Best Effort Broadcast under Cascading Failures in Interdependent Networks

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ABSTRACT

We present a novel study of reliable broadcast in interdependent networks, in which the failures in one network may cascade to another network. In particular, we focus on the interdependency between the communication network and the power grid network, where the power grid depends on the communication network for control and the communication network depends on the grid for power. In this paper, we propose a best effort broadcast algorithm to handle crash failures in the communication network that may cause cascading failures, where all the correct nodes deliver the message if the sender is correct. At the core of our work is a fully distributed algorithm for the nodes to analyze cascading failures prior to their presence so that failures can be handled accordingly. Our evaluation results show that the algorithm handles cascading failures with little overhead.

CCS Concepts

•**Networks** → **Network protocol design;** *Routing protocols;* Network simulations; •**Computing methodologies** → **Simulation evaluation;** *Self-organization;*

Keywords

Interdependent networks, best effort reliable broadcast, cascading failures, crash failures, soft links

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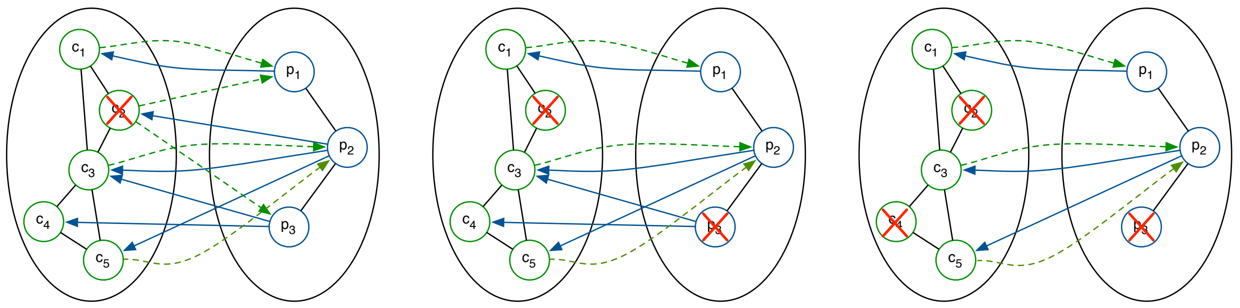
1. INTRODUCTION

Modern network services are becoming increasingly dependent on infrastructure networks such that a single failure may cascade to another network and cause the failures of all the dependent networks. Such failures may cascade multiple times in a zigzag manner between the networks and cause widespread failures. A particular example is the interdependency between the power grid and the communication network. The 2003 Italian blackout [15], 2003 U.S. Northeastern power outage [1, 6], and 2011 Southwest blackout [2] are all examples of such interdependency. For instance, during the 2003 U.S. Northeastern power outage, 3,175 communication networks suffered from abnormal connectivity outage [6]. A number of previous efforts focus on the analysis of the robustness of interdependent networks. To the best of our knowledge, none of the previous work formalized the problem between the communication network and other interdependent networks and studied resilient solutions to handle such failures.

We study reliable broadcast in a multihop communication network *c-network* and a power grid network *p-network*, which are mutually dependent. The c-network is composed of a set of *c-nodes* (e.g., routers, sensors, etc.) connected by communication links and the p-network is composed of a set of *p-nodes* (e.g., power substations) connected by power lines. In order for the nodes to operate, a c-node must receive power from at least one p-node and a p-node must receive control signals from at least one c-node. We model the interdependency using graphs. As illustrated in Figure 1, when c_2 fails, it cannot provide control signals to p_1 and p_3. Node p_1 can still operate since c_1 has an edge to it. However, p_3 fails and it cannot provide power to c_3 and c_4. Node c_3 still operates with power from p_2. Since no other p-nodes have edges to c_4, c_4 fails. In the communication network, a c-node sends a message through certain paths to some c-nodes. C-nodes are subject to crash failures, which can be reliably detected by other c-nodes. In comparison, correct nodes faithfully follow the protocols. Our goal is to design a solution that guarantees best effort broadcast despite the presence of crashing c-nodes, where all the correct nodes deliver the messages if the sender is correct.

We use soft links to handle cascading failures, which are backup links that are activated to handle the failures of primary communication links. The idea of soft links is not new. Specifically, in an independent network, in order to handle the failure of a neighbor, a node c_i only needs to maintain a soft link to the neighbor of its neighbor so that messages can still be sent along the path. However, in interdependent net-



(a) Node c_2 fails. It cannot provide control signals to p_1 and p_3.
(b) Node c_1 has a link to p_1 and p_1 operates. Node p_3 fails.
(c) Node p_2 has a link to c_3 and c_3 operates. Node c_4 fails.

Figure 1: Cascade of a single failure in the interdependent model between a c-network of 5 c-nodes and a p-network of 3 p-nodes.

works, since failures occur in a widespread cascading fashion, it is possible that the neighbor of $c_i's$ neighbor also fails. In fact, it is extremely challenging to determine how many soft links are enough to handle even one single failure without knowing all the cascading effect. Indeed, without a carefully designed algorithm, nodes cannot analyze the cascading failures to handle them. A straightforward solution is to rely on a powerful and centralized computing agent/node to analyze the failures for each node. However, it will cause large communication and computing overhead for the agent since each node must communicate with the centralized agent to learn the result and maintain soft links. Although it might be possible to build a set of distributed agents, it can still cause high communication and maintenance overhead.

We present a best effort broadcast algorithm where nodes analyze cascading failures and maintain the information in a fully distributed manner. At the core of our approach are two key sub-algorithms: *f-information collection* and *link management*. The *f-information collection* is a communication algorithm for the c-nodes to analyze and collect the information of all the cascading failures caused by a single c-node. Based on the f-information of each neighbor, a c-node can learn the next correct c-node in each path so as to maintain soft links. On the other hand, the *link management* is a mechanism for the nodes to update their routing tables in the presence of failures so that nodes can manage their soft links for long term robustness. As a result, soft links can be correctly maintained and best effort broadcast can be guaranteed if there are no failures during message transmission in the algorithm.

Due to the use of the above approach, best effort broadcast is achieved with the following benefits. First, nodes only need to maintain minimum information in order to analyze the failures. Indeed, since we use a distributed failure analysis algorithm, nodes do not need to maintain the whole network. Second, the information of cascading failures is collected in a fully distributed manner. Last but not least, our algorithm enables very effective usage of soft links. In order to handle one c-node failure, each c-node maintains only one soft link although a set of consecutive c-nodes may fail as a cascading effect. This guarantees that messages can be reliably broadcast to every correct c-node in the communication network. Our evaluation results show that our algorithm achieves low packet drop rate and generates little overhead to the normal network traffic. The tradeoff is a slightly longer delay in handling failures.

Our paper makes the following contributions:

- We present the first reliable broadcast model in the interdependent networks. We study best effort broadcast in the presence of crash failures in the communication network, which may cause cascading failures in both power grid network and communication network.
- We present a fully distributed algorithm for the nodes to analyze the cascading failures. Each node maintains minimum information for the dependent network.
- We use inactive soft links in addition to the primary links in the communication network to achieve best effort broadcast. In order to handle one failure, each c-node only maintains one soft link although multiple cascading failures may occur due to a single failure.
- Our evaluation results show that our algorithm achieves low packet drop rate and generates little overhead to the normal network traffic. The tradeoff is a slightly longer delay in handling failures.

2. RELATED WORK

Modeling interdependencies between critical infrastructure networks is challenging due to a wide range of dimensions such as the type of coupling and type of failures [22, 23]. Previous studies of interdependent network systems focus mainly on the analysis of robustness [3, 12–14, 20, 21, 26]. A number of work study the interdependency between communication network and power grid, most of which focus on finding the vulnerabilities of existing network [21] or the design of a robust topology [13]. In comparison, we study a resilient solution that handles the failures in communication network in the interdependency model.

Reliable broadcast [4] has been widely studied that includes several categories such as regular reliable broadcast and uniform broadcast. We study best effort broadcast, where all the correct nodes deliver the message if the sender is correct. In terms of failures, previous studies tolerate both crash failures [18, 24] and Byzantine (arbitrary) failures [4] in both highly connected network [10, 18] and loosely connected network [7, 19]. We study crash failures in the communication network in the model of interdependent networks.

Reliable broadcast of multipath message forwarding has also been studied in publish/subscribe systems [16, 17]. The use of soft links has been proposed [17] to handle failures during message forwarding. Each node maintains several soft links that can be activated in the presence of failures. We use similar idea of soft links to handle failures.

Failure detectors were proposed previously to detect faulty behaviors [5, 8]. Chandra and Toueg [5] introduced the notion of unreliable failures detectors, where each failure detector outputs the identity of processes suspected to have crashed and nodes can rely on it for message transmission. We also use failure detectors for c-nodes to detect crashing c-nodes in their routing tables.

3. INTERDEPENDENCY MODEL

We study the interdependency between two networks: the power grid network *p-network* and the communication network *c-network*. The power grid consists of a set of n *p-nodes* $p_1, p_2, \cdots, p_n$ (e.g. substations). The communication network consists of a set of m *c-nodes* $c_1, c_2, \cdots, c_m$ (e.g., routers, sensors, etc.). The p-nodes are connected with power lines and the c-nodes are connected with communication links. Each c-node constantly receives power from the p-nodes and every p-node constantly receives control signals from the c-nodes. We follow a model similar to the one used in previous work [9, 13, 21], where a p-node *operates* if it receives control signals from at least one c-node and a c-node *operates* if it receives power from at least one p-node. We assume c-nodes do not have backup battery, i.e., a c-node immediately fails if it does not receive power from any p-nodes. In addition, we assume that power substations are connected to power generators, i.e., each power substation is connected to a generator that is sufficient for receiving power and we ignore the amount of power supply or demand. In other words, p-nodes can only fail when there are no incoming control signals.

Notation	Meaning
V_c	all the c-nodes
V_p	all the p-nodes
E_c	bidirectional edges between c-nodes
E_p	bidirectional edges between p-nodes
E_{cp}	directional edges from c-nodes to p-nodes
E_{pc}	directional edges from p-nodes to c-nodes
$E_{cp}\&E_{pc}$	interdependency edges
oin degree	number of outgoing interdependency edges
iin degree	number of incoming interdependency edges
$P(\overrightarrow{c_i})$	all the p-neighbors of c_i
$P(\overleftarrow{c_i})$	all the p-nodes that have interdependency edges to c_i
$C(\overrightarrow{p_i})$	all the c-neighbors of p_i
$C(\overleftarrow{p_i})$	all the c-nodes that have interdependency edges to p_i
l_1	maximum oin degree of any c-node
l_2	maximum oin degree of any p-node
l_3	maximum iin degree of any p-node
l_4	maximum degree of any c-node

Table 1: Notations.

The interdependency between the networks can be represented in a graph $G = (V, E)$, as illustrated in Figure 1. We use several notations to represent the network, as shown in Table 1, and we use edges and links interchangeably. $V = V_c \cup V_p$ is the set of all the nodes and $E = E_c \cup E_p \cup E_{cp} \cup E_{pc}$ is the set of all the edges. The network is composed of both directional and bidirectional edges to distinguish different features of both individual network and interdependent networks. *Outgoing interdependent network degree* (abbreviated as oin degree) and *incoming interdependent network degree* (abbreviated as iin degree) represent the degree regarding interdependency edges. We also use the term *degree* by default to refer to the number of edges of a node in an individual network. Without loss of generality, we call two c-nodes *neighbors* or *direct neighbors* if there is an edge between them, i.e, they can communicate with each other. The E_c edges are also called *primary links.* If a c-node c_i has an edge to a p-node p_i, we call p_i a *p-neighbor* of c_i. Similarly, if a p-node p_i has an edge to a c-node c_i, we call c_i a *c-neighbor* of p_i.

Correct nodes faithfully follow the communication algorithm and send messages according to the network protocols. Meanwhile, the c-nodes are subject to crash failures but the crashes can be reliably detected by other nodes. We assume fair-loss links, where if a message is sent infinitely often by a correct sender to a correct recipient, it is received infinitely often. Furthermore, links do not produce spurious messages.

We now introduce several notions and define cascading failures.

Definition 1. *(Path) A sequence of c-nodes* $(c_1, \cdots, c_n)$ *is a path if,* $\forall i \in \{1, \cdots, n-1\}$*,* c_i *and* c_{i+1} *are neighbors.*

Definition 2. *(Initial Failure) The failure of a c-node* c_i *is an initial failure if its failure is not caused by the loss of incoming interdependency edges.*

Definition 3. *(Consecutive Failures) A sequence of c-nodes* $seq = (c_1, \cdots, c_n)$ *is a set of consecutive failures if,* $\forall i \in \{1, \cdots, n-1\}$*,* c_i *fails,* $n \geq 2$*, and seq is a path.*

Definition 4. *(Single Failure) The failure of a node* c_i *is a single failure if none of its neighbors fails.*

Definition 5. *(Cascading Failures) A number of nodes* $s = (c_1, \cdots, c_n, p_1, \cdots, p_n)$ *are cascading failures if,* $\exists c_i$*, the failure of which makes all the nodes in s lose incoming interdependency edges.*

In other words, we refer to the cascading failures as the failures that are caused by the loss of interdependency edges and the nodes that cause the cascading failures as initial failures. For instance, in the example in Figure 1, c_2 is the initial failure, c_2, c_4, and p_3 are all single failures, and the set of c_3 and p_3 are cascading failures caused by c_2. In this paper, we seek to handle single crashing initial failures in the c-network, each of which may cause several cascading failures. For other cases, our algorithm can be further extended to handle failures.

We assume each c-node has a *perfect failure detector*, which provides information about certain c-nodes being crashed or not and it satisfies the following properties.

- *Strong Completeness.* Eventually, every c-node that crashes is permanently detected by every correct c-node.
- *Strong Accuracy.* If a c-node c is detected by any c-node, then c has crashed.

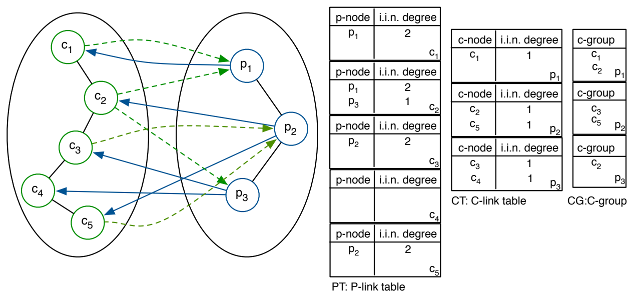
The failure detector can be realized using a timeout mechanism. Specifically, in order for a c-node c_1 to detect the correctness of c-node c_2, it sends a heartbeat message and starts a timer. If c_1 has not received a reply message before the timer expires, c_2 is suspected to be faulty. Although the failure detector abstraction relaxes the timing assumption on nodes and links [4], performance can be guaranteed under partial synchrony [11]: synchrony holds only after some unknown global stabilization timer, but the bounds on communication and processing delays are themselves unknown to the nodes.

We consider the best effort reliable broadcast problem in c-network under the above interdependency model, where all the correct nodes deliver the messages if the sender is correct. It satisfies the following properties.

- *Validity.* If a correct c-node broadcasts a message m to a set of c-nodes DES, then every correct c-node in DES eventually delivers m.
- *No Creation.* If a c-node delivers a message m with sender s, then m was previously broadcast by s.

4. BEST EFFORT BROADCAST

In this section, we first introduce the preliminaries. Then we introduce our best effort broadcast algorithm. Specifically, in addition to primary links, we also use soft links, which are the information of inactive links to handle the failures of primary links. Through the activation of soft links, new connections are built between correct c-nodes so that messages can be reliably delivered in the presence of failures. Notice that if there exists an alternative path to the destination, re-routing might be an option but it can also consume extra communication overhead and cascading failures may occur in the alternative routes.



p-node	i.i.n. degree
p_1	2
	c_1

p-node	i.i.n. degree
p_1	2
p_3	1
	c_2

p-node	i.i.n. degree
p_2	2
	c_3

p-node	i.i.n. degree
	c_4

p-node	i.i.n. degree
p_2	2
	c_5

PT: P-link table

c-node	i.i.n. degree
c_1	1
	p_1

c-node	i.i.n. degree
c_2	1
c_5	1
	p_2

c-node	i.i.n. degree
c_3	1
c_4	1
	p_3

CT: C-link table

c-group
c_1
c_2 p_1

c-group
c_3
c_5 p_2

c-group
c_2
p_3

CG:C-group

Figure 2: Example of p-link tables, c-link tables, and c-groups.

Our soft link technique is used to guarantee *best effort reliable message transmission* through new communication links so that all the correct destination nodes receive and deliver the same message. In order to correctly build soft links, we employ two sub-algorithms: a cascading failure information collection algorithm called *f-information collection* and an information update algorithm when failures are present, called *link management.* As we will introduce in §4.3, we use a fully distributed message transmission algorithm to analyze cascading failures, based on which nodes can maintain soft links. Lastly, we show link management in §4.4, which is used to update the tables and link information at nodes when failures are detected.

4.1 Preliminaries

Routing Tables. As illustrated in Figure 2, each c-node maintains several routing tables in the interdependent networks, the definitions of which are shown in DEFINITION 6 to DEFINITION 8. A *p-link table PT* of a c-node consists of all the p-neighbors and the number of their iin degrees. Similarly, for each p-node, there is a *c-link table CT*, which consists of all the c-neighbors and their iin degrees. For each p-node p_i, all the c-nodes that have interdependency edges to it form a *c-group CG*.

DEFINITION 6. *(P-link table PT) For any c-node c_i, $PT = \{p_1, \cdots\}$ where $\forall p_j \in PT$, $p_j \in P(\overrightarrow{c_i})$ and $\forall p_k \in P(\overrightarrow{c_i})$, $p_k \in PT$.*

DEFINITION 7. *(C-link table CT) For any p-node p_i, $CT = \{c_1, \cdots\}$ where $\forall c_j \in CT$, $c_j \in C(\overrightarrow{p_i})$ and $\forall c_k \in C(\overrightarrow{p_i})$, $c_k \in cT$.*

DEFINITION 8. *(C-group CG) For any p-node p_i, $CG = \{c_1, \cdots\}$ where $\forall c_j \in CG$, $c_j \in C(\overleftarrow{p_i})$ and $\forall c_k \in C(\overleftarrow{p_i})$, $c_k \in CG$.*

We assume all the c-nodes communicate according to routing tables and we refer to it as *regular routing tables.* In other words, for each c-node c_i and a specific destination c_j, if c_i wants to send a message to c_j, c_i looks up its routing table and verify that c_j is reachable, find a neighbor c_k, and sends the message to c_k.

In addition to the regular routing tables for message transmission in a regular communication network, each c-node also maintains a *p-link table PT*, the *c-link tables* for all the p-nodes in PT, denoted by $\{CT\}$, and all the *c-groups* that it is a member of, denoted by $\{CG\}$. For instance, as shown in Figure 2, c-node c_1 has a p-link table with p_1 in it, the c-link table for p_1, and one c-group with c_1 and c_2. Similarly, c-node c_2 has a p-link table with p_1 and p_3, the c-link tables for both p_1 and p_3, and a c-group, which only has c_2 in it. All the tables can be obtained initially through a heuristic method. We ignore the details in this paper since it is not the main focus of our work.

It is straightforward to see that the number of entries in a p-link table is at most l_1 and the number of entries in a c-link table is at most l_2, according to the notations in Table 1. Also, a c-node has at most l_1 c-groups and the number of c-nodes in each c-group is at most l_3. Therefore, in addition to the routing information in a single communication network, the extra storage space for each c-node is $O(l_1 + l_1 l_2 + l_1 l_3)$, where l_1 is the size its p-link table, $l_1 l_2$ is the size of c-link tables for the p-nodes, and $l_1 l_3$ is the size of all the c-groups. In the worst case, l_1 can be as large as n and l_2 and l_3 can be as large as m. Therefore, the storage space complexity is limited by $O(mn)$.

Links. A c-node has two types of links: primary links and soft links. *Primary links* of a c-node are the communication links to the neighbors in the c-network in order to perform message transmission. When the primary links fail, soft links are activated and connections are built with the corresponding c-nodes and messages are transmitted to the activated soft links. Each soft link handles one initial c-node failure where the c-node may cause multiple cascading failures. For simplicity, in this paper, for each c-node, we build one soft link to handle one initial failure of one neighbor for each of its path. If there are consecutive initial failures in each path, the algorithm can be further extended to handle the failures.

Failure Detector. As mentioned in §3, each c-node has a built-in failure detector module that provides information about whether certain c-nodes have crashed or not. A c-node uses the failure detector to monitor the correctness of its neighbors (c-nodes), the c-nodes in its c-link tables, and all the c-nodes in its c-groups. Notice that the c-nodes in the c-link tables and c-groups may not be direct neighbors of a c-node. Therefore, the correctness of those c-nodes relies on the neighbors of those c-nodes. Specifically, if a node c_i wants to learn the correctness of c_j, which is not its direct neighbor, it can learn the correctness of c_j from the neighbors of c_j. This is because each node must monitor the correctness of its neighbors. However, c_i does not need to maintain the information of the neighbors of c_j. Instead, it simply sends a $[fd, c_i, c_j]$ message to c_j. When a neighbor of c_j receives this message, it returns the result to c_i. This applies to all the cases when a c-node needs to monitor a node that is not its direct neighbor. Also notice that if c_j is not reachable by c_i, it cannot detect the failures.

4.2 Best Effort Broadcast Algorithm

Our best effort broadcast algorithm proceeds as follows. We use a fully distributed f-information collection algorithm (as we will introduce in details in §4.3) for each c-node c_i to collect the information of cascading failures initialized by c_i. Since the f-information collection algorithm is initialized by each c-node to analyze all the cascading failures caused by itself, the analysis result is then sent to all the neighbors. Based on such information, each c-node c_i can learn in each path whether the failure of its neighbor will cause other failures in the path. It can then maintain a soft link to the next correct c-node c_j in each path. The soft link contains the necessary information for c_i to build a connection with c_j and the actual connection is made only when the soft link is activated. Notice that in a single communication network, for each soft link of node c_i, it only maintains the information of the neighbor of its neighbor, i.e., the c-node that is two hops away. However, in interdependent networks, if the c-node c_j that is two hops away from c_i will also fail, c_i also needs to learn the identity of c_k–the subsequent node of c_j, and analyzes whether c_k will also fail. This process continues until c_i learns the next correct c-node in the path. For instance, if c_i learns from its neighbor c_j that if c_i and c_j fails, the subsequent node c_k of c_j will also fail but the subsequent node c_l of c_k will be correct, c_i can then build a soft link with c_l in order to handle the failure of c_j. In this case, c_i also needs to learn from c_k the identity of c_l since c_i does not have the information beforehand. After soft links are activated, they become the primary links and the primary links are discarded. New soft links will be maintained after another round of f-information collection.

In the normal case when there are no failures, c-nodes use their regular routing tables for message transmission. If a c-node c_i detects the failure of its subsequent node c_j through the failure detector and it has a pending message to c_j, it first diagnoses the situation using the pre-collected f-information from c_j. If the destination node c_l will also fail if c_j is faulty, it simply stops broadcasting the message since c_l will also be faulty. Otherwise, c_i activates the corresponding soft link, builds the connection, and sends messages to the activated soft link.

For long term robustness, it is important for nodes to monitor the correctness of the c-nodes in the routing tables to maintain the most up-to-date topology. As we will describe in details in §4.4, link management is used to update the tables. The soft links will be updated through another round of f-information collection.

Note that in a mesh topology, it is possible that there are alternative paths to the destination, which we can use to guarantee message delivery. However, it is also possible that failures cascade to the alternative paths. Therefore, the use of soft links is very effective in guaranteeing that all the correct nodes deliver the message as a bottom line. Also note that if some nodes are not initially reachable, the use of soft links is not effective to guarantee best effort broadcast.

```
initialization:
  ${CT'}, PT' \leftarrow {CT}, PT$
  $X.add(c_i)$      {output: a set of nodes that will fail}
  $watchlist()$
  for $p_x$ in $PT'$
    $p_x.(iin\ degree) \leftarrow p_x.(iin\ degree) - 1$
    if $p_x.(iin\ degree) = 0$ then
      for $c_k$ in $\{CT'\}.p_x$
        $c_k.(iin\ degree) \leftarrow c_k.(iin\ degree) - 1$
        if $c_k.(iin\ degree) = 0$ then
          $watchlist.add(c_k)$
  if $!watchlist().empty()$
    send $[fcollect, c_i, X, \{CT'\}, PT']$ to $watchlist().first$
on receiving $[fcollect, c_{ini}, X, \{CT'\}, PT']$ from $c_j$
  $\{CT''\} \leftarrow merge(\{CT'\}, \{CT\})$
  $PT'' \leftarrow merge(PT', PT)$
  $X.add(c_i)$
  $con \leftarrow False$
  $prev(c_{ini}) = c_j$
  for $p_x$ in $PT''$
    $p_x.(iin\ degree) \leftarrow p_x.(iin\ degree) - 1$
    if $p_x.(iin\ degree) = 0$ then
      for $c_k$ in $\{CT''\}.p_x$
        $c_k.(iin\ degree) \leftarrow c_k.(iin\ degree) - 1$
        if $c_k.(iin\ degree) = 0$ then
          $watchlist.add(c_k)$
          $con \leftarrow True$
  if $!watchlist().empty()$ then
    send $[fcollect, c_{ini}, X, \{CT''\}, PT'']$ to $watchlist().first$
  if $con = False$ then
    send $[freturn, c_{ini}, X, \{CT''\}, PT'']$ to $prev(c_{ini})$
on receiving $[freturn, c_{ini}, X', \{CT''\}, PT'']$ from $c_j$
  if $c_j = watchlist().first$ then
    $watchlist().remove(c_j)$
    $X \leftarrow merge(X, X')$
    if $watchlist().empty()$ then
      send $[freturn, c_i, X, \{CT''\}, PT'']$ to $prev(c_{ini})$
    else
      send $[fcollect, c_i, X, \{CT''\}, PT'']$ to $watchlist().first$
```

Figure 3: F-information collection algorithm, where $\{CT\}.p_x$ denotes the c-link table for p_x in set $\{CT\}$.

4.3 F-information Collection

F-information collection is for a c-node c_{ini} to collect the information of the cascading failures by analyzing its failure. In this case, c_{ini} is called the initial failure. This f-information collection algorithm is a distributed message transmission algorithm, as shown in Figure 3. There are two types of messages, $fcollect$ from c_{ini} to the nodes that will fail if c_{ini} fails, and $freturn$ back to c_{ini} when no further cascading failures will occur.

The algorithm proceeds as follows. For each initial node c_{ini}, the output is a set of cascading failures X. In the beginning, c_i (the initial failure) first copies its c-link tables and p-link table, as shown in line (ln) 2, and adds itself to X. Next, It looks up its p-link table and updates the entries by decreasing the iin degree by 1, as shown in ln 5-6. If any p-node p_x has an incoming interdependency degree of 0, indicating that if c_i fails then p_x will also fail, c_i starts to lookup the c-link table of p_x, as shown in ln 7-8. Similarly, it also updates the c-link table by decreasing the iin degree by 1, as shown in ln 9. If any c-node c_k in the c-link table of p_x has iin degree of 0, c_k will also fail if c_i fails and c_k is added to the $watchlist()$. A message with c_i as the *initial node* that initializes the f-information collection, X, $\{CT'\}$, and PT' is sent to the nodes in $watchlist()$ sequentially, i.e., the message is sent to one node in the $watchlist()$ at a time, as shown in ln 12-13. Note that the p-link table and c-link tables are updated on the copies of the original tables and the goal is to mimic the effect of node failures.

When a node c_i receives such a message with $X, \{CT'\}$, and PT', it first adds itself to the set X and copies its c-link tables and p-link table. It also merges $\{CT'\}$ and PT' to its tables and updates the common entries, as shown in ln 15-16. The purpose of this step is to let nodes analyze the cascading effect, taking into consideration previous failures. For instance, if c_1 and c_2 both have an edge to p_1 and c_1 wants to analyze the cascading failures when it fails, it will not include p_1 in the cascading failures since p_1 still has an incoming edge when c_1 fails. However, if in the following c_2 fails from the failure of another p-node (but also caused by the initial failure of c_1), it must include p_1 into the cascading failures since now p_2 has no incoming edges. Therefore, each node must include its copies of c-link tables and p-link tables and each c-node must merge the tables from previous nodes so as to analyze all the failures. The nodes run the same algorithm to analyze the next c-node failures, as shown in ln 20-29. When a c-node will not cause any further cascading failures of c-nodes, it sends a $freturn$ message with X to the previous node, as shown in ln 30-31. This process continues until the message reaches the initial node. When the initial node learns the set of cascading failures when it fails, it sends the f-information to all its neighbors.

In the f-information collection algorithm, each c-node only keeps partial information about the cascading failures, i.e., it receives the $fcollect$ from a c-node, computes the subsequent failures, and sends to the corresponding c-nodes that will fail subsequently and waits for $freturn$ messages. We use a $watchlist()$ scheme for the nodes to collect the information during such a process. This can be represented as a logical Depth First Search (DFS) tree, as shown in Figure 4, where the arrows between nodes represent the message flow and the links between parent and its child nodes may not be real communication links. Instead, the logical tree just demonstrates the sequence of message transmission during f-information collection. The root of the tree is the initial node c_{ini} that starts the f-information collection process, which is included in both $fcollect$ and $freturn$ messages. When a node c_i receives a $fcollect$ message, it keeps the previous node who sent the $fcollect$ message (the parent in the tree, which may or may not be the initial node), as shown in ln 19) and watches all the c-nodes that will fail after it fails, i.e., the child nodes in the tree. It sends the $fcollect$ to one node in its $watchlist()$ at a time and waits for the $freturn$ messages. When c_i receives a $freturn$ message, it removes the node from $watchlist()$, as shown in ln 34, and merges X' to X, as shown in ln 35. If there are still nodes in its $watchlist()$, c_i continues to send $fcollect$ message until it receives $freturn$ from all of them. When there is no node in $watchlist()$, it sends a $freturn$ message to its previous node $prev(c_{ini})$. This mechanism is necessary for each node to collect all the cascading failures since each node only carries partial information.

An Example. As shown in Figure 4, c_1 initializes the f-information collection, where $X = \{c_1\}$ and $watchlist() = \{c_2, c_5, c_8\}$. It first sends a $fcollect$ to c_2 and c_2 further sends a $fcollect$ message with $X = \{c_1, c_2\}$ to c_3 and it has $watchlist() = \{c_3, c_4\}$. When c_2 receives $freturn$ message from c_3 with $X = \{c_1, c_2, c_3\}$, it adds c_3 to its X. Now c_2 has $watchlist() = \{c_4\}$ and it sends a $fcollect$ to c_4. When c_2 receives $X = \{c_1, c_2, c_3, c_4\}$ from c_4, it adds c_4 to its X and the $watchlist()$ becomes empty. It can then send a $freturn$ message to c_1 and c_1 has $watchlist() = \{c_5, c_8\}$. Similarly for other branches, each message only contains partial information and each node needs to watch its child nodes one by one until it learns results from all of them. Eventually, c_1 learns all the results and the f-information collection is completed.

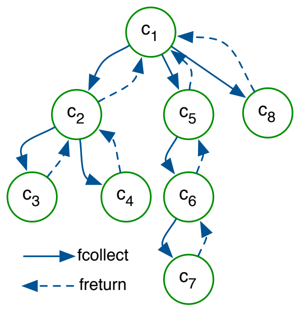


Figure 4: Example of f-information collection.

The Watchlist. Notice that we use a sequential mode for nodes to send and collect f-information, i.e., each node sends $fcollect$ to one node in its $watchlist()$ at a time. This is because each message only contains partial information until the information reaches the last node in the tree (c_8 in the example). Due to the use of the sequential mode, we avoid the case where some failures are not included if the messages are transmitted in parallel to the nodes in the $watchlist()$. For instance, c_4 and c_6 both have an edge to a p-node p_9. If the $fcollect$ messages are sent concurrently to all the child nodes from c_1, none of c_4 and c_6 will consider the failure of p_9 and therefore some failures may be ignored during this process. In addition, the sequence of sending messages to nodes in the $watchlish()$ does not affect the result since eventually all the nodes that will fail will be visited.

Additionally, it is possible that some node in the $watchlist()$ is not reachable. In this case, the c-node just skips the node and sends the message to next node in the $watchlist()$. The reason is that we analyze the failures prior to their presence. For instance, if a node c_1 is not reachable at some node c_2 during the f-information collection process, node c_1 must not be reachable for the initial node c_3 due to the fact that c_2 is reachable for c_3. Therefore, if some nodes are not reachable prior to the failures, the use of soft links is not effective and it is out of scope of this paper.

4.4 Link Management

In order for c-nodes to maintain the routing tables that represent the most up-to-date topology, each c-node c_i monitors the correctness of c-nodes in addition to its direct neighbors. These c-nodes include the c-nodes in the c-link tables and c-nodes in all the c-groups of c_i. The algorithm is shown in Figure 5, where $\{CG\}.c_j$ denotes all the c-groups that c_j is a member of, $cg.p$ is the p-neighbor of the c-nodes in c-group cg, $PT(p)$ is the entry for p-node p in the p-link table, and $|cg|$ is the number of nodes in c-group cg. The goal of monitoring the c-nodes in the c-groups is to update the p-link tables since the incoming interdependency degree of the p-nodes must be updated. The goal of monitoring the c-neighbors of the p-neighbors of c_i is to update the c-link tables.

```
1  on event $c_j$ is faulty
2    if $c_j$ in $\{CT\}$ then
3      for $ct$ in $\{CT\}.c_j$
4        $ct.remove(c_j)$
5    if $c_j$ in $\{CG\}$ then
6      for $cg$ in $\{CG\}.c_j$
7        if $c_i = cg.leader$ then
8          send $[cgupdate, c_j]$ to $cg$
9        else
10         send $[le, c_j, c_k]$ to $cg$
11       $PT(cg.p).(iin\ degree) \leftarrow PT.(cg.p).(iin\ degree) - 1$
12       if $|cg| = 1$ then
13         send $[sf, c_i, cg.p]$ to $\{CT\}.(cg.p)$
14   if $c_j, p$ in $F$ then
15     $CT(p).(iin\ degree) \leftarrow CT(p).(iin\ degree) - 1$
16 on receiving $[cgupdate, c_j]$
17   $p_l \leftarrow \{CG\}.c_j.p$
18   $PT(p_l).(iin\ degree) \leftarrow PT(p_l).(iin\ degree) - 1$
19 on receiving $[sf, c_j, p]$
20   $F.add(c_j, p)$
```

Figure 5: Link management algorithm.

The key idea for the failure detection is that if a c-node fails, we must remove the interdependency edges and update the tables at all the applicable c-nodes. When the outgoing interdependency edges of a c-node are removed, the corresponding number in the p-link table must be updated, i.e., the iin degree of the p-node in all the applicable p-link tables must be decreased by one. Therefore, we introduce the idea of c-groups and we now introduce the maintenance of c-groups using a leader-based scheme.

In each c-group, a leader is elected and agreed by all the c-nodes. Initially, there is a default leader in each group. The leader monitors the correctness of all the c-nodes in the same group. When it detects the failure of some c-node c_j, it updates its p-link table and notifies other c-nodes, as shown in ln 7-8. Other c-nodes then simply update their p-link tables, as shown in ln 16-17. If a c-node c_i is not the leader in a c-group, it monitors the correctness of the leader. If the leader fails, c_i notifies all the nodes in the c-group with the id of the new leader c_k, as shown in ln 9-10. The leader is elected according to the ids in a deterministic rotating manner. When a node receives or has sent a $[le]$ message, it stores the information of the new leader. If the node is the new leader, it sends a message to all the nodes in the c-group and starts monitoring the correctness of them. In addition, all the nodes also update their p-link tables since the previous leader has failed.

On the other hand, when c_i fails, we must remove the incoming edges. Therefore, it is straightforward for a c-node c_j to monitor the c-nodes in its c-link tables since the c-link tables it maintains are the c-link tables of the p-nodes in its p-link table. In this case, if a c-node c_i in the c-link table(s) fails, c_j simply removes the corresponding entry, as shown in ln 4 in Figure 5.

If the failure of the c_i will cause the failures of some p-nodes but the failure will not cascade to the c-network again, we should also update the c-link tables for all the applicable c-nodes. For this purpose, we add another message type called $[sf]$ where if node c_i becomes the only node in a c-group cg, it sends a $[sf]$ message to the nodes in the c-link table of node $cg.p$ (the p-neighbor of c-nodes in cg), as shown in ln 12-13. When a node c_i receive a $[sf]$ message from some node c_j, it starts monitoring the correctness of c_j and also adds c_j to a set F, as shown in ln 19-20. If it detects the failure of a node in F, it decreases the degree of c_j in the c-link table, as shown in ln 14-15.

Assume that a c-node can be the leader of at most t c-groups, the number of c-nodes a c-node c_i needs to monitor is limited by $O(l_4 + l_1 l_2 + t l_3)$, where l_4 is the maximum number of neighbors c_i needs to monitor, $l_1 l_2$ is the maximum number of c-nodes in the c-link tables of c_i, and tl_3 is the maximum number of c-nodes c_i needs to monitor in its c-groups. Since l_1 and t can be as large as n and l_2 to l_4 can be as large as m. The number of c-nodes a node needs to monitor is limited by $O(mn)$.

4.5 Correctness

We show the correctness of our best effort broadcast algorithm in the following theorem and we briefly show the proof. In the theorem, *new failures* refer to the failures of nodes involved in the f-information collection and link management process. Our approach guarantees correctness if no failures occur in the f-information. The idea is straightforward. F-information collection is used to analyze the cascading failures. Failures during the algorithm will cause inaccurate results and soft links may not be correctly maintained.

THEOREM 1. *Let there be no consecutive initial failures in each path. Best effort reliable broadcast is achieved if there are no new failures among the nodes that participate in each f-information collection and link management process.*

PROOF. The no creation property is straightforward. Since we assume nodes can only fail by crashing, each message, if received by some c-node, must be generated by the sender, i.e., no creation property is true.

We now show the validity property in two steps. We first show that if soft links are correctly maintained and there are no consecutive failures, messages are delivered to all the correct receivers. Then we show that if there are no new failures during f-information collection and link management, soft links can be correctly maintained. Based on these, the validity property can be proved.

We assume that there are no consecutive initial failures. Therefore, one soft link for each node, if correctly maintained, is sufficient to guarantee that messages are reliably delivered to the next correct c-node. For each path, by induction, messages can always be sent along the path to the destination. The destination, if correct, will deliver the message according to the algorithm. Since c_s is correct, it sends the message to the paths to all the correct destinations. Therefore, the statement is true.

Then we show that if there are no new failures during f-information collection, soft links can be correctly maintained. First, during link management, since we use perfect failure detectors, faulty c-nodes will eventually be detected by correct c-nodes. As discussed in §4.4, we update the p-link tables through the use of c-groups and we update the c-link tables by monitoring of c-nodes in the c-link tables and the use of $[sf]$ messages. If there are no failures during message transmission, all the routing tables will eventually be correctly maintained by all the c-nodes to reflect the most up-to-date topology. Second, since the routing tables are correctly maintained, during f-information collection algorithm, each node is able to analyze the failures. The f-information collection algorithm eventually visits all the c-nodes, if they are connected before the failures, that will fail initialized by each c-node. Therefore, if there are no new failures among all the nodes involved in each f-information collection process, f-information collection enables each c-node to analyze the cascading failures. The correctness of the theorem then follows. □

4.6 Discussion

The correctness of soft links is guaranteed if there are no new failures during f-information collection and link management. In large-scale and highly dependent and dynamic networks, it may not be the case. In this case, nodes may maintain out-of-date c-link and c-group tables and cause wrong analysis results. It is also possible that the f-information algorithm halts where a node waits for a $freturn$ message but some nodes during message transmission fail. As we will discuss further in §5, this does not guarantee best effort broadcast where some messages are not delivered to all the correct destinations. We can handle this problem by also using alternative routes for message delivery to increase the delivery rate and adding timers during f-information to ensure that the algorithm will end in the presence of failures.

As discussed previously, the storage complexity for each node is $O(l_1 + l_1 l_2 + l_1 l_3)$ and the complexity for the number of nodes each failure detector module is $O(l_4 + l_1 l_2 + t l_3)$. In the worst case, both are limited by $O(mn)$. It is not hard to conclude that in the worst case of a highly connected mesh topology or highly dependent networks, a c-node might eventually need to maintain the information of all the networks and monitor the correctness of all the c-nodes. However, in this case, it is less possible that a failure of a c-node will cause multiple cascading failures.

5. EVALUATION

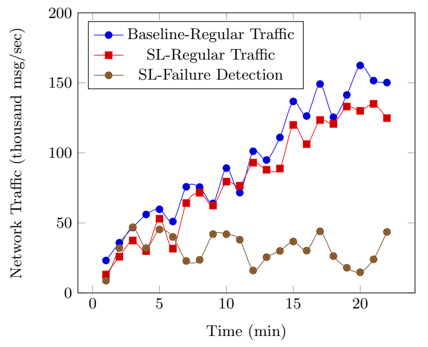
We implement and evaluate our algorithm using OMNeT++ network simulation framework [25]. We construct various sizes of graphs and compare the performance of our distributed algorithm (abbreviated as DA) with the Baseline the Soft Link (abbreviated as SF), both in a single communication network. Baseline is a regular routing algorithm where nodes use routing tables for message transmission and do not use soft links. SL builds soft links between nodes that are two hops away. We limit the number of sink nodes to fewer than three and each node generates a packet by doubling the previous period (i.e., 0.01ms, 0.02ms, 0.04ms, etc.). The average delay between two neighbors is set to 0.01ms. When failure detectors are used, each node sends a heartbeat message every 0.3ms and the timer is set to 0.1ms. We set up the maximum outgoing interdependency edges of each node to evaluate the interdependent networks with different dependency level. After the interdependent networks are generated, we check the validity of them by ensuring every node has at least one incoming interdependency edge.

We first assess the network traffic according to message types to evaluate the overhead of our algorithm. We observe that the regular network traffic in SL and our proposed algorithm are in general lower than the Baseline. However, the failure detection and f-information do not decrease the regular traffic to a large degree. We then evaluate the robustness of the algorithm by measuring the percentage of packet drop and the average delay of failure detection. We have proved that best effort broadcast can be guaranteed if there are no new failures during f-information collection and link management. However, as discussed in §4.6, in a large-scale and dynamic network where failures are frequent, new failures can occur and best effort broadcast may not be guaranteed. Therefore, we also evaluate the packet drop rate to assess the efficiency of our algorithm. We notice that our proposed algorithm has largely reduced the packet drop rate and there is a tradeoff of a longer failure detection delay. Lastly, we evaluate the f-information collection delay using various sizes of topologies. We find that due to the way we model the networks, the performance is more related to the number of interdependency edges rather than the degree in c-network. Instead, the average degree of c-network determines how many alternative paths exist for message re-routing. We observe that there is no generic relationship between the number of nodes and the average latency for f-information collection. This indicates that f-information collection process does not increase the overall complexity in a scalable network.

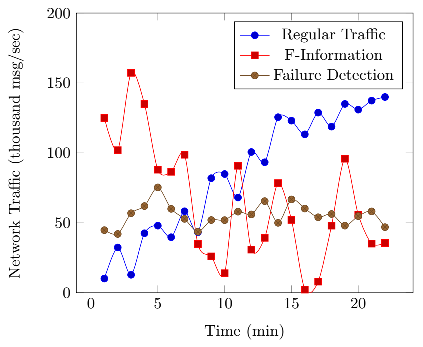
5.1 Failure Handling Overhead

We assess the network traffic of different message types and compare our algorithm with Baseline and SL. This is used to assess the overhead caused by our algorithm for distributed failure analysis. In this experiment, we use 200 c-nodes and 200 p-nodes with maximum oin degree of 2. In the c-network, we generate a random mesh graph where the average degree of each node is 3. Each node has 0.1 probability of being crashed. As observed in Figure 6(a), the Baseline algorithm only has regular traffic. Comparably, since SL uses failure detector for each node to monitor the correctness of its neighbors, the regular traffic is in general lower than Baseline. However, the failure detection traffic is relatively stable. This is because each node usually has a fixed number (unless failures occur) of neighbors to monitor.

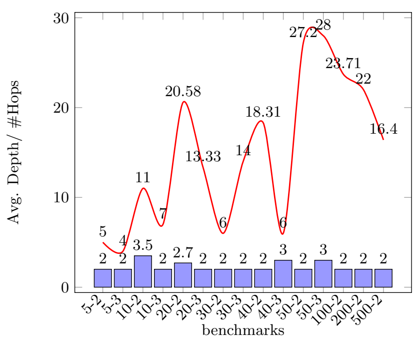
Compared to Baseline and SL, our proposed DA algorithm generates higher volume of traffic since each node needs to monitor the correctness of a larger number of nodes. Notice that as discussed in §4.6, the c-nodes that a failure detector



(a) Network traffic of different message types for Baseline and SL.



(b) Network traffic of different message types for the proposed algorithm.



(c) Average tree depth and average number of hops in f-information collection.

Figure 6: Evaluation of the algorithms.

needs to monitor may not be the direct neighbors, where the correctness of the c-nodes is monitored by their neighbors. We count these notification messages also as failure detection traffic. As shown in Figure 6(b), the regular traffic is lower than both Baseline and SL and the failure detection traffic is higher than that of SL. The f-information collection traffic is very high in the beginning. This is because all the nodes need to run f-information collection in the beginning of the experiment. After the initialization, f-information collection is run only when failures occur.

#Nodes	Algorithm	%Packet Drop	Avg FD Delay
50	Baseline	52.19%	N.A.
	SL	28.45%	0.19ms
	DA	3.03%	0.55ms
300	Baseline	51.80%	N.A.
	SL	32.25%	0.21ms
	DA	13.03%	7.14ms

Table 2: Packet drop rate and average failure detection delay of the algorithms

5.2 Robustness

In order to evaluate the performance of the algorithms under failures, we employ a chain-based topology for c-network with 50 nodes where the nodes are organized sequentially and each node is connected to at most two other nodes. There are 50 p-nodes and the maximum oin degree is set to 2 for both c-nodes and p-nodes. We set up the sink nodes to be the middle of the chain and only nodes in the first half of the chain may fail. As shown in Table 2, since the Baseline does not have a scheme to handle failures, the packet drop rate is high. This can be explained by the fact that each node becomes critical in message transmission. SL has a much lower packet drop rate because it maintains soft links between nodes that are two hops away, which are still effective when the cascading failures do not include too many consecutive failures. Our proposed DA algorithm achieves the lowest packet drop rate since it handles cascading failures. The tradeoff is a slightly longer failure detection delay. Since each node needs to monitor the correctness of a larger number of nodes, the failure detection generates much longer delay due to the communication overhead.

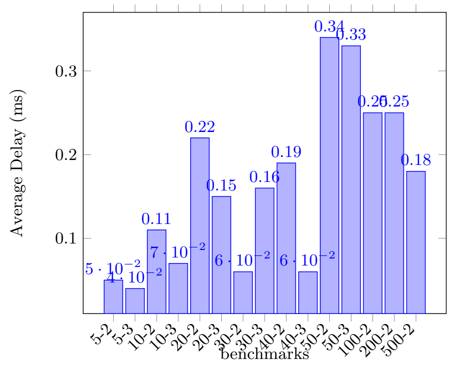


Figure 7: Average delay for f-information collection.

We also evaluate the packet drop rate and the average failure detection delay with 300 c-nodes and 300 p-nodes. According to Table 2, the packet drop rate for Baseline is similar with previous case and the packet drop rate for SL slightly increases. This is because in SL each node simply monitors the correctness of it neighbors. Although our proposed DA algorithm still achieves the lowest packet drop rate, the packet drop rate is larger than the case with fewer nodes. Also, since the topology has a larger number of nodes, the failure detection delay is also larger, especially with the nature of chain-based topology where there might be a large number of hops between any two nodes. Therefore, it is not hard to conclude that in highly interdependent and large-scale networks, the failure detection delay and packet drop rate can further be increased.

5.3 F-information Collection Delay

In order to evaluate the performance of the algorithm, we assess the average delay of f-information collection process using topologies of various network sizes with 5 to 500 c-nodes and p-nodes. We generate random mesh topologies where the average degree of c-nodes is 3. A benchmark x-y represents a graph with x c-nodes, x p-nodes, and the maximum oin degree is y. Based on our observation, when the oin degree is bigger than 4, it is less possible that a failure of a c-node causes multiple failures, i.e., soft links between nodes that are two hops away are sufficient. Also, it is straightforward that if each node only has one outgoing interdependency edge, the networks become highly interdependent, where a single failure causes the failures of almost the whole network. We also show the depth of the tree and the average number of actual hops during each f-information collection in Figure 6(c), which might not be the same with the number of nodes in the tree since the parent node and a child node may not be direct neighbors. We notice that there is not a generic relationship between the number of nodes and the number of hops due to the way we link the nodes. We also notice that the average depth of the tree is 2 to 3. This indicates that an initial failure of a c-node will only cause failures of some c-nodes and the failures will not cascade furthermore. Additionally, as shown in Figure 7, we also evaluate the average latency for f-information collection. Each f-information collection runs for 0.05 to 0.34ms, where the average latency is directly related to the number of actual hops due to the fact that our algorithm essentially visits all the nodes that will fail. This can be explained by the fact that the f-information collection visits the nodes in a DFS manner so that the delay is directly related to the number of nodes that will fail and the distance between them.

6. CONCLUSION

In this paper, we study best effort broadcast in the interdependent networks between a multihop communication network and a power grid network. We handle crash failures through the use of soft links in the communication network. In order to efficiently build soft links to handle cascading failures, we present a fully distributed algorithm for the nodes to analyze the failures. Each node needs to maintain minimum extra information, which is updated from time to time to reflect the up-to-date network topology. Based on our evaluation results, our algorithm is effective in handling cascading failures with little overhead.

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