Complex Network-based Growth and Evolution Model for Internet of Things

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Abstract—**Currently, there are lacks of relational networks consistent with the characteristics of IOT (Internet of Things). According this situation, this paper proposes a GEM model based on the analyses of the popular IoT theories and the corresponding modeling methods as well as the newest applications of the complex network theory. First, we establish an original growth model, then the model is modified and optimized according to some special characteristics of the practical IoT in terms of preferential attachment, communication difficulty and weighted connection. At last, simulation of the model proposed by this article indicates that this model yields the power-law distribution, strength of interactions and shows a good performance of community structure, which conforms to the development law of IoT.**

Keywords-Internet of Things; Complex Network; Network Modeling

I. INTRODUCTION

The development prospect of Internet of Things [1] lies in the highly integration of the physical space, information space and social space. The problem to implement the information integration of these three spaces is to mine characteristics and analyze the regular pattern of the relationship between objects in physical space based on the data of Internet of Things. And the core of the solution to the problem is to construct the objects' relational network model [2].

Currently, studies of the relational network model focus on social network and computer network. Its universal idea is to use the complex network model to deal with the corresponding problems in these fields [3]. In the description of Watts and Strogatz, the complex network has the small-world property. The network has short average path length [4]. Barabasi and Albert proposed the BA Model. This model describes the complex network's degree to be conformed to the power-law distribution and the degree priority of node contact [5]. Then, based on the WS model and the BA model, a large number of scholars have done further studies. For example, Weighted Evolving Model [6], Neighborhood Evolving Network Model [7], Deterministic Smallworld Network Model [8] and so on. Compared with traditional regular network, complex network model has characteristics of randomness and growth. Based on these characteristics, many scholars study complex network theory to solve the problem of modeling IoT. Ref (9) proposes EAEM model based on complex network, which can construct scale-free network considering the feature of energy. Ref (10) used the relationship of shared neighbors to architect NHOC model which can perform better clustering. Ref (6, 11) point out that the strength of interactions between entities obeys power-law distribution.

However, Data of IoT has some characteristics like temporal correlation, location relevance, multidimensionality and limited resource. In the above methods, Ref (4, 5, 6, 7, 8) focus on a common phenomenon that can encompass most law of the network, but in some specific system they fail to emphasize the specific attributes of data. Ref (9, 10, 11) consider some characteristics of IoT, but the models consider less factors, so they are not comprehensive enough.

According the above issues, this paper proposes the Growth Evolution Model (GEM), in which we consider both growth and evolution of IoT. The method will solve following problems: (1) How a new node join into an existing network autonomously. (2) How the relationship of two nodes evolve in the network. (3) How the strength of interactions evolve between two nodes. The construction process of the GEM model is described as follows: (a) First, building growth model based on weighted complex network theory with the particular attributes of IoT. (b) Then, modifying the model based on the Triadic Closure Theory. (c) Finally, optimizing the model with varying strength of interactions.

II. THE CONSTRUCTION PROCESS OF GEM MODEL

A. The GEM model based on growth

The growth of the IoT means that the number of nodes in the network increases over time. Development of the network will make new nodes join into the network. How the new nodes join into the network will have a direct impact on the entire network topology. The basic growth model uses a preferential attachment mechanism, which is implemented as follows: First, constructing the basic model with the mechanism of degree priority. Then, improving the connection mechanism with the unique attributes of IoT.

1) The basic model with degree priority

The basic model is based on the connection mechanism of degree priority. In IoT, the rich nodes are generally used to be

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key nodes in the network, which contain a large collection of information, so a new node tends to interact with large degree nodes. For the growth of IoT and preferential attachment, we propose a basic growth model A:

Assume that the network begins with m_0 nodes, then two nodes are connected to each other if they interact, finally the network will develop to N nodes. The construction steps of Mode A are as follows:

(1): Start from a small number m_0 (m_0>1) of fully connected nodes.

(2): Add nodes randomly : To expand IoT, more nodes are needed, we add one node randomly each time and connect to M nodes which are selected from among all the existing nodes.

(3): Preferential attachment: When a new node joins into the network, it will select M existing nodes with the following probability Pi:

$$P_i = \frac{d_i}{\sum_{j=1}^{n} d_j} \quad (1)$$

Where d_i is the degree of node i . (Notice: the M existing nodes that the new added node is connected to are what discussed in step 2 above.)

(4): Repeat step (2) and (3) until the N-nodes network formed.

Assume that when node i joins to the network at time s, the probability of its degree k is P(k, s_i, s). Then after the newest node joining to the network, the probability of the degree of node i increasing 1 is k/2s. Otherwise the node degree remains unchanged. From this we can obtain the following recursion formula [12]:

$$P(k, s_i, s+1) = \frac{k-1}{2s} P(k-1, s_i, s) + (1 - \frac{k}{2s}) P(k, s_i, s) \quad (2)$$

Degree distribution of the network

$$P(k) = \lim_{s \to \infty} \left(\frac{1}{s} \sum_{s_i} P(k, s_i, s) \right) \quad (3)$$

Satisfies the following recursive formula:

$$P(k) = \begin{cases} \frac{k-1}{k+2} P(k-1), \ k \geq n+1 \\ \frac{2}{n+2}, \ k = n \end{cases} \quad (4)$$

So, we can derive the degree distribution function :

$$P(k) = \frac{2n(n+1)}{k(k+1)(k+2)} \propto 2n^2 k^{-3} \quad (5)$$

The formula shows that the network is typical of scale-free network. And it's degree distribution follows a power law form, the exponent is 3.

According to the above method, we simulate that a network starts with m_0=3 interconnected nodes, and then the new nodes join to the network in numerical order until the network has 60 nodes. Finally, the network topology as shown in Figure 1:

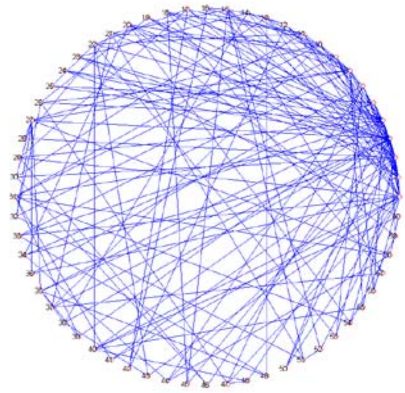

Fig.1. Network topology of Model A (m_0=3,N=60)

Figure 1 shows that not all nodes of IoT are equally important, the majority of nodes have small degree and a few have large degrees. High-degree nodes are gathered at the early nodes, so they will be more important in the network than other nodes.

2) The basic model with IoT characteristics

Model A only considers the impact of degree but not pay attention to the IoT characteristics, so it is clearly not accurate. IoT objects have some properties such as limited storage capacity, limited battery power, limited distance and so on, so two objects can't interact unlimitedly. We define communication difficulty R which is the factors that affect two nodes' interaction. The R will increase if distance increases, storage capacity reduce or energy attenuates.

This section, we will improve the Model A to Model B which considers with the IoT characteristics, the steps are as follows:

(3): Preferential attachment: Consider both the impact of degree and communication difficulty R when a new node joins to the network. The probability P_i of a new node which connects to node i is:

$$P_i = \frac{d_i * R_{il}}{\sum_{j=1}^{n} d_j * R_{jl}} \quad (6)$$

R_{il} represents the communication difficulty between node i and node l.

According to formula (6), we can get:

$$P(d, R) \propto 2n^2 (dR)^{-3} \quad (7)$$

So we can see that the network constructed as Model B is still a power-law distribution network.

We make a simulation experiment for the growth process of the method. In order to make calculation simple, we consider the distance as a major factor of communication difficulty. The network starts with m_0 =3 interconnected nodes, and then the new nodes join to the network in numerical order until the network has 60 nodes. And the nodes 1-20, 21-40, 41-60 belong to different regions. Finally, the network topology as shown in Figure 2:

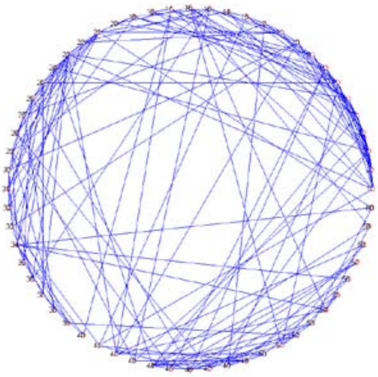

Fig.2. Network topology of Model B (m_0=3,N=60)

Figure 2 shows that, although the new node tends to connect high-degree nodes, because of the communication difficulty, the rich nodes do not gather at one region like Figure 1. Similar nodes will interact more frequently, every region will have their own central nodes. Then, the network will form different communities.

B. The GEM model based on evolution

In section 2.1, the GEM model can describe the growth characteristics of IoT accurately, but the nodes which don't have interaction within the network will never interact. So we propose the Model C to describe internal evolution of IoT.

The basic idea of the evolution is Triadic Closure. It is the property among three nodes A, B, and C, such that if a strong tie exists between A-B and A-C, there is a weak or strong tie between B-C. The schematic diagram is shown as follows:

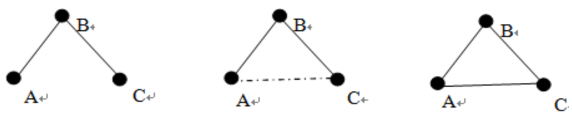

Fig.3. Schematic diagram of triadic closure

According to the theory of Triadic Closure, the intimacy of two nodes depends on the number of their mutual neighbors. The relationship intimacy function is:

$$F(i,j) = 1 - e^{-n(i,j)} \tag{8}$$

F(i,j) reflects the relationship intimacy of node i and node j. The n(i,j) means the number of mutual neighbors of node i and node j. n(i,j) is more, F(i,j) is higher, that is node i and node j are more likely to interact.

The steps of Model C are as follows:

(4): For two unconnected nodes within the network, select a pair with high intimacy F(i,j).

(5): Repeat step (2)(3)(4) until the network has N nodes.

We make a simulation experiment for Model C like previous experiment. Finally, the network topology as shown in Figure 4:

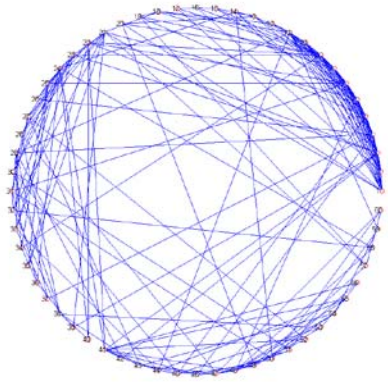

Fig.4. Network topology of Model C (m_0=3,N=60)

Compare Figure 4 with Figure 2, we can see the network topology is similar. But in Figure 4, the relationship becomes more dense in own community and the network topology shows more of cluster.

C. The GEM model based on the strengths of the connections

The Model C can accurately describe the property of growth and evolution, but it can't show the strength of the connections. The strength of the connections is important to determining which is the best route to pass information to or gather information from a node in the network. So we need also the strength of the connections to fully characterize the network. Strong connections may be regarded as preferential and reliable information channels. The more two nodes interact, the more prone they interact, so we improve the Model C as follows (Model D):

(5): Select a pair connected nodes within the network depending on probability $\prod(i,j)$, then increase 1 of the weight of their connection. The probability function is:

$$\prod(i,j) = \frac{w_{ij}}{\sum_{k,l} w_{kl}} \tag{9}$$

w_{ij} is the connection weight of node i and node j.

(6): Repeat step (2)(3)(4)(5) until the network has N nodes.

III. THE SIMULATIONS AND EXPERIMENT ANALYSIS

In this paper, we use Matlab to do the simulation experiments. The main purpose is to verify that the model has power-law distribution and clustering, also accords with the characteristics of IoT.

This section, we will draw the degree distribution of Model A-D. We assume that the network starts with m_0=3 interconnected nodes, then add a new node in each step, which will connect to 3 existing nodes. Finally, the network will develop to 500 nodes network.

From Figure 5, 6, 7 we can know the degree distribution P(K) of those models obey a power-law distribution K^{-r} for a large range of K with exponent $r \approx 3$. The degree distribution P(K) of Model C and Model D are same. Because every community has its own core nodes, the core nodes of

Model C are more than Model A and the degree of core nodes is less than Model A.

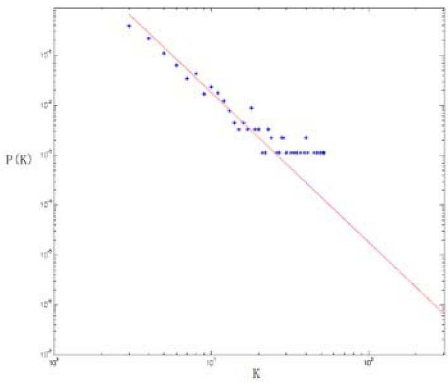

Fig.5. Probability distribution P(K) of degree K of Model A (m_0=3,N=500)

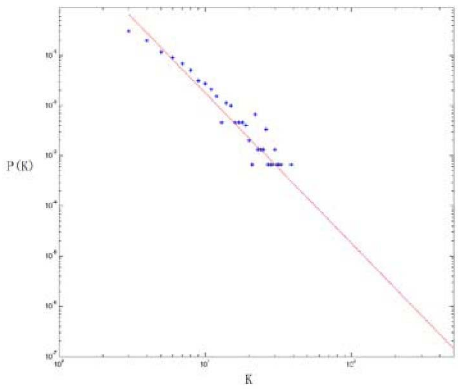

Fig.6. Probability distribution P(K) of degree K of Model B (m_0=3,N=500, R is random)

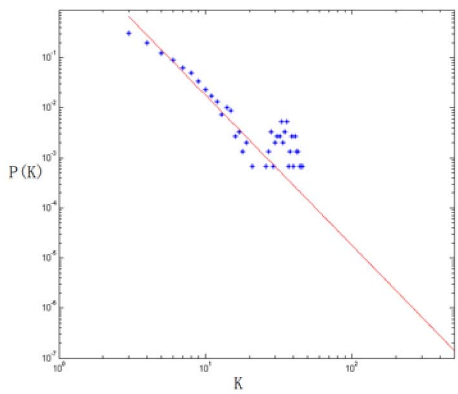

Fig.7. Probability distribution P(K) of degree K of Model C (m_0=3,N=500, R is random)

The strength of the relationship between two nodes is different, we use weight to describe the strength of relationship, as the methods of Model D, we can see probability distribution P(W) in Figure 8. This is another form of power-law in complex networks, which is also similar to many real-world data [11], it can characterize IoT more fully.

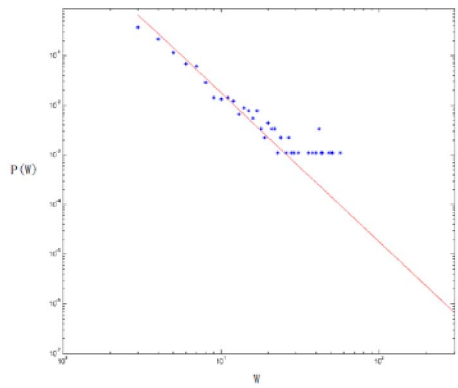

Fig.8. Probability distribution P(W) of the connection weight w of Model D (m_0=3,N=500)

IV. CONCLUSIONS

This paper proposes a GEM model for IoT based on the studies of the popular IoT theories and the corresponding modeling methods as well as the newest applications of the complex network theory. The GEM model is modified and optimized according to some special characteristics of the practical IoT in terms of growth, evolution, preferential attachment, communication difficulty and weighted connection. The result shows that the network based on GEM conforms to development law of IoT. However in this paper, the communication difficulty R we considered is relatively simple. In this case, there will be a large impact on the results because of the different settings of communication difficulty R. So how to set communication difficulty R is the focus of the further study.

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