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# INTERPOLATIVE BOOLEAN ALGEBRA BASED MULTICRITERIA ROUTING ALGORITHM

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**Abstract**: In order to improve quality-of-service of distributed applications, we propose a multi-criteria algorithm based on interpolative Boolean algebra for routing in an overlay network.We use a mesh topology because its implementation is easy and it quite simple addresses the cores during routing. In this paper, we consider four criteria: buffer usage, distance between peers, bandwidth, and remaining battery power. The proposed routing algorithm determines the path by using interpolative Boolean algebra, which satisfies quality-of-service requirements. The decision is made at each node, based on the ranking of available options and considering multiple constraints. The simulation shows that the proposed approach provides better results than the standard shortest path routing algorithm.

**Keywords:** Interpolative Boolean Algebra, Multi-criteria, Routing, Quality-of-Service.

**MSC:** 90C70.

## 1. INTRODUCTION

Quality-of-service (QoS) is the ability to provide different priority to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow. QoS routing is a key function of the transmission and distribution of digitized information across networks. The main objectives are to reduce congestion hot spots, improve resource utilization, and provide adequate QoS for final users. Numerous problems can affect performance: data loss due to buffer overflow when using an improper routing path, packet delay/expiry when residing in large queues, etc. Multi-criteria decision making in the proposed routing algorithm takes into account criteria such as node buffer capacities, residual link capacities, and number of hops on the path. Many routing algorithms use expert systems, artificial neural networks, and fuzzy logic for multi-criteria decision making, and focus on link constraints (e.g., bandwidth) or path constraints (e.g., end-to-end delay or path cost).

Structured peer-to-peer overlay networks are able to distribute content over a dynamically changing number of participants and to provide efficient lookup mechanisms. Further, such networks provide robust routing architectures, redundant storage and distributed implementations of trust, and authentication mechanisms that avoid single points of attacks and failures. When a single peer manages the content that is accessed by a lot of users in the whole network, such peer has a high message load. The peers around the hot-spots are inherently exposed to higher routing load since a lot of messages need to be routed to and from the hot-spot. Messages that are targeted to a hot-spot, or its surrounding nodes, have to be routed into the overloaded region, and other messages should be routed around it. In this way not only the additional load is avoided, and possible resulting message losses for the already stressed region, but also the delay time for the redirected message is optimized. However, it is important to make sure that no messages are lost due to Time-to-live (TTL) expires; the alternative routes should still have a minimum number of hops.

Using a grid pattern with coordinate system provides many benefits because between two peers there are many paths with the same hop-count, and each peer is capable to predict the shortest route without prior communication. The grid can be used to provide content-based coordinate systems generated from the distributed contents of the system, so map can be changed dynamically according to the application's requirements. The distance between peers is measured in rectilinear space. Other approaches propose routing in a mesh-like structure using the ElectronicProductCode (EPC) to establish an address space [8].

The proposed multi-criteria algorithm is based on Interpolative Boolean Algebra (IBA), which unlike conventional routing algorithms changes packet routes dynamically and reacts on network traffic. It takes into account indicators of buffer usage and remaining battery power of each node direct neighbor, the bandwidth of all theirlinks,as well as the distance from the current node to the target. A Thermal-field-based approach is used to convey information about the buffer usage status in a neighborhood area. Available path bandwidth is defined as maximum additional data transfer rate of a path, remaining battery is expressed by the state of charge of a battery, and rectilinear distance is used as a measure of distance. The decision about the next hop is made on each node by ranking the nodes in the neighborhood, using logical implication as an order relation.

In this paper, we examine opportunities for improving the routing process by introducing a new IBA based routing algorithm that satisfies multiple criteria.We give an overview of the criteria used in our algorithm in Section 2, and the process of its implementation in Section 3.The main characteristics and results of the new approach are illustrated on an interesting and illustrative example in Section 4. Section 5 concludes the paper.

## 2. RELATED WORKS

There are many adaptive routing algorithms which take into account multiple criteria and constraints to improve QoS: an algorithm considering the number of hops and available buffer-capacities in general communication networks [24], improvement of one or multiple QoS factors in a packet switching network that allows fuzzy mixed metric approach to be introduced [28], fuzzy ant colony algorithms, FLAR [12] and FACO[5] ensure optimal routing decisions considering multiple constraints in Mobile Ad Hoc Network (MANET). FLAR considers route utilization and delay, while FACO considers buffer occupancy, remaining battery power, and signal scalability.

Our approach was run on a mesh overlay [12] introduced decentralized routing algorithms in grid-like networks within only $O(\log^2 n)$ delivery time complexity. There are many algorithms that use coordinate systems built on different layers of the network stack, such as [2], [3], [4].

### 2.1. Routing in Mesh Structure

It has been mentioned and suggested by some researchers that the application-specific topology can offer superior performance while minimizing area and energy consumption [6]. The most common topologies are 2D mesh and torus due to their grid-type shapes and regular structure, which are the most appropriate and most usable for the two dimensional layout. The main design goals of routing algorithms are: low overhead, optimality, simplicity, robustness, flexibility, stability, and rapid convergence. In order to achieve these goals, the functions of routing algorithms are finding the fastest path, prevention of deadlocks, low latency insurance, network utilization balancing, and fault tolerance. Grid-like structures provide multiple paths which have the same hop count.

Some examples of routing algorithms in mesh topologies are evaluated in [10]. We use the XY algorithm, which is deterministic. Packets are first routed in the X direction until reaching the $Y_t$ coordinate, and afterwards in the Y direction, as shown in Figure 1. If some network hop is in use by another packet, it remains blocked in the node until the path is released. As illustrated in Figure 2, turns where the packet comes from the Y direction are forbidden - dotted lines; continuous lines represent allowed turns. Only 4 turns are allowed.

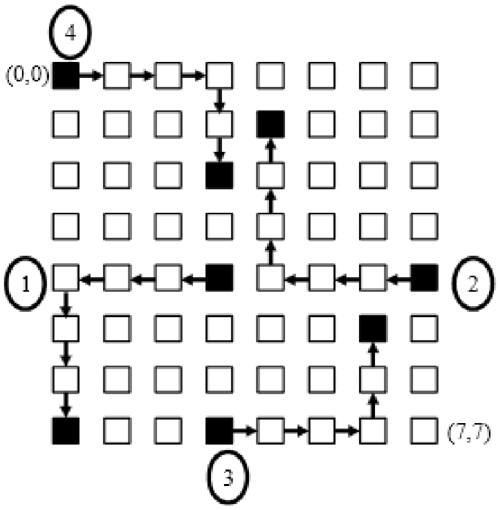


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**Figure 1:** XY routing algorithm

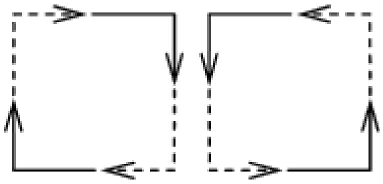

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**Figure 2:** Allowed turns

## 2.2. Thermal Field

A routing method based on the temperature fields theory in thermal physics was first created and introduced by Unger and Wulff [23] to locate nodes managing contents of common interest in P2P networks. Temperature is an indicator for the activity of the particular node. Baumann [1] introduced the HEAT routing algorithm, which operates on the principle that whenever the content of a node is accessed or updated, its temperature increases, whereas during periods of inactivity, the temperature falls exponentially to align with the temperatures of the surrounding neighbors. Similar theory is applied to wireless mesh networks in [24]. However, the temperature of a node is calculated from the density of all hosts in the network. Every node in the network determines the temperature, considering only the temperature of its direct neighbors, which makes protocol scalable to the network size.

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[1]A.V. Mello, L.C. Ost, F.G. Moraes, N.L. Calazans, Evaluation of Routing Algorithms on Mesh Based NoCs, Technical Report Series, 2004.

### 2.3. Bandwidth Allocation

Finding the path with the maximum available bandwidth is of great importance when providing QoS in the Mesh Networks. The available path bandwidth is defined as the maximum additional rate that a flow can push through, saturating its path [21]. So, if the amount of data required to be transported along a certain path is less than the available bandwidth, there will be no congestion of the channel. The bandwidth is a bottleneck metric in wired networks due to interference among channel links, which is not the case in wireless networks. The available path bandwidth information can be represented as a path weight.

### 2.4. Power Awareness Routing

Increase in bandwidth has led to an increase in power consumption. The main objective of introducing this new criterion is to ensure power savings in networks by including power awareness. Power consumption of a node can be divided according to functionality into: the power utilized for the transmission of a message, the power for the reception of a message, and the power used while the system is idle, see [14] , [22].

Control and management in the transmission of data play an important role in optimization of the power consumption. Power Management minimizes power consumption during the idle time by switching it to sleep mode [20]. Complementary to this, Power Control minimizes power consumption during communication, while the system is transmitting and receiving messages. Therefore, it is necessary to compute a path that maximizes the minimal power consumption, i.e., the path that requires the least power to transmit and receive a message.On the other hand, it is significant to compute the path that maximizes the minimal residual power in the network, the use of the path according to the residual energy of the nodes [13]. Avoiding small residual energy causes a node to become even more important when the dimensions and network traffic are increasing. Ideally, when nodes have plenty of residual energy, the link cost function should be such that the power consumption term is applied, and if the residual energy of a node becomes small, the residual energy term should be applied [11].

The main disadvantage of the approach described in [20] is that it always select the least-power cost routes. As a result, nodes along these least-power cost routes tend to “die” soon because of the battery energy exhaustion. This is doubly harmful since the nodes that die early are precisely those needed the most to maintain the network connectivity, and hence useful service life [9]. Therefore, it will be better to use a higher power cost route if this routing solution avoids using nodes that have small amount of remaining battery energy.

### 2.5. Interpolative Boolean algebra

Zadeh recognized the importance and necessity of gradation in relations (fuzzy sets [25], fuzzy logic [26], fuzzy relations [27]) for real applications. By using consistent fuzzy logic, within the Boolean framework, and based on the notion of gradation, problems with lower complexity can be solved in a way similar to the classical mathematical approaches, which conventional fuzzy approaches, based on the truth functional principle [19], can not manage. The approach that treats gradation in logic, theory of sets, relations, etc., is based on the interpolative realization of finite Boolean algebra (IBA) [16].

Variables of generalized Boolean polynomial (GBP) are free elements of Boolean algebra; operators are standard, + , -, and generalized product $\otimes$ . A set of feasible generalized product is a subclass of T-norms which satisfies an additional constraint - probability consistence. In the new approach, a generalized product has a crucially different role. It is only an arithmetic operator, contrary to conventional fuzzy approaches where T-norms have the role of algebraic operator. Interpolative Boolean algebra (IBA) determines the procedure of transforming the analyzed element of Boolean algebra and/or a Boolean function into GBP directly.

Variables of GBP are elements from the analyzed set of primary attributes $\Omega = \{a_1,\ldots,a_n\}$ . Primary attributes have the following characteristic: there is no primary attribute which can be expressed as a Boolean function of the remaining primary attributes from $\Omega$ .

In general case, logical aggregation has two steps:

1) Normalization of primary attributes' values [17]:

$$\|\cdot\| : \Omega \to [0,1] \tag{1}$$

The result of normalization is a generalized logical and/or [0, 1] value of the analyzed primary attribute, and

2) Aggregation of normalized values of primary attributes into one resulting value by pseudo-logical function as a logical aggregation operator:

$$Aggr : [0,1]^n \to [0,1] \tag{2}$$

A Boolean logical function $\varphi$ is transformed into a corresponding generalized Boolean polynomial

$$\varphi^{\otimes} : [0,1]^n \to [0,1] \tag{3}$$

Operator of logical aggregation in a general case is a pseudo-logical function, a linear convex combination of generalized Boolean polynomials (GBP):

$$Aggr^{\otimes} = \pi\varphi_{\mu}^{\otimes}(a_1,\ldots,a_n) \tag{4}$$

Logical aggregation operator depends on the chosen measure of aggregation $\mu$ and on operator of generalized product $\otimes$ ) [15], [17].

R-implication is a consistent Boolean generalization of classical binary implication, and it overcomes the drawback of conventional fuzzy implications. It is realized as a generalized Boolean polynomial. R-implication, which has important roles in many applications, such as morphology in image processing, association rules in data mining and decision making.

R-implication and/or GBP $\left(A(x) \Rightarrow B(y)\right)^{\otimes}$ that corresponds to implication function $A(x) \Rightarrow B(y)$ is

$$\left(A(x) \Rightarrow B(y)\right)^{\otimes} = 1 - A(x) + A(x) \otimes B(y) \tag{5}$$

where $\otimes$ is a generalized product[19].

The real valued realization of a finite (atomic) Boolean algebra is based on Boolean polynomials, as well. The implication can be performed using the Boolean polynomial of free variables $x$ and $y$, which take the values from the unit interval $x, y \in [0,1]$ [19]:

$$\phi^{\otimes}(x,y) = \phi(1,1)x \otimes y + \phi(1,0)(x - x \otimes y) + \phi(0,1)(y - x \otimes y) + \\ +\phi(0,0)(1 - x - y - x \otimes y) \tag{6}$$

$\otimes$ is a generalized product or t-norm with the following property[16]:

$$\max(x + y - 1, 0) \le x \otimes y \le \min(x, y) \tag{7}$$

$$\phi(x,y) =_{def} x \Rightarrow y \tag{8}$$

$$\phi(1,1) = 1; \phi(1,0) = 0; \phi(0,1) = 1; \phi(0,0) = 1; \tag{9}$$

$$x \Rightarrow y = 1 - x + x \otimes y \tag{10}$$

R-implication corresponds to order relation $x \le y$, as we can see from Table 1.

**Table 1:** Fuzzy implication and order relation

| $x$ | $y$ | $x \le y$ | $x \Rightarrow y$ |
|---|---|---|---|
| 0 | 0 | 1 | 1 |
| 1 | 0 | 0 | 0 |
| 0 | 1 | 1 | 1 |

In Section 2,we introduce the basics of routing in the mesh structure, the thermal field approach, bandwidth allocation, power awareness routing, and IBA. In the next section, we present an algorithm based on the IBA, and using the relative distances in the grid, buffer usage level, available bandwidth and power consumption,we provide a more efficient basis for creating a new routing protocol.

## 3. ALGORITHM

In this section, we describe the proposed algorithm. In order to provide the QoS requirements, the decision-making process in routing algorithmis to find the best path, based on IBA, is used. It relies on the communication model of transmitted temperature value by agents and has the information about the distance, bandwidth of each link,and remaining battery of neighboring nodes. Our approach gives equal importance to all four indicators in decision making. The distance between peers is expressed by the rectilinear distance, taking into account the coordinates of the current and the target nodes in the grid. The thermal field represented buffer usage level is used for communicating buffer information over the network. The remaining battery depends on the remaining battery capacity, and the full-charge battery capacity. Each node stores information about its neighbors temperature (indicate available resources to handle new data), coordinates, available bandwidth, and remaining battery. Decision process also takes into account the distance of original to target node, current to target peer, and neighbors to target location.

**3.1. Measuring the temperature**

The temperature $\theta$ represents the buffer usage of a peer that is the level of messages waiting to be forwarded. 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 stands for an empty buffer and 1 for a full buffer).

$$\theta_c = \frac{Messages\,in\,buffer}{buffer\,size}, 0 \le \theta_c \le 1 \tag{11}$$

The updated information about buffer status of each peer are important to make a correct decision about optimal routh. The packets and the acknowledgements work as a median of the temperature pass from one to another node until they reach their target or expire. Each current node $c$ has a set of neighbors, $N(c)$, where messages can be forwarded to. If $i$ is a neighbor's identifier, then $N_i \in N(c), 1 \le i \le 4$ (consequence of grid-like structures - northern, eastern, southern and western neighbors).

There are three possibilities to update information about a neighbor's temperature $\theta(N_i)$ on the node $c$. Let $\beta_i$ be the number of packets, and $\mu_i$ the number of acknowledgements sent from neighbor $N_i$ to current node $c$. If node $c$ receives a packet or an acknowledgment from a neighbor $N_i$, the old temperature is replaced by the new temperature, where $i$ is the identifier (let $N_1$ indicates the northern, $N_2$ eastern, $N_3$ southern and $N_4$ western node)

$$\theta(N_i) = \theta_i, if \;\; \beta_i > 0 \, and \, \mu_i > 0 \; . \tag{12}$$

If there is no message sent from a neighbor $N_i$, the new temperature caused by the spread of source node decreases exponentially, where $t$ is the routing time

$$\theta(N_i) = \theta(N_i) * e^{-\lambda t}, if \;\; \beta_i = 0 \, and \, \mu_i = 0 \; . \tag{13}$$

The new temperature is zero when no messages arrive and no heat remains

$$\theta(N_i) = 0, if \;\; \beta_i = 0, \mu_i = 0 \;\; and \, \theta(N_i) = 0 \, . \tag{14}$$

In the next section, we present our algorithm that determines the next hop for data forwarding, based on four criteria: distance, temperature, bandwidth, and battery power.

**3.2. Measuring the distance**

The inputs to the system to be designed for routing are: buffer usage status, distance, bandwidth, and battery status. All input variables make the route reflect the network status and the node's ability to reliability delivery network packet.

The distance is defined as a current packet-holder position compared to the target. In grid, it is calculated:

$$d = |x_t - x_c| + |y_t - y_c|, \tag{15}$$

where $(x_c, y_c)$ is a current peer, and $(x_t, y_t)$ is the target.

### 3.3. Measuring the bandwidth

Let $B(e)$ be the available bandwidth of the link $e$, representing a maximum amount of information in Kbits. The expected available link bandwidth is available bandwidth of each path link when we consider the bit error rate of a path link in estimation. A clique is a subset of a graph such that every two nodes in the subset are connected by a link, and from the above, it gives $Q_p$, as the set of the maximal cliques containing only links on $p$. If two links on a path are in conflict with each other, the same applies to all links between them along the path. The available bandwidth of a path $p$ is estimated as follows:

$$B(p) = min_{q \in Q_p} C_q ; C_q = \frac{1}{\sum_{l \in q} \frac{1}{B(l)}} \tag{16}$$

The time that 1 Mbit data takes to traverse properly in all the links of the clique $q$ is $\sum_{l \in q} \frac{1}{B(l)}$. The $C_q$ is thus the bandwidth available over the clique *q*. Then the available bandwidth of the path link is the bandwidth of the bottleneck clique.

### 3.4. Remaining battery power

To meet the demand for energy savings, algorithm uses state of the battery charge. Finding a next hop $\pi$ at a route discovery time $t$ is expressed as follows:

$$\min_{\pi} C(\pi, t) = \sum_{i \epsilon \pi} C_i(t) \tag{17}$$

$$C_i(t) = \rho_i \left( \frac{F_i}{E_{r,i}(t)} \right)^{\alpha_i} \tag{18}$$

Where $\rho_i$ transmit power of a node *i*, $F_i$ full-charge battery capacity of the node *i*, $E_{r,i}(t)$ remaining battery capacity of a node *I* at time *t*, $\alpha_i$ a positive weighting factor.

This approach uses an accumulative graded cost function, defined as a function of the ratio of the remaining battery capacity over the full-charge battery capacity. As this ratio decreases and becomes less than a specified set of threshold values, $\alpha$ increases according to a fixed schedule. If a path from source to destination has some nodes with very low residual battery, the cost of the path will be very high, and therefore routing algorithm attempts to avoid the route with nodes having the least battery capacity, among all nodes in all possible routes. Thereby, it results in moderate use of the battery of each node.

### 3.5. Ranking of nodes based on IBA

Neighbors should be ranked on a global rating, which includes buffer usage status, distance, bandwidth, and remain battery indicator. A global rating of neighbors is actually the aggregation of its rating per indicators. In order to compare neighbors, the corresponding indicators should be compared first. In other words, it is required to get value of the order(real-valued implication) of corresponding indicators for all of the analyzed neighbors. For that purpose, operation of R-implication is used. In fact, we use logical expressions for the implication. Technically, R-implication [18] is realized as a generalized Boolean polynomial.

$$a \Rightarrow b = a^{c} \cup b \tag{19}$$

Transform (19) to its corresponding generalized Boolean polynomial.

$$(a \Rightarrow b)^{\otimes} = 1 - a + a \otimes b \tag{20}$$

Min function is defined as the operator of generalized product $\otimes$ since it is used in case of the same attributes. Only the objects with the same attributes can be compared, but it is not necessary that all attributes are the same. For the overall valuation of the neighbor nodes, operator of logical aggregation is used.

$$\begin{aligned} Aggr^{\otimes}(d_{imp}, \theta_{imp}, B_{imp}, C_{imp}) &= d_{imp} \otimes \theta_{imp} \otimes B_{imp} \otimes C_{imp} = \\ &= d_{imp} * \theta_{imp} * B_{imp} * C_{imp} \end{aligned} \tag{21}$$

Where $d_{imp}$, $\theta_{imp}$, $B_{imp}$, and $C_{imp}$ are the values of the implication for each of the combinations of neighbors.

So, the algorithm consists of the following steps (which are repeated at each node from source to target):

- for each of the neighboring node calculate the distance, buffer usage status, bandwidth and remain battery;
- calculate the value of R-implication (order relation) by appropriate indicators for all combinations of the neighboring nodes. The value of one indicates a few possible situations:

    1. the first neighbor in the pair is closer to target;
    2. there is more free memory for the new data;
    3. more available bandwidth on the link to the first neighbor;
    4. more battery power remained.

When the value of R-implication is less than 1, it indicates the degree of their sameness in the unit interval [0,1]. This sameness refers to their equality in terms of having the same property. Let us take an example: nodes $N_3$ and $N_4$ have remaining battery power 0.9 and 0.5, respectively, which means that they have the property of full battery with 0.5 and absence of 0.1 (Figure 3.):

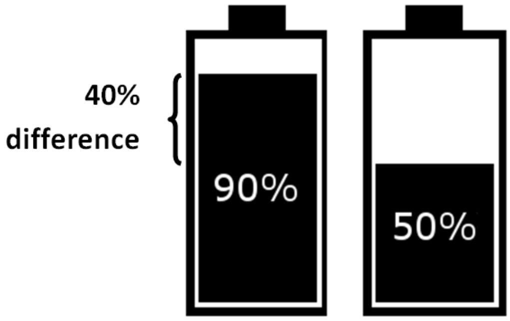



**Figure 3:** R-implication for remaining battery

- logical aggregation of the values obtained in the previous step provides a global rating for pairs of neighbors;
- select the row with the highest value of the logical aggregation from the aggregation table, and choose the first node in the pair. In the case of multiple rows with the same values of aggregation, it is necessary to compare the aggregations of the first nodes in the pairs.

By a simple example, we show how the algorithm works. Information about the distances, buffer usage, bandwidth, and energy of neighbors are shown in Table 2. After calculating the values of implications and aggregations in Table 3, we can see that the neighbor $N_1$ is the only candidate for the next hop in the routing process. So, we are choosing $N_1$ because the value of the corresponding aggregation is the greatest (Table 3).

**Table 2:** Inputs

| Neighbor | Distance ($d$) | Temperature ($\theta$) | Bandwidth($B$) | Battery power($C$) |
|---|---|---|---|---|
| $N_1$ | 0.1 | 0.7 | 0.8 | 0.3 |
| $N_2$ | 0.9 | 0.5 | 0.6 | 0.4 |
| $N_3$ | 0.2 | 0.5 | 0.7 | 0.9 |
| $N_4$ | 0.7 | 0.9 | 0.4 | 0.5 |

**Table 3:** Calculation of R-implication and aggregation

| Order | $d_{imp}$ | $\theta_{imp}$ | $B_{imp}$ | $C_{imp}$ | Aggr |
|---|---|---|---|---|---|
| $N_1 \leq N_2$ | 1 | 0.8 | 0.8 | 1 | 0.64 |
| $N_1 \leq N_3$ | 1 | 0.8 | 0.9 | 1 | 0.72 |

| | | | | | |
|---|---|---|---|---|---|
| $N_1 \leq N_4$ | 1 | 1 | 0.6 | 1 | 0.6 |
| $N_2 \leq N_1$ | 0.2 | 1 | 1 | 0.9 | 0.18 |
| $N_2 \leq N_3$ | 0.3 | 1 | 1 | 1 | 0.3 |
| $N_2 \leq N_4$ | 0.8 | 1 | 0.8 | 1 | 0.64 |
| $N_3 \leq N_1$ | 0.9 | 1 | 1 | 0.4 | 0.36 |
| $N_3 \leq N_2$ | 1 | 1 | 0.9 | 0.5 | 0.45 |
| $N_3 \leq N_4$ | 1 | 1 | 0.7 | 0.6 | 0.42 |
| $N_4 \leq N_1$ | 0.4 | 0.8 | 1 | 0.8 | 0.256 |
| $N_4 \leq N_2$ | 1 | 0.6 | 1 | 0.9 | 0.54 |
| $N_4 \leq N_3$ | 0.5 | 0.6 | 1 | 1 | 0.3 |

In the next section, we present the implementation of the proposed algorithm, and some experimental results obtained by comparison with the shortest path method.

## 4. EXPERIMENT

The experiment was conducted in order to evaluate the effectiveness of the proposed approach compared with the well-known shortest path method. The shortest path method finds the fastest way in terms of the number of hop-counts to the destination. In our decentralized method, decisions are made step by step,which means that a single node knows only its neighborhood peers and makes a decision about next hop while holding the message.

### 4.1. Settings

PeerSim [7] network simulator was used to conduct the experiment, which was developed with extreme scalability and support for dynamic. It is written in Java and composed of two simulation engines, a simplified (cycle-based) and the event driven. We used the cycle-based engine to allow scalability, which uses some simplifying assumptions, like ignoring the details of the transport layer in the communication protocol stack.

The Virtual IPv4 network is overlaid by grid structure with 2500 nodes. The node ID is actually the coordinates of a node within the grid. Peers are connected to each other in four directions: left, right, up, and down. The buffer sizes and outgoing bandwidths are limited and assigned randomly, following the Power-Law distribution. There are two types of packets, data, and acknowledgements. The acknowledgment is prioritized. Otherwise, the system handles the packets using First-In-First-Out algorithm.

To make more realistic traffic, different through-puts for nodes in terms of buffer sizes and outgoing bandwidths are defined. The source node (8,14) sends a message to its target (26,43) in each simulation time until total messages are 1,000 packets. In order to evaluate algorithm performances, we measured message success delivery ratio, message loss ratio, and message expired ratio. Routing time, which includes moving steps and waiting time in the traffic nodes, are also assessed.

### 4.2. Results and analysis

In this section, we present the results of an experiment conducted in order to compare the efficiency of the shortest path method with the proposed one. As the indicators of efficiency, we took into account several parameters obtained in the simulation of network: 1) delivery ratio, which is important as an indicator of success, and the routing quality that the network can support; 2) average time for a packet to be delivered from source to target, which includes all possible delays, such as waiting in a buffer queue.

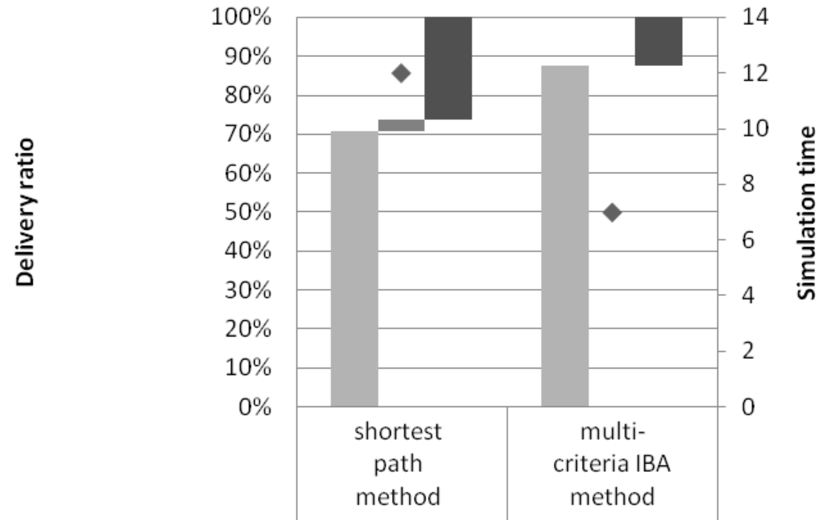
The proposed multi-criteria IBA method achieves improvement in message success delivery ratio; it is higher 12% than the ratio obtained by the shortest path method, as shown in Fig. 2. This approach provides the eligible path, which avoids congestion, and in addition, it takes into account the distance and battery remain, so the ratio of lost messages is lower more than twice than in the other method. According to limited TTL, both methods provide low message expire ratio, although it must be emphasized that the ratio of our method is 0% because it can avoid full-buffer peers and the paths with minimal available bandwidths.

The minimum hop-count from node (8, 14) to node (26, 43) is 47 time-steps in the grid. The shortest path method shows transport to destination of every message with a number of hop-count, 47 time-steps. However, average routing time value of shortest path is higher(12 simulation time-steps) than that of the multi-criteria IBA(7 simulation time-steps) due to waiting time in long queue buffer nodes, and congestion due to low bandwidth.

In comparison with the results obtained by applying two criteria, distance and buffer usage status, on the same network structure(1225 nodes, source(12,1) and the target node (8,31)), we obtained better results taking into account all four criteria, as shown in Table 4.

**Table 4:** Results with different number of criteria

| | 2 criteria | 4 criteria |
|---|---|---|
| success delivery ratio | 89 | 91 |
| message loss ratio | 11 | 9 |
| message expired ratio | 0 | 0 |
| Average waiting time | 4 | 3 |




| | shortest path method | multi-criteria IBA method |
|---|---|---|
| ■ message loss ratio | 27 | 12 |
| ■ message expired ratio | 3 | 0 |
| ■ message success delivery ratio | 72 | 84 |
| ◆ average waiting time | 12 | 7 |

**Figure 4:** Results of simulation

## 5. CONCLUSION

In this paper, we presented a multicriteria routing algorithm based on Interpolative Boolean Algebra. The algorithm is applied to a structured peer-to-peer overlay network. The thermal field theory is used to represent the buffer usage of a peer, and the distance is calculated based on the coordinates of the grid. The available bandwidth is the bandwidth of the bottleneck clique, and remaining battery power depends on charge status. These four criteria ensure the shortest path and optimal use of resources, as it is demonstrated in the experiment.

In a future work, the algorithm will include more criteria relating to transport and infrastructure, such as signal scalability and delay. To improve the reliability of packet transmissions, the proposed approach should handle all causes of failure, such as transmission failures, link failures, and network congestion. Additionally, Network Virtual Environments, Data mining, and similar applications could apply IBA based routing approach to their content-grid structure.

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