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A Scenario Based Heuristic for the Robust Shortest Path Tree Problem ⋆

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Abstract: IPv6 Low Wireless Personal Area Networks (6LoWPAN) is the most promising technology for implementing the Internet of Things (IoT). In order for IoT to become a reality, many challenges still need to be addressed, such as the design of energy-efficient routing protocols. The latter have to be specially resilient to high variations in transmission quality, due to constant changes in the network surrounding, which is characteristic of IoT. The most promising of these protocols is the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL). In this paper, we model the RPL routing protocol as a Robust Shortest Path Tree (RSPT), a robust variation of the Shortest Path Tree that considers the uncertainty in the link quality to improve the resilience in network routing. In RSPT, the cost of each arc is defined by an interval of feasible values instead of a single value. Then, we extend a Scenario-Based heuristic (SBA), a $O(n \cdot \log n)$ 2-approximation algorithm for this problem that can be implemented in the RPL protocol. We also implement a Mixed Integer Linear Programming (MILP) formulation for RSPT, which is used to assess the quality of our algorithm. Computational results showed that the exact algorithm based on the MILP formulation was able to find optimal solutions for all networks with up to 100 sensors in less than 8 seconds. SBA produces an average relative optimality gap below 7% for the largest networks with 200 sensors.

Keywords: Internet of things, robust optimization, mathematical programming, heuristic, RPL.

1. INTRODUCTION

Nowadays, there had been a steady growth in the number of Internet-connected devices such as computers, sensors, actuators, smartphones, home appliances, etc. This new set of devices introduces a novel paradigm in the context of modern wireless telecommunications. These devices communicate with other and collaborate with their neighbors to reach common goals, forming the Internet of Things (IoT) (Giusto et al., 2010). In order for IoT to become a reality, many challenges still need to be addressed, such as the design of highly secured and energy-efficient network protocols. Besides, those protocols must be resilient to high variations in transmission quality due to frequent changes in the network surrounding.

One of the leading solutions for this challenge is the IPv6 Low Wireless Personal Area Networks (6LoWPAN) standard (Shelby and Bormann, 2011). It is characterized by low computational power and focuses on lower energy consumption (Atzori et al., 2010). Each 6LowPAN node represents a device of the IoT. These nodes are interconnected by wireless links with potentially low communication quality and high loss rates. An error in one link can affect many others, making the network inefficient or even disconnected (Winter, 2012), among other issues.

Various routing protocols for 6LoWPAN were designed in an attempt to overcome these deficiencies. Currently, the most promising of these protocols is the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) (Winter, 2012). First, RPL builds a Destination Oriented Direct Acyclic Graph (DODAG) from a central network node s, called *sink*, to all other nodes in the network that serve the same application as the sink. Next, RPL defines the routing table as a spanning tree rooted in s. The tree construction takes into account the sensors transmission range and the distance between the sensors in the network. Each network application has its own communication tree and the routing for each application is done independently. All the communication between sensors are performed through this tree and necessarily relayed by the sink. At DODAG, there may be an exponentially large number of routes from each node to the sink, and vice versa. Thus the efficiency of the network also depends on how good are the routing tree chosen.

In this paper, we propose a routing protocol for RPL that considers the uncertainty associated with the link quality to improve its resilience. We model the RPL routing problem with uncertainties as a Robust Shortest Path Tree (RSPT), a Robust optimization variant of the Shortest Path Tree Problem (Cormen et al., 2009; Wu and Chao, 2004). Then, we propose a Scenario-Based heuristic (SBA), a 2-approximation algorithm for RSPT of $\mathcal{O}(n \cdot$

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$\log n$) complexity, n being the number of nodes. It can be easily implemented with the RPL protocol, as it uses the same messages formats. We also propose a Mixed Integer Linear Programming formulation for RSPT. We use the latter in a a branch-and-bound algorithm in order to compute the best possible DODAG and assess the quality of our algorithm. Computational experiments reported in Section 7 show that, not only the worst case performance of the proposed protocol is at most twice of that of the optimal solution, but also that its average performance is much closer to the optimal case.

The remainder of this paper is organized as follows. In Section 2 we present the background on wireless channel variability and the motivation behind the proposed protocol. In Section 3, we define the Robust Shortest Path Tree Problem and related problems. Related works are discussed in Section 4. A Mixed Integer Linear Programming (MILP) formulation was proposed at Section 5. SBA heuristic is proposed in Section 6. Following, computational results are reported in Section 7. Finally, concluding remarks are drawn in the last section.

2. BACKGROUND AND MOTIVATION

IoT refers to the networked interconnection of daily use objects. It is a highly distributed network of devices that communicate with each other and with people at their surrounding (Xia et al., 2012). It can be characterized as a highly dynamic and distributed network system, composed of a large number of smart objects producing and consuming information (Miorandi et al., 2012). IoT will enable the communication among many devices, from smartphones to home automation sensors. It has potential for many applications, such as smart home to environment monitoring.

Routing decisions at 6LoWPANs are done though the observation of link channel quality, i.e. the percentage of correctly derived packages. However, one of the characteristics of a 6LoWPAN network is the great link variability. Koksal et al. (Koksal et al., 2006) observed that the link channel variability can affects the link-level throughput negatively. In order to overcome this problem, the most common approach in literature is to characterize links as a probability function, a problem known as Link Quality Estimation Baccour et al. (2009). However, link quality is often unpredictable Baccour et al. (2012). As values of link channel quality are used to build routing tables, if these values vary, it can disrupt the network and cause the whole network to fail. Building routing protocols that are resilient to link channel variability is one key feature for constructing the Internet of Things.

In multihop wireless networks, for instance in IoT, messages are routed from a source to a destination through possibly multiple other nodes acting as relays. A path is formed by the set of links (*i.e.*, channels) between the source and the destination. Routing algorithms try to select the paths with better channels in order for messages to be transmitted much more efficiently, consuming less energy and avoiding retransmissions. However, the channel variability may lead the routing selection to the worst possible decision in that instant, causing many problems in the network. The network will fail, it may even get disconnected, the nodes will consume more energy and spend more time trying to retransmit messages and will congest even more the wireless medium with more retransmissions.

Here we propose a solution to deal with the channel variability. We propose to use Robust Optimization techniques to build the RPL routing tree. Thus, this work models the RPL routing problem as a RSPT in order to improve the network, even in the presence of wireless channel variability.

3. PROBLEM DEFINITION

Let $G = (V, A)$ be a connected digraph with a set V of nodes and a set A of arcs. Each arc $(i, j) \in A$ is associated with a cost $c_{ij} \in \mathbb{R}$. Moreover, let $n = |V|$ and $m = |A|$ be respectively the total number of nodes and arcs of G. The well-known Shortest Path problem (SP) consists in finding a path from a source node $s \in V$ to a destination node $t \in V$ such that the total cost is minimized. A solution exists if no negative-weight cycle is reachable from s to t. Polynomial-time algorithms are available to solve SP, such as Dijkstra (Dijkstra, 1959) and Bellman-Ford (Bellman, 1956). An extension of this problem is the Shortest Path Tree problem (SPT) (Cormen et al., 2009; Wu and Chao, 2004), which consists in finding a tree that contains the shortest paths from s to any other node in V. This problem can also be easily solved by Dijkstra's or Bellman-Ford algorithm. The RPL routing problem as defined in (Vasseur et al., 2011; Winter, 2012) consists in a distributed implementation of Dijkstra's algorithm for SPT. In this context, the nodes in V are associated with sensors, the arcs in E are associated with links, the cost c_{ij} corresponds to the value of the metric used to estimate the link quality.

The Robust Shortest Path problem (RSP) is a generalization of SP, where the cost of each arc $(i, j) \in A$ is defined by an interval $[l_{ij}, u_{ij}]$, with $l_{ij}, u_{ij} \in \mathbb{Z}$ and $u_{ij} \geq l_{ij} \geq 0$, for all $(i, j) \in A$, see (Karaşan et al., 2001). There exists versions of RSP with interval data in the literature. They differ from each other by the optimization criteria used (Aissi et al., 2009; Averbakh, 2005; Candia-Véjar et al., 2011; Kasperski et al., 2005; Montemanni and Gambardella, 2005a,b; Montemanni et al., 2004).

The most studied version of RSP uses the *minmax regret* criterion. It is called *minmax regret* RSP. Let $P \subseteq A$ be a path from an origin s to a destination t in G. Moreover let a scenario r be a realization of arcs cost $c^r_{ij} \in [l_{ij}, u_{ij}]$ for each arc $(ij) \in A$. The *regret* of P in the scenario r (also referred as the *robust deviation* of P in r) is defined as the difference between the cost of P in r and the cost of the shortest path S^r from s to t in r. In other words, the *robust deviation* of P in r is the regret of using P instead of S^r in case scenario r occurs. The *robust cost* of P is the largest robust deviation of P over all scenarios. The *minmax regret* RSP consists in finding the path P^* from s to t with the smallest robust cost. This problem is shown to be $\mathbb{NP}$-hard even for acyclic digraphs (Kouvelis and Yu, 1997).

We introduce the Robust Shortest Path Tree Problem (RSPT) as a generalization of RSP. Let $G = (V, A)$ be a connected digraph, where V is the set of nodes and A is the