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Routing Protocols in Scale-Free Networks: A Survey

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Abstract: **:** Scale-Free Network is a connected network of inhomogeneous nodes with a power-law degree distribution. The ubiquitous presence of scale-free networks has initiated the interest of many profound researchers to study the behaviour and dynamics of these networks. This article discusses different routing challenges encountered in the design of scale-free routing protocols. The scale-free routing algorithms have been grouped into three categories based on topology information used in the network, network dynamics and routing strategy for better comprehension. The paper analyses these routing algorithms highlighting their relative merits and demerits. It also suggests various application domains pertaining to the existing routing algorithms. The article also highlights some open research issues to point to future research directions which can help to design efficient scale-free routing algorithms

Keywords: *Betwenness centrality, power law, preferential attachment, Scale-Free Networks, Scale-Free routing*

1. Introduction

Scale-free network is a network where the number of connections between the nodes obeys power law [1]. There are a few nodes with a very high degree that forms the hubs in the network. The phenomenon which govern the evolution of scale-free networks are, namely, growth and preferential attachment [1] [12]. Every time a new node enters the network, it preferentially attaches itself to an existing privileged node where privilege can be measured in terms of various factors such as node degree, node betweennes , residual energy, queue length, node popularity, euclidean distance and many more depending on the type of topology construction model used.

Larger the number of nodes in a scale-free network, larger is the size of hubs. The degree of hubs grows polynomially with size of a scale-free network [4]. These networks observe *scale-free property* which states that the ratio of central nodes or hubs to the rest of the nodes in the network remains same irrespective of the network size. These networks are characterised by short average path length and high clustering coefficient.

The concept of scale-free networks first emerged in 1999 when Barabasi and Albert studied the degree distribution of nodes' in real networks such as the Internet [3]. Contrary to the expected randomness in the degree distribution, very noticeable differences were found where few nodes had very huge degrees while rest of nodes' had low degree. After this remarkable discovery, the research in the field of scale-free networks intensified. As a result in the last two decades, the scale-free property has been detected in the degree distribution of many real-world evolving networks such as the Internet, Communication networks [4][15], Social Networks [31][33], Citation networks [39], Wireless Sensor Networks [20] [46], Sexual networks [27] and Trade networks [36]. The in-depth study of the properties and behavior of scale-free networks can be extremely beneficial in boosting our understanding of the evolution of these diverse yet similar real-world networks. The technological and information revolution has enormously increased the size of real-world networks. Owing to the limited physical capabilities of routers to relay information, routing has become a very daunting task in scale-free networks. An ideal scale-free routing strategy should aim for high traffic capacity and short average path length.

The simplest scale-free routing strategy is the shortest path routing [51] where the packet is sent to a node that has the shortest path to the destination. But if data is frequently routed through central nodes/ hubs, they get overloaded and soon become traffic hotspots and the whole network gets affected. Several variations of the basic shortest path scale-free routing strategy proposed so far are discussed in the subsequent sections of this paper.

The present survey paper aims to summarize the work done so far in the field of scale-free routing algorithms and discuss new intriguing areas of research. Section 2 discusses the various routing challenges encountered in scale-free networks. Section 3 provides a novel taxonomy of scale-free routing algorithms and discusses some of the algorithms pertaining to the taxonomy. The summary and outlook for future research is presented in section 4.

2. Routing challenges in scale-free networks

Routing is the most crucial task performed in any network. A good scale-free routing function should be able to identify and send packets on the most efficient path from source to destination. In scale-free networks, the routing strategy should aim for high traffic capacity and short average path length and also preserve the scale-

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free characteristics of the network. There are a lot of challenges [10][16-17] that affect the design of scale-free routing protocols. Some of these challenges are discussed below and the same has also been represented in Fig. 1:

- ***Network Dynamics:*** Scale-free networks evolve with time [3][5]. The routing algorithms must adapt themselves to dynamic addition and removal of nodes, the addition of external and internal links, and failure of the existing links in the network.
- ***Scalability:*** The application domain of scale-free networks includes a few extremely large and diverse networks such as www (10^{12} documents), citation network ($4*10^5$) and, cellular network (20k). Routing algorithms in these scale-invariant networks should be able to adjust themselves as per network resources [16-17] and constraints without significant performance degradation.
- ***Network Topology***: Topology information of a network impacts routing performance to a great extent. With evolving networks, it becomes very difficult to keep track of nodes' physical location and resources information. Critical routing decisions are made in order to balance memory cost, communication cost, and stretch cost.
- ***Congestion Control:*** Congestion occurs when the traffic generation capacity of a network exceeds the traffic handling capacity of the network [34]. The data in scale-free networks are frequently routed through central nodes which makes them prone to congestion. It is vital for a good routing protocol to perform load balancing to alleviate congestion from hub nodes.
- ***Fault Tolerance:*** Due to frequent transmission of packets through hubs/ central nodes in the network, these nodes experience significant strain on their limited resources which may degrade their performance. Scale-free networks are also prone to targeted attacks on these influential nodes in the network. Thus, the routing strategy should be able to adjust its performance in event of failure/attack on critical nodes in the network.
- ***Node/Link Heterogeneity:*** Depending on the application domain of a scale-free network, there are several differences in node/link characteristics which raises several technical issues while designing an efficient routing strategy. Links may be symmetrical or asymmetrical in the network. Nodes differ in their energy levels, computational power, propagation range, processing speed, and mobility.

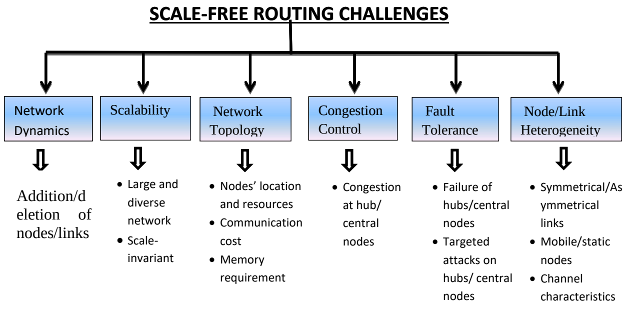

Figure 1: Scale-Free Routing Challenges

3. Taxonomy of Scale-free Routing algorithms

A plethora of research has been done on Scale-free routing protocols in the last few years. In Fig.2, Scale-free routing algorithms have been grouped into different categories: (A) on the basis of topology information, (B) on the basis of network dynamics, and (C) on the basis of routing strategy. In this section, we discuss and summarize the strengths and shortcomings of scale-free routing protocols of each category**.**

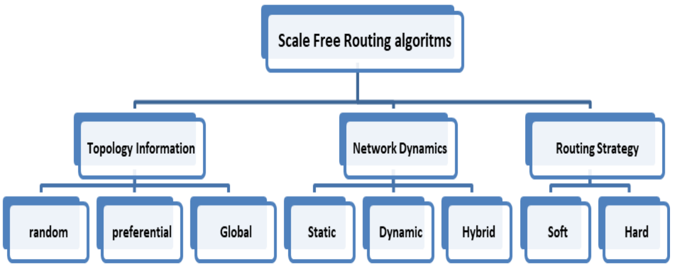

Figure 2: Classification of Scale-free routing algorithms

3.1 Approaches based on the topology information

On the basis of the topological information available in the network, scale-free routing algorithms can be divided into three categories, namely, random routing, preferential routing or local routing, and global routing[8][40].

3.1.1 Random routing: In random routing, a node keeps on forwarding a packet to another node selected randomly till the packet reaches the destination [32]. The nodes have no topology information. It is not a suitable method for delivering packets in the network due to transmission delay and routing loop problems.

3.1.2 Global routing: In global routing, each node has information about the whole topological structure of the network. Nodes can identify the shortest paths to the destination and send packets along that path. Routing can be performed on several parameters such as Betweenness Centrality (BC), node degree, queue length, bandwidth, waiting time, and many more. The maximum traffic capacity is achieved using global routing strategies as each node knows the real-time characteristics of the network and can respond accordingly. The implementation cost and computational cost of global routing are more when compared with local and random routing strategies. Some of the global scale-free routing strategies proposed so far are discussed below:

Efficient routing: One of the simplest global routing strategies is the efficient routing strategy [44], where each node calculates the sum of node degrees of all the possible paths from source 'i' to destination 'j' and chooses the path P_{ij} as the one with a minimum value of the sum of node degrees as shown in equation (1). It encourages nodes to use the peripheral nodes of the network efficiently and avoids overcrowding the hubs.

$$P_{ij} = min \sum_{m=0}^{p} k\,(y_m)^{\alpha} \qquad (1)$$

Where k (y_m) is the degree of node y_m, p is the path length and α is a tunable parameter. The traffic capacity of this routing strategy is better than the shortest path routing.

Betweeness Centrality Routing: One of the statistical characteristics of the network is Betweenness Centrality (BC). The betweenness centrality [6] of node j can be defined as given in equation (2),

$$B_j = \sum_{x \neq y} \frac{\sigma_{xy\,(j)}}{\sigma_{xy}} \quad (2)$$

Where σ_{xy} represents the total number of shortest paths from source(x) to destination(y) and $\sigma_{xy}(j)$ is the number of shortest paths from source to destination with node j as the intermediate node. An example to illustrate this is given in Fig. 3.

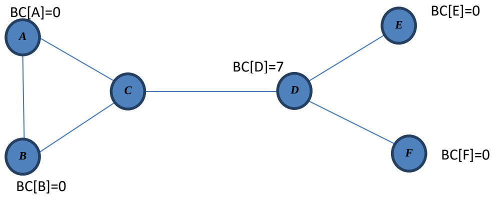

Figure 3: Example of Betweenness Centrality

Betweenness centrality specifies the traffic load characteristics of a network [11][14]. In simple terms, it represents the total number of shortest paths passing through a given node. The nodes with large betweenness centrality are also called the central nodes of the network. One of the simplest global routing strategies is to send packets to the node with highest betweenness centrality. The drawback of this scheme is that the central nodes of the network get congested in case of high traffic. The effort should be made to minimize the maximum node betweenness in a network to achieve more balanced load distribution.

Improved Efficient Routing*:* To alleviate problem of congestion at central nodes in Highest Betweenness Centrality routing, Improved Efficient Routing (IER) [23] strategy has been proposed for weighted scale-free networks where weight of each link (w_{ab}) is based on betweenness centrality as shown in equation (3)

$$w_{ab} = [1 + B_a]^\alpha + [1 + B_b]^\alpha \quad (3)$$

B_a is the betweenness centrality of node a and B_b is the betweenness centrality of node b. The optimal value of optimization parameter α was found to be 0.3. The path which has the minimum weight is chosen to send the packets to the destination.

Improved Optimal Routing: To further improve IER strategy, [45] Improved Optimal Routing (IOR) strategy has been presented which considered both node degree and betweenness centrality while designing the weight function in the network as shown in equation (4),

$$w_{ab} = [(1 + B_a) * k_a]^\alpha + [(1 + B_b) * K_b]^\alpha \quad (4)$$

Where, K_a and K_b represent degrees of node a and b respectively, B_a and B_b are betweennness centrality of nodes a and b and α is a tuning parameter. The optimal value of α was found to be 0.2. The algorithm selects the path with the minimum weight from source to destination. The average path length with this strategy is smaller than IER but slightly longer than shortest path strategy. The scalability of IOR is more when compared with IER and shortest path strategy.

Global Dynamic routing strategy*:* In global dynamic routing strategy [28], the queue length of nodes is used to route the packet to the destination. The nodes choose the path which has minimum value of the sum of node queue lengths from source to destination, represented by equation (6),

$$P_{ij} = min\ \sum_{m=0}^{l}[1 + n\ (x_q)] \quad (6)$$

Where n (x_q) is the queue length of node x_q and l is the path length. This strategy uses the hubs nodes efficiently thereby, increasing the traffic capacity but at the expense of increasing time delay.

Global Dynamic routing strategy for heterogeneous nodes: Global dynamic routing strategy does not consider the heterogeneous capacity of nodes' while making routing decisions. In [43], modified global dynamic strategy is stated to incorporate the heterogeneous nature of nodes. In this strategy, capacity of a node depends on the degree of node. The path function is modified as shown in equation (7),

$$P_{xy} = \min \sum_{i=0}^{l}\left[1 + \frac{n(q_i)}{C_i}\right] \quad (7)$$

Where $n(q_i)$ is the queue length of node q_i, C_i is the capacity of node i which depends on its degree and l is the path length. The path which has the minimum value of the sum of queue length of nodes to capacity of node is selected. The queue length of nodes is to be updated periodically. The strategy significantly improves traffic capacity of the network but it increases the time delay in delivering packets.

Dynamic Source Routing for Two-Level flows: Some of the applications of scale-free networks such as internet provide time sensitive services like video conferencing, telephone communication. These time sensitive services cannot tolerate network delay. For such applications, global dynamic routing was extended in [22] to support diverse traffic flows. Each node maintains two queues, level 1 for time sensitive packets and level 2 for other packets. The path between source x and destination y can be denoted as given in equation (8),

$$P_{xy} = \min \sum_{k=0}^{l}[1 + n_1(q_k) + \beta n_2(q_k)] \quad (8)$$

Where n_1 (q_k) and $n_2(q_k)$ are the queue lengths of level 1 and level 2 on node q_k respectively. While computing path, β is set to 0 and 1 for queue at level 1 and level 2 respectively. Higher priority is given to level 1 packets. The complete path is calculated on the basis of real time traffic conditions and stored in each packet. No routing information is required at intermediate nodes.

Efficient Path routing with different priorities**:** Another model which considers priority while delivering packets is given in [50]. Each packet has a priority number and is placed in corresponding priority queue. Two priorities are considered denoted by (α_1, α_2). The packets in priority queue i are routed along the path which has minimum value of path function given in equation (9):

$$L(P\ (x \to y) : \alpha_i) = \min \sum_{i=0}^{n-1} K(q_i)^{\alpha_i} \quad (9)$$

Where, $K(q_i)$ is the degree of node q_i and α is tunable parameter. Different routing paths are identified for sending different priority packets.

Energy Balance Routing: The scale-free routing has been applied in case of wireless sensor networks [26]. In wireless sensor networks, nodes have limited energy and bandwidth. If data is frequently transmitted through nodes with large betweenness centrality in scale-free WSNs, they exhaust their energy quickly. This leads to unbalanced energy consumption problem which impacts network lifetime significantly. Therefore, author proposed an energy balance routing for weighted scale-free WSNs. Shortest path algorithm based on Betweenness Centrality (BC) is used to identify routes from source to destination. Initially, nodes with high Betweenness Centrality are assigned higher weight. Then, Betweenness Centrality (BC) distribution of network is altered by minimizing the difference between max and average BC. Mean square deviation is calculated to find the node with greatest BC, B_{max} and one is added to every link that connects it to other nodes. This will reduce the traffic through highest BC node and will redistribute the traffic throughout the network. One of the drawbacks of this algorithm is that it increases the average path length.

3.1.3 Preferential routing: In preferential routing or local routing, nodes only know the local topology i.e. information about their neighbors or next nearest neighbors [40]. Each node performs a local search among its neighbors and finds the next target node according to some preferential probability. The packet forwarding decision in preferential routing can be made on the basis of various parameters such as node degree, link bandwidth, waiting time, pheromone value, queue length and residual energy of nodes. This scheme is suitable to rapidly evolving networks such as communication networks, World Wide Web and metabolic networks.

Routing strategy with waiting time [41]: In this strategy, each node knows only local topology information. The author introduced a new parameter i.e. waiting time at the new node to be considered before making routing decision. If the node cannot find destination in immediate neighbors, it forwards packet to a neighbor x with probability as shown in equation (10),

$$\prod_{l\to x} = \frac{k_x^{\alpha} e^{-t_x}}{\sum_{j\epsilon n(x)} k_j^{\alpha} e^{-t_j}} \tag{10}$$

Where n(x) is set of neighboring node of x, t= q_x/c_x is the waiting time at node x with q being queued packet information and c is the maximum packets that node x can send in each time slot. The maximum capacity of system is observed when value of tunable parameter α is set to 1.

Efficient routing with memory information [25]: It is an effective routing strategy for reducing congestion in scale-free networks. Initially, packets are routed on the basis of two parameters, distance between nodes and number of packets accumulated at neighboring nodes as shown in equation (11).

$$y_{xy}(t+1) = \alpha\left\{H\left(\frac{d_{xy}+d_{yg(p_{i(t)})}}{\sum_{k=1}^{N_i}(d_{xk}+d_{kg(P_i(t))})}\right)+(1-H)\left(\frac{q_y(t)}{\sum_{k=1}^{N_i} q_k(t)}\right)\right\} \tag{11}$$

Where, α is tunable parameter, d_{xy} is the distance between node x and yth adjacent node, $d_{yg(p_{i(t)})}$ is the shortest distance between adjacent node y and target node $g(P_i(t))$ and $q_y(t)$ is queue length of node y. As the density of packets in the network increases, the performance of routing algorithm starts degrading. To effectively deal with this issue, memory information is used to identify nodes to which many packets have been sent in past. The algorithm then avoids sending further packets to such nodes.

Self-Organised scale-free routing: This routing algorithm combines source routing with greedy routing [42]. There are two types of forces, attraction force between the adjacent nodes in the network and repulsion force between the non-adjacent nodes as shown in equation (12),

$$F_{attraction} = \frac{1}{\log(h)}, F_{repulsion} = \frac{1}{\sqrt{h}} \tag{12}$$

Where h is the distance between corresponding nodes. As proposed strategy is a local routing where nodes have no information of global topology, the repulsion force of only 2-hop neighbors is considered. Packets are always forwarded to a node that is nearer to the destination. To avoid loops in the route discovery, FPC keeps a list of the nodes already explored by the packet. A node is dead if its entire links have been explored by the packet. Only the route discovery stage uses the greedy routing scheme. For sending the data packets, compressed path obtained during route discovery is used.

3.2 Algorithms based on network dynamics

Algorithms presented below are classified on the basis of network dynamics as static routing, dynamic routing, and hybrid routing.

3.2.1 Static routing: In this routing strategy, the physical structure of network is fixed and the routing paths are decided on the basis of static parameters of network such as node degree [11]. This method is economical and technically simple to understand. Such routing techniques are suitable for small and mid-size networks. Some of the algorithms which adopt static routing are discussed below:

Shortest path routing [51]: This is a static and non-adaptive algorithm where each node delivers the packet to the neighboring node which has the shortest path to the destination. The strategy is simple and easy to implement. One of the issues is that as the number of packets in the network increases, this approach might lead to congestion at the hub nodes as it does not consider node state while making forwarding decisions. It leads to formation of several vulnerable zones in the network by over-utilizing the hubs.

Self Avoiding Paths routing (SAPR) algorithm: It is a static and adaptive routing strategy which identifies the self avoiding shortest paths in scale-free networks [35]. The basic idea is to execute Dijkstra algorithm repeatedly where path cost function can be represented as equation (13),

$$W(P_{ij}) = \sum_{x \in P_{ij}} [N_p(x)]^{\alpha} \tag{13}$$

Where, $N_p(x)$ is the number of paths found by the algorithm in current step with x as an intermediate node. Whenever, a new path is found, the cost of each path is updated and given as input to next cycle. The algorithm avoids overlapping of paths in a self consistent manner.

Probability Routing*:* To deal with the shortcomings of shortest path routing and efficient routing, a new routing strategy called probability routing strategy has been proposed [49]. This strategy balances the role of central and non-central nodes by redistributing the traffic according to a routing function given in equation (14)

$$R\left(\alpha, P(s\to t)\right) = \prod_{x\epsilon P(s\to t)} \left[\frac{1}{\ln(1_+ k_x)}\right]^{\ln(1+\alpha.K_x)} \tag{14}$$

Where P(s→t) denotes path from source s to destination t, x ε P(s→t) denotes an intermediate node x on path P(s→t), K_x is the degree of node x, $[\frac{1}{\ln(1_+ k_x)}]^{\ln(1_+ k_x)}$ is a strictly monotone decreasing function which implies there is a high probability of packet to dodge the hubs in the network. The value of this function is always less than 1 which suggests that average path length is small. The path with the maximum value of routing function from source to destination is chosen to send the packets in the network. The average path length of probability routing strategy is higher than shortest path routing but lower than efficient routing.

3.2.2 Dynamic routing

The value of dynamic parameters of a network changes with time. Some of the examples of dynamic parameters are energy of node in wireless sensor networks which decreases as more nodes connect to it, queue length of a node which increases in case heavy traffic density and packet waiting time which increases during congestion. Routing decisions made on dynamic parameters are able to capture real time statistics of the scale-free network and respond accordingly.

*D*ynamic routing strategy to effectively utilize links with low betweenness has been proposed in [38]. A node i choose the next forwarding node j as the one which has the lowest value of effective distance $d_B(j)$ represented by equation (15)

$$d_B(j) = hd_{jt} + (1-h)\tau_{ij}\,(k_i k_j)^{\theta} \qquad (15)$$

Where, h is traffic awareness parameter, d_{jt} is topological distance between nodes j and t and k_i and k_j represent degrees of nodes i and j respectively. The packets are not delivered using FIFO rule. If the forwarding node for the packet at head of the queue is overloaded, then it is delayed and another packet from queue is forwarded. Thus, strategy efficiently utilizes available bandwidth. The value of parameter h is almost independent of the structure of network, therefore, suits both internet and BA networks.

Adaptive Efficient Routing: It is an adaptive global routing strategy which effectively route the packets in scale-free networks [48]. To effectively utilize all the links in the network it distributes the packets among nodes in the network in accordance with their node degrees. To decide which neighboring node a packet should be forwarded to, it calculates the waiting time to reach destination through each neighbor as shown in equation (16),

$$d(l) = \sum_{s\,\epsilon\,\{SP:l,j\}} \frac{n_s}{1+\beta k_s} \qquad (16)$$

Where, d(l) denotes waiting time to reach destination with l as intermediate node and n_s is total number of packets waiting currently in the queue of node i. The neighbor with min value of d(l) is selected as next node in the routing process. One of the drawbacks is network delay due to periodic exchange of messages containing information about number of packets waiting at each node.

Pheromone Routing [29]: In this strategy, the concept of pheromone has been used for designing routing protocol for scale-free networks. Initially, all links in the network are set to same pheromone value. Upon receiving a packet, node searches its neighbors to find the destination. If destination is found, packet is delivered directly to that node. Otherwise, packet is delivered to a neighbor j with probability P_{ij} as given in equation (17),

$$P_{ij} \to \frac{p_{ij}^{\alpha}}{\sum_j p_{ij}^{\alpha}} \qquad (17)$$

Where, p_{ij} represents pheromone of the link from node i to node j and α is tunable parameter. After each successful transmission from node i to node j, the queue length of node j is compared with the critical queue length. If the queue length of node j is greater than critical queue length value, the pheromone of link p_{ij} will decrease by a unit value. Otherwise, p_{ij} will increase by one unit. The highest traffic capacity is achieved for $\alpha = 1$.

Pheromone routing optimizations [7]: The paper highlights that in pheromone routing the concentration of pheromone on each edge is identical in the initial stage. This may result in few nodes being selected as the forwarding node again and again, resulting in *node duplication* problem. Thus, pheromone routing is more efficient in heterogeneous networks. The author suggests that a list of last W nodes visited by information packet can be maintained to avoid node duplication issue. Another optimization of pheromone routing states that the *next nearest neighbors* of the current node can also be explored to find the destination. The next nearest neighbors implies the neighbors of a node's neighbors. This approach increased traffic capacity by three times when compared with pheromone routing. One issue that still remains is the congestion at large degree nodes. To deal with problem, *restrictive queue length algorithm* [7] is proposed, where a threshold on neighbor's queue length is set to make sure that information packet is not delivered to a node whose queue length exceeds the threshold. In this way, it reduces the waiting time at congested nodes and save transmission time.

3.2.3 Hybrid routing: The routing performance is affected by both static and dynamic properties of the network. Therefore, it is very important to include both these aspects while designing routing algorithms. In one of the hybrid routing strategies for scale-free networks [37], three parameters are used to make forwarding decisions, namely, node degree, waiting time and queue length of nodes as shown in equation (19),

$$\alpha(t) = \frac{\sum_{i:k_i>k_c} q_i(t)}{\sum_j q_j(t)} \qquad (19)$$

Where $\alpha_i(t)$ is a dynamic parameter which represents the ratio between sum of queue lengths of nodes whose degree is higher than threshold value k_c and total queue length of all nodes, $q_i(t)$ is the queue length of node i. Each node has a weight value $w_i(t)$ associated with it which can be written as equation (20),

$$w_i(t) = 1 + \frac{q_i(t)}{c_i} + k_i^{\alpha(t)} \qquad (20)$$

The path from source to destination is the one which has the minimum value of total weight of all the nodes included in the path. The traffic capacity of this routing strategy is high when compared with efficient routing and global dynamic routing strategy. The average traveling time is low in comparison to both efficient routing and global dynamic routing.

Global Hybrid Routing [12]: In this strategy, a linear combination of node degree and queue length information is used to route packets in the network. The path from source i to destination j which has the minimum value of path function P_{ij} is selected as shown in equation (21),

$$P_{ij} = min\sum_{x=0}^{l}\left[\beta * N_q(x) + (1-\beta) * N_d(x)\right] \qquad (21)$$

Where β is the tunable parameter, l is the path length, $N_q(x)$ is the normalized queue length of node x, given as $N_q(x) = q(x)/max(q)$ and $N_d(x)$ is the normalized degree of node x given as, $N_d(x) = d(x)/max(d)$. When value of β is 0, routing strategy follows efficient routing strategy. When value of β starts increasing, queue length factor comes into play and packets start dodging high degree nodes, thereby distributing load evenly. The author found optimal value of β to be 0.6. The strategy is then applied to real data center network to prove its effectiveness.

3.3 Algorithms based on routin] strategy

The topology of a network and routing algorithm has huge impact on the performance of a network. Either by altering the network topology or by finding better routing algorithm, one can relieve congestion in a scale-free network, thereby, improving the network capacity. On the basis of routing strategy, scale-free algorithms can be divided into two categories, namely, soft strategy and hard strategy. Some of the algorithms pertaining to each category are discussed below:

3.3.1 Soft strategy*:* In soft strategy, focus is on optimizing the routing protocol to improve traffic efficiency of the network. Designing better routing strategy to achieve load balancing is a cost effective way to enhance the performance of network. There are different parameters such as node degree, node betweenness, node energy, queue length, Euclidean distance and traffic information which can be explored to design better routing functions. Most of the proposed routing strategies so far are soft strategies due to their smooth practical implementation. Some of the algorithms which use soft strategy are discussed below:

Congestion Awareness routing strategy: This routing strategy can adjust itself according to variable traffic load of the network. The central idea is that routers have limited memory and processing power and cannot handle more than a specific number of packets at a particular time. It incorporated two parameters, namely, shortest path length and waiting time at the forwarding node to make strategy aware of congestion in the network and take routing decisions accordingly [9]. The weight H_x of each neighbor node x of node i is calculated according to equation (22),

$$H_x = \alpha \frac{E_x}{\sum_{y \in g(x)} E_y} + (1-\alpha) \frac{L_x}{\sum_{y \in g(x)} L_y} 0 \le \alpha \le 1 \tag{22}$$

Where, g(y) is the neighbor set of node x, L_x represents shortest oath length from node x to destination and E_x is waiting time at node x which depends on processing power and number of packets in queue of node x. The node with minimum weight is selected as the next forwarding node in routing process.

Euclidean Distance and Betweenness Centrality Routing*:* EDBC (Euclidean distance and Betweenness centrality) [13] routing strategy has been proposed for spatial scale-free networks. The bandwidth of a link is proportional to the Euclidean distance in spatial scale-free networks. A new node which enters the network at time t, attaches itself to its ith predecessor with preferential probability shown in equation (23),

$$P_i(t) \sim K_i(t)\, l^{\gamma} \tag{23}$$

Where l represents the Euclidean distance between i and t and $K_i(t)$ is the degree of node i. The final path between source and destination is the one which has the minimum value for the path function defined in equation (24)

$$L(Path\ (s \to d)\colon \alpha, \beta) = \sum_{i=1}^{n-1} f(x_{i+1,} x_i)^{\alpha} g\ (x_{i+1}, x_i)^{\beta} \tag{24}$$

Where $f(x_{i+1},x_i)$ is the Euclidean distance between nodes x_{i+1} and x_i , and $g(x_{i+1},x_i)$ is betweenness centrality of edge from x_i to x_{i+1}. EDBC routing strategy balances traffic load efficiently and reduces end to end delay.

Incremental Routing [21]: In incremental routing for scale-free networks, the routing process is divided into N steps, where N denotes the network size. The cost function based on node degree information and dynamic efficient betweenness centrality is used to compute the routing table at each step. The path cost function is defined as equation (25)

$$\big(P(x \to y)\big) = \sum_{v=0}^{n-1} (B_{i_v}^{s} D_{i_v})^{\beta} \tag{25}$$

Where B^s_{iv} is the efficient betweenness of node i_v and D_{iv} is the degree of node i_v. Thereafter, Bellman-Ford algorithm is used to identify shortest paths for each node. The proposed strategy is centralized as all the computing process is done by a server node.

3.3.2 Hard strategy: In this strategy, the physical network structure is changed by adding or removing links and nodes in the network, thereby improving the traffic capacity (Huang and Chow, 2010a; Huang and Chow, 2010b; Liu et al., 2007; Zhen e. This strategy is suitable for networks where rewiring/removing links is practical and cost effective such as Internet, Highway networks and P2P networks. There are two ways to control the topological structure of the network by either adding new nodes or deleting existing nodes in the network. The removal of nodes/links in the network is easier to implement and more cost effective than adding new nodes/links. Some of the algorithms which implement hard strategy are discussed below:

High Degree First (HDF) [30]: In this approach, link between nodes with high degree (hub nodes) is removed first to alleviate network congestion and improve network capacity. In another strategy called ***High Betweenness First (HBF)*** [47], a fraction of the edges which connect nodes with large betweenness centrality (Black Sheep edges) are removed while keeping the network connected.

In ***Efficient Node Link Addition strategy*** [18], the shortcut links are incorporated between low degree nodes with longest shortest path lengths in order to build resilience to network congestion. Thus, packets can detour around hub nodes and pass through new shortcut routes added in the network. This strategy calculates shortest paths between every pair of nodes in the network which are updated periodically.

Variance of Neighbor Degree Reduction (VNDR) [19] is a link removal strategy which route packets using shortest path routing and simulated annealing algorithm. The links which are to be removed are identified using simulated annealing technique. For each hub node x, relative variance of neighbor degrees rvar (x) (RVND) is calculated as given in equation (26),

$$rvar(x) = \frac{std_{y \in n(x)}(d(y))}{(1/|n(x)|) \sum_{y \in n(x)} d(y)}$$

$$std_{y \in n(x)}\big(d(y)\big) = \sqrt{\frac{(d\ (y) - (1\ /\ |n\ (x)|) \sum_{y \in n(x)} d(y))^2}{|n(x) - 1|}} \tag{26}$$

Where, n (x) is neighborhood set of node x. The node q with maximum value of neighbor degree is selected and link connecting node x and q is deleted. Node A is the central node in the network. The link between node A and node X has high relative variance of neighbor degree and should be removed first in order to make distribution more even, thus balancing the traffic load in the network. The network should not be left disconnected after removing the link. The algorithm makes the neighbor degree distribution more even. This strategy initially increases the network capacity but as the fraction of removed links increases capacity starts decreasing.

4. Summary and outlook

In this paper, a novel taxonomy has been presented which provides an extensive classification of scale-free routing algorithms. In last two decades, many profound researchers have worked on scale-free routing algorithms but research is still in nascent stage. Having surveyed various scale-free routing algorithms, this section analyses some of the open research issues which require further research. Most of the proposed routing strategies are based on the assumption that queue length of a node is unlimited and message delivering capacity of a node is either constant or determined according to node degree. This assumption does not hold true in real world scenarios. The queue length of a node is limited and its effect needs to be incorporated in the routing strategies. Another issue lies with the assumption that almost every node in the network is capable of both generating and receiving packets. This assumption is not always valid in case of many real-world networks such as wireless sensor networks, internet, and wireless communication systems. It is very important to further study the impact of such node characteristics on design of efficient scale-free routing algorithms.

The traffic efficiency of scale-free routing algorithm is hinged on the performance of primary nodes/hubs in the network. The targeted attacks/failure of hub nodes may initiate a chain of cascading failure throughout the network jeopardizing its whole structure. The effect of this dependency may be studied further so that the findings can be incorporated in upcoming routing strategies. Hybrid routing protocols which combine the features of global and local routing have not been explored to its full extent. There is enough scope for different optimization strategies such as swarm optimization, reinforcement learning, K-nearest neighbour, decision tree, neural and genetic algorithms to be applied to help in improving traffic efficiency in scale-free networks.

Considering the diverse applications of scale-free networks, very little work has been done on designing application specific scale-free routing protocols. Routing strategies, if customized according to the resources and constraints of a particular application of scale-free networks may yield far more promising results. The real-world scale-free networks evolve continuously and bring new set of requirements and challenges. In order to sustain the ever-changing network dynamics, new methods of computations, advanced modeling strategies and continuous updating of existing routing strategies is required. To aid in fair comparison between different scale-free routing algorithms, mathematical modeling and mean field theory analysis can be incorporated in research.

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