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Multi stage recovery from large scale failure in interdependent networks

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MULTI STAGE RECOVERY FROM LARGE SCALE FAILURE IN

INTERDEPENDENT NETWORKS

by

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ABSTRACT

Node and link failures that usually cause limited damage in a single network, may cascade into large scale disasters in the case of interdependent networks, due to the dependencies that exist between them. Recovery from such failures may require multiple stages or steps for complete restoration of connection or flow between them. When critical services are disrupted, the order in which the broken elements are repaired affects the earliest possible recovery time of vital services. In a flow network, one order of restoration may restore more flow at an earlier stage than another. The paper aims to model an efficient recovery process to restore the maximum possible flow at the earliest stage in the event of large scale failure in an interdependent network. The work attempts to identify this restoration order when faced with a fixed budget of resources at each stage. The optimal solution is formulated and its complexity is discussed. This paper compares the performance of the efficient greedy solution with the optimal solution and another sub optimal greedy algorithm.

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LIST OF ILLUSTRATIONS

NOMENCLATURE

Symbol	Description
V_c	nodes in communication network
V_p	nodes in power network
E_c	edges in communication network
E_p	edges in power network
$G_c(V_c,E_c)$	communication network
$G_p(V_p,E_p)$	power network
(s, t)	source destination pair in Communication Network
v_g	generator in power network
c_{ij}	capacity of edge (i, j) ϵ E_c
f_k (i, j)	flow across edge (i, j) ϵ E_c at stage k
ϕ(i, j)	flow across edge (i, j) ϵ E_p
r_{ij}	cost of repair of edge (i, j) ϵ E_c, E_p
r_i	cost of repair of node i ϵ V_c, V_p
R_k	total resource budget in each stage k
x_{ijk}	repair decision of edge (i, j) at stage k
x_{ik}	repair decision of node i ϵ V_c at stage k
y_{ijk}	repair status of edge (i, j) ϵ E_c at stage k
ϕ_{ik}	repair status of node i ϵ V_p at stage k
ϕ_{ijk}	repair status of edge(i, j) ϵ E_p at stage k
y_{ik}	repair status of node i at stage k
$V_c^f \subseteq V_c$, $E_c^f \subseteq E_c$	failed nodes and edges in communication network
$V_p^f \subseteq V_p$, $E_p^f \subseteq E_p$	failed nodes and edges in power network
P_{ik}	power supply to node i ϵ V_p at stage k
z_i	power supply to node i ϵ V_p at stage k
P_{max}	total power from generator v_g ϵ V_p
$c_r(i)$	repair centrality of node i ϵ V_c^f, V_p^f
$P_g(i)$	shortest path to generator vg from node i

1. INTRODUCTION

Restoration of a network after large scale failures can be a complex task. The problem has been studied extensively across multiple domains based on topology and other characteristics of the individual network. The network infrastructures of communication, power, gas supply and water supply systems are considered to be critical infrastructure systems as their failure can have adverse consequences. While re-routing of flow can be achieved to increase network availability in some cases, it may not be feasible in the event of large scale failures that impact a majority of the system. Thus an attempt at recovery of flow will involve identifying the best components whose repair will restore the flow in the earliest possible time. The restoration process undertaken in the case of large scale failures is usually constrained by the availability of human resources, like Emergency Response Officers(ERO) available at any given time. Hence the restoration is completed across multiple stages.

In the case of interdependent networks, recovery action undertaken in the event of failure in one infrastructure, must also consider any dependency on other infrastructures. An example is the case of the communication infrastructure that depends on the energy infrastructure. The coupling of these systems for enhanced efficiency leads to increased vulnerability in both the networks when either system faces disruption. Failures in one component can trigger failure in another, thereby cascading to a much larger scale with devastating effect. An example of such cascading failures range from the closing of the New York Stock Exchange(NYSE) following the World Trade Center Attack that disrupted the power and communication systems[1] and the failure in August 2003 blackout that disconnected 50 million people across eight states in Northwestern America[2]. Consider two interdependent networks, namely the Communication Network and the Power Network it depends on.

1.1. MODELING NETWORK AS GRAPH

The undirected graph $G_c(V_c, E_c)$ denotes the Communication Network with nodes V_c and edges E_c. The capacity of each edge $(i, j) \in E_c$ is denoted by c_{ij}. The flow across the edge is denoted by $F(i, j)$. Similarly the graph $G_p(V_p, E_p)$ denotes the Power network with its nodes V_p and edges E_p .Assuming that for any edge (i, j) ϵ E_p in the Power network, the flow across the edge denoted by $\phi_p(i, j)$ is positive and the capacity is infinite. Let s ϵ V_c be the source node and t ϵ V_c be the destination node with ‘P’ being the set of simple paths p that connect the two nodes.

1.2. DEPENDENCIES

Allowing for a certain level of abstraction based on [3], the power network consists of many substations with a generator node v_g ϵ V_p, that acts as a source for all substation nodes in the network.

The communication network, A is defined to have a many to one dependency on power network, B. Each substation V_p may power many communication nodes while a communication node V_c is powered by a single power node.

The dependency reflects that of a telecommunication network on the power network [7] where the loss of power supply to a base station in the telecommunication system could render the cells connected to it, incapable of further transmission.

1.3. FAILURE

In the event of a large-scale failure across the networks, the following assumptions are made:

- There exist a set of failed nodes V_c^f ϵ Vc and V_p^f ϵ V_p and edges E_c^f ϵ Ec and E_p^f ϵ E_p.
- The generator v_g ϵ V_p is repaired instantaneously as its failure would disrupt the entire system.
- In addition to node and edge failures in the individual networks, a node in the Power network may also fail due to failure of the edges and nodes in the path connecting it to the generator.
- The communication node $v_c(\forall v_c \in V_c)$ may also fail when the power node it is connected to fails.
- The edge (i, j) ϵ E_p is functional if the flow over the edge $\phi_p(i, j) > 0$

1.4. RECOVERY

The recovery of the flow in the Network A also requires the recovery of the corresponding broken edge or node in Network B. As the recovery process is modeled in K stages, note that the flow over any edge (i; j) at a stage k exists only when the edge as well as the nodes at its endpoints are functional. For the set of all source and destination node pairs (s; t) the total flow into t at stage k is the sum of all flow into t from s. Consequently, the flow into the node t is the sum of all flows into it. Thus, for any node s that is connected to t, the total flow reaching the destination node t is:

$$T_k = \sum_{(i,t)\in E_c} f_k(s,t) \qquad (1)$$

1.5. CONSTRAINTS

In case of failure, the network recovery process is undertaken across K stages while the total available resource is R. The resource $r_{ij}<R$ is required to restore the edge (i, j) to capacity c_{ij} and resource $r_i<R$ is required to restore the node i at each stage k.

1.6. OBJECTIVE

The recovery process aims to maximize the total flow between s and t at the earliest, by identifying the set of nodes and edges whose repair will maximize the flow at each stage upto K. Note that this is different from obtaining the full maximum flow at the earliest stage. While there may be some cases when maximum flow can be reached at the earliest stage, the objective of this paper is to ensure that there is more flow towards the early stages thereby the restoration process avoids a sudden late spike in flow after maintaining a small value earlier.

2. EXAMPLE

To demonstrate the effect of recovery order, consider the interdependent network with node s as a source node and t as the destination node. To maximize the flow between s and t, few repairs are undertaken in different orders. Consider an interdependent network represented by Figure 2.1.

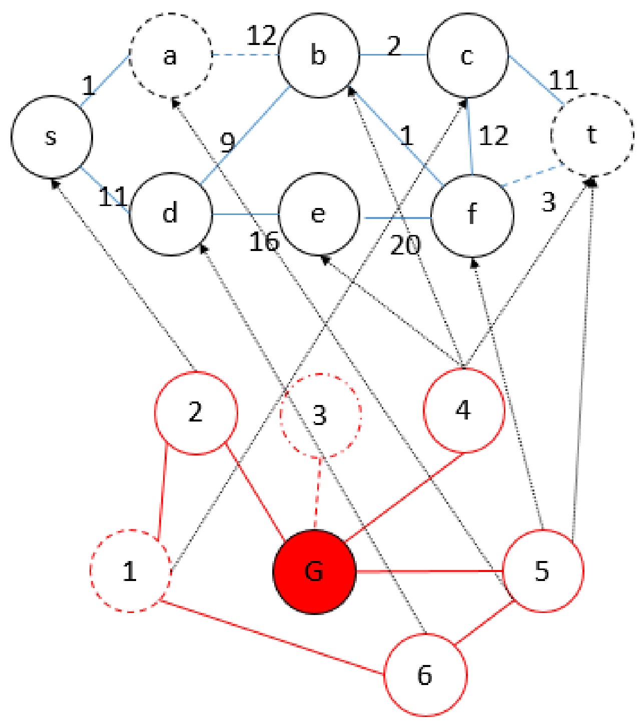

Figure 2.1. Failure in Interdependent Network AB

In the first instance, Network A is repaired first, followed by repair of Network B with the aim to maximize flow at the earliest stage. The order of flow recovery is as observed in Figure 2.2.

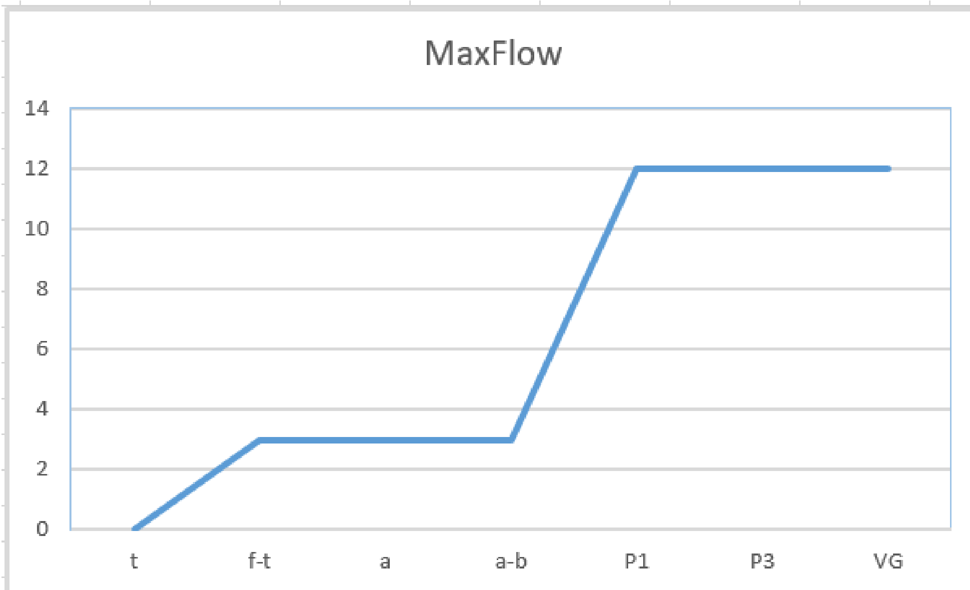

Figure 2.2. Recovery of Network A followed by Network B

In the second instance, Network B is repaired first, followed by repair of Network A with the aim to maximize flow at the earliest stage. The order of flow recovery is as observed in Figure 2.3.

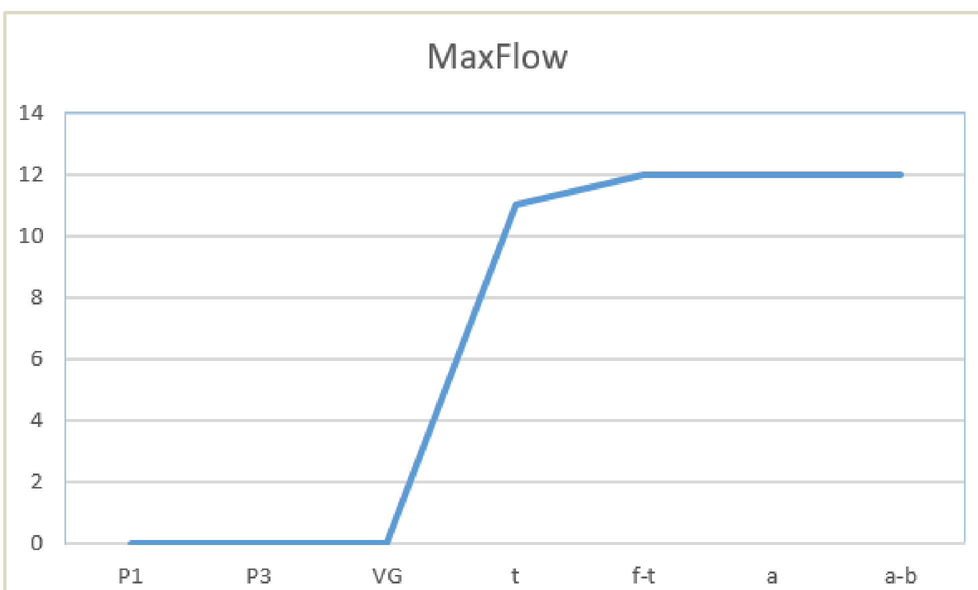

Figure 2.3. Recovery of Network B followed by Network A

In the third instance, the two networks are repaired simultaneously in-order to demonstrate the efficiency of this approach, in recovering the maximum flow in the minimum possible stages. The order of flow recovery is as observed in Figure 2.4

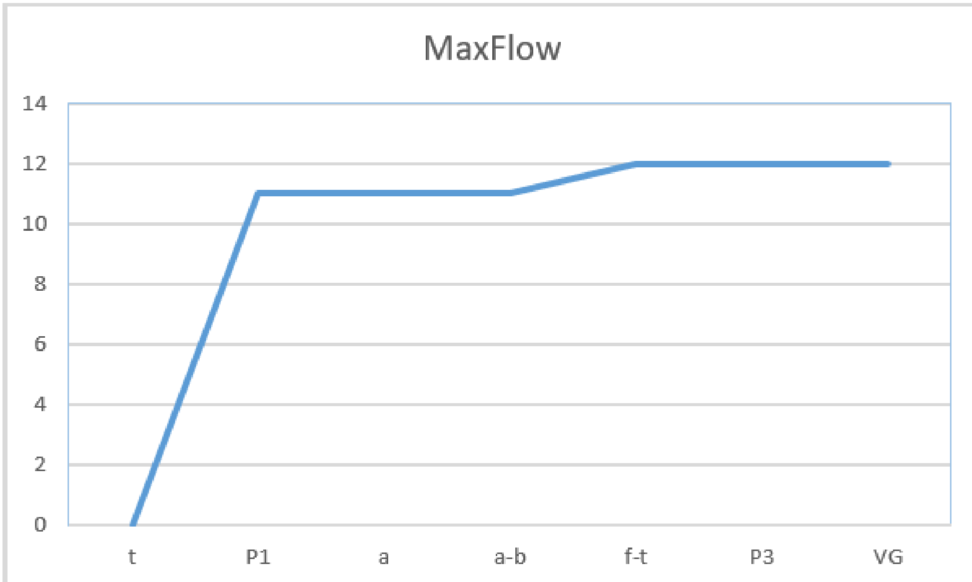

Figure 2.4. Simultaneous Recovery of Network A and B

The ideal order of repair requires coordinated repair of both the networks based on the dependencies to attain maximum flow at the earliest stages. In the case of disaster recovery, this approach helps identify the effectiveness of restoration of an element by identifying whether it's repair will be a sufficient condition for functionality. In many cases a fully unbroken or repaired element may not be functional due to external dependencies. Thus, an optimal solution for recovery must consider the dependencies to validate the efficiency and feasibility of the repair choices.

3. RELATED WORK

In [4], the coupling of communication networks with the power networks is modeled as an Intelligent Electronic Device(IED) that host control components that can transmit signals for load shedding to distribution centers. The work explores the impact of cascading failures in such a model. In the area of network restoration after failures [5], proposes the use of a restoration order based on dependencies within a communication network of servers. This order is auto generated on the basis of dependency mapping. The earliest work done in progressive network recovery. Complementary to the approach defined here, [8] discusses the multi-commodity flow problem to address the issue of maximizing total flow in a failed network by minimizing the flow across the failed edges. [9] seeks to identify the restoration order that maximizes flow at the earliest stages. In a single network with no dependencies or node failures, the solution involves the breakdown of the problem into multiple single stage sub-problems. These sub problems are resolved by the sensitivity analysis of optimal solution that sheds light on the ideal restoration order. [10] proposes a solution for efficient recovery of the nodes in a network after large scale failures with an aim to minimize repairs needed to satisfy the flow demand. They propose a demand based centrality that prioritizes nodes based on the flow demand that they can satisfy upon repair and identifies the paths to route this demand.

However, both these works focus on recovering a single network after failure. [11] focuses on the design of the network recovery model that is solved by Mixed Integer Linear Programming after factoring in various budget and resource constraints. The interdependent network design problem (INDP) creates a mathematical model of the interdependent network. It then proposes an optimal solution based on the output of a Mixed Integer Program that tries to restore flow balance across a failed network, by minimizing the various costs. The cost includes restoration costs, preparation costs, the load and supply balancing costs. The objective function thus aims to optimize costs for a given increase in flow.

4. PROBLEM COMPLEXITY

In a multi-stage recovery process, identifying the repair order to restore maximum flow in the earliest stage is NP-Hard. This conclusion is based on the work done by Wang Et al. [9] which considers the recovery of a single network with multiple stages. To prove that the problem is NP-Hard, they consider the reduction of the multi-stage recovery problem to a single-stage. Then they proceed to prove that the decision version of the SET COVERING problem which is NP-Complete is an instance of the reduced recovery problem. When considering the recovery of the communication network and a fully functional power network, the problem becomes equivalent to previously explored work. Thus, the current problem must be at least as complex as the former. Hence the problem is NP-HARD.

5. OPTIMIZATION

Consider the optimization problem that repairs the failed edges and nodes so that flow may be maximized at the earliest. The decision variables $x_{ijk} = \{0, 1\}$ and $x_{ik} = \{0, 1\}$ indicate whether the damaged edge (i, j) or node i is to be repaired in step k.

The variables $y_{ijk} = \{0, 1\}$ and $y_{ik} = \{0, 1\}$ indicate whether the edge or node i has been repaired in any stage up to k. This helps understand whether the edge can be used at that stage. The value $P_{ik} = \{0, 1\}$ is used to denote whether the node $i \in V_c$ has power supply at stage k or not.

The maximum total flow at K between *s* and *t* is given by:

$$\max \sum_{k=1}^{K} \sum_{(i,t)\in E_c} f_k\,(i,t) \tag{2}$$

Subject to:

$$\sum_{(i,j)\in E_p^f,E_c^f}^{K} x_{ijk} r_{ij} + \sum_{i\in V_p^f,V_c^f} x_{ik} r_i \le R; k = 1,2\ldots K \tag{3}$$

$$\sum_{j:(i,j)\in E_c}^{K} f_k(i,j) \quad - \sum_{j:(i,j)\in E_c} f_k(i,j) = 0; \forall (i,j) \ne \{s,t\} \tag{4}$$

$$\sum_{k=1}^{K} x_{ijk} \quad \le \sum_{k=1}^{K} x_{ik} \le 1 \tag{5}$$

$$y_{ijk} \le \sum_{k=1}^{n} x_{ijk} \;\; ; y_{ik} \le \sum_{k=1}^{n} x_{ik}; \quad 1 \le n \le K \tag{6}$$

$$y_{ik} \le \sum_{k=1}^{n} P_{ik}; \quad 1 \le n \le K \tag{7}$$

$$f_k(i,j) \le c_{ij} y_{ijk}; \quad k = 1,2\ldots K \tag{8}$$

$$f_k(i,j) \le c_{ij} y_{ik}; \quad k = 1,2\ldots K \tag{9}$$

$$f_k(i,j) \le c_{ij} y_{jk}; \quad k = 1,2\ldots K \tag{10}$$

The resource constraint in Equation (3) indicates that the cost of repairs in a stage k will be limited by the total available resources. Flow conservation is established by Equation (4) that ensures that for all nodes other than *s* and *t*, flow going into the node must be equal to the coming out. Equation (5) ensures that any node or edge is repaired not more than once. While y_{ik} denotes whether a node is repaired by stage k per Equation (6), Equation (7) imposes the dependency on the power supply. The node i is not functional when the power supply to it, denoted by P_{ik} is unavailable. In the power network, consider a generator node vg that generates the total power, P_{max} in the power grid network. This power flows throughout all the edges in the power network such that,

$$\sum_{i:(v_g,i)\in E_p} \phi_k(v_g, j) \le P_{\max} \tag{11}$$

If the node i ϵ V_c in the communication network is dependent on z_i ϵ V_p in the power network, the path from v_g to node i is considered functional when the flow into the node z_i is greater than or equal to the flow out of it.

$$\sum_{j:(z_i,j)\in E_p} \phi_k(z_i, j) - \sum_{j:(j,z_i)\in E_p} \phi_k(z_i, j) \ge 0; \forall (i,j) \in V_c \tag{12}$$

As mentioned earlier, the decision variable x_{ijk} = {0, 1} (and x_{ik} = {0, 1}) indicate whether the damaged edge (i, j) (or node i) is to be repaired in step k. The variable γ_{ijk} = {0, 1} (and γ_{ik} = {0, 1}) indicate whether the edge (or node i) has been repaired at stage k. Thus, P_{ik} indicates whether the power supply transmitted by a power node is available or not.

$$\gamma_{ijk} = \sum_{k=1}^{K} x_{ijk}; \tag{13}$$

$$\phi_k(i, j) \le c_{ijk} * \gamma_{ijk}; \quad k = 1,2...K \tag{14}$$

$$\phi_k(i,j) \le c_{ik} * \gamma_{ik}; \quad k = 1,2\ldots K \tag{15}$$

$$\phi_k(i,j) \le c_{jk} * \gamma_{jk}; \quad k = 1,2\ldots K \tag{16}$$

$$P_{ik} \le \sum_{j:(z_i,j)\in E_p} \phi_k(z_i,j) - \sum_{j:(j,z_i)\in E_p} \phi_k(z_i,j); \tag{17}$$

6. PROPOSED SOLUTION

The paper proposes a centrality based solution that considers, the repair cost and position of the node in the shortest path between the source and destination. Using this centrality to assign weights to the edges and nodes, the shortest path between the pair of nodes is identified and repaired. After repair, the centrality is updated to reflect the new repair costs of elements. After the identification of the first shortest path, the next shortest path is identified based on the residual capacity of the edges in the shortest path. This ensures that when an edge which has been repaired and has used its full capacity to support existing flow, the algorithm identifies new edges to repair. The repair of these new edges allows for an increase in the total possible flow between the node pair (s, t).

6.1. REPAIR CENTRALITY

The repair centrality of an element reflects the total repair cost of the elements that need to be repaired in order for it to function. Thus an unbroken node from the power network $i \in V^f_p$ may be non-functional due to a failed connection to the generator $v_g \in V_p$ node. The node's Repair centrality, δ_r (i) is initialized to reflect the cost of repair of the shortest path, $P_g(i)$ from the node to the generator and its distance d from the generator v_g. If the path to the generator is made up of a series of nodes and edges including the node i under consideration and is denoted by $P_g(i)$ then the centrality is defined as,

$$\delta_r(i) = \frac{1}{\sum_{i \in P_g(i)} r_i + \sum_{(i,j) \in P_g(i)} r_{ij} + d}, \forall i \in V_p^f \tag{18}$$

Due to the dependency of the communication node on the power supply, the repair centrality of a node in the communication network will reflect the the repair centrality of its power supply, its repair cost and distance d from the source node s. This is to prioritize the repair of nodes closer to the source. If node i depends on node z_i in the power network, its centrality is given by

$$\delta_r(i) = \frac{1}{\sum_{i \in P_g(z_i)} r_i + \sum_{(i,j) \in P_g(i)} r_{ij} + r_i + d}, \forall i \in V_c^f \tag{19}$$

The repair centrality of the edges in both the networks are decided by their cost of repair as well as the average centrality of the node pair they connect.

$$\delta_r(i,j) = \frac{avg(c_r(i) + c_r(j)) * capacity}{r_{ij}}, \forall (i,j) \in E_c^f, E_p^f \tag{20}$$

Since this computation can be completed offline it does not affect the complexity of the algorithm.

6.2. REPAIR

Once the repair centrality has be initialized for all edges in the network, the inverse of the centrality is assigned as weights to the edge. This implies that the edges with lower centrality will have the highest weights. This weighted graph is used in the identification of the shortest path between the source and the target in the communication network. Since the elements with the lowest repair cost in the path between s and t will be chosen at the earliest, they are repaired first to complete the repair of an entire path between s and t. This ensures that all flow that can be achieved in this path is restored. After this path has been identified, all elements in it are restored to functionality across multiple stages of repair.

6.3. UPDATE CENTRALITY

Since the paper aims to identify new paths that can contribute to flow, the centrality of all elements is updated to account for the new repairs. The edges that have no more residual flow to offer, i.e if the flow in them is equal to the maximum capacity, then their centrality is set to minimum value to encourage the use of new edges in the path. Once the new centrality is updated for the elements, the repair is undertaken again.

6.4. TERMINATION

The algorithm keeps identifying new paths through which it can route flow, repairs it and then updates centrality. After all paths have been identified, the algorithm terminates when the residual capacity of the path identified is non positive. The residual capacity of the path is defined as the lowest residual capacity available among all edges in the path.

Algorithm 1: Progressive Repair

Input : The interdependent networks G_c, G_p with failed nodes V^f_c, V^f_p and edges E^f_c, E^f_p , s, t

Output: Repaired network G_c, G_p with Max Flow

```
Initialize centrality;
Calculate shortest path P(s, t);
while (residual capacity of P(s, t) > 0) do
    |   for each element in shortest path do
    |   |   repair element;
    |   |   if node.powersupply is broken then
    |   |   |   repair Pg(node:powersupply)
    |   |   end
    |   end
    |   Commit flow through shortest path;
    |   Update residual capacity;
    |   Update centrality;
    |   Calculate new P(s, t);
end
```

6.5. COMPLEXITY

The complexity of the algorithm is mainly affected by the update of centrality for all elements in the graph. This is necessary as the repaired elements may affect the repair centrality of multiple other elements. The repair centrality of a previously repaired element is not recalculated however once it has been set to a higher value. Thus the algorithm has a complexity that increases linearly with the percentage of failures. In the worst case, the algorithm termination is also upper bounded in as many steps as there are failures if the algorithm can repair only one element in each stage.

7. GREEDY APPROACH

The performance of the algorithm is tested in comparison to a straightforward greedy solution. This prioritizes the edges and nodes based on cost-effectiveness. For any edge, the value of

$$w_{ij} = \frac{r_{ij}}{c_{ij}}, \forall (i,j) \in E_c^f, E_p^f \tag{21}$$

is used to evaluate the priority of the edges. The edges are then sorted in decreasing order and repaired. Note that when an edge is repaired, the nodes connected to it are repaired with it. Since the capacity of the power edges are considered infinite, the choice alternates between the communication and power edges when choosing the best one for repair in each network.

8. EXPERIMENTS

To test the performance of the heuristic, multiple topologies based on both synthetic and real networks are considered. The Bell Canada Topology is used to model the real-world communication network. The network has 48 nodes and 64 edges. The power network is a synthetic network based on an abstraction of existing power system models. [3] They have an average of 20 nodes and 20 edges. The network size is constrained by the execution time of the optimal solution. The capacity of the links in the communication network is a pseudo-random number with a ceiling of 10 as is the cost of repair with a ceiling of 20. The resource budget at each stage is 20 thus allowing for a minimum of one repair at a stage. The source and destination are selected to be sufficiently far apart from the other based on hop distance. In synthetic and real networks, magnitude of failure across the network is varied. In the synthetic networks, the network size and density of edges are modified to understand the performance.

8.1. VARIATION IN PERCENTAGE OF FAILURE

When using the Bell Canada Topology to simulate failure in the interdependent network, the progressive recovery solution performs close to optimal. This can be observed in Figure 8.1, 8.2, 8.3 and 8.4.

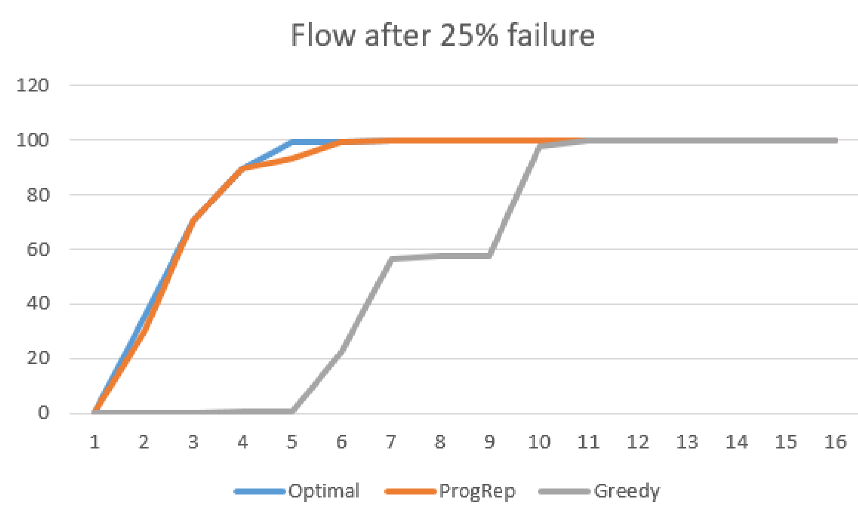

Figure 8.1. Real Network - 25% failure

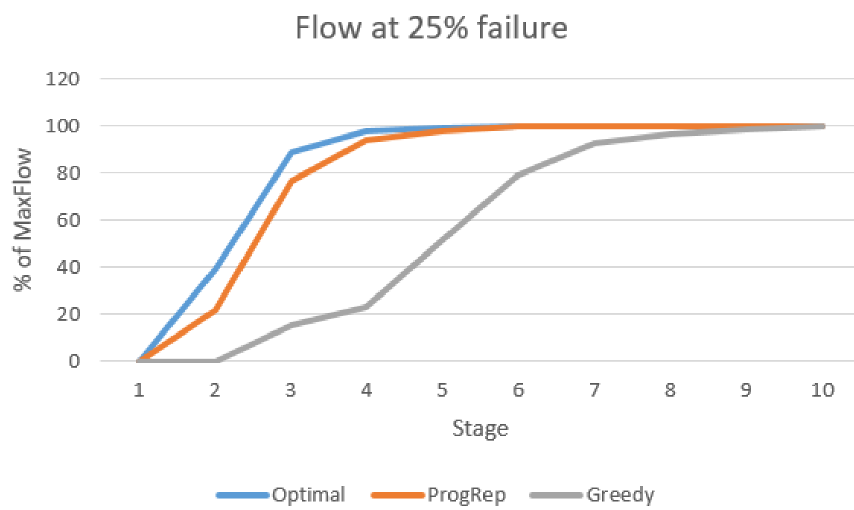

Figure 8.2. Synthetic Network - 25% failure

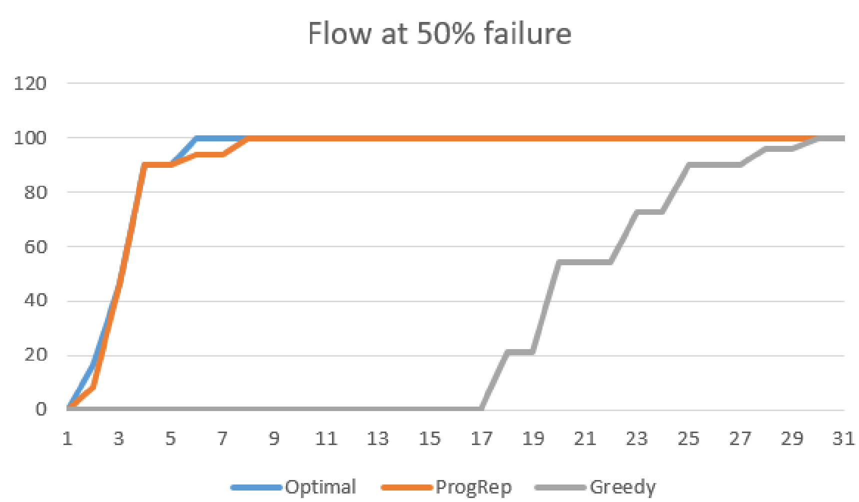

Figure 8.3. Real Network - 50% failure

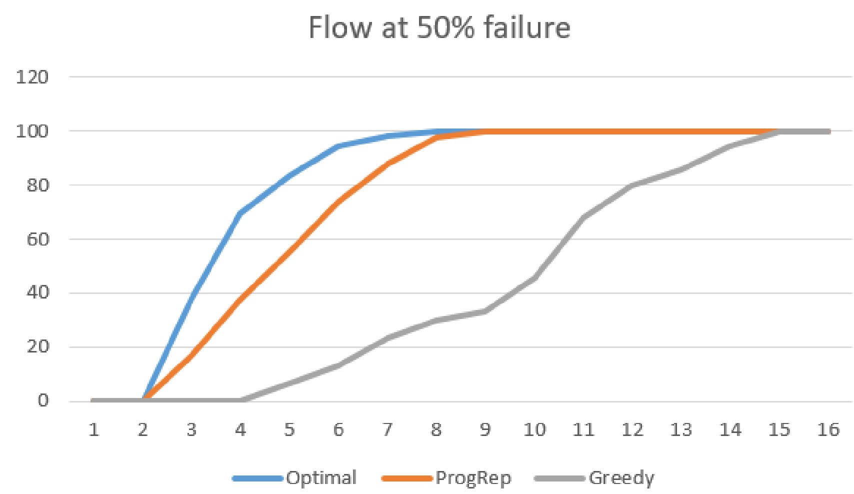

Figure 8.4. Synthetic Network - 50% failure

It can also be seen that as the network has a larger scale of failure, the solution performs even closer to optimal than in the case of smaller failures. Since the approach is based on identifying the nodes in the shortest paths, the algorithm picks nodes that are more likely to be in the shortest paths of other nodes. In the event of smaller number of failed nodes, the entire path is repaired before moving on to the next most important node, while the optimal is not restricted to repair an entire path.

8.2. VARIATION IN PERCENTAGE OF NODES

In the synthetic networks, the total number of nodes in the network is varied thereby increasing network size. The change in flow restoration capability is traced as the size of the network increases. This can be observed in Figure 8.5, 8.6 and 8.7.

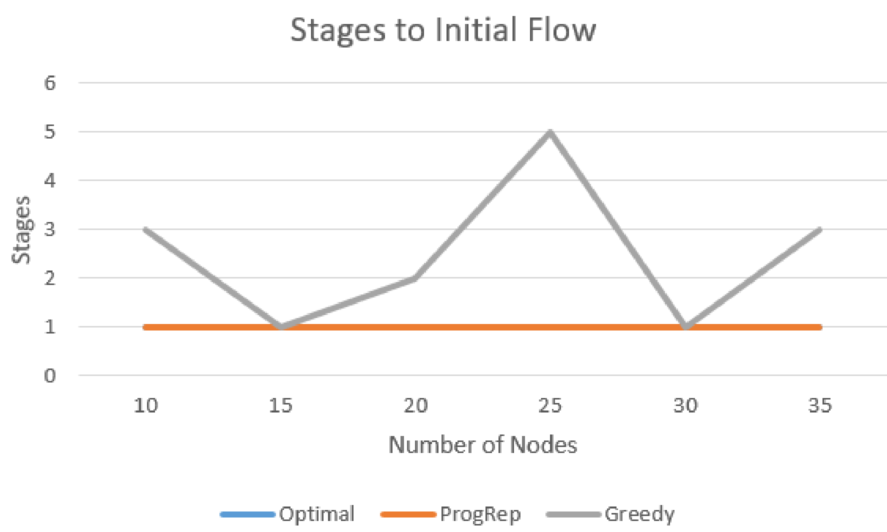

Figure 8.5. Synthetic Network - Initial Flow Restoration

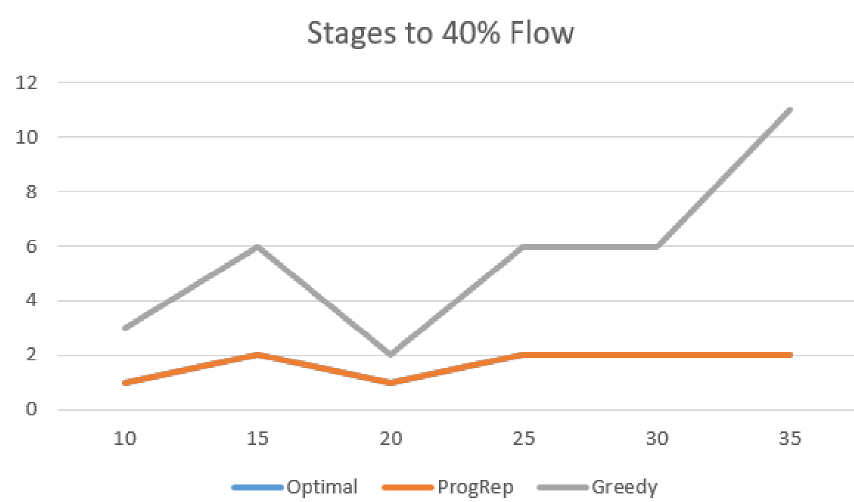

Figure 8.6. Synthetic Network – 40% Flow Restoration

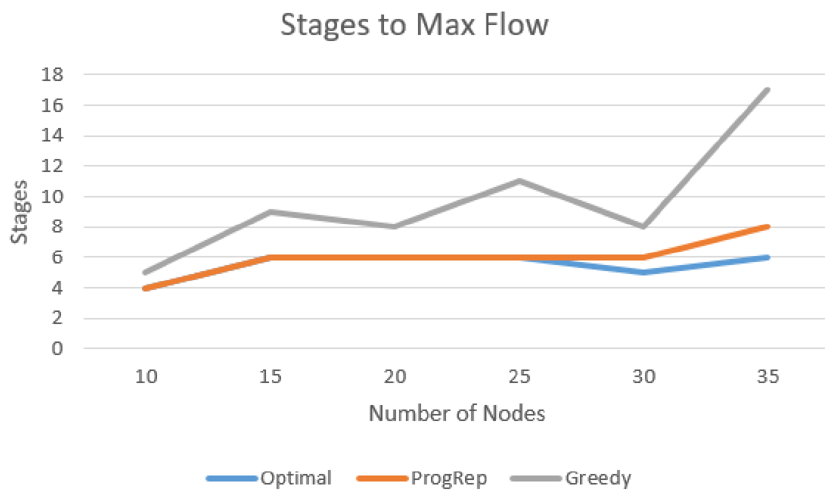

Figure 8.7. Synthetic Network - Max Flow Restoration

It is observed that there is some fluctuation in the greedy solution as it does not focus entirely on the paths being restored but only on the current element and its associated cost of repair. It is also to be noted that the flow restoration is averaged for different rates of failure from 30% to 50% in increments of 10. This however does not affect the initial restoration time. It was also observed that the time taken to reach maximum flow is larger as the network size increases. However, as this is not the priority of the approach, the delay is acceptable.

9. CONCLUSION

The paper proposes a centrality based recovery mechanism for interdependent networks. In the event of large scale failures, a progressive recovery approach will help identify and prioritize the repairs of the elements that make the maximum contribution to early flow recovery. The complexity of the problem is discussed and identified to be NP-Hard. The optimal solution is formulated and the performance of the efficient heuristic is compared with it to evaluate the performance in different failure scenarios.

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