Fuzzy-Based Multi-Criteria Routing Algorithm in Mesh Overlay Networks

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Abstract: A multi-criteria routing algorithm running in mesh structured that overlay an unstructured peer-to-peer network is proposed. This approach aims to improve the quality of service routing (QoS R) of the modern distributed application. Using a grid pattern can improve routing remarkably, since it provides alternative and partly disjunctive paths of equal length as well as the ability to measure distances between nodes in the overlay network. The Thermal Field Approach is used for representing buffer usage level to avoid message loss and long delay times. As well as the Euclidean distance is applied to present relationship of distance among application contents or peer location. The route decision method uses fuzzy logic technique to select the optimal path considering multiple constraints. The proposed algorithm is evaluated using P2PNetSim, a network simulation tool. The approach is compared to shortest path routing and probability functions using either deterministic or adaptive approach. The result of routing with fuzzy logic shows superior routing performance than others both in delivery ratio and routing time.

Key words: Fuzzy logic, buffer, multi-criteria, routing, peer-to-peer, grid-like structure.

1. Introduction

Quality of Service Routing (QoSR) is a key function for the transmission and distribution of digitized information across networks. It has two main objectives; finding routes that satisfy the QoS constraints and making efficient resource utilization. Unfortunately, several factors can cause poor performance. So many problems still exist such as data loss because of overloaded incoming and outgoing message buffers, packet delay or expiry when residing in large queue or when using unsuitable routes. The complexity in QoS routing comes from multiple criteria, which often make the routing problem intractable. Typical criteria are node buffer capacities, residual link capacities, and number of hops on the path. Many routing algorithms have been developed in this research area [1]. Expert systems, swarm intelligent systems, artificial neural networks, and fuzzy logic are applied for multi-constraint decision making. Many approaches focus on bandwidth and throughput optimizations.

The main advantage of structured Peer-to-Peer overlay networks lies in their ability to distribute arbitrary contents over a dynamically changing number of participants and still provide efficient lookup mechanisms. Additionally, such overlays usually provide robust routing architectures, redundant storage and – though more seldom – distributed implementations of trust and authentication mechanisms that avoid single points of attacks and failures. Unfortunately, in some overlays as e.g. in CAN and Grid-like structures, the routing process can cause single peers to have a high message load, since each may have a central or otherwise crucial position in the network so that a lot of messages are routed to or through it. This problem is enforced, whenever a peer manages content that is accessed by a lot of users in the
whole network. The peers around such hot-spots are inherently exposed to higher routing load, since a lot of messages need to be routed to and from the hot-spot. Whereas all messages that are targeted to a hot-spot or its surrounding nodes necessarily have to be routed into the overloaded region, other messages should be routed around it. This not only avoids additional load and possible resulting message losses for the already stressed region, but also decreases and therefore optimizes the delay time for the redirected message. On the other hand, the alternative routes should still have a minimum number of hops to make sure no messages are lost due to TTL expiries.

The grid pattern with coordinate system provides many benefits for the routing process, because many paths with the same hop-count exist between two peers and they enable each peer to predict the shortest route without prior communication. Grid can be used to provide content-based coordinate systems generated from the distributed system’s contents. The generated map can be changed dynamically according to overlaying application’s requirements. The distance between peers is measured in Euclidean space. In Ref. [2] Berg et al. propose routing in a mesh-like structure using the EPC code to establish an address space. Moreover, other applications such as Network Virtual Environments and Data mining application could be able to apply our adaptive routing approach on their content-grid structure.

The proposed algorithm takes the distance from the current node to the destination into account as well as the buffer usage level of each node’s direct neighbors. The distance is measured by Euclidean space. To propagate the buffer levels in a node’s neighborhood, a thermal-field-based approach is used. The locally executed decision-making process is based on fuzzy logic which provides a mathematical model for dealing with imprecision and uncertainty as given in common traffic situations in today’s communication networks. The rest of this paper is organized as follows: Section 2 provides related literature briefly and extensively description of classical routing methods on meshes, thermal field approaches, and fuzzy systems. Section 3 introduces our routing strategy considering multiple factors using fuzzy logic. Section 4 describes the simulation environment in P2PNetSim simulation tool, as well as the results and discussions. Finally, section 5 concludes the paper and gives an outlook for future research.

2. Related Works

Many adaptive routing algorithms considering multi-constraint to improve QoSR have been introduced in before. Zhang and Zhu [3] introduced an algorithm considering number of hops and available buffer-capacities in general communication networks. FLAR [4] and FACO [5] describe routing algorithms applying ant colony systems and fuzzy logic to consider multiple constraints in Mobile Ad Hoc Network (MANET). FLAR considered route utilization and route delay but FACO considered buffer occupancy, remaining battery power and signal scalability. A fuzzy mixed metric approach, introduced in Ref. [6], is used to make optimal routing decisions in packet switching network by considering one or multiple QoS factors.

The introduced routing approach is run on a mesh overlay network, in which the distance is measured by coordinate system. One of the well-known routing algorithms in grid-like networks was introduced by Jon Kleinberg [7]. He introduced a decentralized algorithm in grid within only $O(\log^2 n)$ delivery time complexity. Some networks with coordinate systems are built in the lower layer of the network stack, e.g. [8], but also approaches for building grid in the application layer exist, as in Refs. [2, 9]. In Ref. [9], a grid structure is generated on top of a large-scale decentralized network. Their logical grid is built without centralized control and global instances; only local knowledge of each node is needed.
2.1 Routing in Mesh Structure

Mesh (Grid-like) topologies have been widely used in communication networks as for example in packet/circuit switching between wired [10, 11] and wireless networks [12, 13]. The functions of routing algorithms in general are the provision of the fastest path, prevention of deadlocks, low latency insurance, network utilization balancing, and fault tolerance. Routed by these classical methods, grid-like structures provide multiple paths which have the same hop count. The mesh structure is reliable and offers redundancy which in turn can be used to improve routing performance [10, 12, 14]. Some examples of routing algorithms in mesh-connected topologies are presented in Ref. [14]. A deterministic routing method in grid is called “XY” routing algorithm where packets are routed along X direction until reaching the X value of the target and then route the packet in Y direction to the target. This kind of routing can be refined, named the partial-adaptive routing algorithms; “West-First”, “North-Last”, and “Negative-First” approaches. These methods change packet routes dynamically by using a function that reacts immediately on network traffic, but in some specific conditions they use the deterministic ways.

All these classical routing methods have in common that they choose between multiple paths having the same hop count. The source node wants to send information to the target node. Then the best path depending on the algorithm is selected. The chance to find low QoS relies on the path selection function. If the selected route has many overloaded peers, then the delay time increases or the packet losses occur.

In 2000, John Kleinberg [8] introduced a family of small-world network models based on the work of Watts and Strogatz [15]. His models are built of $k$-dimensional grids with a lateral length of $n$, in which each peer has undirected local links connecting it to its neighbors. Additionally, directed far distant links are generated randomly. Kleinberg showed, that optimal routing performance can be gained, when a long distance link between two nodes $u$ and $v$ is constructed with a probability proportional to $d(u,v)^{-2}$. Hence, for the 2-dimensional case, links are added with a probability proportional to the inverse square of the lattice distance of $u$ and $v$. In such structures, a path with an expected length of $O(\log^2 n)$ can be found by using a simple greedy algorithm which relies only on local knowledge. Martel and Nguyen [16] re-analyzed Kleinberg’s Small-World model and deduced an expected path length of $\Theta(\log^2 n)$ and a diameter of $\Theta(\log n)$ for the 2-dimensional case. By making use of some additional knowledge of the graph they show that the expected path length can be reduced to $O(\log^{(2+1/b)} n)$ for a general $k$-dimensional model ($k \geq 1$). By taking the neighbors of a node’s neighbor into account for decision-making, Naor and Wieder [17] improved the delivery time for greedy algorithms. Finally, Zou et al. [18] claimed that Kleinberg’s model needs to use global information to form the structure. Consequently, they proposed to use cached long distance links instead of fixed ones. The structure is refined as more queries are handled by the system.

2.2 Thermal Field

A routing approach in analogy to temperature fields in thermal physics was first introduced by Unger and Wulff [19] in 2004 to locate nodes managing contents of common interest in P2P networks. Each node features a temperature, which is an index for the activity of that node. The heat of each node radiates towards its direct neighbors and therefore influences their temperature as well. Whenever the content of a node is accessed or updated, its temperature is increased, whereas during periods of inactivity, the temperature falls of exponentially to align with the temperatures of the surrounding neighbors.

In 2007, Baumann et al. [20] introduced the HEAT routing algorithm for large multi-hop wireless mesh networks to increase routing performance. HEAT uses anycasts instead of unicasts to make better use of the underlying wireless network, which uses anycasts by
HEAT relies on a temperature field to route data packets towards the Internet gateways. Every node is assigned a temperature value, and packets are routed along increasing temperature values until they reach any of the Internet gateways, which are modeled as heat sources. It is a distributed protocol to establish such temperature fields which does not require flooding of control messages. Rather, every node in the network determines its temperature considering only the temperature of its direct neighbors, which renders our protocol particularly scalable to the network size.

2.3 Fuzzy Logic

Fuzzy Logic introduced by Zadeh [21] allows a computer to model the same way that people do, not always precise. People think and reason using linguistic terms such as “hot” and “fast”, rather than in precise numerical terms “90 degrees” and “200 km/hours” respectively. The fuzzy set theory models the interpretation of imprecise and incomplete sensory information as perceived by human brain. Thus, it represents and numerically manipulates such linguistic information in a natural way via membership functions and fuzzy rules. Some advantages of fuzzy logic are conceptually easy to understand, flexible, and tolerant of imprecise data. It can model nonlinear functions of complexity, and also can be built on top of the experience of experts.

A key feature of Fuzzy logic is to handle uncertainties and non-linearity, existing in physical systems, similarly to the reasoning conducted by human beings, which makes it very attractive for decision making systems. A fuzzy logic system comprises basically three elements: (1) Fuzzification, (2) Knowledge base (rule and function), and (3) Defuzzification. Fig. 1 shows the generalized block diagram of fuzzy system.

The function of the fuzzification is to determine the degree of membership to a crisp input in a fuzzy set. The fuzzy rule base is used to present the fuzzy relationship between input-output fuzzy variables. The output of the fuzzy rule base is determined based on the degree of membership specified by the fuzzifier. The defuzzification is used to convert outputs to the fuzzy rule base into crisp values.

In section 2, we presented the classical routing in mesh, the thermal field approach and fundamental fuzzy logic technique. The next section, we will explain how the fuzzy logic works to find an optimal routes by considering relative distances in grid and buffer usage level.

3. Algorithm

In this section we describe our algorithm in details. The route decision process is constructed with the communication model transmitted temperature value by agents and use fuzzy logic to find the best path. Our approach considers decision position in terms of distance relationship and buffer usage status concurrently. The distance between nodes is measured by Euclidean distance from coordinate of grid. And the thermal field represented buffer usage level is used for communicating buffer information over the network. So that, every node has to keep its neighbors’ temperatures and coordinate ID. The lower temperatures represent more available resources to handle new data. In the route decision process, the

Fig. 1  A block diagram of generalized fuzzy system.
distance of original to target node, current to target peer, and neighbors to target location are measured.

3.1 Measuring the Temperature

The temperature \( \theta \) represents the buffer usage of a peer that is the level of messages waiting to forward. At a current node \( c \), the temperature \( \theta_c \) is calculated at every simulation time. The value of \( \theta_c \) is between 0 and 1: 0 denotes an empty buffer and 1 a full buffer.

\[
\theta_c = \frac{\text{Messages in Buffer}}{\text{Buffer size}}, \quad 0 \leq \theta_c \leq 1 \quad (1)
\]

The latest buffer status is important to make a correct decision; hence, it is designed to attach the temperature value to all data packets sent through the community and in the corresponding acknowledgement packets. The packets and the acknowledgements work as a median of the temperature. They pass temperatures from one to another node until they reach their target or expire. Every current node \( c \) has a set of neighbors \( N(c) \) where messages can be forwarded to and \( i \) is a number of neighbor, then \( N_i \in N(c) \), \( 1 \leq i \leq 4 \). There are three possibilities to update a neighbors’ temperature, \( \theta(N_i) \) on node \( c \). Let \( \beta_i \) be the number of packets and \( \mu_i \) be the number of acknowledgments which sent from neighbor \( N_i \) to current node.

If node \( c \) receives a packet or an acknowledgment from neighbor \( N_i \), the old temperature is replaced with the new temperature.

\[
\theta(N_i) = \theta_i, \, \text{if } \beta_i > 0 \text{ and } \mu_i > 0 \quad (2)
\]

If there is no message sent from neighbor \( N_p \), the new temperature caused by the spread of source node then decreases exponentially, whereby \( t \) is the routing time.

\[
\theta(N_i) = \theta(N_i) \cdot e^{-\lambda t}, \, \text{if } \beta_i = 0 \text{ and } \mu_i = 0 \quad (3)
\]

The new temperature is zero when no message arrives and no heat remains.

\[
\theta(N_i) = 0, \, \text{if } \beta_i = 0, \, \mu_i = 0, \, \text{and } \theta(N_i) = 0 \quad (4)
\]

Next topic, we introduce how fuzzy logic system works when knows distance and temperature of its neighbors.

3.2 Fuzzy Logic

The inputs to the fuzzy controller to be designed for routing are: (1) buffer usage status; (2) distance; and (3) neighbor type. These three selection parameters make the route reflect the network status and the nodes’ ability to reliability delivery network packet. The distance is defined current packet-holder position compares to source and target. It is calculated by Eq. (5), and neighbor type is in Eq. (6):

\[
\text{Distance} = \frac{\sqrt{(x_d-x_c)^2+(y_d-y_c)^2} + (x_s-x_c)^2+(y_s-y_c)^2}}{\sqrt{(x_d-x_c)^2+(y_d-y_c)^2} + (x_s-x_c)^2+(y_s-y_c)^2}} \quad (5)
\]

\[
\text{Neighbor Type} = \frac{\sqrt{(x_{Ni}-x_c)^2+(y_{Ni}-y_c)^2} - \sqrt{(x_d-x_c)^2+(y_d-y_c)^2}}{\sqrt{(x_{Ni}-x_c)^2+(y_{Ni}-y_c)^2} - (x_d-x_c)^2+(y_d-y_c)^2}} \quad (6)
\]

Where \( (x_c,y_c) \) is current peer, \( (x_s,y_s) \) is source node, \( (x_d,y_d) \) is destination, and \( (x_{Ni},y_{Ni}) \) is neighbors \( i \) of current node. The steps involved in calculation of neighbor preference rate are elaborated in Fuzzy Interference System (FIS). The three input variables to be fuzzified are the thermal value (buffer usage status), the relative distance, and the neighbor type. The terms “Empty”, “Few”, “Half”, “Almost”, and “Full” are used to describe the temperature field. “VeryClose”, “Close”, “StartPoint”, “Far”, and “VeryFar” are termed to explain the relation of distance and “Closer” and “Farer” are described neighbor types. Fig. 2 shows the membership functions of input variable.

Fig. 3 shows the membership functions of output, neighbor rate. We define nine terms for the values of neighbor rate from lowest to highest as “VeryBad”, “Bad”, “Fair”, “Good”, and “VeryGood”. The rules of the FIS are designed for an optimal path. Tables 1 and 2 show fuzzy rule base for the FIS.

There are 37 rules defined for this fuzzy system. The examples are showed in the following:

R1: IF thermal IS Empty AND neighbor IS Closer THEN neighbor_rate IS VeryGood;

R2: IF thermal IS Full AND neighbor IS Farer THEN neighbor_rate IS VeryBad;

... R37: IF thermal IS Almost AND distance IS VeryFar AND neighbor IS Farer THEN neighbor_rate
IS VeryBad;
The defuzzification is the process of conversion of fuzzy output set into a single number. The method “Center of Gravity” (COG) is chosen as shown in Eq. (7)

\[
\text{Neighbor Rate} = \frac{\sum_{i=1}^{n} x_i \cdot \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)}
\]  

Fig. 2 Membership function of input variable.

![Membership function of input variable](image)

Fig. 3 Membership function of Neighbor Rate.

![Membership function of Neighbor Rate](image)

Table 1 Rule base when Neighbor = “Closer”.

<table>
<thead>
<tr>
<th>Neighbor</th>
<th>Thermal</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td>VeryGood</td>
<td>VeryClose</td>
</tr>
<tr>
<td>Few</td>
<td>VeryGood</td>
<td>Close</td>
</tr>
<tr>
<td>Half</td>
<td>Good</td>
<td>StartPoint</td>
</tr>
<tr>
<td>Almost</td>
<td>Fair</td>
<td>Far</td>
</tr>
<tr>
<td>Full</td>
<td>Bad</td>
<td>VeryFar</td>
</tr>
</tbody>
</table>

Table 2 Rule base when Neighbor = “Farer”.

<table>
<thead>
<tr>
<th>Neighbor</th>
<th>Thermal</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
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</tr>
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<td>Few</td>
<td>VeryGood</td>
<td>Close</td>
</tr>
<tr>
<td>Half</td>
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<td>StartPoint</td>
</tr>
<tr>
<td>Almost</td>
<td>Fair</td>
<td>Far</td>
</tr>
<tr>
<td>Full</td>
<td>Bad</td>
<td>VeryFar</td>
</tr>
</tbody>
</table>

Where \(x_i\) is the element and \(\mu(x_i)\) is membership function. COG method is the most widely defuzzification strategy, which is reminiscent of the calculation of the expected value of probability distributions.

The details proposed algorithm is explained. Next in section 4, we will present some experimental results. The outcomes compare to shortest path method and adaptive probability functions to use thermal field.

4. Experiment

We conducted experiments to evaluate the proposed protocol, and compare to the shortest path method and thermal approach by fixed functions algorithm as presented in Ref. [22]. Since our approach run in decentralized network, each node knows only its neighborhood peers. The route decision is made step by step when it hold a message. The shortest path method finds the fastest way in terms of number of hop-count then the message is forwarded to the shortest neighbor to destination. The functions for probability to select either low buffer route or shortest way are predefined. In this paper, we selected the two different formulas in comparison.

4.1 Environment Setting

The experiment was simulated using P2PnetSim...
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[23], a network simulation environment. The tool is powerful and flexible in simulating, modeling and analyzing any kind of networks. Peers are configured collectively and individually using XML files for network setup, and Peer behaviors are implemented in the Java programming language. In our experiments, the network is organized into a grid structure with 5,625 nodes in two dimensions (75 × 75). The coordinates of a node within the grid form its node ID. The grid is overlaid on a virtual IPv4 network. Peers are connected in four directions to each other: left, right, up, and down. The buffer sizes and outgoing bandwidths are limited. Both buffer sizes and bandwidth values are assigned randomly follow the Power-Law distribution. There are two types of packets, data and acknowledgements. The acknowledgment is prioritized. Otherwise, the system handles the packets First-In-First-Out.

To generate traffic, the simulation defines different throughputs for nodes in terms of buffer sizes and outgoing bandwidths. In the trial, the 1,700 source nodes are uniformly randomly selected together with predefined target randomly in a specific area. Source nodes send a message to its target with probability 0.2. They generate a message in every simulation time until total messages are 200,000 packets. In order to evaluate algorithm performances messages success delivery ratio, message loss ratio, and message expired ratio are measured. Besides, a node (67, 30) is set to assess routing time. It generated a packet every simulation time until 500 messages sent to target (1, 5). The routing time that counts from launching the original node to reaching the target node. That time includes moving steps and waiting times in the traffic nodes.

4.2 Results and Discussion

The experiments report in this section compares to shortest path methods and thermal approach with two probability functions (4 & 5) as introduced in the previous work [22]. Packet delivery ratio is important as it describes the successful rate that will be seen by the transport protocol, which in turn affects the routing quality that the network can support.

In Fig. 4, the packet success delivery ratio of thermal approach using fuzzy logic is highest with 96% that shows its ability to select the optimal path. Fuzzy logic method selected least congested routes thus having the lowest amount of loss by 4%. A message expired ratio from fuzzy logic method is 0% which presents is ability to avoid very long indirect route and long queue in buffer peers same as shortest path approach. Both algorithms run without expired messages according to limited TTL. But the success ratio of thermal approach using fuzzy logic is superior than shortest path by 26% due to it can avoid full-buffer peer. Unusually, thermal approach using probability functions results are worst. The success ratios are lower than the shortest path algorithm and the expired ratio is very high.

This result is different from the outcome presented in [22]. We can assume that the thermal approach using probability functions selecting either shortest or lowest buffer route is unsuitable to very high congestion network, particularly when buffer usage of peers are mostly loaded.

Fig. 5 presents an example routing performance of evaluation node (67, 30) which sent packets to its target peer (1, 5). The average routing time is the average time to deliver a packet from launched at source to reached target, and it includes all possible delays such as waiting in buffer queue. And the average number

![Fig. 4 Packet delivery ratio.](image)
of hop-count is the average number of peer that packets are passed during transmission. The minimum hop-count from node (67, 30) to node (1, 5) is 91 time-steps in grid. The shortest path method obviously shows every message transport to destination with a number of hop-count, 91 time-steps. However, average routing time of shortest path is higher than fuzzy-logic due to waiting time in long queue buffer nodes by 28 steps. Moreover, the packet success ratio from evaluate node of fuzzy logic is higher than shortest path because of lost in full-buffer peers. The success ratio of evaluated node from shortest path methods is 34.80% but fuzzy-logic gives 99.80%. The results of thermal field using probability functions in Fig. 5 supports our assumption that these approach are inconsistent when considering one constraint in complex network.

5. Conclusions

In future works, more constraints such as bandwidth will be considered for improving quality of service routing. In addition, the enhancement of routing algorithms will be studied by learning process and dynamic depend on real-time network situation.

References


