Routing Algorithm in Complex Networks based on Gravitational Field of Nodes

Xunfang LIU
Hunan City University, Yiyang Hunan 413000, China

Abstract: For the impact of nodes on packet delivery, this paper presents the he routing algorithm based on gravitational field of nodes. This algorithm takes into account the impact on the length of the transmission path, the level of congestion of the nodes on path and the transmission capacity of nodes. The gravitational field theory is used and expounded, and also the gravitational field equations of nodes and computational formula for gravity on data packet on the transmission path are established. Experiments show that the proposed algorithm effectively balances the network load, alleviates the network congestion and improves the network throughput.

Keywords: Data Packet; Internet; Routing Selection; Node

1. Introduction

Complex network is the abstract of complex systems, and it exists everywhere; many real systems can be abstracted as network model. The complex network theory attracts large number scholars from the field of physics, mathematics, biology, computers, sociology, etc. to make in-depth research. Currently, the research of complex network theory focuses on the complexity of the network topology and the progress of network dynamics. In terms of the complexity of the network topology, scholars hopes to find out the evolutionary mechanism through the researching of the structural complexity of the real system, and then to improve the efficiency of information transmission on the network and discovery the optimal network topology. As for some infrastructure networks such as road network, electricity network, etc. the network structure is complex and covers a very wide range. If you want to change the topology as a whole, it will bring a huge impact on the surrounding environment and the economy is too costly. Therefore, by adjusting the dynamic behavior of the network it will improve the network transmission efficiency, which has become one of the main complex network theory topics.

Congestion is a complex phenomenon prevalent in many real networks, and one of the main methods to solve congestion is designing high efficient routing strategy to improve network capacity and ease its congestion degree. In the study of network routing strategies, Noh et al analyzed the random walk process on complex networks and established a precise form of expression between two nodes by the average time at the first time. They found that the random walk of the nodes with large clustering coefficient is faster than other nodes, and also in a given intervals the random pedestrians access to the nodes with large clustering coefficient are more. Ramascc et al used the extremal optimization idea studying routing strategy with the path length limited. To a certain extent, the scalability of routing policy is improved. Studies have shown that the transmission capacity of network has approximation inverse relationship with the maximum referral of nodes, and when the network size is determined, the larger the maximum referral, the smaller the network transmission capacity. Inspired by this argument, scholars begin to use the ideal of “minimizing the maximum referral of nodes” to research the network routing strategy. Danila et al presented a heuristic routing algorithm for traffic optimization problems on complex networks. This algorithm through minimizing the maximum referral of nodes the equalization of network traffic flow is achieved. Compared with the shortest routing algorithm, the average transmission time is added when the network is with low load, but it greatly decreases the average transmission time of packet when the network is under congestion. On the basis of the algorithm given by Danila et al, Kawamoto et al such proposed the improved heuristic routing algorithm. By reducing the number of iterations for minimizing the maximum referral, the convergence time calculating the traffic flow equalization is reduced.

As can be seen from the data transfer process, the data packets are often brought together in the nodes with large referral and thus congestion is happened. Actually, this phenomenon can be analyzed from the perspective of gravity theory, that is to say the nodes with larger referral have a large attraction on the transmission of large amounts of data on the network. With gravity theory, Qian Jianghai et al studied the potential expected flow between nodes through establishing the gravity model of space networks. Liu Gang et la used the neighbor nodes of packets transmission and the most congested nodes on the shortest path of neighbor nodes to target nodes to characterize the gravity effect of the shortest path to the packets and proposed routing strategy based gravitationally bound. To a certain extent, throughput of network is improved, which eases the network congestion. Node as a carrier of packet directly affects the dynamics mechanism of their network transmission, and this mechanism can be represented as the gravity effect of nodes to data packets. In different routing algorithms, the gravity effect of nodes is different. Taken the shortest routing algorithm as an example, the transmission of most packets will pass through the nodes with large referral, which indicates that these kinds of nodes have larger attraction. If the route selection process is no longer as deterministic as the shortest routing algorithm, then to ensure high transmission efficiency of network there is a need to consider the state of congestion of nodes on the network and choose a relatively unobstructed path for delivery. In this case, gravity effect of single node is no longer dominant. The gravity effect and interaction between nodes can be transferred as the gravity effect of transmission path to data packet. The unblocked and short path is more attractive.

2. Complex Network Theory

Let Figure $G=(V,E)$ is a non-self-loop undirected network, wherein $V=\{v_1,v_2,...,v_N\}$ is the set of all nodes in the network; $|V|=N, E=\{e_1,e_2,...,e_m\}$ $V\times V$ is the set of edges between nodes; $|E|=m$.

2.1. Definition 1 Degree Centrality

The ratio of the number of edges associated with node i and the maximum number of edges possible existed. The expression of the Degree centrality is expressed as follows:

$$DC_i = k_i/(N-1) \tag{1}$$

Wherein ki represents the number of edges associated with the node i in the network. The definition of degree centrality indicates the ability of a node and the communication capacity with other nodes. The greater the value is, the more important the node is in the network.

2.2. Definition 2 Approximate Centrality

Assuming di j represents the number of edges on the path with node I as the starting point and node j as the end point, the approximate centrality of node i can be represented as the reciprocal of the sum of all other nodes in the network. The approximate centrality can be expressed as:

$$CC_i = N/\sum_{j=1}^{N} d_{ij} \tag{2}$$

The value of the approximate centrality of nodes is large, which indicate that the location of the nodes is in the center, and accordingly it is more important.

2.3. Definition 3 Referral Centrality

Referral centrality can be expressed as:

$$BC_i = \sum_{j\neq i\neq k\in V} \frac{g_{jk}(i)}{g_{jk}} \tag{3}$$

Wherein $g_{jk}(i)$ represents the number of shortest paths between node j and node k passing through node i. gjk represent the total sum of the shortest paths between node j and node k. Referral centrality defines that of one node is the inevitable path for other nodes on the network, it has an important role in the network. When the value of the referral centrality is large, the impact of the node is high and the correspondingly it is more important.

3. Gravitational Field of Nodes

Through analyzing the shortest routing strategy it is not difficult to find that the node with large referral can attract a large number of nodes packet in, thus the aggregation is happened. The number of packets in the buffer queue reflects the degree of congestion nodes, but also reflects the size of its gravity at the same time. So, if the gravitational distribution of nodes needs to be improved, the number of cache packets of nodes and the transmission capacity of nodes are required to consider as the main investigating factors. Through timely updating the transmission path of packet, the dynamic allocation of nodes gravity on network transmission progress is achieved.

$$Fi = \begin{cases} k\dfrac{c_i^{2\alpha}}{d_{ij}^{\gamma}}, q_i = 0 \\ k\dfrac{(c_i/q_i)^{\alpha} c_i^{\alpha}}{d_{ij}^{\gamma}}, qi > 0 \end{cases} \tag{4}$$

The above formula can be seen as the equation of gravitational field; wherein Fi is the gravity of node i to packet; κ is a constant; ci is the transmission capability of node i, that is the maximum number of packet data can be deal with per unit time; qi is the number of data packets in the current cache queue of node i; ci/qi can be seen as the degree of unblocked of the current node i; dij is the shortest length of path between node i and node j; α and γ are two adjustable parameters, which can be used to adjust the degree of unblocked of data transmission to node, transmission capacity of nodes and the degree of dependence of the path length, and $\alpha > 0$, $\gamma > 0$. In the gravitational field theory, the virtual quality of one node's gravity in the gravitational field and dark energy is direct proportion to the product of the quality of the star, and it is inversely proportional to the square of the distance of the center of rotation; it is independent with the mass of the object. For complex network node is equivalent star, and the transmission capacity c_i of node is equivalent to the mass of stars; the greater the transmission capacity, the greater the gravity; c_i/q_i reflects the degree of unblocked

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of node i (or relative access capacity), which is equivalent to the virtual mass of dark energy; the larger the c_i / q_i, the greater the gravity of data packet to node; the shortest path length d_{ij} of data packets to node is equivalent to the distance of a certain point to the center of rotation of the star; the larger the d_{ij}, the smaller the attractive force. From the equation of gravitational field it can be seen from that the gravity effect and transmission capacity of the node to data packet are direct proportion to the α power of the product of the degree of unblocked, while it is inversely proportion to the γ power of the shortest path of the node to packet. Thus, formula (4) expresses the similar physical meaning of the gravitational field theory.

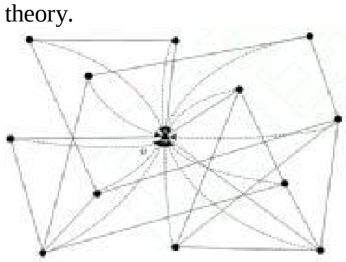

Figure 1. Gravitational Field of Nodes

4. Routing Algorithm

For a given complex network, assuming all the nodes on the network has the function like routing, packets received and packets release, and the initial state of the network load is as 0. After that each time step produces R packets and it randomly selects the source nodes and destination nodes. The generated packet is automatically added to the end of the buffer queue; each node can only send ci packet in a unit time step; the length of the buffer queue is unlimited and the FIFO mode is used. On the network transmission progress, data packets always sent by the current node to the neighbor node, if the neighbor node is the packet's destination node, the data packet is deleted; otherwise, according to the given routing policy it is added into the buffer queue of neighbor nodes.

As shown in Figure 2, assuming the node set of the shortest path of source node s of the data packet, target node t, the current node v, its neighbor set of nodes N_v and neighboring node $i(i \in N_v)$ to destination node t is as N_{it}, and setting Nit contains the nodes i but does not contains the target node t. Because the t is the destination node of the packet transmission, and its traffic state has no effect on the transmission efficiency of data packets on node v, while the congestion situation of other nodes directly affects the transmission of data packet on node v. Since each node in N_{it} will stimulate a gravitational field, that is, each node has gravity effect on the data packets. To some extent, the data packets will transfer with the shortest path along with the node $i(i \in N_v)$ to the destination node t, but this possibility is not determined by one node on the path, but it is commonly determined by all the nodes. Thus the gravity expression of the shortest path to the packet is defined as the average value of gravity of all the nodes to the packet:

$$F_{it} = \frac{1}{n}(F_1 + F_2 + ... + F_n) = \frac{1}{N}\sum_{J \in N_{it}} F_j \qquad (5)$$

Wherein, Fit is the gravity of the shortest path from neighbor node i to destination node t to the packet; n is the number of nodes of Nit.

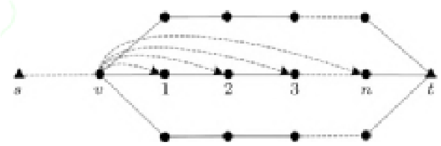

Figure 2. Routing Principles

From the perspective of the gravitational field theory, the gravity Fit of the path to packets is large, and the probability of this packet transferred along this path is large. Therefore, this thesis proposes the routing node selection strategy based on the gravitational field, and the specific routing process is as follows:

1) Obtaining the set neighbor nodes N_v of the data packet on current node v.
2) For each neighbor node $i(i \in N_v)$, if the transmission path of the packet is not passing node i, the shortest path of node i to the destination node t is obtained, and it extracts the set of nodes Nit constituting the path; the gravity of all nodes on Nit to data packets is calculated, thereby gravity Fit of the shortest path from node t to node i to the packets is calculated.
3) Obtaining the corresponding neighbor nodes when the gravity of the shortest path to the packet is the largest (ie F=max {Fit}), and the neighbor node is the next routing node of data packets transmission. If many nodes' gravity are equal and the maximum node, the neighbor node corresponding to the shortest path is selected; if there are many other nodes corresponding to the qualified the situation, and then one node is randomly selected as the next routing node.

Therefore, the packet selects the neighbor node corresponding to the path with the largest gravity on the transmission process as the next routing node. As shown in Figure 3(a), the current node exist the shortest path between two neighbor nodes for choice, and the two paths are passing node i, u, b and node j, e, f, g. When the parameter α = 1, γ = 2 and the transmission capacity of the node c = 1, the path gravity are respectively as Fit= 1/3(1/2 + 1/16 + 1/27) = 0.1998, and Fjt= 1/4(1/2 + 1/16 + 1/27 + 1/32) = 0.1577, so the node i is selected as the routing node of data packet transmission; when the con-

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gestion of node occurs, as shown in Figure 3 (b) the gravity of the two paths passing node i, u, b and node j, e, f, g to packet are respectively as 0.1998 and 0.342, so node j is selected as the next routing node. The proposed routing algorithm ensures the packet along with the path with the maximum gravity and this path is the more smooth path of the shortest paths corresponding to neighbor nodes..

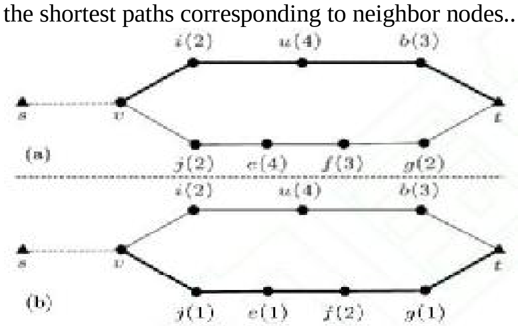

Figure 3. Routing Schematic

4.1. Ordered State Parameters

With the increase of new added load R within unit time step, network traffic status will be transferred from the free flow sate to the congested state, and there is a critical load Rc. In order ot analysis the network traffic flow, a congestion index is defined to describe the transition of free state of the network traffic flow to the congestion flow:

$$\eta(R)=\lim_{t\to\infty}\frac{1}{R}\frac{W(t)}{t} \tag{6}$$

Wherein, W (t) is the number of packets in the network at time t; R is the number of packets in the newly generated network per unit time step of; η(R) represents the ratio of the remaining number of packets in the network at the time t to the total generated number of data packets, which reflects the capabilities of network dealing with packet.

When R<Rc, the u number of newly added packets on network per unit time step is equal to the number of generated packets, the number of remaining packets in the network is W(t)=0; the congestion index is η(R)=0; When R>Rc, the u number of newly added packets on network per unit time step is larger than the number of generated packets; the network quickly enter the congestion state, η(R)>0, and it changes very suddenly. So the maximum load of Rη(R)=0 is the network throughput Rc.

4.2. Node Referral Centrality

Centrality is the main method of measure the importance of the complex network nodes through quantitative analysis of network centrality can be found on the network some nodes are more important than the other nodes. Betweenness centrality, (BC) is a measure of central the method that gives the shortest path to a node in the network by reflecting the aggregation node connectivity capabilities. To analyze the changes of network centrality of the different routing strategies, the definition of the value of referral center of nodes is appropriate changed: the value of referral center of nodes is defined as the ratio of the number of the paths of the selected routing strategy of all paths. Theoretically, the values of referral center of nodes under different routing policies are different. So $b\frac{(s,t)}{i}$ is set as the source node s, t is the number of packet passing by nodes i of target node during the transmission progress, so the number of the system within [t0, T+t0] and passing through node i is as following:

$$bi=\sum_{t_o}^{T+t_o}\sum_{s,t=1,s\neq t}^{N} b_i^{(s,t)} \tag{7}$$

Thus, referral center value of node i is defined as:

$$B_i=\frac{b_i^{N}}{\sum_{j=1}} b_j \tag{8}$$

Wherein, Bi is the referral center value of the node I; N is the number of nodes in the network. Bi reflect the degree of aggregation of the connectivity of node I; when Bi is large, and the number of data packets passing through node i is large, so it more easily lead to congestion.

5. Experimental Simulation and Analysis

5.1. Experimental Set

To test the effectiveness of the proposed algorithm, BA scale-free network model is chosen; the number of nodes is as N = 100, and m0= m = 4. During the simulation, each run has 10,000 steps, and then it can be considered that the flow on the network is basically steady. According to the average value of the last 1000 steps, the throughput Rc of network and the referral center value of the nodes Bi are determined, and for the different value of α and γ, the network routing efficiency are taken comparative experiments. What's more, data packets' maximum transmission time <Tmax>, average transmission time <Tavg> and average length of transmission path <Lavg> are the important indicators of measuring the network transmission performance. In order to further evaluate the efficiency of routing algorithm, this paper will also statistically analysis the <Tmax >, <Tavg> and <Lavg>. Without loss of generality, the dynamic characteristics of network traffic are analyzed under the situations of the transmission capacity of a node is equal to a constant (c=1) and the transmission capacity of a node is equal to a constant is equal to the degree(c=k).

5.2. Results Analysis

Figure 4 shows when the transmission capacity is as c =1, the relationship of the shortest routing algorithm among the ordered state parameter η, the maximum transmission time <Tmax>, average transmission time <Tavg>, average length of the path <Lavg>and the load R. Simulation results show that when R = 5, η has phase transition;

<Tmax> and <Tavg> are suddenly increased, which indicates that the network throughput of the shortest routing algorithm is as Rc = 5. With the increase of load R, the average path length <Lavg> is gradually decreased, because with R increasing, the network is more congested, so the packet the packet with long transmission path is not easy to reach the destination node, which causes the average length of the path decreases. Figure 5 shows when the transmission capacity is as c=1, the relationship of the shortest routing algorithm among the ordered state parameter η, the maximum transmission time <Tmax>, average transmission time <Tavg>, average length of the path <Lavg>and the load R. It also gives statistical results of 5 different combinations of the α and γ. From the simulation results it can be seen: When R <Rc, the parameter η with ordered state is close to 0; the maximum transmission time <Tmax> and the average transmission time <Tavg> are stable; the average transmission distance of packets <Lavg> increases with the increasing of R and it presents accelerating growth trend; when R> Rc, η, <Tmax> and <Tavg> are rapidly increasing. And η, <Tmax> and<Tavg> are occurred when R = 16, it can be seen that network throughput Rc = 16; <Lavg> decreases with increasing R and relatively slow; <Lavg> obtains the maximum at R = Rc. At the same time, from the simulation results it can be seen an important phenomenon. Under the 5 different combined selection of value with α and γ, the tend of changes among η, <Tmax> and <Tavg> are the same with the changing tend of the load R, which indicate that when the transmission capacity of the node c=1, the network transmission efficiency are insensitive to α and γ. By the principle of this algorithm, when the load R is small, the network is in the free flow state; the routing selecting progress is similar to the shortest routing algorithm, and the packet will be mainly along the shortest path for delivery; With the increase of R and R <Rc, the buffer queue of partial nodes on the network start to collect small mount of packets; at this time the packet will select the more smooth path to transfer and avoid the congested node, resulting in the increases of average length of transmission path. The proposed algorithm uses the avoidance strategy to ease the level of congestion, which effectively controls the worsening congestion; and it does not fall into the entire network congestion state; With the continuous increase of R, the avoidance strategy of algorithm will not be able to control increasing degree of congestion of the nodes, which will cause increasing number of nodes into congestion, resulting in the whole network into the congestion state. At this time the packet will no longer avoid certain nodes and the average length of the transmission path will be gradually reduced.

Figure 6 shows when the transmission capacity of nodes c = 1, the distributions of referral centers of nodes for the shortest routing algorithm under different load R, which gives distribution of the referral center value under R = 1, 5, 20, 60. Simulation results show that when R = 1 in the distribution of referral center value is dielectric most uniform; with the R increases, the degree of unevenness is weakened but still obvious unevenness. Figure 7 when the transmission capacity of nodes c = 1, the distributions of referral centers of nodes for the shortest routing algorithm under different load R , and it respectively make statistics of the referral center value with R = 1, 10, 16, 20, 40, 60,80, 100, and α =, γ = 2. As can be seen from the simulation results, with the amount of load R increases, the referral center value of the nodes shows the tendency of "uneven distribution-even distribution- uneven distribution"; when R=1, the distributions of the value of referral center of nodes are uneven, and the distribution is similar to the shortest route policy; with the increase of R, the value of referral center of nodes is tend to even, and when R ≈ 20, the level of even tends to the maximum; after that the distribution of the value of referral center of nodes is uneven with the increase of load R. When R = Rc, the value of referral center of nodes has been evenly, and when the distribution is the most even, the corresponding load is as R ≈ 20; all the value of referral center of nodes equal and approximately equal to 0.01.

The congestion situation of nodes of the shortest routing algorithms and routing algorithm are statistically analyzed; as shown in Figure 8 when the transmission capacity of node c = 1, the congestion situation of all l nodes on network is the number of packets in the node cache queue N (P). Figure 8 (a) and (b) are the results under the condition of load R> Rc, so the network is in a congested state. As can be seen from the simulation result, the network flow is distributed uneven under the shortest routing policy; wherein 58% node congestion level is as 0 and less than 90% congestion degree is less than 3, and the maximum congestion is 25712; The flow of network nodes is distributed evenly under the proposed routing algorithm, the distribution is greatly improved; 97% congestion degree is between 100-700, and the maximum congestion is as 703; compared with the shortest routing algorithm, the maximum extent of congestion is reduced by nearly 37 times. From the principle of the proposed routing algorithm, on the transmission process packets considers the extent of congestion, and then they can promptly and effectively avoid the heavy congested nodes and transferred the packet to other more idle nodes; gradually the he extent of congestion is eased, and ultimately the equalization of entire network load is realized . Meanwhile, since the packet transmission considers the impact of the path length, the data packets do not pass excessive detour on the network, thus ensures a strong network transmission capacity.

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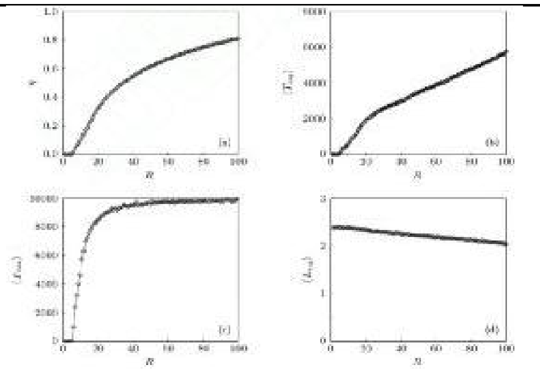

Figure 4. Changing Situations of the Shortest Routing Algorithm Like Ordered State Parameters η,The Maximum Transmission Time <Tmax>, Mean Transit Time <Tavg>, Average Transmission Distance <Lavg> and the load R (N = 100, m0 = m = 4, c = 1)

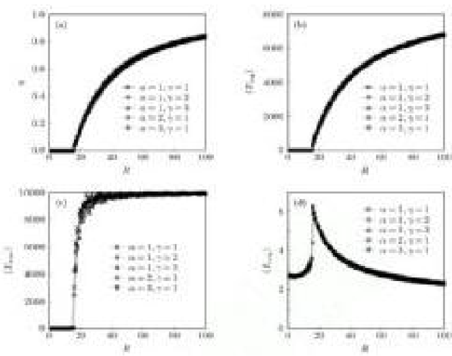

Figure 5. The Proposed Routing Algorithm Ordered State Parameter η,Maximum Transmission Time <Tmax>, Average Transmission time <Tavg>, Average Transmission Distance <Lavg> and load R (N = 100, m0 = m = 4, c = 1)

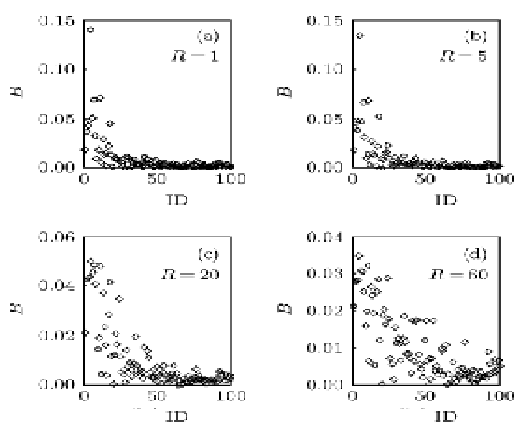

Figure 6. Distribution of the Value of Referral Center of Nodes of the Shortest Routing Strategy Under Different load R N = 100, m0 = m = 4, c = 1

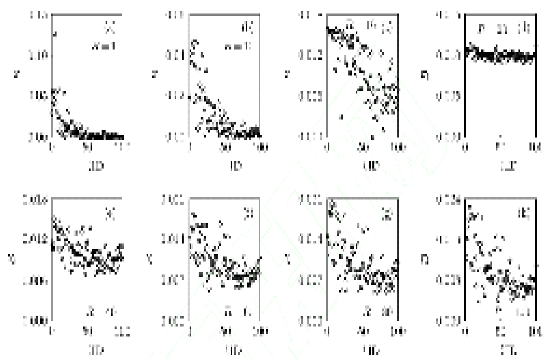

Figure 7. Distribution of the Value of Referral Center of Nodes of the Proposed Routing Strategy Under Different load R N = 100, m0= m = 4, c = 1, α = 1, γ = 2

When the transmission capacity of node c = 1, the congestion situation of all l nodes on network is the number of packets in the node cache queue N (P). Figure 8 (a) and (b) are the results under the condition of load R> Rc, so the network is in a congested state.As can be seen from the simulation result, the network flow is distributed uneven under the shortest routing policy; wherein 58% node congestion level is as 0 and less than 90% congestion degree is less than 3, and the maximum congestion is 25712; The flow of network nodes is distributed evenly under the proposed routing algorithm, the distribution is greatly improved; 97% congestion degree is between 100-700, and the maximum congestion is as 703; compared with the shortest routing algorithm, the maximum extent of congestion is reduced by nearly 37 times.

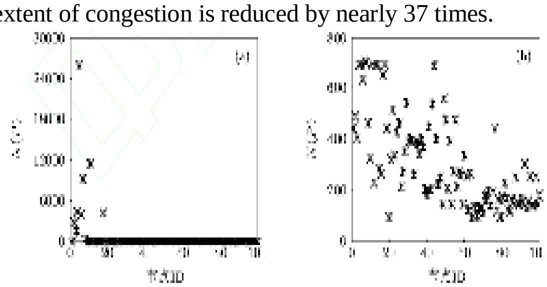

Figure 8. Simulation Results of Network Congestion N = 100, m0 = m = 4 (a); the Shortest Routing Algorithm R = 20, c = 1, N (P) ; the Total Volume is as 63716; (b); the Total Volume of Proposed Routing Algorithm is as R = 20, c = 1, α = 1, γ = 2, N (P)

From the principle of the proposed routing algorithm, on the transmission process packets considers the extent of congestion, and then they can promptly and effectively avoid the heavy congested nodes and transferred the packet to other more idle nodes; gradually the he extent of congestion is eased, and ultimately the equalization of entire network load is realized . Meanwhile, since the packet transmission considers the impact of the path length, the data packets do not pass excessive detour on the network, thus ensures a strong network transmission capacity.

6. Conclusion

The performance of the proposed routing algorithm based on gravitational field of nodes does not depend on the value of α and γ, and the changes of the value of α and γ has no effect on the transmission capacity of the network. Regardless of what value α and γ (feasible region) are, the algorithm considerably improves the transmission capacity of the network and the network throughput is approximately equal. Meanwhile, the algorithm effectively balance the distribution of the referral center value of nodes, especially when the transmission capacity of nodes c = 1, the referral center value of all nodes to some extent are the same. This algorithm takes the length of the transmission path, the level of congestion of nodes on path and transmission capacity of nodes into account. Experimental results show that: the proposed algorithm effectively balance the network load, alleviates the network congestion and improves the network throughput.

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