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Two new multi-path routing algorithms for fault-tolerant communications in smart grid

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ABSTRACT

Recently, smart grid, which is a newer generation of electricity supply network, is getting lots of attentions due to its huge benefits. One key component of the smart gird is an integrated communication network. To make the smart grid more dependable, it is extremely important to ensure that messages are exchanged over the communication network in a reliable and timely manner. A multiple path routing might be one way to achieve this goal. Unfortunately, the existing algorithms which compute multiple node-disjoint paths are not sufficient for this purpose since in a smart grid communication network, node failures can be co-related. Motivated by this observation, we introduce a new quality multiple routing path computation problem in a smart grid communication network, namely the min–max non-disrupting k path computation problem (M^2NkPCP). We show this problem is NP-hard and propose two heuristic algorithms for it. In addition, we evaluate the average performance of the algorithms via simulation.

1. Introduction

The recent advances in power network technologies have resulted in an automated modern power supply network called the *smart grid*. The smart grid collects and utilizes the real-time knowledge of its status as well as of the behaviors of electricity suppliers and consumers to improve the overall efficiency, sustainability, reliability, and the economics of the distribution and the production of electricity [1]. One crucial component of the smart grid which distinguishes itself from the conventional power supply network is the real-time communication network connecting the grid with electricity providers and consumers. It is known that this communication network is the key enabler for the smart grid to provide a rich set of new services, such as the grids open-access market, distributed generation and storage devices, in-home networks, smart appliances, new software applications, which were previously not available [2,3].

The importance of the reliability of the communication network in the smart grid cannot be overemphasized. Many recent reports envision that in the near future, the smart grid will evolve into a highly complicated power network connecting various types of consumers from residential, industrial, and government sectors, and a wide variety of electricity sources such as traditional carbon fuel based power plants as well as emerging distributed renewable sources such as solar and wind [4]. Since the cost of the electricity generated by the renewable energy sources is much cheaper than the cost of that generated by the carbon fuel, the carbon fuel based power generation will be preferred only if the energy consumption of the consumers

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exceeds what the renewable energy sources can afford. In the power grid system, a power outage can occur if the power demand is greater than the power supply. Meanwhile, the smart grid uses the communication network to collect such demand and supply information in real time manner to cost-effectively facilitate carbon fuel based power plants (the amount of electricity supply exceeds the actual demand will be disposed). As a result, it is extremely important to ensure that the communication within the smart grid is secure, timely, and reliable [5]. This is one of the reasons why the smart grid is of great cyber security concern [6].

In a communication network, a path connecting a source node and a destination node is called a *routing path*. Currently, the routing algorithms employed by most communication networks compute a path with minimum cost, e.g. minimum number of hops or minimum total edge weight. A routing path fails if it fails to deliver a message from the source node to the destination node. In most cases, a routing path fails either by a link failure or by a node failure. Depending on the type of a communication network, one of the failures is much more frequent than the other. For instance, in a fiber optic network, link failure is highly unlikely and thus most routing failures happen at a node such as an intermediate router or repeater. On the other hand, in a wireless sensor network, link failure could be a main contributor of temporal failures and node failure can be a main contributor of permanent failures.

Briefly speaking, a multi-path routing is a routing strategy to concurrently transmit the copies of a message from a source node to a destination node throughout multiple paths. Intuitively, this is a good idea to improve the reliability of a communication since by sending multiple copies of the same message over separate paths, we have a much better chance to transfer data from a source to a destination on time despite the existence of faulty links and nodes. Therefore, multi-path routing algorithms have been introduced for reliable communications in various communication networks in the literature [7–15]. For those networks such as wireless sensor networks in which node failure is the predominating cause of permanent routing failure (link failures are more likely to be temporal) and the node failures are independent with each other, it is desirable for the multiple paths to deliver the copies of the same message to be node-disjoint with each other so that a node failure within a path would not affect the reliability of the other paths [16].

It is expected that the most common type of significant communication failure in the smart grid communication network is node failure [17–19]. However, unlike the most type of networks in which the failures are independent of each other, the node failures in the smart grid communication network can be co-related due to its unique architecture (see Fig. 1). In the smart grid, the components of the communication network such as routers need electricity to operate, and thus the power supply network is highly co-related with the communication network. As a result, a failure at the power network can result in an outage on the communication network and a failure at the communication network can result in an outage on the power network. The recent report by Nguyen et al. [20] observed

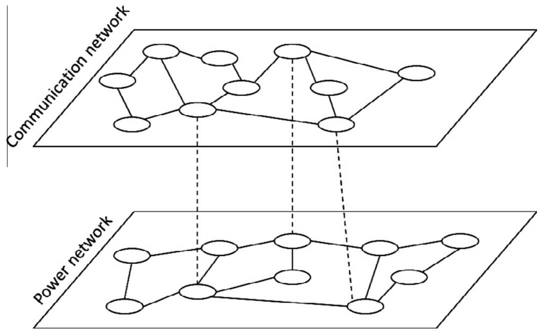

Fig. 1. This figure illustrates the interdependency between the power network and the communication network inside the smart grid.

that a node failure in a smart grid can cause the failures at some other nodes, and proposed a vulnerability assessment algorithm to evaluate the maximum possible effect of a single node failure within a smart grid. This means that the traditional node-disjoint path based multi-path routing is not proper to the smart grid communication network for reliable communication (see Fig. 2). Motivated by our observations that we discussed so far, in this paper, we introduce a new multi-path routing problem in smart grid communication networks. Largely, the contribution of this paper is twofold.

(a) We introduce the min–max non-disrupting k path computation problem (M^2NkPCP) whose goal is to compute k node-failure-disjoint paths (a node failure at one path does not lead to a node failure in another path) from a source to a destination such that the maximum cost (e.g. total Euclidean distance or hop distance) among the paths is minimized. Its formal definition is in Definition 5. To the best of our knowledge, this is the first effort to investigate

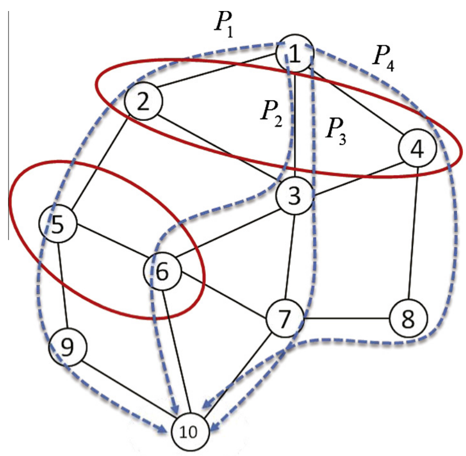

Fig. 2. In this figure, we are looking for two node-failure-independent paths from node 1 to node 10. In this example, node 5 and node 6 are interdependent, i.e. if one node fails, the other fails, and node 2 and node 4 are interdependent. Then, Path P_1 and Path P_2 may fail together if one of node 5 and node 6 fails. Also P_1 and P_4 can fail at them same time by a node failure. As a result, P_2 and P_4 would be better choice.