A congestion avoidance routing protocol for cognitive scale-free networks

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Network performance is strongly dependent on network topology, especially in scale-free network in which nodal-degree distribution is a power-law distribution. In this paper, a routing protocol for cognitive scale-free networks, called as CSRP (Cognitive Scale-free Routing Protocol), was proposed. In CSRP, each node predicts the numbers of queuing packets in its neighbor nodes when routing decisions are made, so that the optimal path is established with the tradeoff between the shortest path length and load bearing. Based on the comprehensive understanding of network traffic distribution and intelligent routing decision, CSRP can reduce network congestion dramatically. Further, we analyze the critical threshold of arrival rate where the network status changes from free to congestion. This value can reflect the maximum capacity of a system handling its traffic. Under the same network scenario, CSRP has the best critical value. Compared with other existing routing protocols, CSRP is more successful in keeping delay low and more traffic flow can be allowed into the network.

***Index Terms* - Cognitive Scale-free Networks; Congestion Avoidance; Routing Protocol**

I. INTRODUCTION

As a promising network type in future network application, cognitive network[1], which can perceive current network conditions, and then plan, decide, and act on those conditions, is attracting more and more researchers. Particularly among cognitive networks display scale-free[2] topology, such as the Internet and wireless P2P networks[3], how to minimize the average destination finding time with the maximal packet processing capacity of the network is an opening issue in this field. Scale-free topology is characterized by a power-law distribution[2] of the node degrees, which means that there is small number of highly connected nodes in the network, while a large number of nodes have relatively low connectivity. This characteristic of scale-free networks is easy to cause network congestion, so above-mentioned problem can be further explained as finding optimal strategies for traffic routing without congestion depending on network topology efficiently.

Many efforts have been done to develop routing protocols in cognitive networks, however, most of them don't consider the influence of network topology, such as SCRP[4], MARP[5], and CRP[6]. Because network performance is closely related to network topology, these methods are not suitable for scale-free networks. In scale-free networks, many routing protocols are aimed of reducing the risk of congestion and improve the utilization of network resource. In [7], a congestion-gradient driven routing protocol is used to improve the network load balance. In [8], a global dynamic routing strategy for network systems based on the information of the queue length of nodes is proposed. Under this routing strategy, the traffic capacity is further improved. Because of needing the global information of the network, the scalability of this routing is worse. In [9], the authors put forward a topology function with a tunable exponential parameter to represent the static part of local routing strategies, and add the dynamic ingredient into routing selection so that packets could avoid congesting nodes when congestion occurs. A routing method called mixed routing is proposed in paper [14]. It operates in two modes to avoid network congestion. Shortest path routing protocol is used when the packet generation rate is small. In other cases, traffic load is redistributed to other non-central nodes. Unfortunately, the embarrassing progresses have been made suffered from the lack of the information of network environments.

In this work, we focus on cognitive scale-free networks. On the condition of network topology, cognitive process is introduced in routing procedure of each node to predict the numbers of queuing packets of its neighbor nodes so that more reasonable routing path can be established. Especially, the critical threshold of arrival rate to collapse the network is obtained. Under the guidance of this value, our protocol takes the most appropriate action based on the current network conditions so that more traffic load is allowed into the network before delay starts getting excessive.

The rest of the paper is organized as follows: Section II describes our routing protocol for cognitive scale-free networks. Section III proves the critical threshold of arrival rate where a phase transition of network condition takes place from free flow to congested traffic, and Section IV presents the simulation results, which are compared with other baseline protocols. Section V concludes the paper.

II. CONGESTION AVOIDANCE ROUTING PROTOCOL

A. Network Model

Our model network consists of a set of N identical nodes, and the well-known Barabasi-Albert (BA[2]) scale-free network model is used as the physical infrastructure. The nodal-degree distribution is described as $P(k) \propto k^{-\gamma}$, where $P(k)$ denotes

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the fraction of nodes with degree k, γ is the exponent (in our work $\gamma = 3$). The capacity of node i is c_i and the number of packets arrival to node i per unit time is a_i. If $a_i < c_i$, $\forall i$ there is no accumulation in node i, and we say the network is in free phase. If $a_i \geq c_i$, $\forall i$, the network is in congestion phase. We define R as the total traffic offered into the network per unit time, and R_c is the critical value where network state changes from free to congestion. β_i is betweenness[2] of node i which defined as the number of paths going through node i. For a path from s to d, D_{sd} is defined as the numbers of hops between these two nodes.

B. Congestion Avoidance Routing Protocol

As we know, whether table driven routing[10] or on-demand routing[10], many of them are based on the notion of shortest path between two nodes. The simplest possibility is for each link to have unit length, in which case a shortest path is simply a path with minimum number of links. But when all the packets follow their shortest paths, it will easily lead to the overload of the heavily linked node, which is precisely the cause of traffic congestion. This phoneme is very serious in scale-free network, because some of the nodes in the network have high nodes degree, and are easy to become bottle nodes when shortest path routing is used. To alleviate the congestion, a good routing protocol should select path based on both the network topology and the current load of each node, so that more traffic flow can be allowed into the network.

In our work, a distributed routing protocol for cognitive scale-free networks (CSRP) is proposed that makes the length of a link depends on its transmission capacity and its projected traffic load, so that CSRP should contain relatively few and uncontested links. Fig.1 is the basic cognitive circle of CSRP.

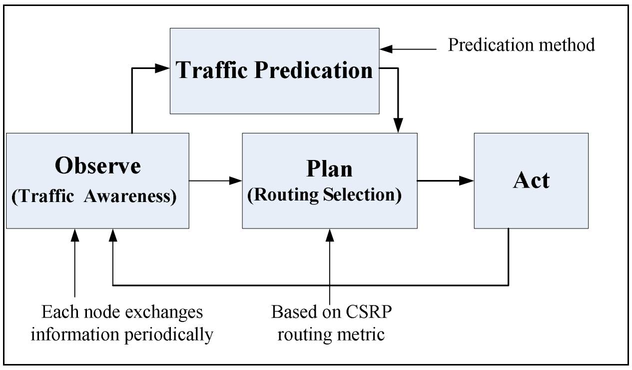

Fig.1 Cognitive circle of CSRP

As shown in Fig.1, there are three important entities of CSRP routing protocol, traffic awareness, traffic prediction, and routing selection.

1) Traffic Awareness

In order to realize traffic awareness entity, each node i is required to transmit its routing table to its neighbors periodically. The routing table of CSRP is shown in Table I. The first entry is the number of queuing packets of node i, referred as B_i. The second one records the nodes in the network that is known by node i. The last one is the hops from node i to this destination, referred as D_{ij}.

Because routing table is exchange by each node periodically, each node in the network can obtain the traffic information of its neighbor nodes. When a source node generates a new packet and want to transmit, the information of its neighbors maybe stale and unreasonable routing will be established. Hence, in CSRP how we can use the history records of traffic flow to predict the current queuing packets of each neighbor nodes in the network is a challenging problem.

Table I Routing Table of an arbitrary node *i*

Buffered packet number	B_i
Destination Node	Hops
j	D_{ij}
⋮	
n	D_{in}

2) Predication the number of queuing packets

A prediction method based on Wiener process [11] is introduced to estimate the dynamic traffic load of each node using local information. Let $B_i(t)$ be the recorder information of queuing packet numbers of node i at time t as a stochastic process, and Δt be the prediction time interval. Using the basic Wiener process, $B_i(t)$ can be modeled as

$$\Delta B_i = B_i(t) - B_i(t - \Delta t) = \mu_i \Delta t + \theta \delta_i \sqrt{\Delta t} \tag{1}$$

where μ_i and δ_i are constant parameters, θ is a standard normal random variable. So ΔB_i is a normal random variable with ($\mu_i \Delta t$, $\delta_i \sqrt{\Delta t}$). For any given time interval τ , the estimated value $\hat{\mu}_i$ of μ_i and the value $\hat{\delta}_i$ of δ_i will be given by

$$\begin{cases} \hat{\mu}_i = \dfrac{\sum_{i=0}^{k-1}(b_i(t-i\tau) - b_i(t-i\tau-\tau))}{k\tau} = \dfrac{[b_i(t) - b_i(t-k\tau)]}{k\tau} \\ \hat{\delta}_i = \sqrt{\dfrac{\sum_{i=0}^{k-1}(b_i(t-i\tau) - b_i(t-i\tau-\tau) - \hat{\mu}_i\tau)^2}{\tau^2 k}} \end{cases} \tag{2}$$

Where k is the sample times, and $b_i(t)$ is the sample value of $B_i(t)$. In practice simulations, k is 25 and τ is 1s. Based on (2), we can predicate the value of queuing packets of each node in network. Fig.2 is a simulation result of queuing packets of a node randomly selected in network. The result shows that the predication method is very valid.

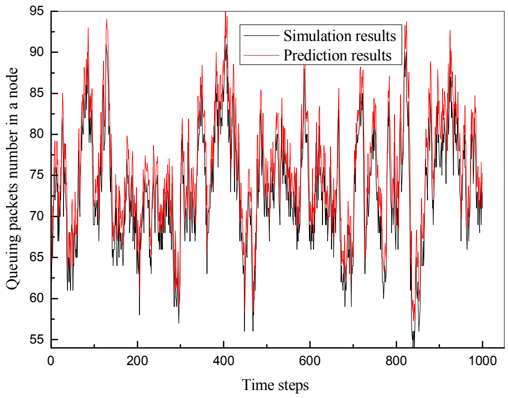

Fig.2 Queuing Packets in a node

3) Routing metric of CSRP

The routing metric of CSPR is based on minimum cost, which is described as

$$d_{ik}^{j}=\min_{j\in N_i}\left[\alpha\frac{D_{jk}}{\sum\limits_{j\in N_i}D_{jk}}+(1-\alpha)\frac{B_j}{\sum\limits_{j\in N_i}B_j}\right] \quad (3)$$

In (3), d_{ik}^{j} is the cost of link (i,j) when the destination node of this forward packet is k, N_i is the set of i's neighbor nodes, and B_j is the number of queuing packets in node j. This is a common formula in many routing protocol design, but there are two key problems in (3). The first one is how to obtain the accurate value of B_j, which has been discussed in preceding parts. The other problem is how to determine the optimal value of α. From (3), we can find that when $\alpha=1$, CSRP protocol becomes shortest path routing, and when $\alpha=0$, it becomes pure flow driven routing that selects routing only depends on the queuing packets of each neighbor nodes, thus a long path maybe selected. We will analyze the critical value of offered load R_c and then to calculate α.

III. THORETICAL ANALYSIS OF CSRP

The critical value R_c is a very important system performance because once the offered load is larger than this value, the network will become congestion. That is to say, R_c can reflect the maximum capacity of a system handling its traffic.

In the following, we focus on a packet whose destination is node k. Let the probability for a packet going from node i and forwarded to a new node j as its next-hop node be

$$p_{ik}^{j}=\begin{cases}1/d_{ik}^{j}, & \forall i,j,\ j\neq k\neq i\\ 0, & \forall i,j, i=k\ or\ j=k, i=j\neq k\end{cases} \quad (4)$$

and $\sum\limits_{j\in N_i}p_{ik}^{j}=1$. The probability of a packet going from i to j of n hops is

$$P_{ik}^{j}(n)=\sum_{m}p_{ik}^{n_1^m}p_{n_1^m k}^{n_2^m}\cdots p_{n_{n-1}^m k}^{j} \quad (5)$$

There, $(i,n_1^m,n_2^m\cdots n_{n-1}^m,j\cdots k)$ is defined as a path from i to k, different m is corresponding to different path from i to k.

Defining the matrices P_k and $\mathrm{P}_k(n)$ as

$$\mathrm{P}_k=\begin{bmatrix}p_{1k}^{1} & p_{1k}^{2} & \cdots & p_{1k}^{j} & \cdots & p_{1k}^{N}\\ p_{2k}^{1} & p_{2k}^{2} & \cdots & p_{2k}^{j} & \cdots & p_{2k}^{N}\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ p_{ik}^{1} & p_{ik}^{2} & \vdots & p_{ik}^{j} & \vdots & p_{ik}^{N}\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ p_{Nk}^{1} & p_{Nk}^{2} & \cdots & p_{Nk}^{j} & \cdots & p_{Nk}^{N}\end{bmatrix}$$

$$\mathrm{P}_k(n)=\begin{bmatrix}P_{1k}^{1}(n) & P_{1k}^{2}(n) & \cdots & P_{1k}^{j}(n) & \cdots & P_{1k}^{N}(n)\\ P_{2k}^{1}(n) & P_{2k}^{2}(n) & \cdots & P_{2k}^{j}(n) & \cdots & P_{2k}^{N}(n)\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ P_{ik}^{1}(n) & P_{ik}^{2}(n) & \vdots & P_{ik}^{j}(n) & \vdots & P_{ik}^{N}(n)\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ P_{Nk}^{1}(n) & P_{Nk}^{2}(n) & \cdots & P_{Nk}^{j}(n) & \cdots & P_{Nk}^{N}(n)\end{bmatrix}$$

Because in CSRP routing protocol, the selection of next node does not depend on previous positions of the packet, we can look it as a Markov search[15-16]. Thus, we have $\mathrm{P}_k(n)=(\mathrm{P}_k)^n$. Let a_{ik}^{j} be the numbers of paths going from i to k and including node j, then

$$a_{ik}^{j}=\sum_{r=1}^{\infty}P_{ik}^{j}(r) \quad (6)$$

The betweenness of an arbitrary node j equals to

$$\beta_j=\sum_{i=1}^{N}\sum_{k=1}^{N}a_{ik}^{j} \quad (7)$$

The average arrival rate of a node in the network is [12-13]

$$a_i=\frac{R}{N}\frac{1}{(N-1)}\beta_i \quad (8)$$

The critical value where network state changes from free to congestion is[12-13]

$$R_c=\min_{i\in N}\left[\frac{c_i}{\beta_i}N(N-1)\right] \quad (9)$$

If each node in network has the same capacity, (9) can be rewritten as

$$R_c=\min_{i\in N}\left[\frac{c}{\beta_i}N(N-1)\right]=\frac{cN(N-1)}{\max\limits_{i\in N}\beta_i} \quad (10)$$

In order to obtain the critical value, we should know the maximum value of β_i. Let H_k be a matrix such that $h_{ij}=\begin{cases}1,\text{when } i=j\neq k\\ 0, \quad \text{otherwise}\end{cases}$, and A_k denotes the matrix of a_{ik}^{j} for any given destination node k. A_k can be described as

$$\mathrm{A}_k=\sum_{r=0}^{N-1}\mathrm{P}_k(r)\mathrm{H}_k=\sum_{r=0}^{N-1}(\mathrm{P}_k)^r\mathrm{H}_k=(\mathrm{I}-\mathrm{P}_k)^{-1}\mathrm{H}_k \quad (11)$$

Here, I is a unit matrix. We can calculate (11) based on (4) and (5). Thus, the maximum value of β_i can be worked out by (6). Once the maximum value of β_i is calculated, based on (10), the critical value of offered load R_c can be obtained.

In order to verify the correctness of our analysis model, we use a very small value of R=1 packet/sec so that the network is always in free phase, and sample the numbers of queuing packets in each node when the network is in steady-state. The capacity of each node is $c = 10$ packets/sec. Table II is the theory value of R_c with 100 nodes distributed according to BA scale-free network model.

TABLE II. THEORY VALUE OF R_C

α (Routing Protocol)	Theory value (Packets/s)
$\alpha = 1$ (Shortest Path)	65
$\alpha = 0.9$ (CSRP)	105
$\alpha = 0.7$ (CSRP)	214
$\alpha = 0.6$ (CSRP)	221
$\alpha = 0.5$ (CSRP)	198
$\alpha = 0.3$ (CSRP)	181
$\alpha = 0$ (Flow Driven)	32
Random Walk	16

Besides CSRP, we also calculate some other routing protocols, including shortest path, random walk[17] (each node selects next-hop node randomly from its neighbor nodes), and routing protocol in reference [7](referred as Flow Driven).

From Table II, we find the theory value of CSRP is the best comparing with other routing protocols. As for CSRP, the largest critical value is 221when α is 0.6.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of CSPR. In order to compare with the analysis value of section III, we use the same network scenario. Meanwhile, we compare CSRP with shortest path routing, random walk routing, and flow driven[7] routing protocol.

The traffic accepted into the network will experience an average delay per packet that depends on the routes chosen by the routing algorithm. We can see from Fig.3 that the average delay increases with the arrival rate. Under the free phase, the average delay is very small. The critical values of CSRP are better than shortest path, random walk, and flow driven routing protocol. The best scenario is appeared when $\alpha = 0.6$ .This is consistent with our theory value. For the same value of average delay, CSRP is to allow more traffic into the network. Furthermore, CSPR can keep average delay as low as possible for the same value of given offered load. Different routing strategies distribute traffic in different way, the larger the value of R_c, the better performance of network.

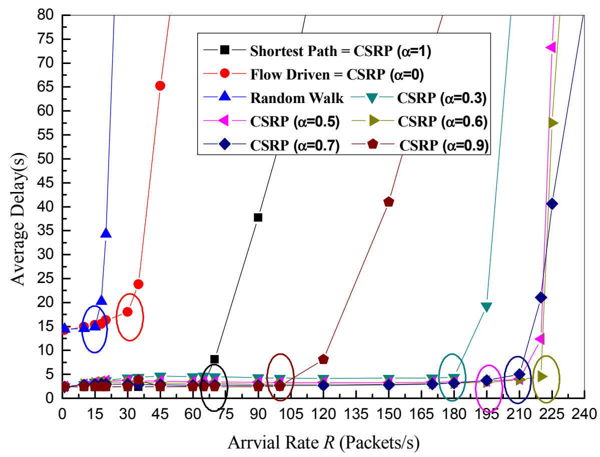

Fig.3 Average delay *v.s.* Arrival rate

As shown in Table III, the simulation value and theory value of different R_c for different routing protocol are very approximation, and the relative errors of R_c for CSRP ($\alpha = 0.3, 0.5, 0.6, 0.7, 0.9, 1$) are less than 2.8%.

TABLE III. SIMULATION VALUE OF R_C

α (Routing Protocol)	Simulation value (Packets/s)	Relative Error (%)
$\alpha = 1$ (Shortest Path)	64	1.5
$\alpha = 0.9$ (CSRP)	102	2.8
$\alpha = 0.7$ (CSRP)	210	1.8
$\alpha = 0.6$ (CSRP)	219	0.9
$\alpha = 0.5$ (CSRP)	195	1.5
$\alpha = 0.3$ (CSRP)	180	0.5
$\alpha = 0$ (Flow Driven)	30	5.8
Random Walk	15	6.2

The curves in Fig.4 are normalized throughputs performance of different routing protocols. The normalized throughput is defined as the ratio of the numbers of successful transmission packets and the total numbers of generated packets. From Fig.4, we can get the same conclusion in Fig.3. Because the critical value of CSRP is increased, more traffic can be accepted into the network before network congestion. Given the same arrival rate, the throughput of CSRP is the best in different routing protocol. Under the critical value, the probability of packet successful transmission is 100% of CSRP.

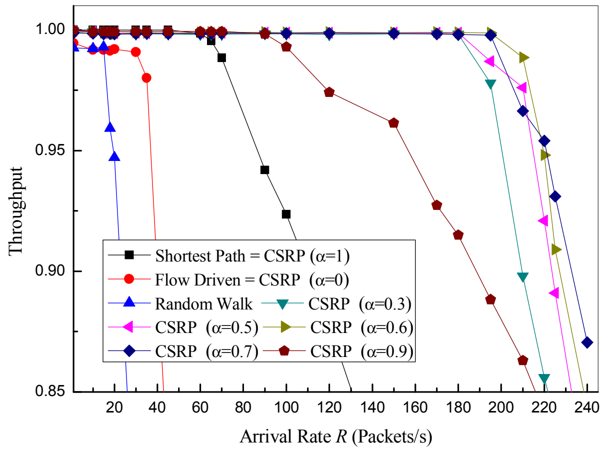

Fig.4 Normalized throughput *v.s.* Arrival rate

CSRP protocol can balance the length and the load bearing of a path effectively, so that the best performances are obtained. Table IV shows the variance of β_i (the number of paths going through node i, $\forall i$) and the maximum value of β_i. The smaller the maximum value of β_t, the larger value of R_c. Thus the best routing protocol can be obtained. From Table.4, we find that the maximum value of β_t is the smallest when $\alpha = 0.6$. This is accordance with our analysis. At the same time, when $\alpha = 0.6$, the variance of β_t has the minimum value, that means the traffic are more balancing than other scenario.

TABLE IV. SIMULATION VALUE OF R_C

Value	**SP**	**FD**	**α=0.5**	**α=0.6**	**α=0.9**
Variance of β_i	56807	172637	7566	7215	30284
Maximum β_i	1501	2638	458	413	945

V. CONCLUSION

CSRP routing is designed for scale-free network and can reduce the risk of congestion. In the same value of average delay per packet under high offered load conditions, and our routing algorithm is more successful in keeping delay low and more traffic flow can be allowed into the network.

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