Network Resilience Improvement Using Link Additions

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I. Introduction and Background

- **Motivation**
  - Computer network resilience to attacks
    - Targeted attacks and natural disasters
    - Disrupt its normal operation and services
  - Problem statement
    How to increase network resilience by adding a set of links while minimising the total cost
  - Possible solutions:
    - Random addition
    - Full mesh
    - Not feasible due to high cost
    - Selection Algorithms
    - Maximise resilience
    - Minimise cost

- **Finding Optimal Solution Complexity**
  - Given \( G = (V, E) \), where \( V \) nodes \( E \) links. The number of complement links in the graph is \( \bar{E} \)
  - Let \( T(G) \) be the number of graph instances that has the optimal solution
    - Optimal solution with budget constraint: \( T(G) = 2^{E} \)
    - Optimal solution with number of links constraint: \( T(G) = \left( \binom{E}{n} \right) \)
  - Both intractable as the size of \( V \) gets larger

- **Graph Robustness Metrics**
  - **Algebraic Connectivity \( a(G) \)**
    - 2nd smallest eigenvalue of the Laplacian matrix
    - Indicator of network resilience
  - **Total Graph Diversity (TGD)**
    - Average diversity between every connected pair
  - Large TGD value indicates high resilience

- **Centrality Metrics**
  - Examples: betweenness, closeness, and degree
  - Attacking nodes with high centrality can disrupt the network normal operation
  - Add links to lower the centrality variance among the nodes, which in turn remove the vulnerability via nodes with high centrality

II. Optimisation Algorithm

- **Greedy Algorithms**
  - We implement heuristic optimisation algorithms based on a greedy approach. Given a graph, the links are added one at a time to maximise the objective function and minimise the cost. The objective functions are:
    - Maximising the algebraic connectivity
    - Maximising the total path diversity
    - Minimising centrality variance

- **Optimisation Cost**
  - The cost is defined as the Euclidean distance between the two ends of the link
  - After adding a link, we accumulated total cost of the added links as shown in Figure 1
  - Adding link length constraint to the selection of candidate links because very long links that are not practical to be added to a physical graph
  - For example, adding a physical fibre link between Los Angeles and Boston is unlikely to be feasible for providers given the high cost incorporated by adding this link

- **Optimisation Evaluation**
  - Measure the resilience of graphs in terms of flow robustness
    - The ratio of connected node pairs to the maximum number of node pairs
  - Apply three centrality-based attacks namely betweenness-based, closeness-based, and degree-based attacks. After every node removal, we measure the flow robustness value of the graph as shown in Figure 2

III. Conclusion

- **Summary and Conclusion**
  - Investigate several optimisation objective functions based on the robustness metrics maximising the algebraic connectivity, maximising the total path diversity, and minimising centrality variance
  - We show the cost incurred while adding links using each objective function
  - For evaluation
    - Apply three centrality-based attack on the non-optimised graphs
    - The results show the cost of using \( a(G) \) optimisation is higher than the other objective functions
    - \( a(G) \) optimisation yields the best resilience in most cases for the studied physical graphs
  - **Future Work**
    - Plan to investigate more graph robustness metrics
    - Perform a comprehensive comparison among all common metrics
    - Using weighted graphs

IV. References


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