A Simulation Study for Emergency/Disaster Management by Applying Complex Networks Theory

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ABSTRACT
Earthquakes, hurricanes, flooding and terrorist attacks pose a severe threat to our society. What's more, when such a disaster happens, it can spread in a wide range with ubiquitous presence of a large-scale networked system. Therefore, the emergency/disaster management faces new challenges that the decision-makers have extra difficulties in perceiving the disaster dynamic spreading processes under this networked environment. This study tries to use the complex networks theory to tackle this complexity and the result shows the theory is a promising approach to support disaster/emergency management by focusing on simulation experiments of small world networks and scale free networks. The theory can be used to capture and describe the evolution mechanism, evolution discipline and overall behavior of a networked system. In particular, the complex networks theory is very strong at analyzing the complexity and dynamical changes of a networked system, which can improve the situation awareness after a disaster has occurred and help perceive its dynamic process, which is very important for high-quality decision making. In addition, this study also shows the use of the complex networks theory can build a visualized process to track the dynamic spreading of a disaster in a networked system.

Keywords: Disaster Management, Emergency Management, Complex Networks Theory, Small World Network, Scale Free Network.

1. Introduction

Disasters have a serious impact on human society, and despite the development of science and technology, they still cause heavy casualties. On one hand, disasters usually occur unexpectedly and effective emergency/disaster management is very critical needs high-quality decision making. This requires the decision-makers to well perceive the nature of a disaster, gather relevant information, make the right judgment, and then generate an appropriate action plan. On the other hand, the real world is a networked one that is composed of many network systems, such as water supply networks, gas supply networks, power supply networks, road networks and communication networks. All these network systems are very complex and a so-called domino or avalanche effect feature is commonly shared among disastrous events. A strong initial event triggers a failure avalanche, which spreads in a cascade-like manner within a network and finally has an impact on large parts of the system. For example, the major power blackout on August 14, 2003, which lasted up to 4 days in various parts of eastern USA, not only caused severe traffic congestions, but also affected many other critical infrastructures.

This avalanche effect makes the decision making process for emergency/disaster management very complex and difficult because the decision-makers hardly perceive the phenomenon about how the disaster spreads in a complex networked system.

Effectively understanding and perceiving a disaster is very important for emergency/disaster management. In this paper, the complex networks theory is applied to help perceive the disaster spreading (the avalanche effect) in a networked system by adopting a simulation approach. Because of the capacity and capability to deal with high complexity of systems and execute a wide range of analyses under different environment, simulation experiments are a useful tool and can be used in many fields. For example, Munoz-Pacheco and Tlelo-Cuautle [1] conducted a simulation study to show the usefulness of the proposed synthesize 2D chaotic systems, Vargas-Martinez and Garza-Castafnon [2] made a simulation experiments to exam the usefulness of Pattern Search Optimization and ANNs on improving the performance of the fault-tolerant control (FTC) scheme.

The study focuses on some critical lifeline systems, such as, water supply networks, gas supply networks, power supply networks, road networks and communication networks.

The rest of this paper is organized as follows: in Section 2 a brief literature review on emergency/disaster management and complex networks theory is presented. A complex networks theory-based model that is used in this study is introduced in Section 3 and two simulation experiments and the associated results are presented and discussed in Section 4. Finally, a summary and a conclusion are given in Section 5.

2. Literatures Review

In a real-time situation, the response to a natural disaster or terrorist attack, creates a very critical, threatening decision-making context that must be consistently dealt with in a timely manner. The characteristics that make disaster responding scenarios very complex include: high levels of uncertainty [3], compressed timelines [4], significant lack of information [5], difficulty in assessing information quality [6]. Meanwhile, emergency/disaster management encounters new challenges under the complex network environment because of the avalanche effect. It is important to note that a large number of systems can be seen as a complex network whose nodes represent system components and while the links indicate the interactions between those components.

Over the last decade, the study of large-scale networked systems spanning has grown enormously[7], [8]. “Network science,” as emerging research field, has brought an interdisciplinary view to the study of complex networks. Studies on these large-scale real networks have produced many new concepts and measures attempting to characterize the structure of networks[9], [10]. A series of unifying principles and statistical distributions related to different properties of real networks have been identified from those studies. The complex network theory can be used in many fields: information systems[11], marketing[12], and design problem[13]. The complex network study can have a good help for the emergency decision making with a understanding of the situation awareness [14], which is considered indispensable for decision making in the context of a real-time, complex and dynamics environment. With the ubiquitous presence of large-scale networked systems and the study of complex networks, the complex networks theory can be well applied in emergency or disaster management.

Three famous network models are widely used to examine complex systems, random network, small world network and scale free network, and a large amount of real networks have a high degree of similarity with small world network and scale free network. One of the foremost discoveries in the complex networks theory is the existence of small-world property in many real networks.

The Small-world property [9] refers to the fact that despite their large size most networks have relatively short paths between any of their two nodes. It is pointed out in many cases real networks exhibit a scale free (or power law) degree distribution [15]. Therefore, in this study, we limit our simulation scope to the small world network and scale free network for a better match to the real networked systems.

In order to measure the avalanche effect of a complex networked system, a number of important models have been discussed in the literature and many valuable results have been found. [16] propose a model for cascading failures in complex networks and their findings showed that the breakdown of a single node is sufficient to collapse the efficiency of the entire system if the node is among the ones with the largest load. [17] present a dynamic spreading of the failures model in networked systems with the recovery process in the network. [18] and [19] follow this idea by taking different nodes or strategies into consideration. In addition, many cascading failure models have also been proposed, such as the sand pile model [20], [21], the ORNL-PSerc-Alaska (OPA) model [22] to study blackout dynamics in the power transmission grid. In particular, the CASCADE model [23] is used to examine power transmission system critical loading and power tails in probability distributions of blackout size, etc.

3. The Model

In this study the model is proposed by (Wang, Rong et al. 2008) is adopted to describe the complexity of emergency/disaster management and visualize the network-specific spreading process of a disaster. Inspired by this process of cascading failures, the model is proposed as follow.

(1).For simplicity, initial load L_j of each node j in the network is a function of its degree k_j and defined as:

$$L_j = ak_j^{\alpha} \tag{1}$$

Where a and α are tunable parameters in our study, which control the strength of the initial load of the node j.

(2).The load at the broken node i is redistributed to its neighboring node j, according to the preferential probability:

$$\prod_j = \frac{ak_j^{\alpha}}{\sum_{m\in\Gamma_i} ak_m^{\alpha}} = \frac{k_j^{\alpha}}{\sum_{m\in\Gamma_i} k_m^{\alpha}} \tag{2}$$

where Γ_i represents the set of all neighboring nodes of the broken node i According to the rule of (2), the additional load ΔL_{ji} received by the node j is proportional to its initial load, i.e.,

$$\Delta L_{ji} = L_i \frac{k_j^{\alpha}}{\sum_{m\in\Gamma_i} k_m^{\alpha}} \tag{3}$$

Meanwhile, each node j in the network has a capacity threshold, which is the maximum flow that the node can transmit. Since the node capacity on real-life networks is generally limited by cost, it is natural to assume that the capacity C_j of the node j is proportional to its initial load for simplicity:

$$C_j = T \times L_j, \quad j = 1,2,3,\ldots,N. \tag{4}$$

where the constant T (>1) is the tolerance parameter characterizing the tolerance of the network. Because every node has a limited capacity to handle the load, so for the node j, if, $L_j + \Delta L_{ji} > C_j$ then the node j will be broken and induce further the redistribution of the load $L_j + \Delta L_{ji}$ and potentially further other nodes breaking.

4. Simulation and Results

4.1 Building a Networked System

In this study, two networked systems are built: a small world network and a scale free network.

The algorithm for constructing the small world network is as follow:

Step 1: Constructing a regular graph that has ***N*** nodes and is a nearest-neighbor coupling network. These nodes form a ring and each node connect with ***K/2*** nodes around its right and left, where ***K*** is an even number.

Step 2: Randomly reconnecting the regular graph's edges with the probability ***P***.

That is, keeping one node of the target edge, and randomly selecting a node from the network as the other node of the edge, and every two nodes have just one edge and every node can not be connected with itself.

The algorithm for constructing the scale free network as follow:

Step 1: constructing a network with m0 nodes, this network can have no edges or be fully connected or randomly connected.

Step 2: Bringing in one new node every time, and connecting this node with m nodes from this network, where $m \le m_0$

The probability Π_i for the new node connecting with an existed node ***i*** can be expressed as

$\Pi_i = \frac{k_i}{\sum_j k_j}$, where kj is the degree for node ***j***.

4.2 Attack Strategies

Albert (2000) took two attack strategies into consideration for complex networks: one is failure strategy and the other is selective attack strategy. To many real networks, such as water supply networks, gas supply networks, power supply networks, road networks and communication networks, an abrupt disaster includes failure of nature disasters and failure of terrorist attacks. A nature disaster is a failure of operation and, the destroyed nodes are selected randomly. A terrorist attack is a selective attack and, the destroyed nodes are selected by the importance of the node. In our study, we examine the selective attack strategy and intend to measure the dynamics process of a network when it is attacked by destroying important nodes, which is important for emergency or disaster management to better understand and perceive the disaster's avalanche effect.

A simulation study is conducted to simulate such a selective attack strategy and examine its dynamic process. Two groups of experiments are included in this study. One is to adopt the selective attack strategy in a small world network and the other one is to adopt it in a scale free network. For these two networks, the final node number equals 30, which is an appropriate node number for develop a good visualization effect since the network becomes more complex and lower visualize when the number of the node is large. The degree of the node is used to measure the importance of the node, that is, a node with higher degree is more important. This actually reflects the situation of real networks. For example, people always consider a power station connected with many wires as an important node in the real power supply network. At the same time, some other researchers also adopt this rule, such as(TAN, WU et al. 2006). Additionally, the experiments also show the changes of some statistical properties of a network when it is being attacked, such as the degree distribution, the probability of the node degree.

4.3 Simulation Results

Fig.1 is the simulation result for small world network that has nine sub-figures to form a 3 by 3 matrix. The three sub-figures in the first row provide a dynamical process of the network evolution, the first sub-figure shows the network situation before an attack, the second sub-figure shows one intermediate situation of the dynamical process when this network is being attacked, and the third sub-figure shows the final situation of this network when the dynamical process has been over. This three figures offer an intuitive effect about the changes of the small world network. As we know this dynamical process can improve disaster/emergency managers' situation awareness ability and, this situation awareness is vital for better understanding the disaster and making high-quality decision, especially in a short time when a disaster has happened.

The second row and third row present the changes of statistical properties of this network. The three sub-figures in the second row show the changes of node degree distribution of the small world network. The first sub-figure shows the node degree distribution before this network is attacked, the second one shows the distribution at one condition when it is being attacked, and the last one shows the final distribution. The three sub-figures in the last row show the changes for node degree probability before, when and after this network is attacked.

These changes of the statistical properties provide some details of information about the dynamical process of the network evolution. One can easily obtain the information about which node is destroyed at any time of this dynamical process and how many nodes survive and the final connection information the network after this process is over.

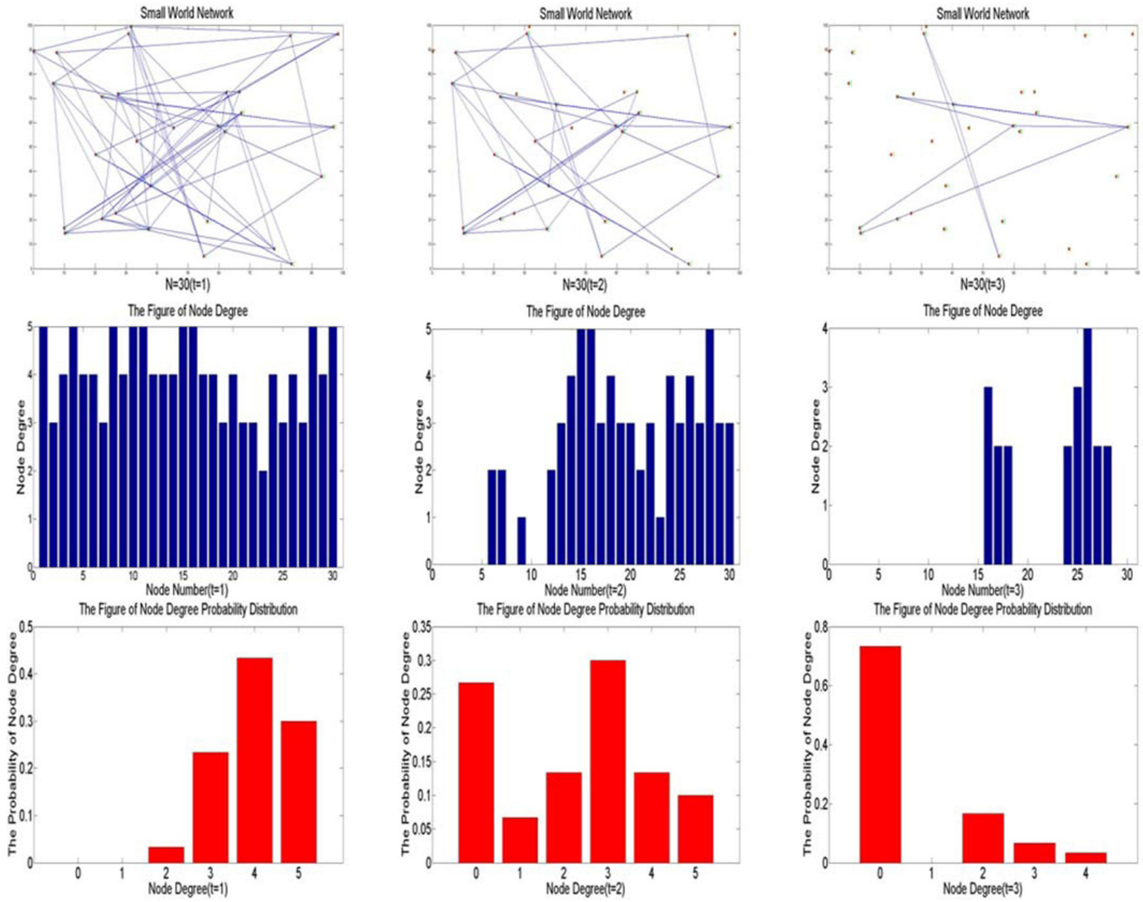

Figure 1. The simulation result for small world network.

For example, it can be seen that the node 1, 2, 3, 4, 5, 8, 10 and 11 are destroyed and the node 15, 16 and 28 have the same maximum degree and the value is 5 from the second sub-figure of the second row.

One also get the information that there are just eight nodes and the degree are 3, 2, 2, 2, 3, 4, 2 and 2 for this eight nodes, respectively.

Fig.2 presents the simulation results for the scale free network. It is constructed based on the same principles adopted for Fig. 1.

The first row shows the dynamical process of the scale free network evolution, the second row provides changes of node degree distribution, and the third row offers the changes for probability of node degree.

The scale free network has the power law property for degree distribution, and the first sub-figure in the second row shows this property.

One can get one important result from second row: the network always shows the power law property at any time when this network is attacked.

This simulation also can offer useful information when the avalanche effect occurred which can increase the effectiveness of disaster/emergency decision making. This simulation fits particularly the situation when real networks own the power law property.

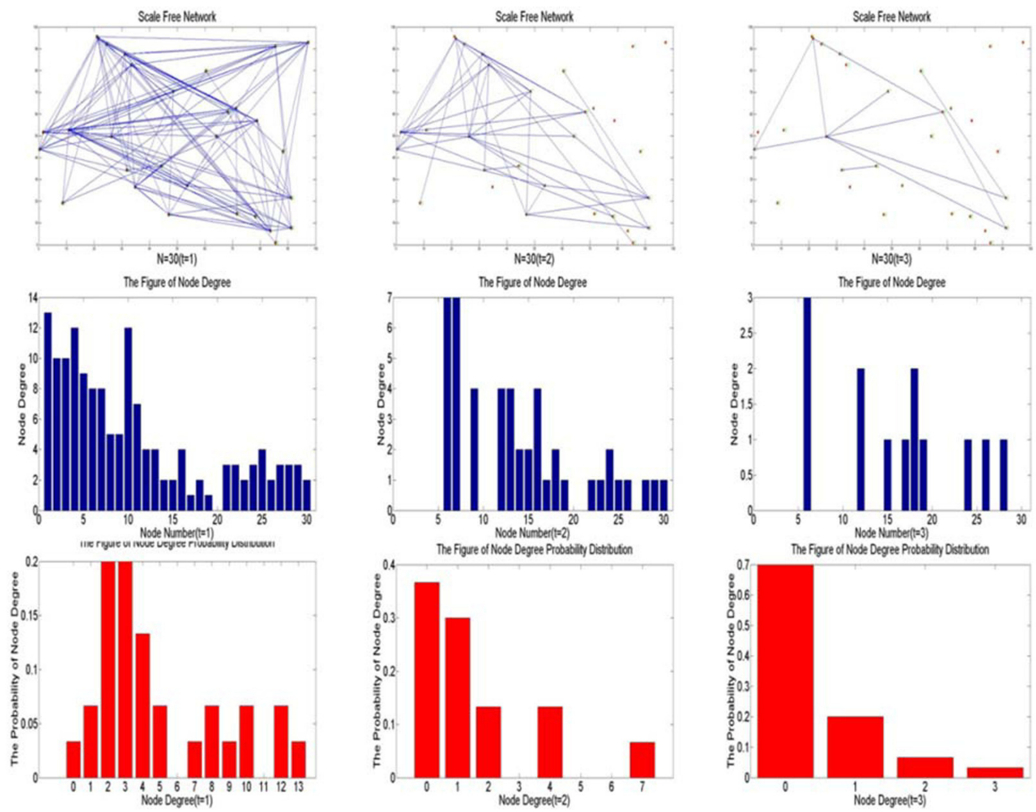

Figure 2. The simulation results for scale free network

5. Conclusions

In this study we investigate the effect of complex networks theory to be used in disaster/emergency management, especially for grasping and perceiving some key characteristics of a disaster, which is very important for decision making in a short time. This work is a novel attempt for enhancement of disaster/emergency management. Based on the simulation, one can conclude that the complex networks theory can help understand the disaster by offering visualized dynamical process for the avalanche effect when a target network is being attacked by destroying the important nodes.

One can obtain the useful information such as which node is destroyed at any time of the dynamical process, the degree distribution and node degree probability changes at any time. One can also conclude that it is possible to apply complex networks theory to disaster/emergency management, because complex networks theory can be used to capture and describe the evolution mechanism, evolution discipline and overall behavior of the networks.

Additionally, we discovery an important result from the simulation: the scale free network always shows the power law property at any time when the network is attacked.

To summarize, the simulation results shows that the complex networks theory is a powerful tool for forming situation awareness and perceiving the spreading of a disaster. However, more experiments should be conducted in the future study in order to further understand the complexity and other key features of a disaster.

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