Multi-level Forwarding and Scheduling Recovery Algorithm in Rapidly-changing Network for Erasure-coded Clusters
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Abstract—A key design goal of erasure-coded clusters is to reduce the repair time. The existing Erasure-coded data repair schemes are roughly classified into two categories: 1. Designing rapid data repair (e.g., PPR) in a homogeneous environment. 2. Constructing data repair (e.g., PPT) based on bandwidth in a heterogeneous environment. However, these solutions are difficult to cope with the heterogeneous and rapidly-changing network in erasure-coded clusters. To address this problem, a bandwidth-aware multi-level forwarding repair algorithm, called BMFRepair, is proposed. BMFRepair monitors the network bandwidth in real time when data is forwarded, and selects idle nodes with high-bandwidth links to assist in forwarding. Thus, it can reduce the time bottleneck caused by low link transmission. At the same time, multi-node repair becomes very complicated when the bandwidth changes drastically. A multi-node scheduling repairing algorithm, called MSRepair, is proposed for multi-node repairing problems, which can repair multiple failed blocks in parallel by scheduling node resources. The two algorithms can flexibly adapt to the rapidly changing network environment and make full use of the bandwidth resources of idle nodes. Most importantly, algorithms can continuously adjust the repair plan according to the bandwidth change in fast and dynamic network. The algorithms have been evaluated by both simulations on Mininet and real experiments on Aliyun cloud platform ECS. Results show that compared with the state-of-the-art repair schemes PPR and PPT, the algorithms can significantly reduce the repair time in rapidly-changing network.

Keywords—Distributed storage system, Erasure coding, Heterogeneous network, Recovery.

I. INTRODUCTION

With the rapid development of information technology, the explosive growth of data volume has brought great pressure on storage systems. In order to prevent failures from causing data unavailability, existing large-scale distributed storage systems will introduce data redundancy to maintain system reliability with high storage efficiency. For example, 3-replication is originally applied to the Google File System [1], Windows Azure Storage [2] and the Hadoop Distributed File System [3]. As an important ways of ensuring data reliability in storage systems, erasure codes have attracted more and more attention from industry and academia. Because of its high storage efficiency and high fault tolerance, erasure codes are widely used in systems such as RAID, archive storage, backup storage, and hot/cold data storage [4], [5]. Although attractive in terms of reliability and storage overhead, a major drawback of erasure codes is the expensive repair process. For the (n, k) RS code system, it is necessary to obtain k times data from k nodes in order to recover the lost single data node. In the three-replication system, the loss of the block can be recovered by 1 times the data.

In order to reduce the repair cost of erasure codes, previous research either proposed a new coding structure to reduce network transmission (e.g., [8], [15], [17], [25], [28], [30], [34]), or use fast repair technology for existing erasure codes to reduce latency (e.g., RCTREE [23], [24] or parallel partial repair (PPR) [20]). However, in a heterogeneous environment of network bandwidth, reducing transmission bandwidth or PPR cannot solve the problem of data repair delay. So far, we have raised the following question: Can we reduced the data repair time in a heterogeneous environment? This creates an opportunity to apply erasure coding to hot data.

Since the RS code only needs k nodes to repair when a node was broken down, the remaining n-k-l nodes are in an idle state, and their bandwidth resources are not fully utilized. And in a heterogeneous network environment, when the sum of the bandwidth of the two sides of the triangle is greater than the bandwidth of the third side, we can bypass the third side and transmit on the two sides to optimize the overall performance. We observe that this situation is very common in the actual network environment, so we propose a Bandwidth-aware Multi-level Forwarding Repair (BMFRepair) algorithm. This algorithm is based on the PPR single node repair process. In each round of timestamp, we use idle nodes (non-helper nodes) in the system to construct the best repair path according to the bandwidth of the current link, and reduce the repair time of the link to each node. At the same time, our method can make full use of idle bandwidth resources. More importantly, the previous work was to construct an optimal repair plan based on the current bandwidth before repairing (e.g., [6], [7], [21], [23], [24], [25], [26]), but because the bandwidth in the link is constantly changing, this will cause the repair process to be sub-optimal. BMFRepair adopts different repair methods for each partial repair timestamp according to the real-time bandwidth, so that it can adapt to changes in the link more
flexibly and improve the overall repair performance. At the same time, the existing work is less for the scenario of multi-node failure. For the situation of multi-node failure, we designed a Multi-node Scheduling Repair (MSRepair) algorithm, which allows each failed node to be repaired in parallel. And we also use the previous BMFRepair algorithm to speed up the repair process of each round of timestamp. Thus, BMFRepair and MSRepair can support many practical EC based on RS code.

We implement BMFRepair and MSRepair in python and evaluate the performance on Mininet and Aliyun ECS. We summarize our contribution as follows:

1) To cope with the rapidly changing network environment, a generic BMFRepair algorithm is proposed, which optimizes the link with the longest repair time during each round of repair. BMFRepair monitors the network bandwidth in real time when data is forwarded, and selects idle nodes with high-bandwidth links to assist in forwarding. By optimizing each round of local repair to reduce the global repair delay, it can better adapt to the actual requirements of today's thermal storage systems. To the best of our knowledge, this is the first time that non-helper nodes in the stripe are used to participate in the repair process.

2) Multi-node repair becomes very complicated when the bandwidth changes drastically. In order to address the problem, a generic MSRepair algorithm is proposed, which allows multiple failed nodes can be repaired in parallel to maximize the utilization of the link bandwidth resources of each node. In each round of repair, we use the previous BMFRepair method to further shorten the repair time.

3) In order to verify the performance of BMFRepair and MSRepair, a mininet simulation experiment was carried out on a single machine, and a real experiment was carried out on the Aliyun platform ECS. Experimental results show that compared with the state-of-the-art repair schemes PPR and PPT, BMFRepair can reduce the repair time by 25% and 17% on single node repair. Compared with m-PPR, MSRepair can reduce the repair time by up to 59.7% in multi-node repair. And this is more obvious in the rapid changes in network bandwidth and large-scale storage systems.

The rest of this paper is organized as follows. In Section II, we introduce background and related work. Section III describes motivation and Section IV describes MSRepair and MSRepair in detail. Section V we evaluate BMFRepair and MSRepair compared to above proposed techniques and in Section VI we draw a conclusion.

II. BACKGROUND AND RELATED WORK

A. Erasure Code

The basic idea of erasure coding is to divide a piece of data into k original data nodes, and encode these k original data nodes to obtain n−k parity nodes. When any n−k of these n nodes fail, the system can reconstruct k original data nodes. Compared with replication technology, erasure code has the advantages of high storage space utilization and low storage cost. For example, Fig. 1 shows a stripe of the \((n=6, k=3)\) RS code, which contains three data nodes and three parity nodes. Since erasure codes are basically based on linear coding, their repair operations can be performed through linear operations.

![Data Chunks](image)

![Parity Chunks](image)

Fig. 1 Encoding of \((n=6, k=3)\) RS codes for a stripe, in which there are three data nodes and three parity nodes. Each parity node is a linear combination of all data nodes. If one of the data or parity nodes fails, any three surviving nodes within the stripe can be retrieved for reconstruction.

The first data node can be repaired by \(D1=P1+D2+D3\). In the repair operation, linear addition does not increase the data size. The addition based on XOR ensures that all the addition results are the same size as the original data block. For example, in the results of all the additions in repairing \(D1, P1, P1+D2\) and \(P1+D2+D3\) are the same size. At the same time, the order of addition is irrelevant. For example, \(P1+(D2+D3)\) and \(P1+(D2+D3)\) can both decode \(D1\). Since the RS code can be flexibly executed in any linear combination during the repair process, and the block size transmitted for each linear encoding operation is fixed, this advantage makes the existing storage system more inclined to use the RS code. Therefore, our work is also based on RS codes.

B. Related Work

In such big systems, nodes fail frequently and the failures should be handled on a routine basis. Since more than 98% of the storage system failures are single node failures, many erasure code structures (e.g., [8-15]) have been proposed to improve single node repair performance. But those single failure recovery technologies focus on specific code constructions, but cannot be directly applied to today’s CFSe (e.g., [16-18]) that employ RS codes for general fault tolerance. At the same time, from the user's point of view, to access a damaged data, it is necessary to repair it in the fastest time and reduce the repair delay. However, since the network in the existing storage system is heterogeneous, this poses new challenges for erasure code designers. For example, the available bandwidths among servers are different because of different background traffics [19]. The difference of link bandwidths becomes even larger when using multiple geo-distributed data centers for distributed storage, which is a conventional practice for large companies.

In order to solve the above problems, in a homogeneous network environment, Mitra et al. [20] propose Partial Parallel Repair (PPR), which decomposes a recovery operation into many small partial operations and schedules those partial operations in parallel, so as to achieve faster data recovery. In [21], [22] is specifically designed for RS codes to reduce the cross-rack repair traffic. The above work makes full use of bandwidth resources between storage nodes and speeds up recovery, but it is considered in a uniform traffic network. The
bandwidth of any low link will lead to an increase in the recovery time, and will cause a very large impact as the link environment continues to change.

It’s important and meaningful to reduce recovery time in a heterogeneous network environment. Due to various reasons, the network links of distributed storage systems in practice always have non-uniform bandwidth. Li et al. [23], [24] proposed a tree-structured regeneration scheme, called RCTREE, to bypass the low-capacitated link encountered in direct transmissions. However, wang [25] find that RCTREE may rapidly lose data integrity after several regenerations, so they reconsider the problem of minimizing regeneration time in networks with heterogeneous link capacities. However, the above works does not propose a specific coding scheme for the regeneration code, because it is difficult to find a regeneration code in the actual system that can regenerate a certain amount of data according to the change of the link bandwidth, and it did not involve multi-node repair. To reduce recovery time, Bai [26] propose Parallel Pipeline Tree (PPT) and Parallel Pipeline Cross-Tree (PPCT) to reduce single-node and multi-node repair delay, respectively. By utilizing bandwidth gap among links and sharing traffic pressure of requesters with helpers, PPT and PPCT constructs a tree path based on bandwidth. But in this work, the authors think that when multiple nodes send data to a node in parallel, the bandwidth of each link is the total bandwidth divided by the number of links [27]. However, this situation is difficult to achieve in actual network distribution.

Fig. 2 The bandwidth of each link changes when multiple nodes send data to a node at the same time. As the number of links increases, the bandwidth distribution is uneven

We made an experimental analysis for this situation, allowing multiple nodes to send data to one node at the same time and observe the changes in the bandwidth of each link. Fig. 2 is our test result. We found that as the number of links increases, the total bandwidth and present a downward trend, and the proportion of bandwidth allocated to each link is very uneven. Therefore, in this case, the receiving node will have a serious performance bottleneck as the link continues to increase.

And in the hot storage, the network bandwidth changes very quickly. The previous work (e.g., [23-25], [28]) is based on the global construction of an optimal repair plan, but the bandwidth cannot be constant during the repair process. It may not be the global optimal due to a change in bandwidth, so it is not applicable based on the current thermal storage system. Although single node failures account for 98% of the total failure rate, the failure of a single node may affect the rest of the nodes, so it is necessary to design a solution for multi-node failures. Based on the above investigation, in our work, we do not adopt a situation where a single node receives data sent by multiple links, but a node can only receive or send data on one link.

III. Motivation

Fig. 3 Bandwidth-aware multi-level forwarding repair

We first observe a three-node Erasure-code cluster, node1, node2 and node3. In Fig. 3 we show the bandwidth between the three nodes. When node1 wants to send data to node2, if the source node node1 sends data directly to the target node node2, we call this single-stage forwarding (Fig. 3(a)). When the forwarding process passes through multiple nodes (e.g., node3) to reach the target node, it is called multi-level forwarding (Fig. 3(b)). It should be noted that the node assisting in forwarding only participates in the buffer transmission of data, and does not participate in the storage or calculation process. As you can see in the figure, this forwarding method can bypass the low-bandwidth link and transmit data to the target node faster. This is also the inspiration for our work.
repair operations on nodes within each timestamp to generate intermediate results in parallel, and then forwards the intermediate results to the next designated node. For example, in Fig. 1, D1 node is lost, now D1 can be reconstructed using the equation: D1 = D2 + D3 + P1 (In II P1 = D1 + D2 + D3, ‘+’ represents XOR), In timestep 1, D2 sends its partial result to D1. In parallel, P1 sends its partial result to D3. In timestep 2, D3 sends its aggregated (D3 + P1) results to D1 reducing the overall network transfer time by a factor of 33%.

Although PPR reduces repair time, the bandwidth usage distribution remains not fully balanced. Fig. 4 shows the repair steps of the RS(6, 3) code for the PPR method at the first time stamp. Assuming that the D1 node fails, choose D2, D3, P1 as the helper nodes. In the first stage of PPR repair, D2 node transmits data to D1, and P1 transmits data to D3 at the same time. Assuming that the bandwidth between P1 and D3 in a heterogeneous environment is less than that between D2 and D1, then the link between P1 and D3 will become the longest elapsed time in this timestamp (t2=5s). However, we found that since only k nodes are required to participate in the repair in the RS code repair process, the remaining n-k-1 nodes (P2 and P3) are in an idle state, and their bandwidth is not used. If the bandwidth from P1 to P2 and from P2 to D3 in Fig. 4 is very high, then do we consider that we can use node P2 or P3 to assist in forwarding to speed up this round of timestamp repair? Assuming that the transmission time of the same size block from P1 to P2 is t21=2s, and the transmission time of the same size block from P2 to D3 is t22=2s, then t21+t22=4s<t2=5s, and this forwarding mechanism can increase by 1 Seconds. Based on the above observations, we first proposed a BMFRepair algorithm, which can adapt to the continuous changes of bandwidth in the network to accelerate the repair of each timestamp time.

Existing work rarely involves multi-node repair scheduling problems. Subrata [20] designed m-PPR, an algorithm that schedules multiple reconstruction-jobs in parallel while trying to minimize the competition for shared resources between multiple reconstruction operations. But in fact, this repair has not reached parallelization. The left side of Fig. 5 shows the timestamp when m-PPR repairs the two blocks D1 and D2 for RS(6, 3). The red solid line and the black solid line represent the forwarding flow of repairing D1 and D2, respectively. It can be seen that m-PPR takes 4 timestamps to complete the repair process. If we can reasonably schedule the repair process, multiple damaged nodes can be repaired in parallel, thus speeding up the repair time of multiple nodes. As shown in the right figure of Fig. 5, we only need three timestamps to complete the repair process of two nodes. Therefore, we designed a MSRepair algorithm, while still considering the inconsistent bandwidth of each link in a heterogeneous environment. BMFRepair algorithm can be used in each time stamp of the method to speed up the repair.

IV. ALGORITHM DESIGN

A. Design: Bandwidth-aware Multi-level Forwarding Repair

| BANDWIDTH MEASUREMENTS (IN M/S) ACROSS NODE D3 P1 P2 P3 |
|-----------------|---------|---------|-------|-------|
| To D3 | From P1 | From P2 | From P3 |
| D3   | *       | 4       | 10    | 7     |
| P1   | 3       | *       | 6     | 8     |
| P2   | 3       | 10      | *     | 5     |
| P3   | 5       | 5       | 20    | *     |

We propose an effective reconstruction optimization technology that focuses on further reducing network transmission time in each round of timestamp. The initial algorithm of the entire repair is PPR. However, PPR is easily limited by the impact of low link bandwidth in a heterogeneous environment. Therefore, improvements are made to address...
this defect to improve the efficiency of each round of repair, so as to achieve the best in the entire repair process.

We observed the bandwidth of a four-node, $D_3 P_1 P_2 P_3$ with iperf [29]. In the Table 1, we show the bandwidth triangle between $P_2$ and $P_3$ have a exploitable trait. This trait is common in practical network, and we can utilize it to speed up bandwidth recovery. Assuming that the size of each node is 20M, the bandwidth from node $D_2$ to node $D_1$ is $BW_{(D_2,D_1)}=5M/s$, and the bandwidth from node $P_1$ to node $D_3$ is $BW_{(P_1,D_3)}=4M/s$. Then the minimum bandwidth in the first time stamp is $4M/s$, and the time spent is $20/4=5s$. The link bandwidth between $P_1$ and $D_3$ becomes the bottleneck of the timestamp. We also found that $P_2$ and $P_3$ did not participate during the repair process, and their bandwidth resources were not fully utilized. Based on this observation, our BMFRepair can use the abundant bandwidth resources of idle nodes to realize forwarding, thereby speeding up the repair of a single timestamp time. Next, we describe in detail how we find such an optimal forwarding path, and propose Algorithm 1.

![Fig. 6 An example of RS(6, 3) repairing D1, using BMFRepair optimization in the first timestamp of PPR](image)

Fig. 6 shows the specific process of our optimization, assuming that each forwarding node can only assist in forwarding once (avoiding network storms caused by reincarnation). The entire forwarding process includes two nodes and a set. The two nodes are the source node $P_1$ and the target node $D_3$, and the idle nodes $P_2$ and $P_3$ form an intermediate set. Our goal is to find a path that takes the shortest time from the source node, passes through the intermediate set and reaches the target node. Among them, the links from the source node to the set and from the set to the target node are unidirectional, and each node in the set is bidirectionally reachable, but it can only pass through each node once. Then the problem is to find a shortest path in a directed weighted graph composed of nodes in the intermediate set. The common algorithms to solve this problem are Floyd algorithm and Dijkstra algorithm, but the complexity of these two algorithms is very high ($O(n^3)$ and $O(nlog2n)$). Here we use to build a tree structure to solve the problem. As shown on the right in Fig. 6, the root of the tree is the source node $P_1$, each leaf node is the target node $D_3$, and the remaining nodes are the nodes in the intermediate set. Each path from the root to the leaf represents a forwarding path and we start from the root and calculate the time spent on each path layer by layer. Although this is a brute force algorithm, we require this path to take at least 5 seconds, so we can reduce the complexity of the algorithm by pruning. For example, when calculating the link $P_1$-$P_3$-$P_2$-$D_3$, since the time taken to reach the node $P_2$ is $(4+5)s=9s$, we do not need to continue traversing. At the same time, we will prove that our algorithm takes a very small proportion of the entire repair time in the following experimental part. So far, we have found an optimized forwarding path $(P_1$-$P_2$-$D_3)$, which takes 4s less than 5s for the PPR in the first time stamp. If the optimized link is no longer the bottleneck of this time stamp, then we continue to find and optimize the link corresponding to the longest transmission time.

**Algorithm 1:** BMFRepair algorithm for single node reconstructions

**Input:** Links={$L_1$, $L_2$, ...} // $L_i$ contain a Source and Des node

**Output:** New Links // Optimize the Links

**Function BMFRepair():**

```
New_Links = Links;

While true: //Optimizing the link takes the longest time
    L = Find_max_time_link(New_Links);
    S, D = L.Source, L.Destination;
    //Idle nodes not participating in repair
    R_idle = Get_idle_node(L);
    //Find the shortest time path
    New_L = Find_min_time_path(S, D, R_idle);
    Update(New_L, New_L);
    If Find_max_time_link(New_Links) == L:
        Break;
```

**Return** New_Links;

Algorithm 1 shows the pseudo-code of BMFRepair algorithm. It should be noted that our algorithm is to generate the corresponding optimized link for the real-time state of the bandwidth within each time stamp. In many previous works, the algorithm is to construct a global optimal path of the current bandwidth during repair, and the repair process will no longer change the repair path. But when the network link bandwidth is constantly changing, this optimization will no longer be guaranteed. However, BMFRepair adopts a local optimal repair in each round of repair, and flexibly adjusts with the change of link bandwidth, so as to achieve the overall optimization. We will prove the advantages of the algorithm in the following experimental part.

**B. Design: Multi-node Scheduling Repair**

Existing techniques mainly focus on recovery from single-node failure. However, recovering multiple nodes is not uncommon in distributed storage system. Storage failure events are not always independent. For example, many storage devices are likely simultaneously failed which were used at the same beginning time and have same lifetime [30]. Network failures can cause multiple servers disconnected and their data unavailable [31], [32]. Thus, the challenge of speeding up multiple-node recovery is also very important.

In the repair of multiple nodes, m-PPR transforms the repair of multiple blocks into repairing one block at a time, but this scheduling strategy cannot realize the parallel repair of nodes. In Section 3, we gave an example of RS(n=6, k=3) to illustrate
Fig. 7 Two scheduling examples of RS \((n=7, k=4)\) code when repairing node 1 and node 2. Fig. 7(a) shows the helper nodes and the linear data transmitted when repairing nodes 1 and 2. Fig. 7(b) shows the repair process of the random scheduling algorithm and the MSRepair algorithm.

Our multi-node scheduling method, but we found that this scheduling algorithm is not optimal under certain circumstances, so a priority scheduling strategy is designed to achieve optimal scheduling. Next, the specific details of the MSRepair algorithm will be explained, and a pseudo code of the algorithm will be given. Finally, we will unify the first two algorithms to achieve the optimal repair of the entire system.

Fig. 7 shows the scheduling diagram of a RS \((n=7, k=4)\) code in repairing node 1 and node 2. In Fig. 7(a), we assume that when repairing node 1, its helper node is \(R_{1}^{\text{repair}} = \{n3, n4, n5, n6\}\). When repairing node 2, its helper node is \(R_{2}^{\text{repair}} = \{n4, n5, n6, n7\}\).

Due to the linear aggregation of RS codes, each node will send the product of its own block and coefficient to the damaged node. At the same time, the aggregation repair of RS codes is logically related, so this aggregation forwarding is directional. The left part of Fig. 7(b) is a random scheduling process, which requires four timestamps to complete the repair of two nodes. But with our MSRepair, it only takes three timestamps.

Here, we define three sets:

\[
\begin{align*}
R_{12}^{\text{repair}} &= R_{1}^{\text{repair}} \cup R_{2}^{\text{repair}} = \{n4, n5, n6\} \\
R_{\text{repair}} &= R_{1}^{\text{repair}} \cup R_{2}^{\text{repair}} = \{n3, n7\}
\end{align*}
\]

where \(RP\) stands for the collection of repair nodes. According to the above definition, we give a forwarding priority: \(\{R, R\} > \{R, NR\} > \{NR, RP\} > \{NR, NR\} > \{R, RP\} > \{NR, R\}\).

**Algorithm 2:** MSRepair algorithm for multi-node reconstructions

**Input:** \(ni\) and \(nj\) //Failed node

**Function MSRepair:**

**Step = { }; //Link within each timestamp**

**//A collection of forwarding nodes within a timestamp**

**Links = { };**

**R, NR = Construct_node_set(ni, nj);**

**RP = {ni, nj};**

**While true:**

**Priority = \{<R,R>, <R,NR>, <NR,RP>, <NR,NR>, <R,RP>, <NR,R>\};**

**//Optimizing the link takes the longest time**

**For Pri in Priority:**

**//Find the forwarding node**

**Links = Find_link(RP, R, NR, Pri);**

**If Links == NULL:**

**Break;**

**//Optimize forwarding link**

**BMFRepair(Links);**

**Step.Add(Links); Links.Clear();**

**Return Step:**

In the scheduling process, we try to make the nodes in the intersection helper node set \(R\) aggregate with each other. The nodes in the intersection helper node set \(R\) are forwarded to the nodes in the non-intersection helper node set \(NR\). We do not expect nodes in the non-intersecting helper node set \(NR\) to be forwarded to the intersection helper node set \(R\). At the same time, when determining the helper nodes needed for multiple repair blocks, make the number of nodes in the non-intersecting
node set $NR$ as large as possible. The priority above decreases from left to right. When scheduling, we always choose a forwarding strategy with high priority as much as possible to ensure the maximum utilization of link bandwidth resources between various nodes. Algorithm 2 gives the pseudo code of this strategy.

**TABLE II**

| Algorithm | m-PPR | Random scheduling | MSRepair |
|-----------|-------|-------------------|----------|
| 1         | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ |
| 2         | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ |
| 3         | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ |
| 4         | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ |
| 5         | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ |
| 6         | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ | $(\cdot, n) \rightarrow a3$ |

Table 2 shows the scheduling steps of m-PPR, random scheduling, and MSRepair when repairing node 1 and node 2 in Fig. 7. It can be found that m-PPR takes up to 6 timestamps. In the first timestamp in random scheduling, since node 3 belongs to $NR$ and node 4 belongs to $R$, this forwarding direction belongs to low priority. This will cause uneven scheduling of subsequent nodes, which will affect the entire repair process, so it takes 4 timestamps. MSRepair only needs 3 timestamps to complete the repair process of two nodes, which is 50% and 33% lower than the previous two methods. And in a heterogeneous environment, we can use the BMFReapir algorithm to optimize the repair process at each timestamp, and our method will not cause link congestion as the link bandwidth changes, because we are based on the local optimal to achieve the global optimal excellent.

**V. PERFORMANCE EVALUATION**

This section will show the experimental results of simulation and real experiments of BMFRepair and MSRepair, mainly the comparison of repair time with PPR. In the experiment, RS codes with parameters $(n, k)$ are mainly used, including: $(4,2)$, $(6,3)$ and $(7,4)$. In the simulation experiment, we configure the size of a node ranging from 8 to 32 MB, and in the real experiment we configure the node size to 128 MB. Since mininet can simulate a complex network environment, it is beneficial for us to better analyze the performance of the algorithm. And the test results of mininet can also match the real environment well, so we adopt two experimental methods to verify the algorithms.

**A. Mininet Simulation**

Mininet [33] is a lightweight software-defined network and test platform. It uses lightweight virtualization technology to make a single system look like a complete network. Run the kernel system and user code you thought about. It can also be simply understood as SDN A kind of network system based on
process virtualization platform, which supports various protocols such as OpenFlow and OpenvSwitch. Our simulation experiment is written in Python, and multiple host nodes and links are created by using the built-in API. In order to reproduce the load and distributed network conditions, the Linux QoS queue is used in the experiment to limit the link bandwidth of each node. And we can change the bandwidth of the link at any time to simulate the dynamic change of the link in the thermal storage system.

The simulation experiment was tested in a Mininet deployed on a single machine (Intel(R) Core(TM) i7-6500U CPU @ 2.50GHz), which used Mininet to build a cluster containing up to 1 switch and 14 hosts. The cluster The connection is made through an OpenFlow Switch managed by an OpenFlow Controller.

![Graph of network transmission in the repair time](image)

**Fig. 8** The proportion of network transmission in the total repair time

Fig. 8 shows the percentage of network transmission in the repair time during the repair process. For each coding strategy, the size of each of our nodes ranges from 8M to 32M. The blue blocks in the figure represent the percentage of time spent on block coding and the execution of our two algorithms in a repair process. Although our BMFRepair algorithm is based on a brute force search, the figure can be found to account for about 3%, so our algorithm will not affect the overall repair performance, and the algorithm can be extended to large networks.

In this part, we compared the single-node recovery performance of BMFRepair over the baseline traditional technique and PPR. At the same time, we compared the multi-node recovery performance of MSRepair over the baseline m-PPR and random scheduling. We run each group of experiments over 20 times.

Fig. 9 shows the recovery time per lost chunk versus the chunk size. It indicates that BMFRepair greatly reduces the recovery time when compared to PPR in RS(6,3) and RS(7,4). For example, when the chunk size is 32MB for RS(7,4), BMFRepair reduces 23.1% of recovery time (see Fig. 9(c)). The time reduction is even higher for a bigger value of n-k and reaches up to 64.9% and 42.1% over traditional technique and PPR, respectively. But in the RS(4,2) repair process, the repair time of PPR algorithm is the same as traditional algorithm, and the repair effect of BMFRepair is not obvious. The reason here is that BMFRepair uses idle node bandwidth to participate in forwarding, thus speeding up the repair time of each time stamp. The RS code has n-k-I idle nodes when a single node is repaired. The more idle nodes there are, the more paths for optimal forwarding. Fig. 10 illustrates the average recovery time by MSRepair compared to the baseline m-PPR and random scheduling for three different parameters of RS code. It’s noticeable that MSRepair significantly reduces recovery time compared the m-PPR by 21.3% for RS (4, 2), 46.5% for RS (6, 3) and 59.7% for RS (7, 4). But in Fig. 10(a), the random scheduling and MSRepair recovery time are similar. Since m is very small, the intersection node set R of repairing each node is basically the same, and the number of nodes in the non-intersection node set NR is close to 0, so the optimization effect of MSRepair is not obvious.

![Graph of time to repair a node](image)

(a) Average recovery time of MBFRepair and PPT in low change bandwidth

![Graph of time to repair a node](image)

(b) Average recovery time of MBFRepair and PPT in high change bandwidth

In order to compare that our method can better adapt to the hot storage system (network bandwidth changes rapidly), we select the current best repair technology PPT for comparison. In the parameter configuration, we choose RS(4, 2) code to compare the repair time of a single node. At the same time, in order to simulate the change of the storage system network link bandwidth in the mininet, we set the parameter change probability in the qos queue during the data transmission process, so that the bandwidth changes at a fixed time. In the cold storage system simulation, we let the bandwidth change
randomly every 5s, while in the hot storage system simulation, the bandwidth changes every 2 seconds.

As can be seen from Fig. 11(a), when the bandwidth changes are not very frequent, the time for PPT and BMFRepair to repair a single block is basically the same when the node size is 8M and 16M. When the node size is 32M, BMFRepair has a lower repair time. And we found that the repair time of PPT fluctuates widely, which is because PPT requires multiple nodes send data to one node. It is very difficult to improve the transmission efficiency in the actual network environment in this way. In Fig. 2, our experiments have proved that this will seriously weaken the bandwidth performance as the number of links increases, so this method is not suitable in a large-scale heterogeneous network environment. In the hot storage environment simulation experiment, as shown in Fig. 11(b), BMFRepair can significantly reduce the repair time, and the fluctuation range is smaller than PPT. When the block size is 32M, compared to PPT, we can reduce the repair time by 25%, and the larger the block size, the more obvious the repair effect. We analyze PPT for two reasons: 1. Sending data from multiple nodes to one node will cause a very heavy load on the receiving node, and it will seriously affect the bandwidth of each link as more links become more (Fig. 2). 2. PPT constructs a global optimal repair tree according to the current link bandwidth before repair. However, the bandwidth of the network link is constantly changing. As the repair time passes, the repair tree may not be in the global optimal state during the repair process. Our method is based on a greedy algorithm that finds the local optimum in each round of repair, which will be adjusted in time according to the change of link bandwidth, so it can stably adapt to the changing bandwidth in the thermal storage system.

From the simulation experiment, we can see that compared with PPR and PPT, BMFRepair and MSRepair can well adapt to the heterogeneous link bandwidth environment, and the bandwidth resources of each node can be fully utilized. At the same time, in a hot storage system where the bandwidth is constantly changing, the repair strategy can be flexibly adjusted according to the bandwidth at each moment, thereby effectively reducing the repair delay.

B. Aliyun ECS Evaluation

To validate that MBFRepair and MSRepair in real-world systems, we further evaluate MBFRepair and MSRepair in Aliyun ECS [34], we consider geo-distributed data centers that span multiple geographic regions. They typically stripe redundancy across regions to protect against large-scale correlated failures.

| TABLE III | LINK BANDWIDTHS (MS) ACROSS REGIONS |
|------------|-----------------------------------|
| From       | Beijing | Zhangjiakou | Shanghai | Shenzhen | Hong Kong | Singapore |
| Beijing    | 99.54   | 99.54       | 99.54    | 99.54    | 99.54     | 99.54     |
| Zhangjiakou| 99.54   | 99.54       | 99.54    | 99.54    | 99.54     | 99.54     |
| Shanghai   | 99.54   | 99.54       | 99.54    | 99.54    | 99.54     | 99.54     |
| Shenzhen   | 99.54   | 99.54       | 99.54    | 99.54    | 99.54     | 99.54     |
| Hong Kong  | 99.54   | 99.54       | 99.54    | 99.54    | 99.54     | 99.54     |
| Singapore  | 99.54   | 99.54       | 99.54    | 99.54    | 99.54     | 99.54     |

Table 3 shows one of our iperf measurement tests for the bandwidths on Aliyun ECS across six regions respectively Beijing, Zhangjiakou, Shanghai, Shenzhen, Hong Kong in China and Singapore in Southeast Asia. We launch instances (virtual machines) in six different continents and each virtual machine is created based on a ecs.sn2ne.large type Ubuntu 16 Intel Xeon E5-2682v4 with 2 vCPU, 1 GB RAM, and 4 GB SSD. At the same time, we found that the upper and lower bandwidths of the two regions are not only different, but the bandwidth difference will also increase when the geographic area spans very large.

Fig. 12 Average repair time for PPR, PPT, and BMFRepair repair of single-node failures with different RS codes on Aliyun ECS machines

![Fig. 12](image)

Fig. 13 Average repair time for m-PPR and MSRepair repair of multi-node failures with different RS codes on Aliyun ECS machines

In real experiments, we set the size of each block to 128M, and use the RS(4,2), (4,3), (6,3), (6,4) settings to verify the repair performance of BMFRepair and MSRepair. Fig. 12 shows the average time to repair a single node on Alibaba Cloud machines. We found that PPT has the longest repair time in the case of RS(4,2) and RS(6,3), while BMFRepair basically maintains an optimal repair performance. The reason for this result is that in a real environment, each machine will run a different load, so the bandwidth obtained by a single node in the PPT accessing multiple links has deviated from the theoretical value. As the link bandwidth in the real environment changes more drastically, its performance is very poor. But BMFRepair is not limited by bandwidth changes, and can
flexibly adjust the repair strategy according to the bandwidth. The larger the value of \( n-k-1 \), the better the effect. In the Aliyun experiments, BMFRepair can reduce the average repair time by an average of 15.9% and up to 23.4% compared to the PPR repair. Compared to PPT, RPR can reduce the average repair time by an average of 19.3% and up to 22.4%. Fig. 13 shows the results, which indicate that, in the multi-node failure case, MSRepair can reduce the average repair time by an average of 20.6% compared to the m-PPR.

VI. CONCLUSION

This paper proposes a BMFRepair and MSRepair algorithm based on erasure code cluster for fast data repair. Through observation, we found that in hot storage, the performance of data repair is often restricted by congested links, and the bandwidth of network links changes very sharply. For this reason, a fast repair algorithm, called BMFRepair, is designed using idle nodes to assist forwarding in a heterogeneous and dynamically changing network environment. At the same time, an effective scheduling algorithm, called MSRepair, is proposed for the problem of multi-node repair to realize the maximum utilization of node bandwidth resources. We conducted experiments on Mininet and Aliyun ECS. The results of the two platforms showed that the algorithm can significantly improve the performance of node repair.

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