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A greedy model with small world for improving the robustness of heterogeneous Internet of Things

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A B S T R A C T

Robustness is an important and challenging issue in Internet of Things (IoT), which contains multiple types of heterogeneous networks. Improving the robustness of topological structure, i.e., withstanding a certain amount of node failures, is of great significance especially for the energy-limited lightweight networks. Meanwhile, a high-performance topology is also necessary. The small world model has been proven to be a feasible way to optimize the network topology. In this paper, we propose a Greedy Model with Small World properties (GMSW) for heterogeneous sensor networks in IoT. We first present the two greedy criteria used in GMSW to distinguish the importance of different network nodes, based on which we define the concept of local importance of nodes. Then, we present our algorithm that transforms a network to possess small world properties by adding shortcuts between certain nodes according to their local importance. Our performance evaluations demonstrate that, by only adding a small number of shortcuts, GMSW can quickly enable a network to exhibit the small world properties. We also compare GMSW with a latest related work, the Directed Angulation toward the Sink Node Model (DASM), showing that GMSW outperforms DASM in terms of small world characteristics and network latency.

1. Introduction

The Internet of Things (IoT) [1] is a huge integration of many fields, including wireless sensor networks, embedded systems, intelligent control, data processing and data fusion, etc. In order to sense environmental factors, the large-scale nodes are deployed in the distributed areas, such as sink nodes and sensor nodes. Those nodes form a multi-hop ad hoc network system and complete assigned tasks according to the environmental requirements [2]. As a new information acquisition system, IoT has been widely used in many applications, such as industrial automation, environmental monitoring, smart home, situational awareness, target identification and tracking enemy movements, etc. [3–5]. Nevertheless, there are still many challenges to address. One recurring question is how to design an efficient and robust network topology for heterogeneous IoT.

Nodes in the network may fail due to a number of reasons such as limited energy, hardware failure, software errors, and malicious attacks. The effect of such node failures leads to a load increase on its neighboring nodes through greater energy consumption, which may in turn

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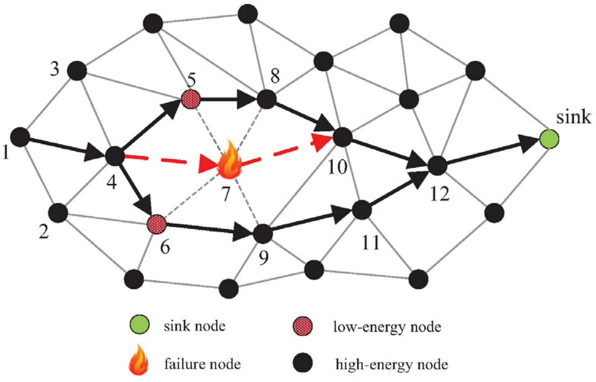

Fig. 1. Diagram indicating a cascading effect of node failure in IoT.

cause a cascading failure [6,7], and eventually leading to breakdown of the entire network. As shown in Fig. 1, Node 1 transmits data to the sink node through the path 1->4->7->10->12->Sink. Upon failure of Node 7, the transmission becomes 1->4->5->8->10->12->sink or 1->4->6->9->11->12->Sink, which leads to greater energy consumption on Node 5 or Node 6. Over time, the probability of node failure will increase and the overall organization of the network will gradually become congested and may eventually collapse. Topology robustness is thus critical, particularly in networks where energy is very limited, such as in IoT.

Robustness can be evaluated based on the capacity of a network to provide and maintain an acceptable quality of service in the presence of faults [8,9]. In the design of any network topology model, robustness can be regarded as a fundamental attribute. However, as mentioned earlier, the current heterogeneous IoT design has some shortcomings.

A summary of the topological properties of IoT shall now be explored. Network topology refers to the geometric relationship formed by nodes in a network, based on the communication links among network nodes. Typically, researchers use a graph $G = (V, E)$ to represent the network topology. In this case, V is the set of nodes, and E is the set of links between nodes. The IoT topology also describes the wireless communication of network. It forms the basis for designing network communication and routing protocols, which play a vital role in numerous network properties, such as, network lifecycle, energy consumption, reliability, and data latency. IoT topology usually consists of homogeneous topology and heterogeneous topology [10]. A Homogeneous topology is designed such that the number of nodes possessing distinct responsibilities is constant, whereas a heterogeneous topology consists of a small set of Super Sensor Nodes (SSNs) and a large number of Regular-Sensor Nodes (RSNs). SSN usually possess two or more radios and generally have a greater hardware capacity than RSNs.

Complex network theory [11] has been applied to various fields such as computing theory, biology and engineering [12]. The small world model [13,14] in complex network has desired characteristics for wireless network such as small average path length and high clustering coefficient. Small average path length is the principle that only a small number of hops are required to transfer data between any two nodes. This can reduce the time of forwarding messages and decrease the energy consumption of network nodes. A high clustering coefficient leads to a greater spread of messages throughout the network. Hence, complex network theory provides an effective modeling method for improving performance of networks. Moreover, the heterogeneous topology setting and long-range links allow for a simplified application of the small world model to the IoT. But the robustness of small world model needs to be improved [15].

The goal of this work is to design a robust topology model for heterogeneous sensor networks of IoT using the small world concept. Long-range links have been added as an attempt to implement shortcuts [13], such that particular focus is given to the local importance of nodes. Firstly, two theoretical models are studied, namely, Watts and Strogatz Small World Model [13] and Random Addition Small World Model [14]. Secondly, a Greedy Model with Small World properties (GMSW) is presented. GMSW is defined to use a greedy approach and implements a shortcut algorithm based on the local importance of nodes. This approach is particularly applicable when RSNs and SSNs are randomly deployed in the monitoring area. And it works between the data link layer and the network layer. The result of this scheme is to maintain a neighbor list for SSNs, i.e., to block out some inefficiencies forwarding path. Finally, the GMSW model is evaluated, and the results indicate that it has greater performance by only adding a small number of shortcuts than the Random Addition Model (RAM) [14] and the Directed Angulation towards the Sink Node Model (DASM) [16,17]. Furthermore, the robustness of GMSW is evaluated under general and specific failures. In both cases, the proposed model has been found to produce a greater reduction in network latency, and increased robustness.

The remainder of the paper is organized as follows. Section 2 discusses the studies related to the proposed model. Section 3 presents a summary of the properties of the greedy model with small world properties. Section 4 gives our proposed algorithm, and details the procedure undertaken to calculate the local importance of nodes as well as the manner of adding shortcuts between SSNs. Section 5 discusses and analyzes the results of our simulation study, in which the network latency was the primary source of evaluation to reflect robustness. Moreover, the parameters of average path length and clustering coefficient are evaluated. Finally, Section 6 concludes this paper.

2. Related works

The Small World Network model combines the advantages of regular and random networks. Such noteworthy advantages include small average path length and a higher clustering coefficient. It is used to describe the changes of network characteristics, as regular networks evolve to random networks. Watts and Strogatz first proposed the Small World model in 1998. It has become popularly known as the WS Small World Model [13]. The WS model starts from a lattice ring and rewires each edge at random with