. We have also carried out data recovery experiments by selecting any point-in-time in the past and recovering data to the time point. Experiments have shown that all recovery attempts are successful. Recovery time of the new *TRAP* architecture is compared with existing reliable storage architectures to show that the new *TRAP* architecture can recover data to any point-in-time very quickly.

We analyze the capabilities and limitations of existing data protection technologies in the next section. The detailed design and implementation of the new *TRAP* is presented in Section 3. Section 4 discusses system design and implementation and Section 5 presents the experimental settings and the workload characteristics. Numerical results and discussions are presented in Section 6. Related work is discussed in Section 7. We conclude our paper in Section 8.

2. Capabilities and Limitations of Current Data Protection Technologies

Traditionally, data protection has been done using periodical backups. At the end of a business day or the end of a week, data are backed up to tapes. Depending on the importance of data, the frequency of backups varies. The higher the backup frequency, the larger the backup storage is required. In order to reduce the backup volume size, technologies such as incremental backups and copy-on-write(COW) snapshots have been commonly used. Instead of making full backups every time, incremental backups and COW snapshots that only store the changed data are done more frequently in between full backups. For example, one can do daily incremental backups and weekly full backups that are stored at both the production site and the backup site.

The way incremental backup works is as follows. Starting from the previous backup point, the storage keeps track of all changed blocks. At the backup time point, a backup volume is formed consisting of all latest changed data blocks. As a result, the incremental backup contains the newest data that have changed since the last backup. COW snapshots work differently from the incremental backup. At the time when a snapshot is created, a small volume is allocated as a snapshot volume with respect to the source volume. Upon the first write to a data block after the snapshot was started, the original data of the block is copied from the source volume to the snapshot volume. After copying, the write operation is performed on the block in the source volume. As a result, the data image at the time of the snapshot is preserved. Write I/Os after the first change to a block is performed as usual, i.e. only the first write to a block copies the original data to the snapshot volume. There have been many variations of COW snapshots in terms of implementation details for performance and efficiency purposes such as pointer remapping [49] and redirect-on-writes [19,50] etc. The main advantage of both incremental backups and COW snapshots is storage savings because only changed data are backed up.

In order to study the capabilities and limitations of these existing technologies, we formally define several mathematical terms and their relationships with block level storages.

Let us assume that the data storage we try to study consists of independent and equally sized data blocks (the specific size of a block is not significant in this discussion). Each of these data blocks is identified by an LBA (logic block address) and contains a specific data value. Let $\boldsymbol{A}$ be the entire set of LBA's of the data storage considered and $\boldsymbol{D}$ represent the set of all possible data values contained in data blocks. A binary relation, $\boldsymbol{R}$, between $\boldsymbol{A}$ and $\boldsymbol{D}$ defines a mapping of addresses to their corresponding data values of the data storage. Since there is exactly one ordered pair in R with each LBA, this binary relation is a function. We refer this function as storage data and use F_t to represent this function (storage data) from $\boldsymbol{A}$ to $\boldsymbol{D}$ at time $\boldsymbol{t}$. And we use $F_t(a)$ to represent the image or data value of an LBA $\boldsymbol{a}$. That is, F_t contains a set of ordered pairs such as $\{(a_1,d_1), (a_2,d_2) \ldots\}$ whereas $F_t(a)$ is an image/data value of $\boldsymbol{a}$ such as $F_t(a_1)= d_1$. If A' is a subset of $\boldsymbol{A}$, i.e. $A' \subseteq A$, then we use F_t /A' to represent the restriction of F_t to A'. That is, $F_t /A' = F_t \cap (A' \times D)$ [20].

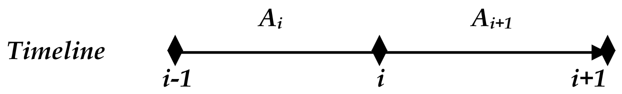


***Figure 1**. A three-point timing diagram:**i-1** starting point, **i+1** current point, and **i** recovery point.*

Without loss of generality, let us consider three time points as shown in Figure 1. Suppose that time point $\boldsymbol{i-1}$ represents the original time point when data storage operation starts and time point $\boldsymbol{i+1}$ represents the current time point. Suppose a failure occurred at some time near point $\boldsymbol{i+1}$. We are interested in recovering data to the data as it was at time point $\boldsymbol{i}$. We use integer numbers to represent time points since all storage events occur at discrete time points with a clear sequential ordering.

Definition 1. Let $A_i \subseteq A$ be a set of LBAs. We define A_i to be a *write set* i if it contains all LBAs whose data value have been overwritten between time point i-1 and time point i.

Looking at the diagram shown in Figure 1, we have A_i containing all LBAs whose data values have been changed by write operations between time points i-1 and i while A_{i+1} containing all those between time point i and time point $i+1$.

Example 1. If we have $F_i = \{(0,2), (1,5), (2,8)\}$ at time point i and $F_{i+1} = \{(0,4), (1,5), (2,0)\}$ at time point $i+1$ because of write operations, then we have $A_{i+1} = \{0,2\}$. That is, data values at addresses 0 and 2 have been changed from 2 and 8 to 4 and 0, respectively, whereas the data value of address 1 has not been changed, since time point i.

It is possible that the overwritten value as seen at time i is the same as the original value at time i-1 caused by one or several write operations between time points i-1 and i. We therefore define *substantial write set* that actually changed data values as follows.

Definition 2. Let $A'_i \subseteq A_i$. We define A'_i to be a *substantial write set* i if the data value of every LBA in A'_i has been changed between time point i-1 and time point i.

It should be noted here that the changed data value is generally not related to the original value because of the nature of write operations at block level storages. That is, $F_{i+1}(a)$ is independent of $F_i(a)$. Furthermore, $F_i(a)$ is independent of $F_i(b)$ for all $b \in A$ and $b \neq a$ as stated in the beginning of this section: data blocks are independent. We believe this assumption is reasonable because block level storages regard each data block as an independent block without any knowledge of file systems and applications above them.

Definition 3: A COW snapshot as seen at time $i+1$ that was started at time i is defined as F_i/A_{i+1}, where A_{i+1} is write set $i+1$.

As we know, COW snapshot makes a copy of original data upon the first write to the block. As a result, it keeps a set of original data of all changed blocks since the snapshot started. Consider the storage data in Example 1. Suppose the COW snapshot was started at time point i. At time point $i+1$, we have the snapshot: {(0,2), (2,8)}, which is F_i/A_{i+1}. That is, A_{i+1} gives all the LBAs that have been written, {0,2}, and their respective images in the snapshot should be the same as they were at time point i, {2,8}.

Lemma 1. *If we have storage data at time* $i+1$ *and a COW snapshot started at time* i*, then we can recover data as they were at time* i *as follows:*

$$F_i = (F_{i+1} - F_{i+1}/A_{i+1}) \cup F_i/A_{i+1}, \qquad (1)$$

where "-" and "$\cup$" are difference and union operators of sets, respectively.

The proof of this lemma is straightforward by noting that F_i/A_{i+1} is the COW snapshot as seen at time $i+1$ that was started at time i and F_{i+1}/A_{i+1} are all storage data that have been changed since time point i. Equation (1) replaces all changed data with the COW snapshot that represents the original data before changes occur. This is a typical undo recovery process.

Lemma 1 gives the data recovery capability of COW snapshot technology. It is able to recover data to a previous time point provided that the most recent data is available. This data recovery capability is very useful in practice in case of data corruption, virus attack, user errors, software bugs, and so forth. If we know that data was good at a previous time point when snapshot was started, we can go back to that point to recover from failures caused by this type of events.

Although COW snapshot can recover data to a previous time point as stated in Lemma 1, it has limitations. In particular, if the current data (production data) is damaged or lost because of hardware failures, OS failures, outages, or disasters, we cannot recover data to a previous time point even if we have COW snapshots and previous backup data that may be safely stored in a remote backup site. This limitation is formally stated in the following theorem.

Theorem 1. *Suppose the storage data at time point* $i+1$*,* F_{i+1}*, is not available and the substantial write set* A'_i *is not empty* ($A'_i \neq \phi$)*. COW snapshots cannot recover storage data* F_i *as they were at time point* i *if* $A'_i \subsetneq A_{i+1}$.

Proof: We prove this theorem by contradiction. Let us assume that COW snapshots can recover storage data F_i as they were at time point i without F_{i+1}. That is, for all $a \in A_i$, we can reconstruct $F_i(a)$ from what we have available:

a) Data backup made previously: F_{i-1}
b) COW snapshot as seen at time **i** that was started at time i-1: F_{i-1}/A_i, and
c) COW snapshot as seen at time **i+1** that was started at time i: F_i/A_{i+1}.

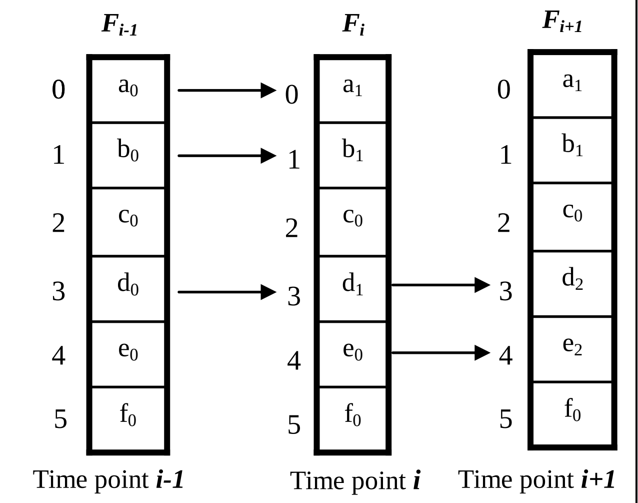
Since different data blocks are independent in our storage system, for every LBA $a \in A_i$, the only way to reconstruct its data value, $F_i(a)$, is to reconstruct it from $F_{i-1}(a)$, $F_{i-1}/A_i(a)$, and/or $F_i/A_{i+1}(a)$.

Because $A'_i \subsetneq A_{i+1}$ and $A'_i \neq \phi$, there is an LBA that is in A'_i but not in A_{i+1}. Let β be such an LBA such that $\beta \in A'_i$ but $\beta \notin A_{i+1}$. Now consider the three cases:

a) Since $\beta \in A'_i$, we have $F_i(\beta) \neq F_{i-1}(\beta)$ by **Definition 2**.
b) Because $F_{i-1}/A_i \subseteq F_{i-1}$ and $A'_i \subseteq A_i$, we have $F_{i-1}/A_i(\beta) = F_{i-1}(\beta) \neq F_i(\beta)$
c) The fact that $\beta \notin A_{i+1}$ implies that $F_i/A_{i+1}(\beta)$ is undefined because β is not in the domain of F_i/A_{i+1}.

Furthermore, $F_i(\beta)$ is not related in any way to $F_{i-1}(\beta)$ because of the nature of write operations at block level storages. As a result, it is impossible to rebuild $F_i(\beta)$ from $F_{i-1}(\beta)$, $F_{i-1}/A_i(\beta)$, and/or $F_i/A_{i+1}(\beta)$, a contradiction to our assumption. Therefore, COW snapshots cannot recover storage data F_i. □

Example 2. Consider one example with 6 blocks in the storage data as shown in Figure 2. At time point ***i-1***, we have {(0, a_0), (1, b_0), (2, c_0), (3, d_0), (4, e_0), (5, f_0)}. From time point ***i-1*** to time point ***i*** , three blocks have been changed to: {(0, a_1), (1, b_1), (3, d_1)}, with the substantial write set being {0, 1, 3}. From time point ***i*** to time point ***i+1***, two blocks have been changed to: {(3, d_2), (4, e_2)} with the substantial write set being {3, 4}. By Definition 3, we have snapshot F_{i-1}/A_i as {(0, a_0), (1, b_0), (3, d_0)} and snapshot F_i/A_{i+1} as {(3, d_1), (4, e_0)}. When original data F_{i-1} is unavailable, storage data F_i can be reconstructed from COW snapshot F_i/A_{i+1} and F_{i+1} by replacing the changed blocks (3, d_2) and (4, e_2) in F_{i+1} with original data blocks (3, d_1) and (4, e_0) in F_i/A_{i+1}, respectively. If fresh data F_{i+1} is damaged, however, F_i cannot be recovered from F_{i-1} and snapshots because substantial write set A'_i is not a subset of write set A_{i+1} as stated in Theorem 1. In this particular case, data blocks (0, a_1) and (1, b_1) cannot be rebuilt from original data F_{i-1} and snapshots in any way.



F_{i-1}
F_i
F_{i+1}
0 1 2 3 4 5
a_0 b_0 c_0 d_0 e_0 f_0
a_1 b_1 c_0 d_1 e_0 f_0
a_1 b_1 c_0 d_2 e_2 f_0
Time point ***i-1***
Time point ***i***
Time point ***i+1***

Write Sets
A_i: {0,1,3}
A_{i+1}: {3,4}
Substantial Write Sets
A'_i: {0,1,3}
A'_{i+1}: {3,4}
Snapshots
started at time point ***i-1***: F_{i-1}/A_i: {(0,a_0),(1,b_0),(3,d_0)}
started at time point ***i***: F_i/A_{i+1}: {(3,d_1),(4,e_0)}
Undo recovery is possible but not redo recovery: *storage data at time **i**, F_i, can be recovered from snapshot F_i/A_{i+1} and F_{i+1} by replacing the changed data blocks between time points **i** and **i+1** with the corresponding data blocks in F_i/A_{i+1}. However, if the newest data F_{i+1} is damaged, with the original data F_{i-1} and the snapshots, we can not recover storage data F_i as they were at time point **i** because A'_i is not a subset of A_{i+1}. Particularly, data blocks (0, a_1) and (1, b_1) that are part of the storage data at time **i** cannot be generated from F_{i-1}, F_{i-1}/A_i, and F_i/A_{i+1} in any way.*

Figure 2. Undo recovery of COW snapshots

Definition 4: The incremental backup as seen at time ***i*** that was started at time ***i-1*** is defined as F_i/A_i, where A_i is *write set **i**.*

Incremental backups keep the latest changes on data storage. Consider Example 1 again, the incremental backup at time point ***i*** is {(0, 4), (2, 0)}. In Example 2, the incremental backup at time point ***i*** is {(0,a_1),(1,b_1),(3,d_1)}.

Lemma 2. *If we have storage data at time **i-1** and an incremental backup as seen at time **i**, then we can recover data as they were at time **i** as follows:*

$$F_i = (F_{i-1} - F_{i-1}/A_i) \cup F_i/A_i, \qquad (2)$$

where "-" and "∪" are difference and union operators of sets, respectively.

The proof of the lemma 2 is straightforward by noting that F_i/A_i is the incremental backup as seen at time ***i*** that was started at time ***i-1*** and F_{i-1}/A_i are all original data at locations that have been changed. Since F_i/A_i contains all the latest changes from time point ***i-1*** to time point ***i***, storage data F_i can be obtained by replacing the original storage data with the incremental backup as shown in Equation (2). This is a typical redo recovery process.

Lemma 2 gives the redo recovery capability of incremental backup technology. It is able to recover data to a recent time point when the original storage data is available. This redo recovery can be used in practice in case of disk failures, volume crash, OS failures, outages, disasters, and so on. If we created a full data backup prior to the incremental backup was started, we can reconstruct the storage data to the latest time point in case of this type of failures.

While incremental backup can recover data as stated in Lemma 2, it also has limitations. Particularly, if the current data gets corrupted because of virus or user errors and it happens that we do not have a prior full backup, we cannot recover data to a good time point using incremental backups and current data that are available. This limitation is formally stated in the following theorem.

Theorem 2. *Suppose the storage data at time point **i-1**, F_{i-1}, is not available and substantial write set A'_{i+1} is not empty ($A'_{i+1} \neq \phi$). Incremental backups cannot recover storage data F_i as they were at time point **i** if $A'_{i+1} \nsubseteq A_i$.*

Proof: We prove this theorem by contradiction and assume incremental backups can reconstruct the storage data at time *i*, F_i . Since the original storage data, F_{i-1}, is not available, the only storage data sets available to us for recovery purpose are:

a) Current production data: F_{i+1} ,
b) Incremental backup as seen at time ***i*** that was started at time ***i-1***: F_i/A_i , and
c) Incremental backup as seen at time ***i+1*** that was started at time ***i***: F_{i+1}/A_{i+1}.

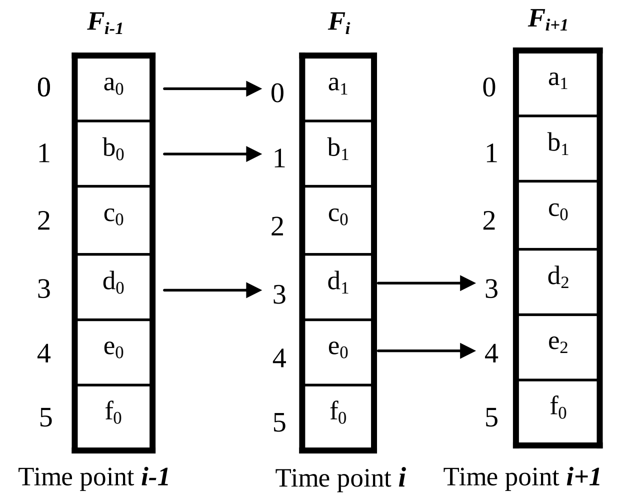
For every data block, let α be an LBA that is in A_i. $(a, F_i(a)) \in F_i$ is part of the storage data at time ***i*** to be reconstructed. Because data blocks are independent and there is no relation among different data blocks, $F_i(a)$ should be reconstructed by $F_{i+1}(a)$, $F_i/A_i(a)$, and/or $F_{i+1}/A_{i+1}(a)$.

Now, let us consider one specific block. Since $A'_{i+1} \nsubseteq A_i$

and $A'_{i+1} \neq \phi$, there is an LBA that is in A'_{i+1} but not in A_i. Let β be an LBA such that $\beta \in A'_{i+1}$ but $\beta \notin A_i$. Clearly, $(\beta, F_i(\beta)) \in F_i$ is part of the storage data at time i and it can be reconstructed by the available data values corresponding to block β. That is, $F_i(\beta)$ can be generated from $F_{i+1}(\beta)$, $F_i/A_i(\beta)$, and/or $F_{i+1}/A_{i+1}(\beta)$. Now, consider these three data values.

a) Since $\beta \in A'_{i+1}$, we have $F_{i+1}(\beta) \neq F_i(\beta)$ by **Definition 2**.
b) Because F_{i+1}/A_{i+1} is a restriction of F_{i+1} and $A'_{i+1} \subseteq A_{i+1}$, we have $F_{i+1}/A_{i+1}(\beta) = F_{i+1}(\beta) \neq F_i(\beta)$.
c) Now, we know that $\beta \notin A_i$, $F_i/A_i(\beta)$ is undefined.

Among these three data values corresponding to block β, the first two of them have the same value, $F_{i+1}(\beta)$, and the third one is undefined. Therefore, it is impossible to rebuild $F_i(\beta)$ from $F_{i+1}(\beta)$, $F_i/A_i(\beta)$, and/or $F_{i+1}/A_{i+1}(\beta)$ because there is no dependency between $F_{i+1}(\beta)$ and $F_i(\beta)$ from the storage point of view. This fact contradicts to the assumption. We can conclude incremental backup cannot recover storage data F_i as they were at time point i. □



F_{i-1}
F_i
F_{i+1}
0 1 2 3 4 5
a_0 b_0 c_0 d_0 e_0 f_0
a_1 b_1 c_0 d_1 e_0 f_0
a_1 b_1 c_0 d_2 e_2 f_0
Time point i-1
Time point i
Time point i+1

Incremental Backups
as seen at time point i: F_i/A_i: {(0,a_1),(1,b_1),(3,d_1)}
as seen at time point $i+1$: F_{i+1}/A_{i+1}: {(3,d_2),(4,e_2)}
Redo recovery is possible but not undo recovery: Storage data F_i *can be recovered from original data* F_{i-1} *and incremental backup* F_i/A_i *by overwriting all the data blocks in* F_i/A_i *at the positions of storage data* F_{i-1}. *However, if original data* F_{i-1} *is unavailable, we cannot recover storage data* F_i *because* A'_{i+1} *is not a subset of* A_i. *In particular, data block (4,* e_0*) in* F_i *cannot be generated from* F_{i+1}, F_{i+1}/A_{i+1}, *and* F_i/A_i *in any way .*

Figure 3. Redo recovery of incremental backups

Example 3. Using the same storage scenario as Example 2, we give an example of incremental backups. As shown in Figure 3, we have incremental backup F_i/A_i as seen at time point i as {(0, a_1), (1, b_1), (3, d_1)} and incremental backup F_{i+1}/A_{i+1} as seen at time point $i+1$ as {(3, d_2), (4, e_2)}. When fresh data F_{i+1} is damaged, storage data F_i can be recovered from F_{i-1} and incremental backup F_i/A_i by overwriting all data blocks in F_i/A_i at the positions of storage data F_{i-1}. However, if original data F_{i-1} is unavailable, storage data F_i cannot be rebuilt from F_{i+1} and incremental backups because A'_{i+1} is not a subset of A_i as stated in Theorem 2. Particularly, data block (4, e_0) in F_i cannot be generated by fresh data F_{i+1} and incremental backups in any way.

3. A NEW ARCHITECTURE FOR DATA PROTECTION

As we described in Section 2, snapshots cannot redo storage data to a recent time point while incremental backups cannot undo storage data to a previous good point. The reason is that snapshots do not keep the fresh data and incremental backups do not store the original data. To overcome the limitations, a straightforward approach is to keep both versions of data every time a data change occurs. Particularly, at time point i, both snapshot F_{i-1}/A_i for the original data and incremental backup F_i/A_i for the fresh data as seen at time point i are stored at the backup volume. Similarly, F_i/A_{i+1} and F_{i+1}/A_{i+1} at time point $i+1$ are kept in the storage. From Lemma 1 and Lemma 2, one can easily find that storage data at time point i, F_i, can be recovered by using COW snapshot F_i/A_{i+1} and fresh data F_{i+1} when storage data F_{i-1} is unavailable, or by using incremental backup F_i/A_i and original data F_{i-1} when fresh data F_{i+1} is damaged or lost.

Although above approach can recover data in two directions, it requires double amount of storage space because two versions of changed data are stored at backup storage. The question to be asked is: "Can we have an architecture to provide two-way recovery with the smaller size storage space?"

This question motivates us to seek for a new data protection technology. The idea of our new approach is very simple. Instead of keeping all versions of a data block as it is being changed by write operations, we keep a log of parities [21] as a result of each write on the block. Since all parties of write operations are stored at backup storage volume, our approach can provide Timely Recovery to Any Point-in-time by parity computation. Therefore we named our approach as *TRAP*. Figure 4 shows the basic design of *TRAP* architecture. Suppose that at time point i, the host writes into a data block with logic block address a_s that belongs to a data stripe $a=(a_1, a_2 \ldots a_s, \ldots a_n)$. The RAID controller performs the following operation to update its parity disk:

$$P_i(a) = F_i(a_s) \oplus F_{i-1}(a_s) \oplus P_{i-1}(a) , \qquad (3)$$

where $P_i(a)$ is the new parity for the corresponding stripe, $F_i(a_s)$ is the new data for data block a_s, $F_{i-1}(a_s)$ is the old data of data block a_s, and $P_{i-1}(a)$ is the old parity of the stripe. Leveraging this computation, *TRAP* appends the first part of the above equation, i.e. $P_i'(a) = F_i(a_s) \oplus F_{i-1}(a_s)$, to the parity log stored in the *TRAP* disk after a simple encoding box, as shown in Figure 4.

Figure 4 considers the simple case of a single block update for parity computation. When a data stripe involves multiple block modifications, we can still take advantage of parity computation for *TRAP* design. Suppose a_s and a_t are two data blocks of data stripe ***a***. $F_i(a_s)$ and $F_i(a_t)$ are the new data for data block a_s and a_t, respectively. The RAID controller performs the parity computation using the follow equation:

$$P_i(a) = (F_i(a_s) \oplus F_{i-1}(a_s)) \oplus (F_i(a_t) \oplus F_{i-1}(a_t)) \oplus P_{i-1}(a), \quad (4)$$

This algorithm of parity computation is called Read-Modify-Write, which requires reading the original data values for all updated data blocks [22]. During the process of the parity computation, *TRAP* can append the first two parts of Equation (4), which respectively reflect the exact changes of data blocks a_s and a_t, to the parity log stored in the *TRAP* disk for recovery purpose. It should be mentioned that there is another algorithm called Reconstruct-Write to compute the parity for multiple block modifications besides Read-Modify-Write. Reconstruct-Write reads the data values for all non-modified blocks and rebuilds the parity from the fresh data blocks in one data stripe instead of reusing the old parity. This algorithm is very efficient for cases where the whole stripe or most of data blocks in a stripe need to be updated because it can reduce READ I/O operations [23]. If parity computation is done in this way, *TRAP* cannot take advantage of RAID parity computation and has to pay an addition cost for parity computation and encoding. Fortunately, this additional overhead is not noticeable compared to disk accesses, we will discuss this overhead further in later sections.

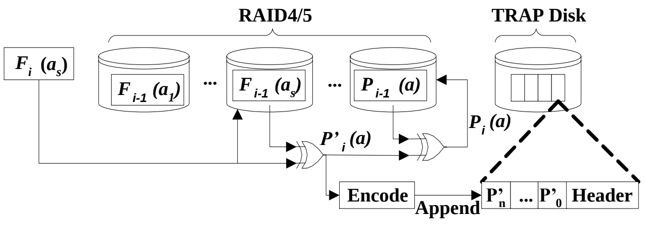


Figure 4. Block Diagram of TRAP Design

TRAP architecture makes it possible to recover data either backward referred to as "undo" or forward referred to as "redo". With traditional snapshot or backup storages, this two-way recovery is impossible as shown in Section 2. Existing technologies can only recover data in one direction: copy-on-write snapshot can only recover data by "undo" while incremental backup can recover data by "redo". Being able to recover data in two directions gives a lot of practical benefits in terms of recoverability and recovery time.

Consider the parity log corresponding to a data block, ***a***, after a series of write operations, the log contains ($P'_1(a)$, $P'_2(a)$ ……, $P'_{i-1}(a)$, $P'_i(a)$,……) with time points **1,2, …,i-1,** and ***i*** associated with the parities. Suppose that we only have the data image at time point ***r*** ($1 \le r \le i$) and all parities, and we would like to recover data backward or forward. To do a forward recovery to time point ***s*** ($s > r$), for example, we perform the following computation for each data block ***a***:

$$F_s(a) = F_r(a) \oplus P'_{r+1}(a) \oplus \ldots \oplus P'_{s-1}(a) \oplus P'_s(a), \quad (5)$$

where $F_s(a)$ denotes the data value of block ***a*** at time point ***s*** and $F_r(a)$ denotes the data value of ***a*** at time point ***r***. Note that

$$P'_l(a) \oplus F_{l-1}(a) = F_l(a) \oplus F_{l-1}(a) \oplus F_{l-1}(a) = F_l(a),$$

for all ***l*=1,2, … *i***. Therefore, Equation (5) gives $F_s(a)$ correctly assuming that the data value, $F_r(a)$, exists.

The above process represents a typical redo recovery process while earlier data is available. A backward process is also possible with the parity log if the newest data is available by doing the following computation instead of Equation (5):

$$F_s(a) = F_r(a) \oplus P'_r(a) \oplus P'_{r-1}(a) \oplus \ldots \oplus P'_{s+1}(a), \quad (6)$$

where $s < r$. This is a typical undo process by using the newest data that is available. In order to recover data in either direction, only one reference image is needed along time dimension because of the commutative property of XOR computation. This reference image could be original data image, fresh data image, or any data image in the middle. It does not need doubling the size of data images for two-way recovery.

Besides being able to recover data in two directions, TRAP is very space efficient. Our extensive experiments have demonstrated a very strong content locality that exists in real world applications and have shown that only 5% to 20% of bits inside a data block actually change on a write operation. The parity, $P_i'(a)$, reflects the exact changes at bit level of the new write operation on the existing block. As a result, this parity block contains mostly zeros with a very small portion of bit stream that is nonzero. Therefore, it can be easily encoded to a small size parity block to be appended to the parity log reducing the amount of storage space required to keep track of the history of writes.

4. SYSTEM DESIGN AND IMPLEMENTATION

We have designed and implemented a software prototype of *TRAP*. The software prototype is a block level device driver below a file system or database systems. As a result, our implementation is file system and application independent. Any file system or database applications can readily run on top of our *TRAP*. The prototype driver takes write requests from a file system or database system at block level. Upon receiving a write request, *TRAP* performs normal write into the local primary storage and at the same time performs parity computation as described above to obtain ***P′***. The results of the parity computation are then appended to the parity log corresponding to the same LBA to be stored in the *TRAP* storage.

Our implementation is done using the standard iSCSI protocol, as shown in Figure 5. In the iSCSI protocol, there are two communication parties, referred to as iSCSI initiator and iSCSI target [24]. An iSCSI initiator runs under the file system or database applications as a device driver. As I/O operations come from applications, the initiator generates I/O requests using SCSI commands wrapped inside TCP/IP packets that are sent to the iSCSI target. Our *TRAP* module is implemented inside the iSCSI target as an independent module. The main functions inside the *TRAP* module include parity computation, parity encoding, and logging. The parity computation part calculates ***P'$_i$(a)*** as discussed above. Our implementation works on a configurable and fixed block size, referred to as *parity block size*. Parity block size is the basic unit based on which parity computation is done. All disk writes are aligned to the fixed parity block size. As a result, a disk write request may be contained in one parity block or may go across several blocks depending on the size and starting LBA of the write. The parity encoding part uses the open-source [25] library to encode the parity before appending it to the corresponding parity log. The logging part organizes the parity log, allocates disk space, and stores the parity log in the *TRAP* disk. The *TRAP* module runs as a separate thread parallel to the normal iSCSI target thread. It communicates with the iSCSI target thread using a shared queue data structure.

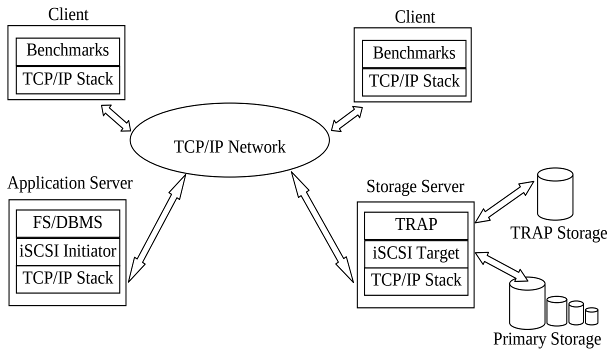


Figure 5. System Architecture of TRAP-4 Implementation

It should be mentioned that we applied very simple encoding algorithm from zlib to our implementation because parties have strong content locality. Although there are better compressing and encoding algorithms available such as motion estimation, running-length encoding [26], etc. we take a simple approach in this paper.

As shown in Figure 5, our implementation is on top of the standard TCP/IP protocol. As a result, our *TRAP* can be set up at a remote site from the primary storage through an Internet connection. Together with a mirror storage at the remote site, *TRAP* can protect important data from site failures or disaster events.

We have also implemented a recovery program for our *TRAP*. For a given recovery time point ***r***, the recovery program retrieves the parity log to find maximum time point ***s***, such that ***s≤ r***, for every data block that have been changed. We then decode the parity blocks and compute XOR using either Equation (5) or Equation (6) to obtain the data block as it was at time point ***r*** for each block. Next, the computed data are stored in a temporary storage. Consistency check is then performed using the combination of the temporary storage and the mirror storage. The consistency check may do several times until the storage is consistent. After consistency is checked, the data blocks in the temporary storage are stored in-place in the primary storage and the recovery process is complete.

It should be noted that a bit error in the parity log could potentially break the entire log chain, which would not be the case for traditional CDP that keeps all data blocks. There are two possible solutions to this: adding an error correcting code to each parity block or mirror the entire parity log. Fortunately, *TRAP* uses orders of magnitude less storage, as will be evidenced in section 6. Doubling parity log is still more efficient than traditional CDP. More research is needed to study the trade-offs regarding tolerating bit errors in parity logs.

5. EVALUATION METHODOLOGY

This section presents the evaluation methodology that we use to quantitatively study the performance of *TRAP* as compared to other data protection technologies. Our objective here is to evaluate three main parameters: storage space efficiency, recovery time, and performance impacts on applications.

5.1 Experimental Setup

Using our implementation described in the last section, we install our *TRAP* on a PC serving as a storage server, shown in Figure 5. There are four PCs that are interconnected using the Intel's NetStructure 10/100/1000Mbps 470T switch. Two of the PCs act as clients running benchmarks. One PC acts as an application server. The hardware characteristics of the four PCs are shown in Table 1.

PC 1, 2, &3	P4 2.8GHz/256M RAM/80G+10G Hard Disks
PC 4	P4 2.4GHz/2GB RAM/200G+10G Hard Disks
OS	Windows XP Professional SP2
	Fedora 4 (Linux Kernel 2.6.9)
Databases	Oracle 10g for Microsoft Windows (32-bit)
	Postgres 7.1.3 for Linux
	MySQL 5.0 for Microsoft Windows
iSCSI	UNH iSCSI Initiator/Target 1.6
	Microsoft iSCSI Initiator 2.0
Benchmarks	TPC-C for Oracle (Hammerora)
	TPC-C for Postgres(TPCC-UVA)
	TPC-W Java Implementation
	File system micro-benchmarks
Network	Intel NetStructure 470T Switch
	Intel PRO/1000 XT Server Adapter (NIC)

TABLE 1. HARDWARE AND SOFTWARE ENVIRONMENTS

In order to test our *TRAP* under different applications and different software environments, we set up both Linux and Windows operating systems in our experiments. The software environments on these PCs are listed in Table 1. We install Fedora 4 (Linux Kernel 2.6.9) on one of the PCs and Microsoft Windows XP Professional on other PCs. On the Linux machine, UNH iSCSI implementation [27] is installed. On the Windows machines Microsoft iSCSI initiator [28] is installed. Since there is no iSCSI target on Windows available to us, we have developed our own iSCSI target for Windows. After installing all the OS and iSCSI software, we install our *TRAP* module on the storage server PC inside the iSCSI targets.

On top of the *TRAP* module and the operating systems, we set up three different types of databases and two types of file systems. Oracle Database 10g is installed on Windows XP Professional. Postgres Database 7.1.3 is installed on Fedora 4. MySQL 5.0 database is set up on Windows. Ext2 and NFTS are the file systems used in our experiments. To be able to run real world web applications, we install Tomcat 4.1 application server for processing web application requests issued by benchmarks.

5.2 Workload Characteristics

Right workloads are important for performance studies [29]. In order to have an accurate evaluation of *TRAP* architecture, we use real world benchmarks. The first benchmark, TPC-C, is a well-known benchmark used to model the operational end of businesses where real-time transactions are processed [30]. TPC-C simulates the execution of a set of distributed and on-line transactions (OLTP) for a period of between two and eight hours. It is set in the context of a wholesale supplier operating on a number of warehouses and their associated sales districts. TPC-C incorporates five types of transactions with different complexity for online and deferred execution on a database system. These transactions perform the basic operations on databases such as inserts, deletes, updates and so on. At the block storage level, these transactions will generate reads and writes that will change data blocks on disks. For Oracle Database, we use one of the TPC-C implementations developed by Hammerora Project [31]. We build data tables for 5 warehouses with 25 users issuing transactional workloads to the Oracle database following the TPC-C specification. The installation of the database including all tables takes totally 3GB storage. For Postgres Database, we use the implementation from TPCC-UVA [32]. 10 warehouses with 50 users are built on Postgres database taking 2GB storage space. Details regarding TPC-C workloads specification can be found in [30].

Our second benchmark, TPC-W, is a transactional web benchmark developed by Transaction Processing Performance Council that models an on-line bookstore [33]. The benchmark comprises a set of operations on a web server and a backend database system. It simulates a typical on-line/E-commerce application environment. Typical operations include web browsing, shopping, and order processing. We use the Java TPC-W implementation of University of Wisconsin-Madison [34] and build an experimental environment. This implementation uses Tomcat 4.1 as an application server and MySQL 5.0 as a backend database. The configured workload includes 30 emulated browsers and 10,000 items in the ITEM TABLE.

Besides benchmarks operating on databases, we have also formulated file system micro-benchmarks as listed in Table 2. The first micro-benchmark, *tar*, chooses five directories randomly on ext2 file system and creates an archive file using *tar* command. We run the *tar* command five times. Each time before the *tar* command is run, files in the directories are randomly selected and randomly changed. Similarly, we run *zip, latex,* and basic file operations *cp/rm/mv* on five directories randomly chosen for 5 times with random file changes and operations on the directories. The actions in these commands and the file changes generate block level write requests. Two compiler applications, *gcc* and VC++*6.0*, compile Postgress source code and our *TRAP* implementation codes, respectively. *Linux Install, XP Install,* and *App Install* are actual software installations on VMWare Workstation that allows multiple OSs to run simultaneously on a single PC. The installations include *Redhat 8.0, Windows XP, Office 2000*, and *Visual C++* for Windows.

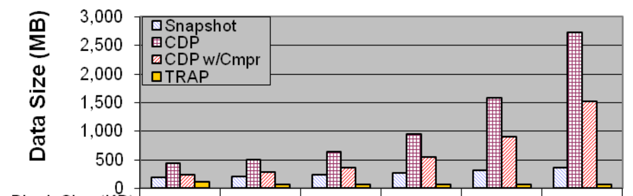
Benchmark	Brief Description
tar	Run 5 times randomly on ext2
gcc	Compile Postgres 7.1.2 source code on ext2
zip	Compress an image directory on ext2
Latex	Make DVI and PDF files with latex source files on ext2
cp/rm/mv	Execute basic file operations (cp, rm and mv) on ext2
Linux Install	Install Redhat 8.0 on VMWare 5.0 virtual machine
XP Install	Install Windows XP system on VMWare 5.0 virtual machine
App Install	MS Office2000 and VC++ on Windows
VC++ 6.0	Compile our *TRAP* implementation codes

TABLE 2. FILE SYSTEM MICRO BENCHMARKS

6. NUMERICAL RESULTS AND DISCUSSIONS

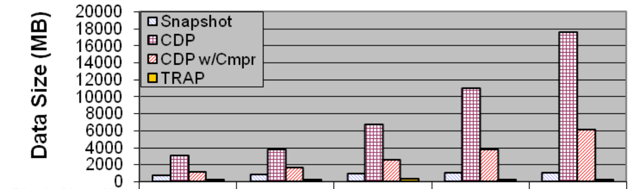
Our first experiment is to measure the amount of storage space required to store *TRAP* data while running benchmarks on three types of databases: Oracle, Postgres, and MySQL. We concentrate on block level storages and consider three types of data protection technologies in our experiments. *Snapshot* stores only changed data blocks at the end of each run. Traditional CDP stores all versions of a data block as disk writes occur while running the benchmarks. *TRAP* keeps parity logs as described in Section 3. To make a fair space usage comparison, we have also performed data compression in the traditional CDP architecture. The compression is done on entire log as opposed to individual blocks. The later would consume more space because it cannot take advantage of access patterns among different data blocks. The compression algorithm is based on the open source library [25]. Each benchmark is run for about 1 hour on a database for a given block size. We carry out our experiments for 6 different parity block sizes: 512B, 4KB, 8KB, 16KB, 32KB, and 64KB. Recall that parity block size is the basic unit for parity computations. Actual data sizes of disk write requests are independent of the parity block size but are aligned with parity blocks. If a write request changes a data block that is contained in a parity block, then only one parity computation is done. If a write request changes a data block that covers more than one parity block, more parity computations have to be done. Whether or not a write data is within one parity block depends on the starting LBA and the size of the write.

Figure 6 shows the measured results in terms of Mbytes of data stored in the *TRAP* storage. There are six sets of bars corresponding to the six different block sizes. Each set contains four bars corresponding to the amount of data stored using *snapshot, CDP, CDP* with compression, and *TRAP*, respectively. It is shown in this figure that *TRAP* presents dramatic reductions in required storage space compared to other architectures. For the block size of 8KB, *TRAP* reduces the amount of data to be stored in the *TRAP* storage by an order of magnitude compared to *CDP*. For the block size of 64KB, the reduction is close to 2 orders of magnitude. Even with data compression being used for *CDP*, *TRAP* reduces data size by a factor of 5 for the block size of 8KB and a factor of 23 for the block size of 64KB, as shown in the figure.



Block Size (KB)	0.5	4	8	16	32	64
Snapshot	185	193	231	256	304	346
CDP	424	485	631	940	1,571	2,724
CDP w/Cmpr	236	272	359	532	895	1,517
TRAP	102	64	63	64	61	64

Figure 6. Data Size Comparison for TPC-C on Oracle Database



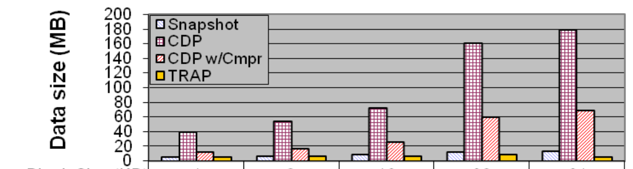
Block Size (KB)	4	8	16	32	64
Snapshot	735.48	770.51	902.13	994.97	1002.75
CDP	3002.97	3775.49	6675.73	10924.76	17548.13
CDP w/Cmpr	1134.11	1602.88	2547.92	3725.07	6070.76
TRAP	203.30	198.36	261.89	253.57	233.03

Figure 7. Data Size Comparison for TPC-C on Postgres Database

As shown in Figure 6, we observed in our experiments that space efficiency and performance are limited by using the block size of 512B, the sector size of disks. The reason is that many write operations write large data blocks of 8KB or more. Using 512B block size for parity computation, a write into an 8KB block fragments the data into at least 16 different parity groups, giving rise to more overheads and larger indexing/meta data. In the following experiments, we consider only the other 5 larger parity block sizes.

Results of the TPC-C benchmark on Postgres database are shown in Figure 7. Again, we run the TPC-C on Postgres database for approximately 1 hour for each block size. Because Postgres was installed on a faster PC with Linux OS, TPC-C benchmark generated more transactions on Postgres database than on Oracle database for the same one-hour period. As a result, much larger data set was written as shown in Figure 7 and Figure 6. For the block size of 8KB, *CDP* needs about 3.7GB storage space to store different versions of changed data blocks in the one-hour period. Our *TRAP*, on the other hand, needs only 0.198GB, an order of magnitude savings in storage space. If data compression is used in *CDP*, 1.6GB of data is stored in the *TRAP* storage, 8 times more than *TRAP*. The savings are even greater for larger data block sizes. For example, for the block size of 64KB, *TRAP* storage needs 0.23GB storage while *CDP* requires 17.5GB storage, close to 2 orders of magnitude improvement. Even with data compression, *TRAP* is 26 times more efficient than *CDP*. Notice that larger block sizes reduces index and meta data sizes for the same amount of data, implying another important advantage of *TRAP* since space required by *TRAP* is not very sensitive to block sizes as shown in the figure.

Figure 8 shows the measured results for TPC-W benchmark running on MySQL database using Tomcat as the application server. We observed similar data reduction by *TRAP* as compared to *CDP*. For example, for block size of 8KB, *TRAP* stores about 6.5MB of data in the *TRAP* storage during the benchmark run whereas traditional CDP keeps 54MB of data in the *TRAP* storage for the same time period. If block size is increased to 64KB, the amounts of data are about 6MB and 179MB for *TRAP* and traditional CDP, respectively.



Block Size (KB)	4	8	16	32	64
Snapshot	5.25	6.34	8.25	11.41	12.69
CDP	39.40	53.92	71.78	160.83	178.89
CDP w/Cmpr	11.95	16.65	25.36	59.50	68.67
TRAP	6.02	6.50	6.80	9.53	5.73

Figure 8. Data size comparison for TPC-W on MySQL database

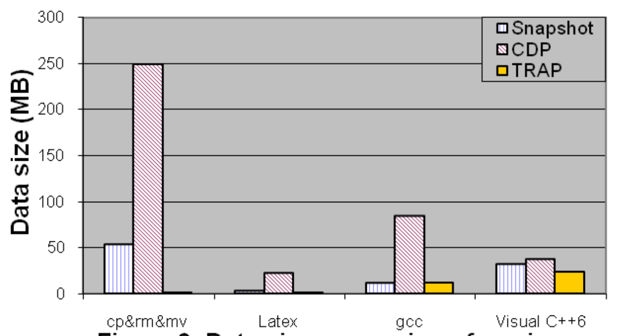


Figure 9. Data size comparison for micro benchmarks (blocksize=8KB)

Results for file system benchmarks are shown in Figures 9-12. Nine micro benchmarks are run for two different block sizes, 8KB and 16KB. Space savings of *TRAP* over other architectures vary from one application to another. We observed largest gain for *cp/rm/mv* commands and smallest for Visual C++6. The largest gain goes up to 2 orders of magnitude while the smallest gain is about 60%. In general, Unix file system operations demonstrate better content locality. Our analysis of Microsoft file changes indicates that some file changes result in bit-wise shift at block level. Therefore, XOR operations at block level are not able to catch the content locality. The data reduction ratios of all micro benchmarks are shown in Figure 13 in logarithmic scale. As shown in the figure, the ratio varies between 1.6 and 256 times. The average gain for 8KB block size is 28 times and the average gain for 16KB block size is 44 times.

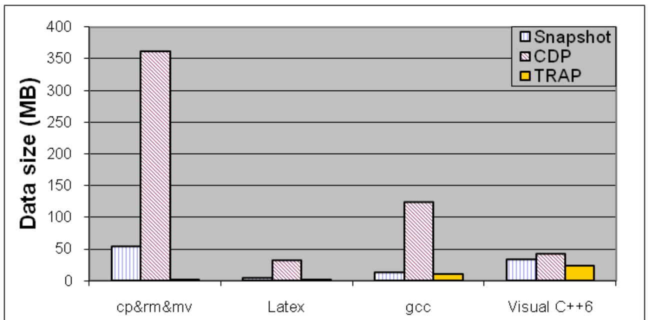


Figure 10. Data size comparison for micro benchmarks (blocksize=16KB)

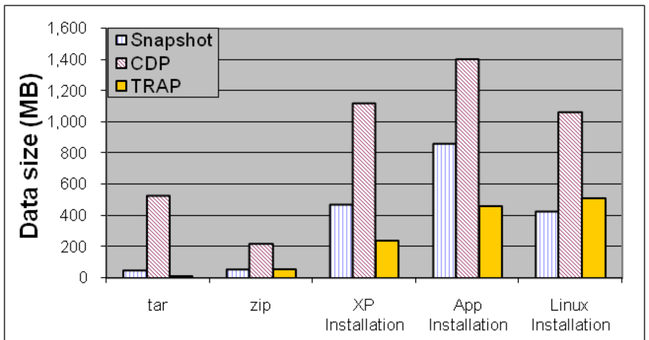


Figure 11. Data size comparison for micro benchmarks (blocksize=8KB)

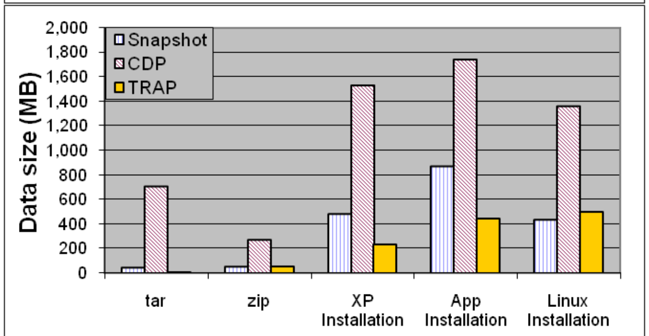


Figure 12. Data size comparison for micro benchmarks (blocksize=16KB)

Recovery of data in the real world is measured by two key parameters: recovery point objective (RPO) and recovery time objective (RTO) [13,8]. RPO measures the maximum acceptable age of data at the time of outage. For example, if an outage occurs at time t_0, and the system found such an outage at time t_1, the ideal case is to recover data as it was right before t_0, or as close to t_0 as possible. A daily incremental backup would represent RPO of approximately 24 hours because the worst-case scenario would be an outage during the backup, i.e. t_0 is the time point when a backup is just started. RTO is the maximum acceptable length of time to resume normal data processing operations after an outage. RTO represents how long it takes to recover data. For the above example, if we successfully recover data at time t_2 after starting the recovery process at t_1, then the RTO is t_2 - t_1.

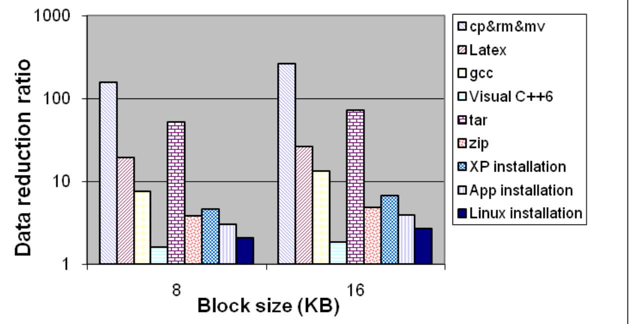


Figure 13. Data reduction ratio of TRAP over CDP for micro benchmarks

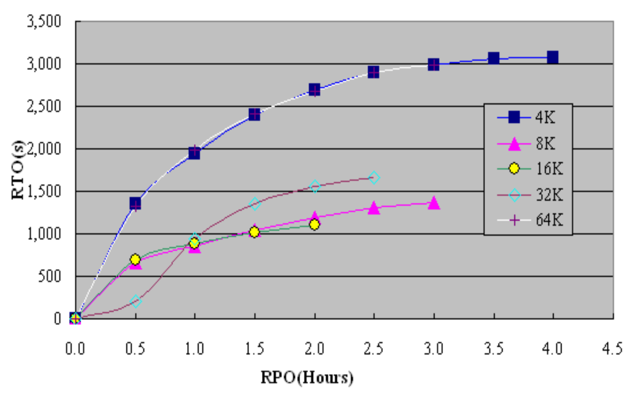


Figure 14. The relationship between RPO and RTO

Using our recovery program, we carry out experiments to recover data to different time points in the past. For a given block size, we first run the TPC-C benchmark on Oracle database installed on *TRAP* for sufficiently long time. As a result of the benchmark run, *TRAP* storage was filled with parity logs. We then perform recoveries for each chosen time point in the past. Because of the time limit, all our parity logs and data are on disks without tape storage involved. We have made 30 recovery attempts and all of them have been able to recover correctly within first consistency check. Figure 14 shows the RTO as functions of RPO for the 5 different block sizes. Note that our recovery process is actually an undo process using Equation (6) as opposed to Equation (5) that represents a redo process. An undo process starts with the newest data and traces back the parity logs while redo process starts with a previous data image and traces forward the parity logs. With the undo process, RTO increases as RPO increases because the farther we trace back in the parity logs, the longer time it takes to recover data. The results would be just the opposite if we were to recover data using Equation (5). Depending on the types of outages and failure conditions, one can choose to use either process to recover data. For example, if the primary storage is damaged without newest data available, we have to recover data using a previous backup together with parity logs using Equation (5). On the other hand, if a user accidentally performed a wrong transaction, an undo process could be used to recover data using Equation (6).

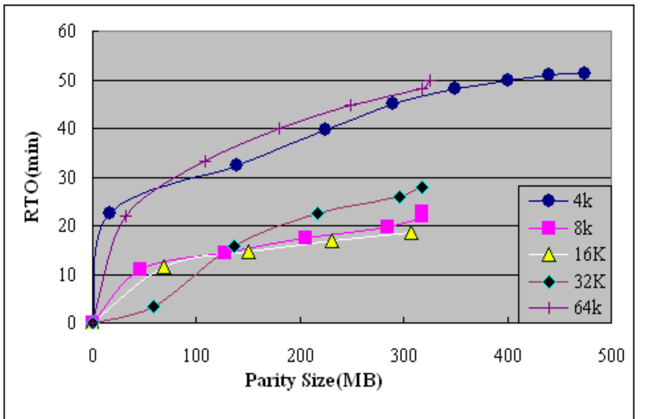


Figure 15. RTO VS Parity Sizes

Whether we do an undo recovery using Equation (6) or a redo recovery using Equation (5), RTO depends on the amount of parity data traversed during the recovery process. To illustrate this further, we plot RTO as functions of parity log sizes traversed while doing recovery as shown in Figure 15. The recovery time varies between a few seconds to about 1 hour for the data sizes considered. In comparison to traditional CDPs that ideally have the same RTO for different RPOs, this variable recovery time is disadvantageous. Fortunately, the smaller storage space required by *TRAP* may compensate to some extent. It should be noted that the amount of storage for traditional CDP architecture is over 10GB corresponding to the parity size of 300 MB. Figure 15 can be used as a guide to users for choosing a shorter RTO recovery process depending on the RPO, the parity log size, and the availability of newest data or a previous backup.

During our recovery experiments we observed that block sizes of 8KB and 16KB give the shortest recovery time, as shown in Figures 14 and 15. This result can be mainly attributed to the fact that most disk writes in our experiments fall into these block sizes. As a result, write sizes match well with parity block sizes. If the block size for parity computation were too large or too small, we would have to perform more parity computations and disk I/Os than necessary, resulting in longer recovery time and higher overhead as will be discussed shortly.

In order to compare the recovery time, RTO, of our *TRAP* with that of traditional CDP, we measure the time it takes to do the XOR and decoding operations of *TRAP* as shown in Table 3. Since we have only implemented the recovery program for *TRAP* but not for traditional CDP, we will carry out the following simplified analysis just to approximately compare the two. Suppose that traditional CDP reads the index node first to find out the exact location of the data block with a given time point for each changed data block. Next the data block is read out from the CDP storage to a temporary storage. If we have a total of N_B changed data blocks, the data retrieval time for traditional CDP to recover data is approximately given by

$$\mathbf{(inode\_size/IO\_Rate+Block\_size/IO\_Rate+2S+2R)N_B,}$$

where S and R are average seek time and rotation latency of the hard drive, respectively. To recover data, *TRAP* needs not only to retrieve parity log for each data block but also to decode parity and to compute XORs. Let T_{DEC} and T_{XOR} denote the decoding time and XOR time. The data retrieval time for *TRAP* to recover data is approximately given by

$$\mathbf{(T_{DEC}+T_{XOR}+Avg\_log\_size/IO\_Rate+S+R)N_B,}$$

where *Avg_log_size* is the average parity log size for each data block. Our experiments show that the average log size is 38KB. Therefore, an entire log is read from *TRAP* disk every time when we try to recover one block of data. It is important to note that the data log sizes of traditional CDP are generally too large to be read in one disk operation. That is why it needs two disk operations, one for reading the I-node (header) of the corresponding log and the other for the data block pointed by the I-node. Using the above two formulae, we plot the data retrieval time of the *TRAP* and traditional CDP architectures as shown in Figure 16 assuming the average seek time to be 9ms, the average rotation latency to be 4.15ms, and the *IO_Rate* to be 45MB/s. Note that the time it takes to do consistency check and write in-place should be the same for both systems. As shown in the figure, *TRAP* generally takes shorter time to retrieve data from the *TRAP* storage even though additional computations are necessary for decoding and XOR. However, the actual recovery time depends on the real implementation of each recovery algorithm and many other factors such as caching effect and indexing structure.

Block Size(KB)	XOR(ms)	Decode(ms)
4	0.026414	0.073972
8	0.053807	0.132586
16	0.105502	0.213022
32	0.214943	0.335425
64	0.421863	0.603595

TABLE 3. MEASURED COMPUTATION TIME FOR XOR AND DECODING PROCESS IN TRAP IMPLEMENTATION ON PC1

Computing and logging parities in *TRAP* architecture may introduce additional overhead in online storages. Such overhead may negatively impact application performance. In order to quantify such impacts, we have measured the additional computation time as shown in Table 3. In addition, we have also measured the TPC-C throughputs while running TPC-C on Oracle and Postgres databases with two storage systems. One storage system has *TRAP* installed and the other has no *TRAP* installed. We then compare the two measured throughputs and calculate the overhead rate. The overhead rate is the ratio of the two measured throughputs minus 1. This overhead rate is a measure of slow down of the *TRAP*. Figure 17 plots the overhead rates for different block sizes. Most of the overhead rates are less than 8% with one exception of 64KB on Postgres database. The lowest overhead is less than 2% for the block size of 16KB. It should be noted that our implementation does not assume a RAID controller. All the parity computations are done using software and considered extra overheads. As mentioned previously, TRAP can leverage the parity computation of RAID controllers. Therefore, if *TRAP* was implemented inside a RAID array, the overheads would be much lower.

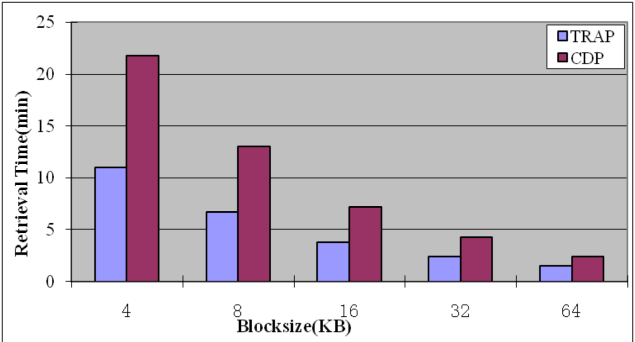


Figure 16. Retrieval Time Comparsion for Recovery between CDP and TRAP

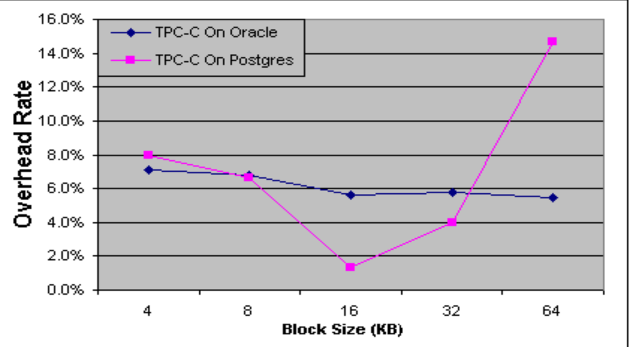


Figure 17. Overhead of TRAP-4

7. RELATED WORK

Depending on the different values of RPO and RTO, there exist different storage architectures capable of recovering data upon an outage. We summarize existing related works in 3 different categories based on different RPOs.

Snapshot or incremental backup: Data protection and recovery have traditionally been done using periodical backups [10,12] and snapshots [11]. Typically, backups are done nightly when data storage is not being used since the process is time consuming and degrades application performance. During the backup process, user data are transferred to a tape, a virtual tape, or a disk for disk-to-disk backup [10,35]. To save backup storage, most organizations perform full backups weekly or monthly with daily incremental backups in between. Data compression is often used to reduce backup storage space [12,36]. A good survey of various backup techniques can be found in [12]. Snapshot is a functionality that resides in most modern disk arrays [37,38,39], file systems [35,40,41,42,43,44,45,46], volume managers [47,48], NAS filers (network attached storages) [49,50,51] and backup software. A snapshot is a point-in-time image of a collection of data allowing on-line backup. A full-copy snapshot creates a copy of the entire data as a read only snapshot storage clone. To save space, copy-on-write snapshot copies a data block from the primary storage to the snapshot storage upon the first write to the block after the snapshot was created [48]. A snapshot can also redirect all writes to the snapshot storage [11,50] after the snapshot was created. Typically, snapshots can be created up to a half dozen a day [47] without significantly impacting application performance.

File Versioning: Besides periodical data backups, data can also be protected at file system level using file versioning that records a history of changes to files. Versioning was implemented by some early file systems such as Cedar File System [42], 3DFS [52], and CVS [53] to list a few. Typically, users need to create versions manually in these systems. There are also copy-on-write versioning systems exemplified by Tops-20 [54] and VMS [55] that have automatic versions for some file operations. Elephant [46] transparently creates a new version of a file on the first write to an open file. CVFS [56] versions each individual write or small meta-data using highly efficient data structures. OceanStore [57] uses versioning not only for data recovery but also for simplifying many issues with caching and replications. The LBFS [58] file system exploits similarities between files and versions of the same files to save network bandwidth for a file system on low-bandwidth networks. Peterson and Burns have recently implemented the ext3cow file system that brings snapshot and file versioning to the open-source community [41]. Other programs such as *rsync*, *rdiff*, and *diff* also provide versioning of files. To improve efficiency, flexibility and portability of file versioning, Muniswamy-Reddy et al [59] presented a lightweight user-oriented versioning file system called *Versionfs* that supports various storage policies configured by users.

File versioning provides a time-shifting file system that allows a system to recover to a previous version of files. These versioning file systems have controllable RTO and RPO. But, they are generally file system dependent and may not be directly applicable to enterprise data centers that use different file systems and databases.

Traditional CDP: To provide timely recovery to any point-in-time at block level, one can keep a log of changed data for each data block in a time sequence [13,16, 60]. In the storage industry, this type of storage is usually referred to as CDP (Continuous Data Protection) storage. Laden et al proposed four alternative architectures for CDP in a storage controller, and compared them analytically with respect to both write performance and space usage overhead [61]. Zhu and Chiueh proposed a user-level CDP architecture that is both efficient and portable [62]. They implemented four variants of this CDP architecture for NFS servers and compared their performance characteristics. Lu et al presented an iSCSI storage system named Mariner to provide comprehensive and continuous data protection on commodity ATA disk and Gigabit Ethernet technologies [63]. Different from these works for CDP architectures, our study concentrates on data recoverability of block level storages and what kind of data needs to be stored for recovery purpose.

The main drawback of the CDP storage is the huge amount of storage space required, which has thus far prevented it from being widely adopted. There have been research efforts attempting to reduce storage space requirement for traditional CDP. Flouris and Bilas [64] proposed a storage architecture named Clotho providing transparent data versioning at block level. Clotho coalesces the updates that take place within a period of time by creating new versions for them. This versioning happens at discrete time points not necessarily continuous as done in CDP. What is interesting in their work is that they observed storage space savings by binary differential compression to store only the delta data that has been modified since the last version. Morrey III and Grunwald [16] observed that for some workloads, a large fraction of disk sectors to be written contain identical content to previously written sectors within or across volumes. By maintaining information (128 bit content summary hash) about the contents of individual sectors, duplicate writes are avoided. Zhu, Li, and Patterson [36] proposed an efficient storage architecture that identifies previously stored data segments to conserve storage space. These data reduction techniques generally require a search in the storage for an identical data block before a write is performed. Such a search operation is generally time consuming, although smart search algorithm and intelligent cache designs can help in speeding up the process [16,36]. These data reduction techniques are more appropriate for periodic backups or replications where timing is not as much a critical concern as the timing of online storage operations.

It should be noted that keeping a log of changed data has been studied and used in other contexts other than data recovery. For example, Log-structured file system has been researched extensively for improving disk write performance [65,66]. There are variations of such log-structured file system such DCD [29] proposed by Hu and Yang and Vagabond [67] proposed by Norvag and Bratbergsengen for optimizing disk write performance. Norvag and Bratbergsengen also noticed the space savings of storing a delta object in buffer space when an object is changed, which suggests data locality that exists in data write operations.

8. CONCLUSIONS

We have presented a novel disk array architecture capable of providing **T**imely **R**ecovery to **A**ny **P**oint-in-time for continuous data protection, referred to as *TRAP* architecture. A prototype of the new *TRAP* architecture has been implemented as a block level device driver. File systems such as ext2 and NTFS, and databases such as Oracle, Postgres, and MySQL, have been installed on the prototype implementation. Real world benchmarks including TPC-C, TPC-W, and file system benchmarks are used to test the performance of the new storage architecture. Extensive experiments have demonstrated up to 2 orders of magnitude improvements in terms of storage efficiency. In addition, we gave theoretical proofs for one-way recovery of traditional snapshots and incremental backups compared to two-way recovery of *TRAP* architecture. Recovery experiments have also been carried out several dozen times to show the quick recovery time of the new architecture. Measurements have also shown that the new architecture has little negative performance impact on application performance while providing continuous data protection capability.

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