

Topology-Aware Cooperative Data Protection in Blockchain-Based Decentralized Storage Networks

Siya Yang¹, Ahmed Hareedy², Robert Calderbank², and Lara Dolecek¹

¹ Electrical and Computer Engineering Department, University of California, Los Angeles, Los Angeles, CA 90095 USA

² Electrical and Computer Engineering Department, Duke University, Durham, NC 27708 USA

siyiyang@ucla.edu, ahmed.hareedy@duke.edu, robert.calderbank@duke.edu, and dolecek@ee.ucla.edu

Abstract—The continuous rise of the blockchain technology is moving various information systems towards decentralization. Blockchain-based decentralized storage networks (DSNs) offer significantly higher privacy and lower costs to customers compared with centralized cloud storage associated with specific vendors. Coding is required to retrieve data stored on failing components. While coding solutions for centralized storage have been intensely studied, those for DSNs have not yet been discussed. In this paper, we propose a coding scheme where each node receives extra protection through cooperation with nodes in its neighborhood in a heterogeneous DSN with any given topology. Our scheme can achieve faster recovery speed compared with existing network coding methods, and can correct more erasure patterns compared with our previous work.

Index Terms—Joint hierarchical coding, cooperative data protection, blockchain technology, decentralized storage networks.

I. INTRODUCTION

Blockchain, a technology supporting the digital currency called bitcoin, has been intensively discussed and regarded as a substantial innovation in cryptosystems [1]–[3]. Blockchain enables recording transactions through a decentralized deployment, which effectively addresses the potential issues of compromised data privacy and key abuse, arising from the existence of a central node that monopolizes all the actions and resource allocations in traditional centralized systems. Decentralization has the potential to universally revolutionize a variety of applications, one of which is cloud storage.

In contrast to traditional centralized storage based on the client-server model, where big companies monopolize renting the storage space to users, blockchain-based decentralized storage networks (DSNs) enable non-enterprise users to not only get access to the network storage space but also to contribute to increasing it via renting their remaining storage space on personal devices. Blockchain-based DSNs allocate the storage space and distribute the encrypted user data with the validation and integrity certification of a third-party, and thus have potential to offer higher privacy, higher reliability, and lower cost than currently available solutions. It has been found that the benefits in data integrity of decentralization are typically at the cost of higher latency and difficult maintenance.

While blockchain technology empowers DSNs to ensure the network-layer security, appropriate error-correction codes (ECC) are needed to further improve the physical-layer reliability. In a coded DSN, data are encoded and stored in nodes, where each node is allowed to communicate with its neighboring nodes. If data in each node are encoded independently, the system will be vulnerable to information leakage, data loss, and data tampering by malicious users. Therefore, enabling joint

the neighborhood cooperatively protect and validate their stored data collectively in the DSN is an essential requirement.

In existing literature on coding for distributed storage [4]–[6], there has been no explicit consideration of random distributions and clustering nature of network nodes. Clustered distributed storage has received attention in recent years in the context of multi-rack storage, where either the sizes of clusters and the capacities of the communication links are considered to be homogeneous [7]–[10], or the network topology has a simple structure [11], [12]. However, DSNs typically have more sophisticated topologies characterized by heterogeneity among capacities of communication links and erasure statistics of nodes due to the random and dynamic nature of practical networks [12]–[16]. Instead of solutions for simplified models, schemes that fit into any topology (referred to as “topology-awareness” later on) are desired to exploit the existing resources, thus achieving lower latency and higher reliability.

To further reduce latency and decoding complexity, we propose to provide each node with multiple ECC capabilities enabled by cooperating with neighboring nodes in a series of nested sets with increasing sizes: we refer to this as **ECC hierarchy** later on in the paper. As the size of the set increases, the associated ECC capability increases. In our method, we consider the case where each node stores encoded messages with local data protection, where the data length and codeword length can be customized by the user at each node.

In this paper, we introduce a topology-aware coding scheme that enables hierarchical cooperative data protection among nodes in a DSN, which is built upon our prior work in [17] in the context of centralized cloud storage and preserves desirable properties like scalability and flexibility. The rest of the paper is organized as follows. In Section II, we introduce the DSN model and necessary preliminaries. In Section III, we define ECC hierarchies as well as their depth, and present a coding scheme with depth 1. In Section IV, we define the notion of compatible cooperation graphs, and propose an explicit construction of hierarchical codes for nodes with their cooperation graph being compatible. Finally, we summarize our results and discuss future directions in Section V.

II. SYSTEM MODEL AND PRELIMINARIES

In this section, we discuss the model and mathematical representation of a DSN, as well as necessary preliminaries. Throughout the remainder of this paper, $[N]$ refers to $\{1, 2, \dots, N\}$. For vectors \mathbf{u} and \mathbf{v} of the same length p , $\mathbf{u} \succ \mathbf{v}$ and $\mathbf{u} \prec \mathbf{v}$ implies $u_i > v_i$ and $u_i < v_i$, for all $i \in [p]$, respectively; $\mathbf{u} \succeq \mathbf{v}$ means “ $\mathbf{u} \succ \mathbf{v}$ or $\mathbf{u} = \mathbf{v}$ ”, and $\mathbf{u} \preceq \mathbf{v}$ means “ $\mathbf{u} \prec \mathbf{v}$ or $\mathbf{u} = \mathbf{v}$ ”.

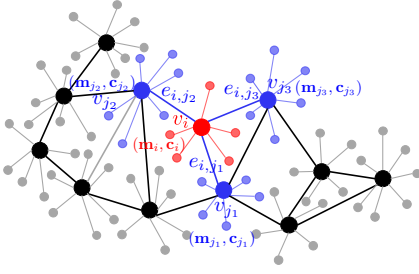


Fig. 1: Decentralized storage network (DSN). For the cluster with the master node v_i , message \mathbf{m}_i is encoded to \mathbf{c}_i and symbols of \mathbf{c}_i are stored distributively among non-master nodes that are locally connected to v_i . In the figures after Fig. 1, we omit the local non-master nodes for clarity of figures.

A. Decentralized Network Storage

As shown in Fig. 1, a DSN is modeled as a graph $G(V, E)$, where V and E denote the set of nodes (master only) and edges, respectively. Codewords are stored among the nodes in a cluster. A failed node in a cluster is regarded as an erased symbol in the codeword stored in this cluster. A cluster is represented in G by its master node $v_i \in V$ solely. Each edge $e_{i,j} \in E$ represents a communication link connecting node v_i and node v_j , through which v_i and v_j are allowed to exchange information. Denote the set of all neighbors of node v_i by \mathcal{N}_i , e.g., $\mathcal{N}_i = \{j_1, j_2, j_3\}$ in Fig. 1, and refer to it as the **neighborhood** of node v_i . Messages $\{\mathbf{m}_i\}_{v_i \in V}$ are jointly encoded as $\{\mathbf{c}_i\}_{v_i \in V}$, and \mathbf{c}_i is stored in v_i . For a DSN denoted by $G(V, E)$, let $p = |V|$. Suppose G is associated with a tuple $(\mathbf{n}, \mathbf{k}, \mathbf{r}) \in (\mathbb{N}^p)^3$, where $\mathbf{k}, \mathbf{r} \succ \mathbf{0}$ and $\mathbf{n} = \mathbf{k} + \mathbf{r}$. Note that k_i represents the length of the message \mathbf{m}_i associated with $v_i \in V$; n_i and r_i denote the length of \mathbf{c}_i stored in v_i and its syndrome, respectively.

B. Preliminaries

Based on the aforementioned notation, a systematic generator matrix of a code for $G(V, E)$ has the following structure:

$$\mathbf{G} = \begin{bmatrix} \mathbf{I}_{k_1} & \mathbf{A}_{1,1} & \mathbf{0} & \mathbf{A}_{1,2} & \dots & \mathbf{0} & \mathbf{A}_{1,p} \\ \mathbf{0} & \mathbf{A}_{2,1} & \mathbf{I}_{k_2} & \mathbf{A}_{2,2} & \dots & \mathbf{0} & \mathbf{A}_{2,p} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{A}_{p,1} & \mathbf{0} & \mathbf{A}_{p,2} & \dots & \mathbf{I}_{k_p} & \mathbf{A}_{p,p} \end{bmatrix}, \quad (1)$$

where all elements are from a Galois field $\text{GF}(q)$, $q = 2^\theta$ and $\theta \geq 2$. The major components of our construction are the so-called Cauchy matrices specified in Definition 1.

Definition 1. (Cauchy matrix) Let $s, t \in \mathbb{N}$ and $\text{GF}(q)$ be a finite field of size q . Suppose $a_1, \dots, a_s, b_1, \dots, b_t$ are $s \times t$ distinct elements in $\text{GF}(q)$. The following matrix is known as a **Cauchy matrix**,

$$\begin{bmatrix} \frac{1}{a_1 - b_1} & \frac{1}{a_1 - b_2} & \dots & \frac{1}{a_1 - b_t} \\ \frac{1}{a_2 - b_1} & \frac{1}{a_2 - b_2} & \dots & \frac{1}{a_2 - b_t} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_s - b_1} & \frac{1}{a_s - b_2} & \dots & \frac{1}{a_s - b_t} \end{bmatrix}.$$

We denote this matrix by $\mathbf{Y}(a_1, \dots, a_s; b_1, \dots, b_t)$.

III. COOPERATIVE DATA PROTECTION

In this section, we first mathematically describe the ECC hierarchy of a DSN, and its depth, which specifies the ECC

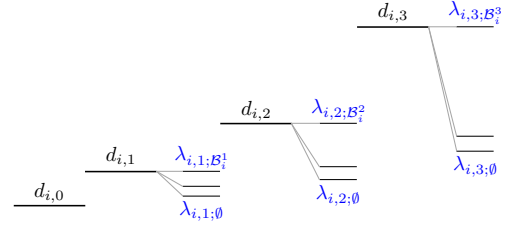


Fig. 2: ECC hierarchy of node $v_i \in V$.

capabilities of nodes while cooperating with different sets of other nodes. We then propose a cooperation scheme where each node only cooperates with its single-hop neighbors.

A. ECC Hierarchy

Denote the **ECC hierarchy** of node $v_i \in V$ by a sequence $\mathbf{d}_i = (d_{i,0}, d_{i,1}, \dots, d_{i,L_i})$, where L_i is called the **depth** of \mathbf{d}_i , and $d_{i,l}$ represents the maximum number of erased symbols v_i can recover in its codeword \mathbf{c}_i from the l -th level cooperation, for all $l \in [L_i]$. The 0-th level cooperation refers to local erasure correction, i.e., the local node v_i recovers its data without communicating with neighboring nodes.

For each $v_i \in V$ such that $L_i > 0$, there exist two series of sets of nodes, denoted by $\emptyset \subset \mathcal{A}_i^1 \subset \mathcal{A}_i^2 \subset \dots \subset \mathcal{A}_i^{L_i} \subseteq V$ and $\{\mathcal{B}_i^l\}_{l=1}^{L_i}$, where $\mathcal{A}_i^l \cap \mathcal{B}_i^l = \emptyset$ for all $l \in [L_i]$, and a sequence $(\lambda_{i,l;\mathcal{W}})_{\emptyset \subseteq \mathcal{W} \subseteq \mathcal{B}_i^l}$. In the l -th level cooperation, node $v_i \in V$ tolerates $\lambda_{i,l;\mathcal{W}}$ ($\emptyset \subseteq \mathcal{W} \subseteq \mathcal{B}_i^l$) erasures if all nodes in $\mathcal{A}_i^l \cup \mathcal{W}$ are able to decode their own messages, where the maximum value is $\lambda_{i,l;\mathcal{B}_i^l} = d_{i,l}$ and is reached when $\mathcal{W} = \mathcal{B}_i^l$; the minimum value is $\lambda_{i,l;\emptyset}$ and is reached when $\mathcal{W} = \emptyset$. See Fig. 2. We first take a look at the cooperation schemes with ECC hierarchy of depth 1.

B. Single-Level Cooperation

We next discuss the case where each node only has cooperation of depth 1. Consider a DSN represented by $G(V, E)$ that is associated with parameters $(\mathbf{n}, \mathbf{k}, \mathbf{r})$ and a class of sets $\{\mathcal{M}_i\}_{v_i \in V}$ such that $\emptyset \subset \mathcal{M}_i \subseteq \mathcal{N}_i$, for all $v_i \in V$. In Construction 1, we present a joint coding scheme where node v_i only cooperates with nodes in \mathcal{M}_i , for all $v_i \in V$. Heterogeneity is obviously achieved since n_i, k_i, r_i , are not required to be identical for all $v_i \in V$.

Construction 1. Let $G(V, E)$ represent a DSN associated with parameters $(\mathbf{n}, \mathbf{k}, \mathbf{r})$ and a local ECC parameter δ , where $\mathbf{r} \succ \delta \succeq \mathbf{0}$. Let $p = |V|$ and $\text{GF}(q)$ be a Galois field of size q , where $q > \max_{v_i \in V} (n_i + \delta_i + \sum_{j \in \mathcal{M}_i} \delta_j)$.

For $i \in [p]$, let $a_{i,x}, b_{i,y}, x \in [k_i + \delta_i]$, and $y \in [r_i + \sum_{j \in \mathcal{M}_i} \delta_j]$ be distinct elements of $\text{GF}(q)$. Consider Cauchy matrix $\mathbf{T}_i \in \text{GF}(q)^{(k_i + \delta_i) \times (r_i + \sum_{j \in \mathcal{M}_i} \delta_j)}$ such that $\mathbf{T}_i = \mathbf{Y}(a_{i,1}, \dots, a_{i,k_i + \delta_i}; b_{i,1}, \dots, b_{i,r_i + \sum_{j \in \mathcal{M}_i} \delta_j})$. Matrix \mathbf{G} in (1) is assembled as follows. For $i \in [p]$, obtain $\{\mathbf{B}_{i,j}\}_{j \in \mathcal{M}_i}, \mathbf{U}_i, \mathbf{A}_{i,i}$, according to the following partition of \mathbf{T}_i ,

$$\mathbf{T}_i = \left[\begin{array}{c|c|c} \mathbf{A}_{i,i} & \mathbf{B}_{i,j_1} & \dots & \mathbf{B}_{i,j_{|\mathcal{M}_i|}} \\ \hline \mathbf{U}_i & & & \mathbf{Z}_i \end{array} \right], \quad (2)$$

where $\mathcal{M}_i = \{j_1, j_2, \dots, j_{|\mathcal{M}_i|}\}$, $\mathbf{A}_{i,i} \in \text{GF}(q)^{k_i \times r_i}, \mathbf{U}_i \in \text{GF}(q)^{\delta_i \times r_i}, \mathbf{B}_{i,j} \in \text{GF}(q)^{k_i \times \delta_j}$ for $v_i \in V$ and $v_j \in \mathcal{M}_i$.

$$(4) \quad \begin{array}{cccccccccccccccc} A_{1,1} & B_{1,2}U_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_{2,1}U_1 & A_{2,2} & B_{2,3}U_3 & 0 & B_{2,5}U_5 & 0 & 0 & B_cV_{8,2} & B_cV_{9,2} & B_dV_{10,3} & B_dV_{11,3} & 0 & 0 & 0 \\ 0 & B_{3,2}U_2 & A_{3,3} & B_{3,4}U_4 & 0 & 0 & 0 & B_eV_{8,2} & B_eV_{9,2} & B_fV_{10,3} & B_fV_{11,3} & 0 & 0 & 0 \\ 0 & 0 & B_{3,3}U_3 & A_{4,4} & B_{4,5}U_5 & B_{4,6}U_6 & 0 & B_gV_{8,2} & B_gV_{9,2} & B_hV_{10,2} & B_gV_{11,2} & 0 & 0 & 0 \\ 0 & B_{5,2}U_2 & 0 & B_{5,4}U_4 & A_{5,5} & B_{5,6}U_6 & 0 & B_{5,8}U_8 & 0 & B_hV_{10,2} & 0 & 0 & B_hV_{12,2} & 0 \\ 0 & 0 & 0 & B_{6,4}U_4 & B_{6,5}U_5 & A_{6,6} & B_{6,7}U_7 & B_iV_{8,2} & B_iV_{9,2} & B_jV_{10,2} & 0 & B_jV_{12,2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & B_{7,6}U_6 & A_{7,7} & B_{7,8}U_8 & B_{7,9}U_9 & B_jV_{10,2} & B_{7,11}U_{11} & B_lV_{12,2} & 0 & 0 \\ 0 & B_mV_{2,2} & B_nV_{3,2} & B_oV_{4,2} & B_{8,5}U_5 & B_pV_{6,2} & B_{8,7}U_7 & A_{8,8} & B_{8,9}U_9 & B_kV_{10,2} & B_nV_{11,2} & 0 & 0 & 0 \\ 0 & B_qV_{2,2} & B_rV_{3,2} & B_sV_{4,2} & 0 & B_tV_{6,2} & B_{9,7}U_7 & B_{9,8}U_8 & A_{9,9} & B_{9,10}U_{10} & B_pV_{11,2} & B_pV_{12,2} & 0 & 0 \\ 0 & B_rV_{2,3} & B_rV_{3,3} & B_rV_{4,2} & 0 & B_rV_{6,3} & B_sV_{7,3} & B_sV_{8,3} & B_{10,9}U_9 & A_{10,10} & B_{10,11}U_{11} & B_{10,12}U_{12} & 0 & 0 \\ 0 & B_zV_{2,3} & B_zV_{3,3} & B_tV_{4,2} & B_uV_{5,2} & 0 & B_{11,7}U_7 & B_uV_{8,3} & B_wV_{9,3} & B_{11,10}U_{10} & A_{11,11} & B_{11,12}U_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & B_vV_{5,2} & B_vV_{6,3} & B_wV_{7,3} & 0 & B_wV_{9,3} & B_{12,10}U_{10} & B_{12,11}U_{11} & A_{12,12} & 0 & 0 \end{array}$$

originally flow through edges marked in blue no longer exist.

IV. MULTI-LEVEL COOPERATION

In this section, we extend the construction presented in Section III-B to codes with ECC hierarchies of depth larger than 1. We first define the so-called **cooperation graphs** that describe how the nodes are coupled to cooperatively transmit information, and then prove the existence of hierarchical codes over a special class of cooperation graphs: the so-called **compatible graphs**.

A. Cooperation Graphs

Based on the aforementioned notation, for each $v_i \in V$ and $l \in [L_i]$, let $\mathcal{I}_i^l = \mathcal{A}_i^l \setminus \mathcal{A}_i^{l-1}$ and refer to it as the l -th **helper** of v_i . We next define the so-called **cooperation matrix**.

Definition 2. For a joint coding scheme \mathcal{C} for a DSN represented by $G(V, E)$ with $|V| = p$, the matrix $\mathbf{D} \in \mathbb{N}^{p \times p}$, in which $\mathbf{D}_{i,j}$ equals to l for all $i, j \in [p]$ such that $j \in \mathcal{I}_i^l$, and zero otherwise, is called the **cooperation matrix**.

As an example, the cooperation matrix in Example 1 is exactly the adjacency matrix of the graph in Fig. 3. Note that not every matrix is a cooperation matrix of a set of joint coding schemes. In Section IV-B, we prove the existence of codes if the cooperation matrix represents a so-called **compatible graph**. Before going into details of the construction, we look at an example to obtain some intuition.

Example 4. Recall the DSN in Example 1. We present a coding scheme with the cooperation matrix specified in the left part of Fig. 5. The non-systematic part of the generator matrix is shown in (4), which is obtained through the following process:

- 1) Partition all the non-zero-non-one elements into structured groups, each of which is marked by either a rectangle or a hexagon in \mathbf{D} , as indicated in the left part of Fig. 5;
- 2) Replace the endpoints of each horizontal line segment in Step 1 with $s \in S$ (S is a set of symbols), as indicated in the right part of Fig. 5; denote the new matrix by \mathbf{X} ;
- 3) Assign a parameter $\gamma_s \in \mathbb{N}$ to each $s \in S$, and a matrix $\mathbf{B}'_s \in \text{GF}^{k_i \times \gamma_s}$ to any (i, j) such that $\mathbf{X}_{i,j} = s$;
- 4) For each $i \in [p]$, $l \in [L]$, let $\eta_{i,l} = \max_{s: k_i \in \mathcal{I}_l^s} \mathbf{X}_{k_i, l} \gamma_s$, assign $\mathbf{V}_{i,l} \in \text{GF}(q)^{\eta_{i,l} \times r_i}$ to $v_{i,l}$; let $\mathbf{B}_s = [\mathbf{B}'_s, \mathbf{0}_{\eta_{i,l} - \gamma_s}]$; assign $\mathbf{A}_{i,j} = \mathbf{B}_s \mathbf{V}_{j,l}$ for $s = \mathbf{X}_{i,j}$, $l = \mathbf{D}_{i,j}$.
- 5) Assign $\mathbf{A}_{i,j}$ for $\mathbf{X}_{i,j} = 1$ according to Construction 1.

Let us again focus on node v_2 . Let $\mathcal{I}_2^1 = \{v_1, v_3, v_5\}$, $\mathcal{I}_2^2 = \{v_8, v_9\}$, $\mathcal{I}_2^3 = \{v_{10}, v_{11}\}$. Then, $\mathcal{B}_2^1 = \{v_4, v_6, v_8\}$, $\mathcal{B}_2^2 = \{v_4, v_6\}$, $\mathcal{B}_2^3 = \emptyset$, $d_{2,0} = r_2 - \delta_2 - \eta_{i;2} - \eta_{i;3}$, $d_{2,1} = d_{2,0} + \delta_2 + \delta_1 + \delta_3 + \delta_5$, $d_{2,2} = d_{2,1} + \gamma_c$, $d_{2,3} = d_{2,2} + \gamma_d$.

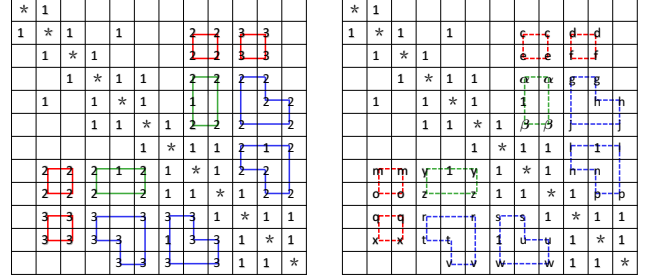


Fig. 5: Matrices \mathbf{D} (left) and \mathbf{X} (right) in Example 4.

We first show that knowing $\{\mathbf{m}_j\}_{v_j \in \mathcal{A}_2^1}$ is sufficient for removing $\mathbf{s}_2 = \sum_{j \in \mathcal{I}_2^1} \mathbf{m}_j \mathbf{B}_{j,2} \mathbf{U}_2 + \sum_{l=2}^3 \sum_{j \in \mathcal{I}_2^l} \mathbf{m}_j \mathbf{B}_{\mathbf{x}_{j,2}} \mathbf{V}_{2;l}$ from the parity part of \mathbf{c}_2 . Note that if $\mathbf{A}_{i,i}$, \mathbf{U}_i and $\{\mathbf{V}_{i,l}\}_{l \in \{2,3\}}$ are linearly independent, then for all l , $\sum_{j \in \mathcal{I}_i^l} \mathbf{m}_j \mathbf{B}_{\mathbf{x}_{j,i}}$ is recoverable if \mathbf{m}_i is recoverable. In our example, this means that $\{\mathbf{m}_j \mathbf{U}_{j,2}\}_{j=1,3,5}$, $\mathbf{m}_8 \mathbf{B}_m + \mathbf{m}_9 \mathbf{B}_o$, $\mathbf{m}_{10} \mathbf{B}_o + \mathbf{m}_{11} \mathbf{B}_x$ are known: the sum of them is exactly \mathbf{s}_2 . Therefore, \mathbf{s}_2 is removed through the 1-st level cooperation. We next show that additional parities are obtained through l -th level cooperations with $l = 2, 3$.

In the 2-nd level cooperation, $\mathbf{m}_8, \mathbf{m}_9$ are known. Therefore, $\mathbf{m}_2\mathbf{B}_c + \mathbf{m}_3\mathbf{B}_e + \mathbf{m}_4\mathbf{B}_\alpha + \mathbf{m}_6\mathbf{B}_\beta$ is also known. We remove $\mathbf{m}_3\mathbf{B}_e$ that is obtained via v_3 . In order to obtain the γ_c parities from $\mathbf{m}_2\mathbf{B}_c$, one needs $\mathbf{m}_4, \mathbf{m}_6$ to be recoverable. Therefore, $\mathcal{B}_2^2 = \{v_4, v_6\}$, $d_{2,2} = d_{2,1} + \gamma_c$, $\lambda_{2,2;\varnothing} = d_{2,1}$.

As shown in the first step in Example 4, the cooperation matrix adopts a partition of non-zero-non-one elements into groups where each of them forms a cycle. Suppose there are T cycles. Represent each cycle with index $t \in [T]$ by a tuple $(X_t, Y_t, \{X_{t;j}\}_{j \in Y_t}, \{Y_{t;i}\}_{i \in X_t}, l_t)$, where X_t, Y_t denote the indices of the rows and the columns of the cycle, respectively; l_t denotes the number assigned to the vertices of the cycle; $X_{t;j} = \{i_1, i_2\}$ for $j \in Y_t$ and $(i_1, j), (i_2, j)$ are the vertices of cycle t ; $Y_{t;i} = \{j_1, j_2\}$ for $i \in X_t$ and $(i, j_1), (i, j_2)$ are the vertices of cycle t . For example, let $t = 1$ for the blue cycle at the bottom left part of the matrices in Fig. 5. Then, it is represented by $(\{10, 11, 12\}, \{4, 5, 6\}, \{X_{1;j}\}_{j \in \{4,5,6\}}, \{Y_{1;i}\}_{i \in \{10,11,12\}}, 3)$, where $X_{1;4} = \{10, 11\}$, $X_{1;5} = \{11, 12\}$, $X_{1;6} = \{10, 12\}$, $Y_{1;10} = \{4, 6\}$, $Y_{1;11} = \{4, 5\}$, $Y_{1;12} = \{5, 6\}$.

Observe that cycle $t \in [T]$ in Fig. 5 essentially represents a pair of disconnected edges or triangles with vertices from X_t and Y_t . We mark X_t, Y_t , draw a directed edge with label l from X_t to Y_t for each $t \in [T]$, and obtain the so-called **cooperation graph**. The cooperation graph for the coding scheme in Example 4 is shown in Fig. 6.

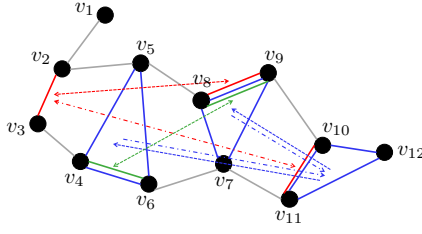


Fig. 6: Cooperation graph of Example 4.

B. Construction Over Compatible Graphs

We have defined the notion of cooperation graphs in Section IV-A. Observe that the cooperation graph shown in Fig. 6 satisfies a set of conditions that define the so-called **compatible graph**. We show in Theorem 2 the existence of a hierarchical coding scheme with cooperation graph \mathcal{G} if \mathcal{G} is a compatible graph. The coding scheme is presented in Construction 2.

Definition 3. Let \mathcal{G} be a cooperation graph on $G(V, E)$ that is represented by $\{(X_t, Y_t, \{X_{t,j}\}_{j \in Y_t}, \{Y_{t,i}\}_{i \in X_t}, l_t)\}_{t \in [T]}$, and let the 1-st level cooperation graph be \mathcal{G}_1 . Let \mathcal{M}_i denote the set of nodes that have an outgoing edge pointing at v_i in \mathcal{G}_1 . For each $v_i \in V$, $l \in [L_i]$, let $R_{i,l} = \{t : i \in Y_t, t \in [T], l_t = l\}$, $R_i = \bigcup_{l \in [L_i]} R_{i,l}$, $T_{i,l} = \{t : j \in R_{i,l} \cap Y_{t,i}, t \in [T]\}$, and $V_{i,l} = \bigcup_{t \in R_{i,l}} Y_t$. We call \mathcal{G} a **compatible graph** on G if the following conditions are satisfied:

- 1) For each $v_i \in V$, sets in $\{Y_t\}_{t \in R_i}$ are disjoint;
- 2) For each $v_i \in V$, $l \in [L_i]$, and any node v_j such that $j \in V_{i,l} \setminus \{v_i\}$, $V_{j,l} \subseteq \mathcal{M}_i$.

Construction 2. Let $G(V, E)$ represent a DSN with parameters (n, k, r) . Suppose \mathcal{G} is a compatible graph of depth L on G , with parameters $\{(X_t, Y_t, \{X_{t,j}\}_{j \in Y_t}, \{Y_{t,i}\}_{i \in X_t}, l_t)\}_{t \in [T]}$, and the 1-st level cooperation graph is denoted by \mathcal{G}_1 (other necessary parameters are as they are in Definition 3).

Let δ be the 1-st level cooperation parameter. For each $v_i \in V$, $1 \leq l \leq L_i$, and any $t \in T_{i,l}$, assign cooperation parameter $\gamma_{i,t}$ to C_t ; let $\eta_{j,l} = \max_{t \in R_{j,l}, i \in X_{t,j}} \gamma_{i,t}$.

Let $u_i = k_i + \delta_i + \sum_{l=2}^{L_i} \eta_{i,l}$, $v_i = r_i + \sum_{j \in \mathcal{M}_i} \delta_j + \sum_{2 \leq l \leq L_i, t \in T_{i,l}} \gamma_{i,t}$, for $i \in [p]$. For each $i \in [p]$, let $a_{i,s}$, $b_{i,t}$, $s \in [u_i]$ and $t \in [v_i]$ be distinct elements of $\text{GF}(q)$, where $q \geq \max_{i \in [p]} \{u_i + v_i\}$. Matrix \mathbf{G} in (1) is assembled as follows. Consider the Cauchy matrix \mathbf{T}_i on $\text{GF}(q)^{u_i \times v_i}$ such that $\mathbf{T}_i = \mathbf{Y}(a_{i,1}, \dots, a_{i,u_i}; b_{i,1}, \dots, b_{i,v_i})$, for $i \in [p]$. Then, we obtain $\mathbf{A}_{i,i}$, $\mathbf{B}_{i,j}$, $\mathbf{E}_{i,l}$, \mathbf{U}_i , $\mathbf{V}_{i,l}$, for $i \in [p]$, $j \in [p] \setminus \{i\}$, according to the following partition of \mathbf{T}_i ,

$$\mathbf{T}_i = \left[\begin{array}{c|c|c|c|c} \mathbf{A}_{i,i} & \mathbf{B}_i & \mathbf{E}_{i,2} & \dots & \mathbf{E}_{i,L_i} \\ \hline \mathbf{U}_i & & & & \\ \hline \mathbf{V}_{i,2} & & & & \\ \hline \vdots & & & & \\ \hline \mathbf{V}_{i,L_i} & & & & \end{array} \right] \mathbf{Z}_i, \quad (5)$$

$$\text{where } \mathbf{B}_i = [\mathbf{B}_{i,j_1} \mid \dots \mid \mathbf{B}_{i,j_{|\mathcal{M}_i|}}], \quad (6)$$

$$\text{and } \mathbf{E}_{i,l} = [\mathbf{E}_{i,l;t_1} \mid \dots \mid \mathbf{E}_{i,l;t_{|T_{i,l}|}}], \quad (7)$$

such that $\mathcal{M}_i = \{j_1, j_2, \dots, j_{|\mathcal{M}_i|}\}$, $T_{i,l} = \{t_1, t_2, \dots, t_{|T_{i,l}|}\}$, $\mathbf{A}_{i,i} \in \text{GF}(q)^{k_i \times r_i}$, $\mathbf{U}_i \in \text{GF}(q)^{\delta_i \times r_i}$, $\mathbf{V}_{i,l} \in \text{GF}(q)^{\eta_{i,l} \times r_i}$, $\mathbf{B}_{i,j} \in \text{GF}(q)^{k_i \times \delta_j}$ for all $v_j \in \mathcal{M}_i^1$, and $\mathbf{E}_{i,l;t} \in \text{GF}(q)^{k_i \times \gamma_{i,t}}$.

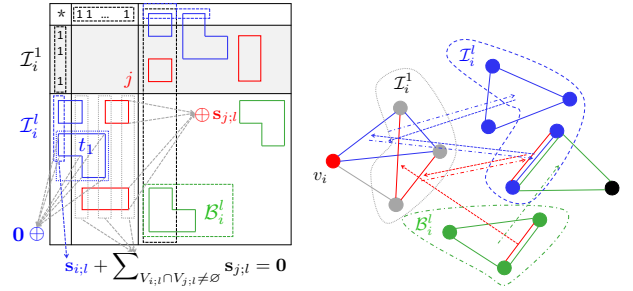


Fig. 7: Proof of Theorem 2.

Let $\mathbf{B}_{i,j} = [\mathbf{E}_{i,l;t}, \mathbf{0}_{k_i \times (\eta_{j,l} - \gamma_{i,t})}]$, and $\mathbf{A}_{i,j} = \mathbf{B}_{i,j} \mathbf{V}_{j,l}$, for all $j \in Y_{t,i}$, $t \in T_{i,l}$; let $\mathbf{A}_{i,j} = \mathbf{B}_{i,j} \mathbf{U}_j$ for $v_j \in \mathcal{M}_i$; otherwise $\mathbf{A}_{i,j} = \mathbf{0}_{k_i \times r_i}$. Substitute components of \mathbf{G} in (1) correspondingly. Let \mathcal{C}_2 represent the code with generator matrix \mathbf{G} .

Theorem 2. The code \mathcal{C}_2 has ECC hierarchies $\mathbf{d}_i = (d_{i,0}, d_{i,1}, \dots, d_{i,L_i})$, for all $v_i \in V$, where $d_{i,0} = r_i - \delta_i - \sum_{l=2}^{L_i} \eta_{i,l}$, $d_{i,1} = r_i + \sum_{j \in \mathcal{M}_i} \delta_j$, and $d_{i,l} = r_i + \sum_{j \in \mathcal{M}_i} \delta_j + \sum_{2 \leq l' \leq l, t \in T_{i,l'}} \gamma_{i,t}$. Moreover, $\mathcal{I}_i^1 = \mathcal{M}_i$, $\mathcal{B}_i^1 = \bigcup_{v_j \in \mathcal{M}_i} (\mathcal{M}_j \setminus (\{v_i\} \cup \mathcal{M}_i))$; for $2 \leq l \leq L_i$, $\mathcal{I}_i^l = \bigcup_{t \in R_{i,l}} X_{t,i}$, $\mathcal{B}_i^l = \bigcup_{t \in T_{i,l}, j \in Y_{t,i}} (\mathcal{I}_j^l \setminus (\{v_i\} \cup \mathcal{A}_i^l))$ (recall $\mathcal{A}_i^l = \bigcup_{l' \leq l} \mathcal{I}_i^{l'}$), $\lambda_{i,l;W} = r_i + \sum_{v_j \in \mathcal{M}_i, (\mathcal{M}_j \setminus \{v_i\}) \subseteq (\mathcal{M}_i \cup W)} \delta_j + \sum_{2 < l' \leq l, t \in T_{i,l'}, Y_{t,i} = \{j, j'\}, \gamma_{i,t}, \text{ for } \emptyset \subseteq W \subseteq \mathcal{B}_i^l$. $\mathcal{I}_j^l \setminus \mathcal{A}_i^l \subseteq (\{v_i\} \cup W)$ or $\mathcal{I}_j^l \setminus \mathcal{A}_i^l \subseteq \{v_i\} \cup W$

Proof. We briefly introduce the main idea of proving that for $v_i \in V$, the cross parities due to cooperation with nodes in \mathcal{I}_i^l , $2 \leq l \leq L_i$, can be computed if $\{\mathbf{m}_j\}_{j \in \mathcal{I}_i^1}$ are recovered. The ECC hierarchies of level 1 has been discussed in Theorem 1, and we have shown that for the 2-nd level in Example 4 to develop the intuition. The complete proof is in [18].

Fig. 7 shows a subgraph of the cooperation graph of \mathcal{C}_2 containing v_i , \mathcal{I}_i^1 , \mathcal{I}_i^l only (right), and its corresponding cycle representations in the cooperation matrix (left). Condition 1 in Definition 3 implies that the cycles are all disjoint; Condition 2 implies that all the cycles (marked in red) containing an edge in column $j \in V_{i,l}$ are contained within the columns representing \mathcal{I}_i^1 . Using the fact that the sum of the cross parities on the vertices of each cycle is $\mathbf{0}$, we can prove that the sum (denoted by $\mathbf{s}_{i,l}$) of the l -level cross parities of node v_i can be computed by $\mathbf{s}_{i,l} = \sum_{V_{i,l} \cap V_{j,l} \neq \emptyset} \mathbf{s}_{j,l}$. ■

V. CONCLUSION

While codes with hierarchical localities have been intensely discussed in the context of centralized networks, those of DSNs (no prespecified topology) have not been explored. In this paper, we presented a topology-aware cooperative data protection scheme for DSNs, which extends and subsumes our previous work for centralized storage. Our scheme can achieve faster recovery speed compared with existing network coding methods, and can correct more erasure patterns compared with our previous work.

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REFERENCES

- [1] S. Nakamoto, "Bitcoin: A peer-to-peer electronic cash system," Manubot, Tech. Rep., 2019.
- [2] M. Crosby, P. Pattanayak, S. Verma, V. Kalyanaraman *et al.*, "Blockchain technology: Beyond bitcoin," *Applied Innovation*, vol. 2, no. 6-10, p. 71, 2016.
- [3] V. Bagaria, S. Kannan, D. Tse, G. Fanti, and P. Viswanath, "Deconstructing the blockchain to approach physical limits," 2018. [Online]. Available: <https://arxiv.org/abs/1810.08092>
- [4] A. G. Dimakis, P. B. Godfrey, Y. Wu, M. J. Wainwright, and K. Ramchandran, "Network coding for distributed storage systems," *IEEE Trans. Inf. Theory*, vol. 56, no. 9, pp. 4539–4551, Sept 2010.
- [5] Z. Kong, S. A. Aly, and E. Soljanin, "Decentralized coding algorithms for distributed storage in wireless sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 28, no. 2, pp. 261–267, 2010.
- [6] M. Ye and A. Barg, "Cooperative repair: Constructions of optimal mds codes for all admissible parameters," *IEEE Transactions on Information Theory*, vol. 65, no. 3, pp. 1639–1656, 2018.
- [7] A. Tebbi, T. H. Chan, and C. W. Sung, "Multi-rack distributed data storage networks," *IEEE Transactions on Information Theory*, vol. 65, no. 10, pp. 6072–6088, 2019.
- [8] H. Hou, P. P. Lee, K. W. Shum, and Y. Hu, "Rack-aware regenerating codes for data centers," *IEEE Transactions on Information Theory*, 2019.
- [9] Z. Chen and A. Barg, "Explicit constructions of msr codes for clustered distributed storage: The rack-aware storage model," 2019. [Online]. Available: <https://arxiv.org/abs/1901.04419>
- [10] N. Prakash, V. Abdrashitov, and M. Médard, "The storage versus repair-bandwidth trade-off for clustered storage systems," *IEEE Transactions on Information Theory*, vol. 64, no. 8, pp. 5783–5805, 2018.
- [11] J. Li, S. Yang, X. Wang, and B. Li, "Tree-structured data regeneration in distributed storage systems with regenerating codes," in *2010 Proceedings IEEE INFOCOM*. IEEE, 2010, pp. 1–9.
- [12] J. Pernas, C. Yuen, B. Gastón, and J. Pujol, "Non-homogeneous two-rack model for distributed storage systems," in *2013 IEEE International Symposium on Information Theory*. IEEE, 2013, pp. 1237–1241.
- [13] Y. Wang, D. Wei, X. Yin, and X. Wang, "Heterogeneity-aware data regeneration in distributed storage systems," in *IEEE INFOCOM 2014-IEEE Conference on Computer Communications*. IEEE, 2014, pp. 1878–1886.
- [14] A. M. Ibrahim, A. A. Zewail, and A. Yener, "Green distributed storage using energy harvesting nodes," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 5, pp. 1590–1603, 2016.
- [15] M. Sipos, J. Gahm, N. Venkat, and D. Oran, "Network-aware feasible repairs for erasure-coded storage," *IEEE/ACM Transactions on Networking*, vol. 26, no. 3, pp. 1404–1417, 2018.
- [16] —, "Erasure coded storage on a changing network: The untold story," in *2016 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2016, pp. 1–6.
- [17] S. Yang, A. Hareedy, R. Calderbank, and L. Dolecek, "Hierarchical coding to enable scalability and flexibility in heterogeneous cloud storage," in *IEEE Global Communications Conference (GLOBECOM)*, 2019. [Online]. Available: <https://arxiv.org/abs/1905.02279>
- [18] —, "Topology-aware cooperative data protection in blockchain-based decentralized storage networks," 2020. [Online]. Available: <https://arxiv.org/abs/2001.04526>
- [19] Y. Zhu, C. Lv, Z. Zeng, J. Wang, and B. Pei, "Blockchain-based decentralized storage scheme," in *Journal of Physics: Conference Series*, vol. 1237, no. 4. IOP Publishing, 2019, p. 042008.
- [20] S. Underwood, "Blockchain beyond bitcoin," 2016.