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Research Article

Multipath Route Optimization with Multiple QoS Constraints Based on Intuitionistic Fuzzy Set Theory

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In wireless networks, a change in network state is unpredictable because of the movement of network nodes, which is not conducive to the stability of the network and poses an especially serious challenge to network routing technology. To adapt to the flexibility of business, consider the impact of environmental changes on the bottom layer of a network, and improve the utilization of network resources, this paper proposes a multipath routing decision strategy restricted by multiple QoS attributes based on an intuitionistic fuzzy set of entropy weights. Cross-layer technology is applied to minimally meet the QoS needs based on multipath routing to discover and maintain multiple transmission paths. Moreover, intuitionistic fuzzy set theory is utilized to reflect the performance indexes of these multiple paths through fuzzy normalization to create a multiparameter multipath routing decision matrix. The weight of each parameter is objectively computed according to information entropy theory. The performance ranking of the multiple paths is determined with the TOPSIS method. As reflected by the results, the TOPSIS decision method based on an intuitionistic fuzzy set of entropy weights effectively solves the optimization problem for multiple paths in mobile ad hoc networks restricted by multiple parameters, and the resulting network is suitable for sensitive network applications involving multiple businesses in mobile environments. According to the simulation results, the proposed routing scheme reduces average network delay by 17% and routing overhead by 21% when compared to the current routing protocols.

1. Introduction

Wireless networks have developed from simple to complex, single to diverse, and fixed to mobile and have expanded from simple person-to-person communication to person-to-machine and machine-to-machine communication; these changes have required wireless networks to transition from simple functional realizations to intelligent applications with environmental changes. In fact, the influence of the environment on a network is multifaceted and often uncertain. The uncertainty is affected by both the external environment of the network transmission system and the internal changes in the system itself. The external spatial structure, the characteristics of the transmission medium, and the mobility of terminals have certain effects on the fading of electromagnetic waves and the interruption of links. Additionally, changes in the type of service, number of services, and QoS requirements within a transmission system will lead to network congestion, jitter, and delay. Wang et al. [1] defined this network uncertainty as randomness and fuzziness. Randomness means that the time of an event is uncertain, and fuzziness reflects the uncertainty of the cause and degree of influence of an event; moreover, randomness and fuzziness can coexist. However, the occurrence of these situations in reality is unpredictable; for instance, the cause of a delay may be the movement of an external terminal or internal congestion. Over time, changes in the internal and external environments of networks occur randomly. The causes are variable, and the degree of influence is different, thus affecting the stability of wireless networks. A wireless body area network includes several wearable or implantable wireless terminal sensing devices attached to the human body [2–4] and is a short-distance wireless network composed of portable mobile devices. Such networks are connected to cloud health service systems. With change in human activities, the mobile characteristics of the network nodes and external network environment will change, thus making wireless body domain networks difficult to establish [5–7].

A wireless body area network is a form of wireless sensor network (WSN). A WSN is a distributed self-organizing network in which each node is both a source node and a routing node. For a routing node, the node choices are complex and variable, and a source node, routing node, and destination node constitute a path. With the development of routing technology and the increase in service business, the approach of multipath routing with multiple QoS constraints has become a popular research area under the condition of satisfying the QoS demand; multiattribute decision-making has played an important role in solving these types of routing decision problems [8–11].

In order to meet diverse business requirements and guarantee mobile target monitoring, the network has implemented cross-layer technology to meet QoS requirements minimally based on multipath routing so as to discover and maintain multiple transmission paths. In this study, a multiattribute constraint multipath routing protocol with improved intuitionistic fuzzy sets is used to examine how routing nodes are affected by changes in the wireless network environment for various QoS requirements (FMQMRP). The main contributions of this study are as follows:

(1) For attribute parameters with unknown features and weights along multiple paths, we apply intuitionistic fuzzy set theory to normalize multiple metrics

(2) We apply a multiattribute reduction algorithm based on an intuitionistic fuzzy set and information entropy theory to calculate the attribute weight in each scheme; then, we apply the technique for order preference determination based on similarity to the ideal solution to optimize the multipath routing scheme under the constraint of multiple metrics

(3) We design a cross-layer multipath routing protocol with multiple QoS constraints

2. Related Works

With the rapid increase in the number of mobile users and the rising demand for high-bandwidth and high-traffic services, improving energy efficiency has become a crucial indicator of future environmentally friendly communication. Researchers studied a variety of topics, including energy-efficient and fault-tolerant technology, green cloud computing, and multiparty key exchange protocols with privacy protections. In reality, meeting other business needs as well as energy conservation requirements necessitates network optimization issues under various QoS restrictions. The routing mechanism based on QoS requirements is an adaptive network routing method that meets the relevant business demands and adapts to environmental change. The main objectives of this approach are to determine the end-to-end QoS parameter constraints and optimize network performance. The method includes collecting and constantly updating the network state information and choosing the best path for connection requests according to new status messages [12–14]. Information acquisition mainly depends on the message control mechanism of the routing protocol and the related detection technology to obtain the required network state parameters. Compared to the traditional layered protocol approach, the cross-layer scheme achieves better coupling to adapt to changes in wireless transmission, and it can effectively solve the problem of network optimization in complex and variable environments [15]. Multipath routing technology with multiple QoS constraints can satisfy the demands of different business services in complex environments [16]. However, as the network size and type of service increase, it is difficult to accurately and comprehensively obtain the information that affects network performance.

In [17], focusing on the fuzziness, randomness, and unpredictability of WSN trust relationships based on a cluster structure, cloud theory was applied to analyze the developed credibility evaluation scheme, which involves three attributes: the communication success rate, energy utilization rate, and data reliability. Thereafter, they merged all attribute trust clouds into a unified comprehensive trust cloud according to the assigned attribute weight coefficients. Ultimately, the final trust value was calculated from the comprehensive trust cloud, which effectively solved the fuzzy randomness issue in network trust evaluation. The development of intuitionistic fuzzy theory, which has a positive effect on solving multiattribute decision-making problems and has been widely adopted in numerous fields, has been substantial. Researchers use intuitionistic fuzzy theory to solve problems where network parameters are uncertain and parameter values cannot be provided precisely [18–21]. Dou et al. [22] adopted fuzzy theory to compare parameter values to actual requirements and determined the magnitude of parameters. Score functions in vague set theory and a probability matrix were adopted to calculate the shortest circuit for multiparameter constraints along a single path. However, the disadvantage of this method is that each node has to be processed through a vague set, which is too complex to calculate, and a single path cannot comprehensively provide enough route nodes. On the basis of AOMDV, the AM-AOMDV protocol was proposed in [23] to improve the path maintenance time, increase throughput, and reduce the delay, route lookup frequency, and overhead of routing by exchanging information within a hop range of nodes when the network destabilized in a mobile environment, thus improving network performance. The AM-AOMDV protocol selected the RSSI, delay, and buffer occupancy as QoS attribute criteria. However, this approach could not solve optimization problems with multiple paths and multiple QoS attributes. Sarma and Nandi [24] proposed the SMQR protocol, which is based on the stability of routing and provides multiple QoS parameters that affect the stability of routing on the basis of multipath routing. Since stability was considered the key target, the signal strength was adopted as the primary basis for stability assessment in the mobile environment, and the bandwidth

Table 1: Comparison of multimetric routing protocols.

Protocols	Metrics	Approach	Advantages	Limitations
[17]	Trust relationships	Cloud theory-based decision-making	Implement the conversion between qualitative and quantitative of trust attributes	High computational complexity
[22]	Energy, bandwidth, end to end delay	Vague set theory-based decision-making	Considering multiple attribute constraints	Single path, high computational complexity
[23]	RSSI, delay, and buffer occupancy	QoS attribute criterion-based decision-making	High throughput, low delay, low route lookup frequency	Not solve optimization problems with multiple paths and multiple QoS attributes
[24]	Signal strength, bandwidth, time delay	Analytic hierarchy process-based decision-making	High throughput, low delay	High resource consumption
[25]	Traffic load, mobility, SNR, and transmission delay	Multimetric dynamic weighting-based decision-making	Dynamic adaptation of weight factor	Grade intervals automatically depend on human experience
[26]	Links, paths, subflows	GNN model-based decision-making	High-throughput prediction in multipath routing decisions	Extra overhead for learning

and time delay were secondary considerations. This method improved the network throughput and average delay on the basis of link stability. In the process of route discovery, admission control and resource reservation were achieved on a hop-by-hop basis. Finally, the best path was selected as the primary path, and the other two nonintersecting nodes were used to establish the backup path. When the primary path could not execute data transmission, the backup path was used. However, this method involved the subjective grading of certain attributes, thus ignoring the objective impact of these attributes on the target.

To improve the AODV protocol, a dynamic multimetric weighting scheme was proposed forth in [25]. Traffic load, node mobility, SNR, and transmission delay were chosen as routing indicators, and the weighting factors were established using an analytical hierarchy process (AHP). In [26], the GCLR multipath routing model, based on GNN, was proposed. In order to take advantage of the fact that GNN models can learn the structural characteristics of graphs, GCLR modeled the routing problem as a graph problem. For the routing optimization problem under multiple QoS attributes, Zheng [27] applied multicast routing for each node through a router tree and used a linear programming method for multiobjective optimization. However, the route maintenance overhead was high. A comparison of the multimetric routing protocols is summarised in Table 1.

Most researchers have studied routing methods under QoS constraints only from the perspective of a single parameter or single path and seldom considered multipath selection with multiparameter constraints. When applying cross-layer routing methods in network optimization, the network is only considered from a single perspective, and the interactions among parameters are not considered when multiple cross-layer information perspectives are used. In such cases, it is difficult to make the best choice among multiple parameter attributes because of the fuzziness of the relationships among parameters. Moreover, the weights of the different parameters also change in different stages and environments, thus diminishing their objectivity. In the case of securing sufficient resources, evaluation strategies can be implemented to identify relatively superior methods through comparison, which ensures the accuracy of selection with a certain probability.

Based on the cross-layer design technique and intuitionistic fuzzy set theory, this paper proposes a multipath route optimization method with multiple QoS constraints based on the intuitionistic fuzzy set theory to solve MANET multipath routing problem with multiconstraint QoS. The specific problem is described below.

3. Problem Description

Multipath routing technology provides several data transmission schemes for network nodes. The selection of the optimal scheme is a common problem in network optimization. If there is a single optimization goal, optimal scheme selection is relatively simple. However, when there are many targets that are constrained by multiple attributes, difficulties will be encountered. The value of each attribute is different in each scheme, and it is difficult to determine the weight. Hence, the decision-making process under such uncertainty is a complicated problem. In this paper, we solve this problem by performing multipath routing with a multiattribute constraint model and applying a fuzzy decision method.

3.1. Network Model. According to graph theory, the network in this study is defined as a weighted directed acyclic graph $G = (V, E, C)$, where $V = \{1, 2, \cdots, N\}$ is the set of vertices. $E = \{e_{ij} | i, j \in V\}$ is the set of vertex edges, and e_{ij} is the edge from vertex i to vertex j, which also represents the link from node i to node j. $C = \{c_{ij} | i, j \in V\}$ is the edge weight set, and c_{ij} is the edge or weight corresponding to link e_{ij}; here, c_{ij}, as represented by an intuitionistic fuzzy set (IFS), is mainly the attribute value transmitted over a link in a routing decision. In multipath route optimization with multiple QoS constraints, $R = \{r_1, r_2, \cdots, r_m\}$ is the path set from source node

Table 2: Main notations used in this paper.

Symbol	Description
k	The number of nodes along path r_i
c_{ij}	The weight (or arc length) of the attribute over link e_{ij}
C_{ij}	The weight of the j_{th} attribute parameter along path i_{th}
c_{ij}^{Add}	The additive attribute weights along a link from node i to node j
c_{ij}^{Mult}	The multiplicative attribute weights along a link from node i to node j
c_{ij}^{Ext}	The extreme attribute (maximum or minimum) weights along a link from node i to node j
m	The number of alternative path schemes from the source node to the destination node
n	The number of attributes involved in the decision
$r_{s,t}$	The set of nodes from source node s to destination node t
$\sum_{i,j=1}^{k} c_{ij}^{\text{Add}} \cdot e_{ij}$	The sum of the additive properties of all routing nodes along a path
$\prod_{i,j=1}^{k} c_{ij}^{\text{Mult}} \cdot e_{ij}$	The product of the multiplicative properties of all routing nodes along a path
$\max/\min\left(c_{ij}^{\text{Ext}} \cdot e_{ij}\right)$	The maximum or minimum value of the polarity of all routing nodes along a path

S to destination node t. According to previous research [28, 29], the attribute values form the multiattribute decision matrix for multiple links. All proposed variables and their descriptions are presented in Table 2.

According to the classification of parameter attribute measures, we construct the multiattribute decision matrix $\mathfrak{R}$ for multipath routing.

$$\mathfrak{R} = \begin{vmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ C_{i1} & \cdots & C_{ij} & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ C_{m1} & C_{m2} & \cdots & C_{mn} \end{vmatrix}, \quad (1)$$

$$C_{ij} = \begin{cases} \sum_{i,j=1}^{k} c_{ij}^{\text{Add}} \cdot e_{ij}, \\ \prod_{i,j=1}^{k} c_{ij}^{\text{Mult}} \cdot e_{ij}, \\ \max/\min\left(c_{ij}^{\text{Ext}} \cdot e_{ij}\right), \end{cases} \quad (2)$$

$$\text{s.t}: \sum_{i,j} e_{ij} - \sum_{i,j} e_{ji} = \begin{cases} 1 & \text{if } i = s, \\ 0 & \text{if } i \neq s, \\ -1 & \text{if } i = t, \end{cases} \quad (3)$$
$$(i = 1, 2,. \cdots, k-1, k).$$

In this case, $e_{ij} = 0$ or 1, and $e_{ij} = 0$ indicates that link e_{ij} does not exist. Moreover, $e_{ij} = 1$ indicates that link e_{ij} exists, and the direction is from node i to node j ($i \longrightarrow j$). Similarly, $e_{ij} = -1$ indicates that the link direction is from node j to node i ($j \longrightarrow i$).

3.2. Parameter Preprocessing

Definition 1 (intuitionistic fuzzy set (IFS)). Assuming that $X = \{x_1, x_2, \cdots, x_n\}$ is a nonempty object space, then an IFS A that exists in X is defined as

$$A = \{\langle x_i, t_A(x_i), f_A(x_i)\rangle | x_i \in X\}, \quad (4)$$

where $t_A(x_i)$ is the membership function of A and $f_A(x_i)$ is the nonmembership function of A. $t_A(x_i)$ and $f_A(x_i)$ relate each element x_i in X to a real number in the interval of [0,1], i.e.,

$$\begin{aligned} t_A(x_i)&: X \longrightarrow [0, 1], \\ f_A(x_i)&: X \longrightarrow [0, 1], \\ 0 \leq t_A(x_i) &+ f_A(x_i) \leq 1. \end{aligned} \quad (5)$$

The intuitionistic index of the A density is π_A, with

$$\pi_A = 1 - t_A(x_i) - f_A(x_i). \quad (6)$$

This variable is a measure of the uncertainty of the inclusion of x_i in A.

It is assumed that A is an IFS, and when X is a continuous space, we can obtain

$$A = \int_X \frac{[t_A(x), 1 - f_A(x)]}{x}, \quad x \in X. \quad (7)$$

When X is a discrete space, we can obtain

$$A=\sum_{i=1}^{n}\frac{t_A(x_i),1-f_A(x_i)}{x_i},\quad x_i\in X. \tag{8}$$

3.2.1. Classification of Parameter Attributes. According to the classification of the calculation method, QoS parameter attributes can be divided into three categories: additive measures, multiplicative measures, and extremity measures. Assuming that $r_{s,t}=(s,\cdots,i_k,\cdots,t)$ is the set of nodes from source node s to destination node t, $C(i,j)$ for $(i,j\in r_{s,t})$ is a QoS metric parameter (or weight); additionally, $C=\{C_1, C_2,\cdots,C_n\}$ over link e_{ij}. The three measures are defined as follows:

(i) Additive measures: measurement $C(r_{s,t})$ for $r_{s,t}$ should satisfy the following equation:

$$C(r_{s,t})=c(s,i_1)+c(i_1,i_2)+\cdots c(i_{k-1},i_k)+c(i_k,t) \tag{9}$$

The additivity measure is determined by the properties of the attribute itself, such as the delay, communication cost, and path length (number of hops).

(ii) Multiplicative measure: measurement $C(r_{s,t})$ for $r_{s,t}$ should satisfy the following equation:

$$C(r_{s,t})=c(s,i_1)\times c(i_1,i_2)\times\cdots c(i_{k-1},i_k)\times c(i_k,t) \tag{10}$$

Common attributes include the packet loss rate and reliability (or stability).

(iii) The extremity measure can be convex or concave. The maximum or minimum value of $C(r_{s,t})$ for an attribute should satisfy the following equations:

$$C(r_{s,t})=\max\left[c(s,i_1),c(i_1,i_2),\cdots,c(i_{k-1},i_k),c(i_k,t)\right], \tag{11}$$

$$C(r_{s,t})=\min\left[c(s,i_1),c(i_1,i_2),\cdots,c(i_{k-1},i_k),c(i_k,t)\right] \tag{12}$$

Extremity measures are based on a bottleneck link along the transmission path, such as those for the residual energy, bandwidth, transfer rate, or residual cache space.

With the expansion of application-layer business types, people often impose simultaneous requirements for the bandwidth, delay, jitter, communication cost, and other parameters to achieve optimal resource utilization. However, these parameters are not completely independent of each other, and optimizing the requirements of multiple parameters is a completely nondeterministic polynomial problem.

3.2.2. Normalization of the Fuzzy Set Parameters. The measurement of QoS parameter attributes is based on the type of service and the actual state of network performance. Here, we select several typical QoS parameter attributes and solve the problem in terms of IFSs.

Assuming that $R(s,t)=\{r_1,r_2,\cdots,r_m\}$ is the set of paths from a source node to a destination node and C is the set of properties along the route, the path decision scheme can make multiattribute decisions after the fuzzy normalization of attribute set C, where t_{ij} is the lower bound of membership, such that decision scheme r_i satisfies attribute index $c_{\cdot j}$, and f_{ij} is the upper bound of membership, such that decision scheme r_i does not satisfy attribute index $c_{\cdot j}$. Here, the following constraints apply: $t_{ij}\in[0,1]$, $f_{ij}\in[0,1]$, $0\le t_{ij}+f_{ij}\le 1$, $1\le i\le m$, and $1\le j\le n$.

The normalization of intuitionistic fuzzy sets relies on mathematical transformations to transform index values with different properties and dimensions into IFS values that can be comprehensively processed, which is the basis and premise of utilizing IFSs.

Benefit indexes are applied for the normalization of IFSs.

Definition 2. It is assumed that there is a nonnull point or object field $U=\{x_1,x_2,\cdots,x_n\}$, and $A_i\ (i=1,2,\cdots,m)$ is a set in U, where $x_i\ (i=1,2,\cdots,n)$ is the nonnegative single-value efficiency index of A_i.

$$x_i^{\min}=\min\left(x_1,x_2,\cdots,x_n\right), \tag{13}$$

$$x_i^{\max}=\max\left(x_1,x_2,\cdots,x_n\right). \tag{14}$$

Equations (13) and (14) are the minimum and maximum values, respectively, of the evaluation indicators x_i. The benefit indicator IFS equations for x_i are as follows (the larger the value is, the better):

$$t_i=\left(1-\left(\frac{x_i^{\max}-x_i}{x_i^{\max}-x_i^{\min}}\right)^p\right)\left(\frac{x_i-x_i^{\min}}{x_i^{\max}-x_i^{\min}}\right)^p, \tag{15}$$

$$1-f_i=\sqrt{t_i}. \tag{16}$$

Definition 3. The cost indicator IFS equations for x_i are as follows (the smaller the attribute value is, the better):

$$t_i=\left(1-\left(\frac{x_i-x_i^{\min}}{x_i^{\max}-x_i^{\min}}\right)^p\right)\left(\frac{x_i^{\max}-x_i}{x_i^{\max}-x_i^{\min}}\right)^p, \tag{17}$$

$$1-f_i=\sqrt{t_i}. \tag{18}$$

Definition 4. The interval-type index x_i refers to the optimal value in the interval $[a,b]$, and the corresponding IFS specification equations are as follows:

When $x_i<a$,

$$t_i=\left(1-\left(\frac{a-x_i}{a-x_i^{\min}}\right)^p\right)\left(\frac{x_i-x_i^{\max}}{a-x_i^{\min}}\right)^p, \tag{19}$$

for $a\le x_i\le b$, $t_i=1$, and $1-f_i=1$.

When $x_i > b$,

$$t_i = \left(1 - \left(\frac{x_i - b}{x_i^{\max} - b}\right)^p\right)\left(\frac{x_i^{\max} - x_i}{x_i^{\max} - b}\right)^p, \tag{20}$$

$$1 - f_i = \sqrt{t_i}. \tag{21}$$

Additionally, when $a = b$, the interval index becomes a fixed index.

Definition 5. x_i is an interval deviation indicator (the larger the deviation from a fixed interval or value is, the better), and the corresponding IFS specification equations are as follows:

When $x_i < a$,

$$t_i = \left(1 - \left(\frac{x_i - x_i^{\min}}{a - x_i^{\min}}\right)^p\right)\left(\frac{a - x_i}{a - x_i^{\min}}\right)^p, \tag{22}$$

$$1 - f_i = \sqrt{t_i}, \tag{23}$$

for $a \le x_i \le b$, $t_i = 0$, and $1 - f_i = 0$.

When $x_i > b$,

$$t_i = \left(1 - \left(\frac{x_i^{\max} - x_i}{x_i^{\max} - b}\right)^p\right)\left(\frac{x_i - b}{x_i^{\max} - b}\right)^p, \tag{24}$$

$$1 - f_i = \sqrt{t_i}. \tag{25}$$

Additionally, when $a = b$, the deviation interval index becomes the deviation index.

In the deviation interval-type index equation, $x_i^{\max}$ and $x_i^{\min}$ are the theoretical maximum and minimum values, respectively, of the index rather than individual maximum and minimum values.

3.2.3. Problem Definition. In this paper, an intuitionistic fuzzy positive ideal solution and intuitionistic fuzzy negative ideal solution are defined as well as Hamming distances of the positive or negative ideal path. Based on these distances, relative closeness degrees are calculated and ranking order of all alternatives is generated, which extends the TOPSIS. In the case of unknown weights, we apply the TOPSIS technique based on the entropy weights of the IFS to solve multiattribute and multipath decision-making problems. The specific problems and their definitions are as follows.

$$\text{TOPSIS} : R \longleftarrow \max : S(r_i), r_i \in R. \tag{26}$$

$S(r_i)$ is the closeness degree of path r_i to the ideal path. The path with the largest closeness degree is the best path.

$$S(r_i) = \frac{d_{r_i}^-}{d_{r_i}^+ + d_{r_i}^-}, \tag{27}$$

where $d_{r_i}^+$ and $d_{r_i}^-$ are the weighted Hamming distances from path r_i to the virtual positive or negative ideal path.

The weighted Hamming distances of the positive or negative ideal path are as follows:

$$d_{r_i}^+ = \frac{1}{2n}\sum_{j=1}^{n} w_j\left(\left|t_{r_i,j} - t_j^+\right| + \left|f_{r_i,j} - f_j^+\right| + \left|\pi_{r_i,j} - \pi_j^+\right|\right), \tag{28}$$

$$d_{r_i}^- = \frac{1}{2n}\sum_{j=1}^{n} w_j\left(\left|t_{r_i,j} - t_j^-\right| + \left|f_{r_i,j} - f_j^-\right| + \left|\pi_{r_i,j} - \pi_j^-\right|\right). \tag{29}$$

Definition 6. A_R^+ and A_R^- are the virtual positive and negative ideal path schemes, respectively, in path set R.

When the attribute is of the benefit type, we can obtain the following equations:

$$A_R^+ = \left(\left[t_{r_i,1}^+, 1 - f_{r_i,1}^+\right], \left[t_{r_i,2}^+, 1 - f_{r_i,2}^+\right], \cdots, \left[t_{r_i,n}^+, 1 - f_{r_i,n}^+\right]\right), \tag{30}$$

$$A_R^- = \left(\left[t_{r_i,1}^-, 1 - f_{r_i,1}^-\right], \left[t_{r_i,2}^-, 1 - f_{r_i,2}^-\right], \cdots, \left[t_{r_i,n}^-, 1 - f_{r_i,n}^-\right]\right). \tag{31}$$

When the attribute is of the cost type, the equations are as follows:

$$A_R^+ = \left(\left[t_{r_i,1}^-, 1 - f_{r_i,1}^-\right], \left[t_{r_i,2}^-, 1 - f_{r_i,2}^-\right], \cdots, \left[t_{r_i,n}^-, 1 - f_{r_i,n}^-\right]\right), \tag{32}$$

$$A_R^- = \left(\left[t_{r_i,1}^+, 1 - f_{r_i,1}^+\right], \left[t_{r_i,2}^+, 1 - f_{r_i,2}^+\right], \cdots, \left[t_{r_i,n}^+, 1 - f_{r_i,n}^+\right]\right), \tag{33}$$

where

$$t_{r_i,j}^+ - f_{r_i,j}^+ = \max_{r_i \in R}\left(t_{r_i,j} - f_{r_i,j}\right), \tag{34}$$

$$t_{r_i,j}^- - f_{r_i,j}^- = \max_{r_i \in R}\left(t_{r_i,j} - f_{r_i,j}\right). \tag{35}$$

In the case that

$$t_{r_i,j} - f_{r_i,j} = t_{r_k,j} - f_{r_k,j}. \tag{36}$$

And the attribute is of the benefit type, if $t_{r_i,j} > t_{r_k,j}$, then we can conclude that $[t_{r_i,j}, 1 - f_{r_i,j}]$ is superior to $[t_{r_k,j}, 1 - f_{r_k,j}]$. Similarly, when the attribute is of the cost type, the opposite relation holds.

The concept of entropy is adopted to measure the influence of an evaluation index on a multiobjective decision-making scheme. The higher the entropy of each scheme is, the less information a scheme can obtain; i.e., it is more difficult to make a reasonable choice. Conversely, the lower the entropy is, the greater the amount of information that can be acquired. In other words, it is easy to make a choice. If only a small portion of information is important, the entropy of the fuzzy set is normalized as the objective weight of the attribute. If a large portion of information is important, then the supplementary value of the entropy of the fuzzy set for each attribute is normalized as the objective weight of the attribute. In the latter case, the objective weight of each attribute is

$$w_j = \frac{1 - E_i}{m - \sum_{i=1}^{m} E_i} (i = 1, 2, \cdots, m \,; j = 1, 2, \cdots, n). \tag{37}$$

4. Detailed Description of FMQMRP

4.1. Multipath Routing Control Packets. In the multipath routing protocol, the routing control packets primarily discover and maintain the relevant routes. Based on the AOMDV protocol, the RREQ and RREP packets are extended. In the RREQ message, user QoS constraint requirements are added, and the accumulation of QoS parameter values at nodes or on links is recorded. Here, the bandwidth, delay, stability, and energy are selected as examples (in practice, they can be increased or decreased according to design needs) to add an extension field to the RREQ message to store cross-layer information.

Tables 3 and 4 show the RREQ message structure and RREP message structure in the multipath routing protocol, and they contain cross-layer parameter information. Designers can increase, decrease, or replace the information according to their needs. In addition to the QoS parameter requirements of the application layer, the RREQ message should also record or update the QoS parameter information associated with nodes and links along a route. In addition to the above steps, the message structure should include a calculation of the ideal closeness degree for the path selected by TOPSIS after the prior message reaches the destination node.

The multipath routing protocol with multiple QoS parameter constraints must record the relevant parameter information along each route; therefore, fields are added for the FMQMRP protocol on the basis of the AOMDV routing table. Figure 1 shows the multipath routing table entry structure for the FMQMRP protocol.

4.2. Multipath Routing. Based on the AOMDV protocol, this paper mainly improves several packets for routing control. One improvement involves the addition of several extension fields to the RREQ package to store cross-layer information parameters (such as energy, bandwidth, delay, and reliability variables). The other improvement is the reduction of the overhead of flooding and routing and the elimination of nodes that do not meet the QoS requirements when selecting the next hop node.

To establish a disjoint path from the source node to the destination node, the following conditions must be satisfied.

Property 1. A source node S floods a packet BO in the network, and any node I ($I \neq S$) receives a copy set for packet BO. If each of these BO copies passes through a different neighbor node of S to reach I, the set of disjoint paths of nodes from I to S is then defined.

Table 3: RREQ message format.

Type	Flag	Reserved	Hop count
RREQ ID			
Destination IP address			
Destination sequence number			
Originator IP address			
Originator sequence number			
First hop			
BW_{sj} (QoS information: the bandwidth from the source node to the current node)			
BW_{th}(QoS constraint: the threshold of the bandwidth requirements)			
De_{sj}(QoS information: the delay from the source node to the current node)			
De_{th} (QoS constraint: the threshold of the latency requirements)			
S_{sj} (QoS information: the reliability from the source node to the current node)			
S_{th} (QoS constraint: the threshold of the reliability requirements)			
E_{sj} (QoS information: the effective energy from the source node to the current node)			
E_{th} (QoS constraint: the threshold of the minimum energy requirements)			
Expiration/timeout			

Table 4: RREP message format.

Type	Flag	Reserved	Prefix size	Hop count
RREP ID				
Destination IP address				
Destination sequence number				
Originator IP address				
TOPSIS				
BW_{sj} (QoS information: the bandwidth from the source node to the current node)				
De_{sj} (QoS information: the delay from the source node to the current node)				
S_{sj} (QoS information: the reliability from the source node to the current node)				
E_{sj} (QoS information: the effective energy from the source node to the current node)				
Expiration/timeout				

To add a new first hop to the RREQ group considering the nodes adjacent to the source node, each node maintains a firsthop_list for each RREQ packet. This variable records the nodes adjacent to each RREQ packet source node that receive a copy of the RREQ packet.

In FMQMRP, an intermediate node is allowed to accept repeat RREQ packets. When an intermediate node repeatedly

Destination IP	Destination ID	Advertised hopcount	Routing list				
			next_hop$_1$	*last_hop*$_1$	*hop_count*$_1$	*timeout*$_1$	QoS_info$_1$
			next_hop$_1$	*last_hop*$_1$	*hop_count*$_1$	*timeout*$_1$	QoS_info$_2$
			…	…	…	…	
			…	…	…	…	

Figure 1: Multipath routing table entry structure.

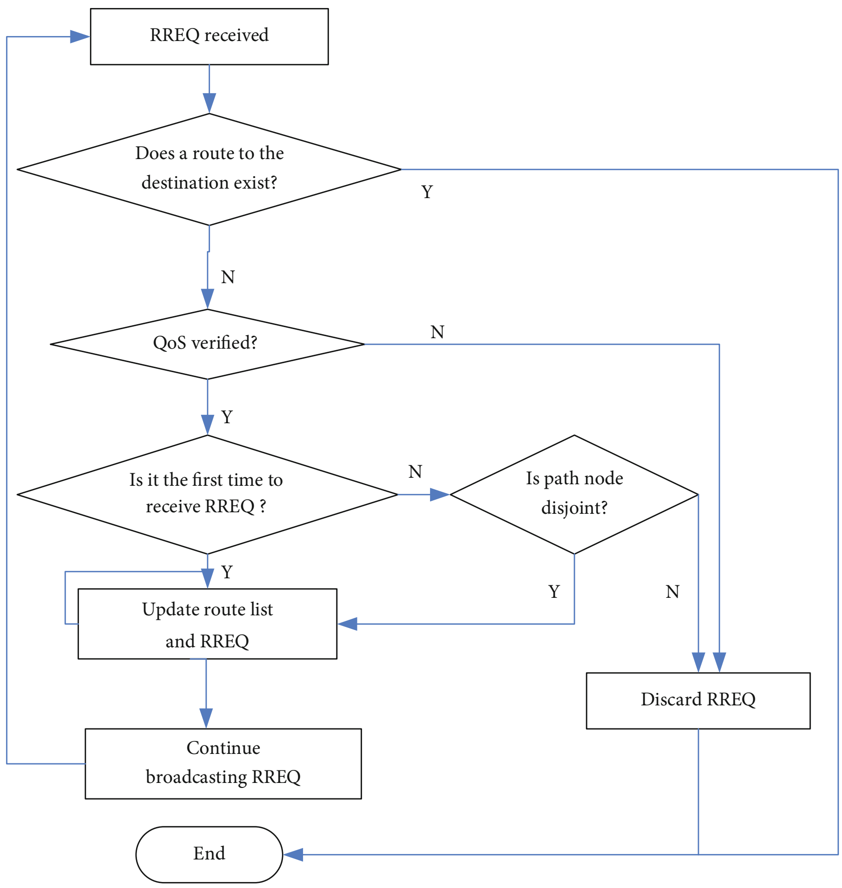


Figure 2: Flowchart for a node processing RREQ packets.

receives an RREQ packet copy, it does not immediately discard the copy but determines whether it contains a new disjoint path from the source node according to the AOMDV protocol. If a new disjoint path satisfying the QoS requirements is provided, the intermediate node will then invoke a routing update rule and determine whether a reverse path can be established. If a reverse path can be established and the intermediate node meets the requirements of Property 1 to reach the destination node, the node will reply to the source node with an RREP reply packet. If the intermediate node does not meet the requirements of Property 1 and cannot be identified as a routing node along a disjoint path from the source node to the destination node, the receiving node dismisses the RREQ packet and only forwards the previous RREQ packet. When the destination node receives several RREQ packet copies, two optimal paths are selected by the TOPSIS method in response; this reduces the number of RREP packets and prevents flurries of RREP responses in the FMQMRP protocol. When new data are generated in the network, a node, as a source node, first determines whether there is a path in its cache that meets the QoS requirements before sending data to the target node. If a path that satisfies the QoS requirements exists, data are transmitted along this path. Otherwise, the node will initiate a routing search. The routing search is initiated by RREQ packets. Because of the flooding mechanism, an intermediate node may receive multiple groups of RREQ packet copies. In the FMQMRP protocol, the intermediate node does not perform a flooding search immediately after receiving an RREQ packet but selectively performs a broadcast search. The forwarding process of the RREQ message is shown in Figure 2.

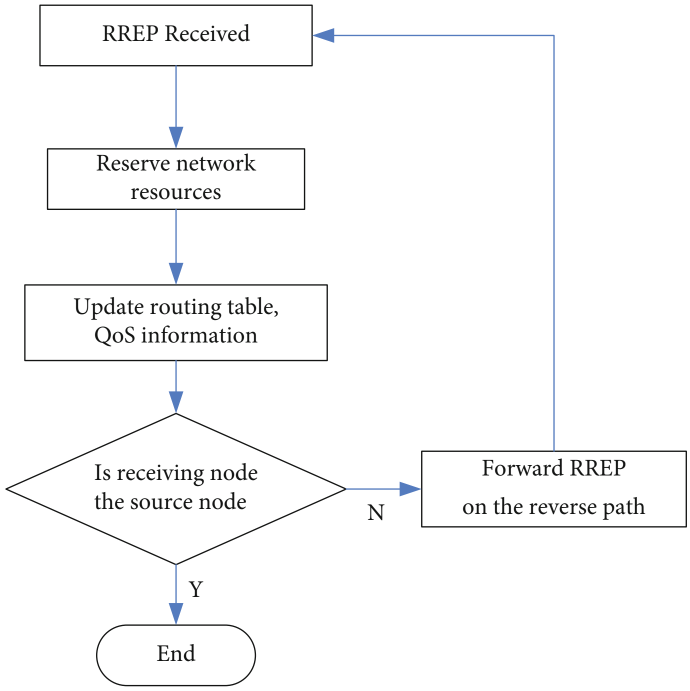


Figure 3: Flowchart for a node processing RREP packets.

Table 5: Reference parameters in FMQMRP.

Parameter	Value	Parameter	Value
Mobility model	Random waypoint	Type of antenna	Omnidirectional
Channel capacity	2 Mb/s	Node transmission radius	200 m~300 m
Channel propagation model	Two-ray ground	Packet length	CBR: 512 bytes
Node moving speed	0~15 m/s	S_{ij}	≥0.52
Maximum number of paths	≤4	MAC	IEEE 802.11 DCF
Log of the source beacon	12	Maximum delay	0.1 s
Minimum bandwidth	40 kbps	Contract rate	5 packets/s~10 packets/s
Minimum energy	0.2 J	Simulation time	5 min

Step 1: first, determine whether the RREQ packet is the target node; if it is the target node, end the RREQ packet transmission, update the routing list and RREQ packet information, and send the RREP message to the source node

Step 2: if the node is accepted as a nontarget node, determine whether the node meets the relaxed QoS constraint. If the user QoS constraint requirements are not met, go to step 6, and if not, proceed to step 3

Step 3: determine whether the RREQ packet has been previously received; if not, go to step 5, and if so, proceed to step 4

Step 4: if the node has previously received the RREQ packet, determine whether to provide a new disjoint path, and compare QoS information. If the QoS information is better than the previous information, proceed to step 5; otherwise, go to step 6

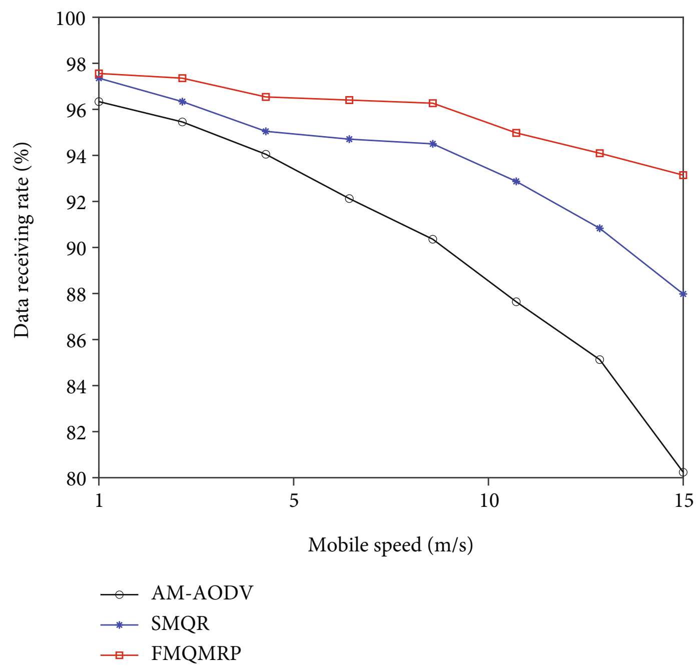
Step 5: update the routing list and RREQ packet information, send the RREP message to the source node, and proceed to step 7

Step 6: abandon forwarding the broadcast RREQ packets

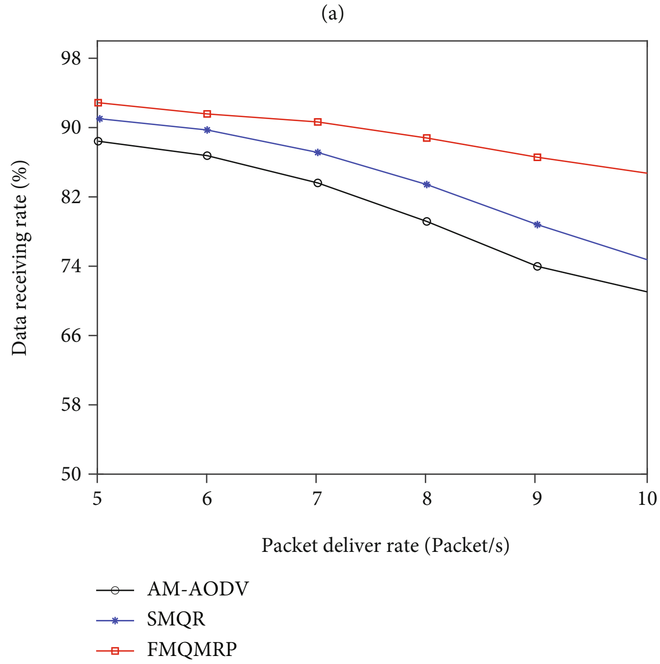
Step 7: continue forwarding the broadcast RREQ packets

When an intermediate node receives an RREP packet, it will first reserve resources. After successful reservation, it will obtain the QoS information associated with the current node based on the information in the RREP message, update the routing table, and continue to forward the message to the upstream node. After receiving the RREP message, the source node can perform data transmission. Figure 3 shows the forwarding process for an RREP message.

4.3. Routing Maintenance. The routing maintenance mechanism is immediately triggered after the source node receives a routing reply from the target node and starts transmitting data. Similar to the AODV protocol, the routing maintenance process of FMQMRP announces the effectiveness of the link and the changes in QoS parameters by periodically sending "Hello" messages. To reduce the recovery time of a path, local repair is first adopted. Once a link interruption

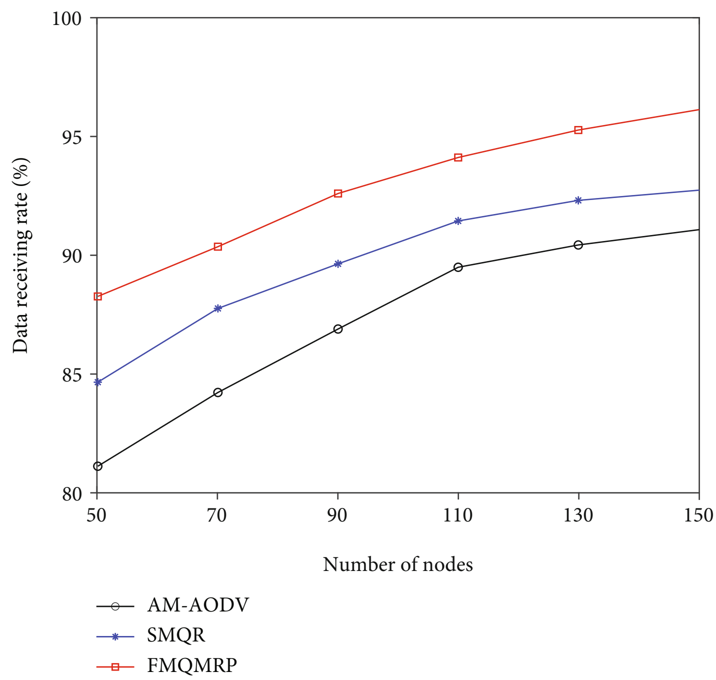


(a)



(b)

Figure 4: Continued.



(c)

Figure 4: Packet delivery rate: (a) varying the mobile speed, (b) varying packet deliver rate, and (c) varying the number of sensor nodes.

is encountered along the main path, an RERR message is launched. This local repair is only conducted toward the target node in the direction the packet is heading. Other routes using the same connection must be marked as unreachable, but the nodes dealing with local repairs may mark each newly lost route as locally repairable. When the routing process times out, the local repair flag in the routing table must be reset, thereby enabling the global repair mechanism to modify the routing table that passes through this node along the entire path. When the source node receives the RERR messages, the route search process is restarted. Before timeout occurs, these other routes will be fixed as required when packets arrive at the other destination nodes. This paper also considers the QoS constraints of users, and the repair process still conforms to the multipath routing search strategy agreed upon and satisfies the QoS conditions.

4.4. Process of Routing Decision-Making Based on TOPSIS. Through the multipath routing protocol based on cross-layer information, a set of routes is obtained. Each path in the set is constrained by multiple QoS attributes. This problem can be solved with TOPSIS by determining the optimal path among multiple objectives and schemes. The basic concept of TOPSIS is the definition of a positive ideal solution and a negative ideal solution for the decision problem and the identification of the solution that is the closest to the positive ideal solution and the farthest from the negative ideal solution among multiple feasible solutions. TOPSIS sequentially calculates a set of available paths, sorts the closeness degree according to the magnitude, and identifies the path with the highest closeness degree as the optimal path. The specific implementation steps are as follows.

Step 1. The path set $R = \{r_1, r_2, \cdots, r_m\}$ and the path constraint attribute set are used to form decision matrix $\mathfrak{R}$.

Step 2. The decision matrix $\mathfrak{R}$ is normalized by the IFS, and the transformation matrix $\mathfrak{R}'$ is obtained.

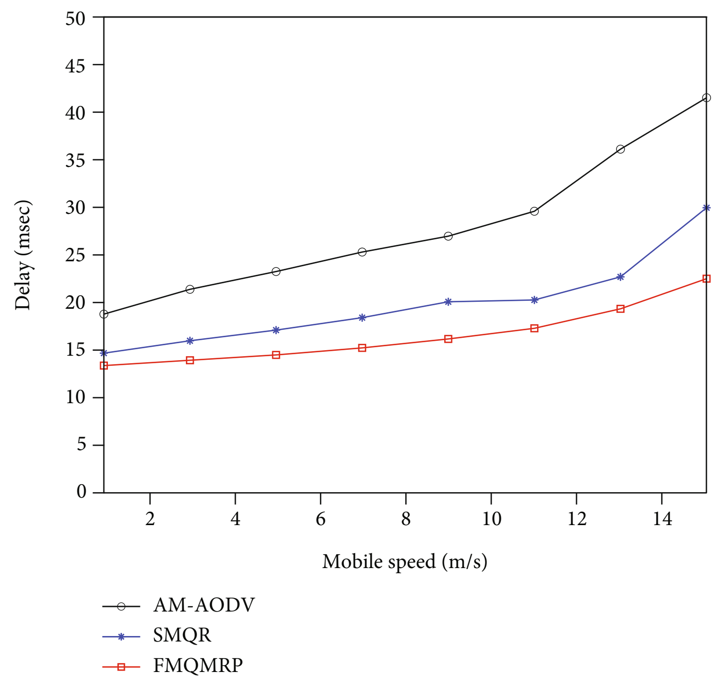
$$\mathfrak{R}' = \begin{vmatrix} \langle t_{11}, 1-f_{11} \rangle & \langle t_{12}, 1-f_{12} \rangle & \cdots & \langle t_{1n}, 1-f_{1n} \rangle \\ \langle t_{21}, 1-f_{21} \rangle & \langle t_{22}, 1-f_{22} \rangle & \cdots & \langle t_{2n}, 1-f_{2n} \rangle \\ \vdots & \vdots & \vdots & \vdots \\ \langle t_{i1}, 1-f_{i1} \rangle & \cdots & \left\langle t_{ij}, 1-f_{ij} \right\rangle & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ \langle t_{m1}, 1-f_{m1} \rangle & \langle t_{m2}, 1-f_{m2} \rangle & \cdots & \langle t_{mn}, 1-f_{mn} \rangle \end{vmatrix}, \tag{38}$$

where $\langle t_{ij}, 1-f_{ij} \rangle$ indicates that the upper limit of the membership value of the j_{th} attribute parameter along the path is t_{ij} and the lower limit of the nonmembership value is f_{ij}.

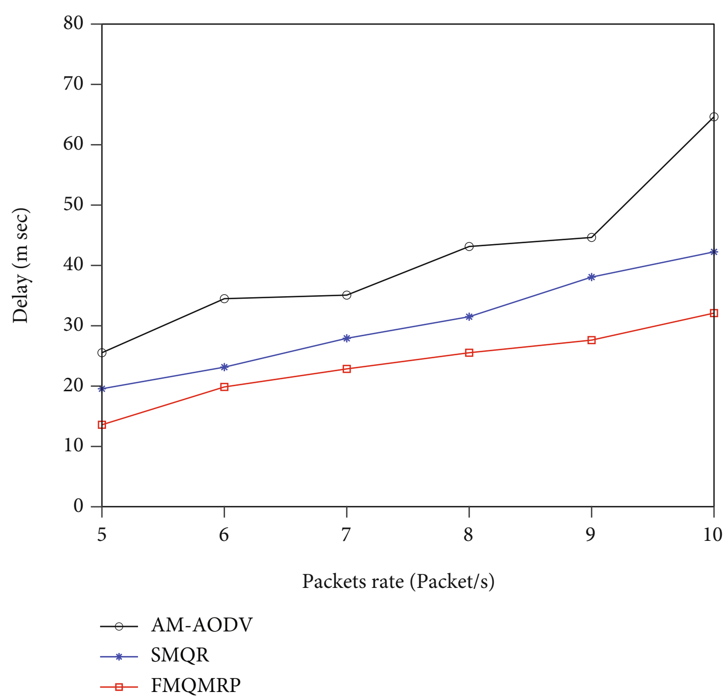
Step 3. The weight of each attribute is calculated from the information entropy of the IFS, i.e., via Equation (37), where

$$E(A) = \frac{1}{n} \sum_{i=1}^{n} \frac{1 - |t_A(x_i) - f_A(x_i)| e^{|t_A(x_i) - f_A(x_i)| - 1} + \pi_A(x_i)}{2}. \tag{39}$$

Step 4. The virtual positive and negative ideal path schemes A_R^+ and A_R^- in path set R are calculated.

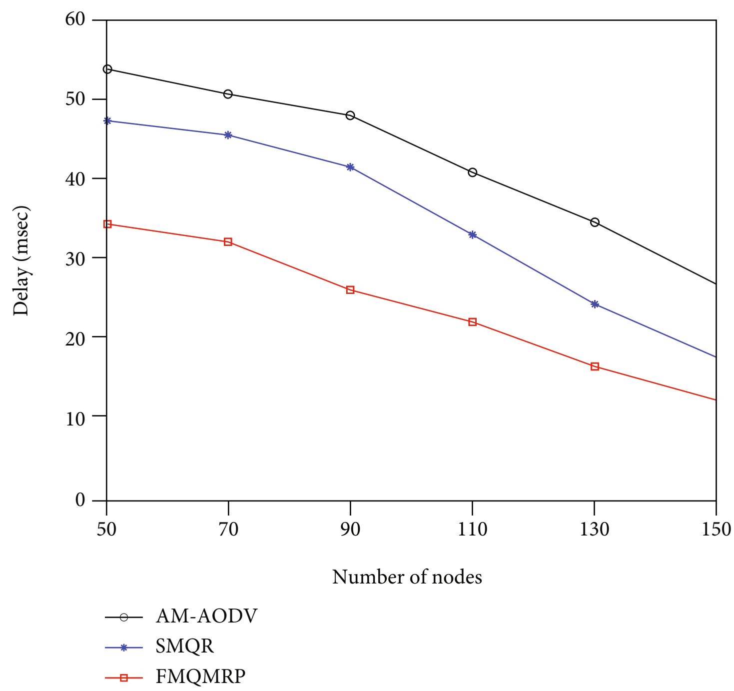


(a)



(b)

FIGURE 5: Continued.



(c)

FIGURE 5: Average delay: (a) varying the mobile speed, (b) varying packet deliver rate, and (c) varying the number of sensor nodes.

Step 5. The weighted Hamming distances $d_{r_i}^{+}$ and $d_{r_i}^{-}$ from each path to the virtual positive or negative ideal path are determined.

Step 6. The ideal closeness degree $S(i)$ of each path is calculated, and the path with the maximum $S(i)$ value is selected as the optimal path. The other paths can be used as alternatives.

5. Simulation and Analysis

To evaluate the performance of the FMQMRP protocol, we conducted simulation experiments on the NS2 simulation platform and compared the results to those obtained with similar protocols. Common QoS attributes include the time delay, path length, bandwidth, jitter, throughput, packet loss rate, reliability, routing cost, system lifetime, and residual energy. Here, we select the time delay, bandwidth, stability, and lifetime as the considered variables.

5.1. Time Delay. The time delay along a path is the sum of the delay for each link along the path, i.e., the sum of the transmission delays of all hops. The measurement of the time delay for each hop yields the time delay information from the MAC layer through the cross-layer method; namely, the time difference $(t_r - t_s)$ is calculated, where t_s is the time that elapses from the transmitter and t_r is the time when the ACK frame is received from the receiver. We apply the moving weighted average method (EWMA) to calculate the delay of the MAC layer.

$$D_{ij\_avg}^{t} = \eta \cdot D_{ij\_avg}^{t-1} + (1-\eta) D_{ij}^{t}, \quad (40)$$

where D_{ij}^{t} is the time delay value measured at the current time t between node i and node j, $D_{ij\_avg}^{t}$ and $D_{ij\_avg}^{t-1}$ are the average delay at the current time and the average delay measured at the previous time, respectively, and η is the smoothing weight, which is set to 0.4 according to previous research [24].

5.2. Bandwidth. Referring to the calculation method in [30], the equation is as follows:

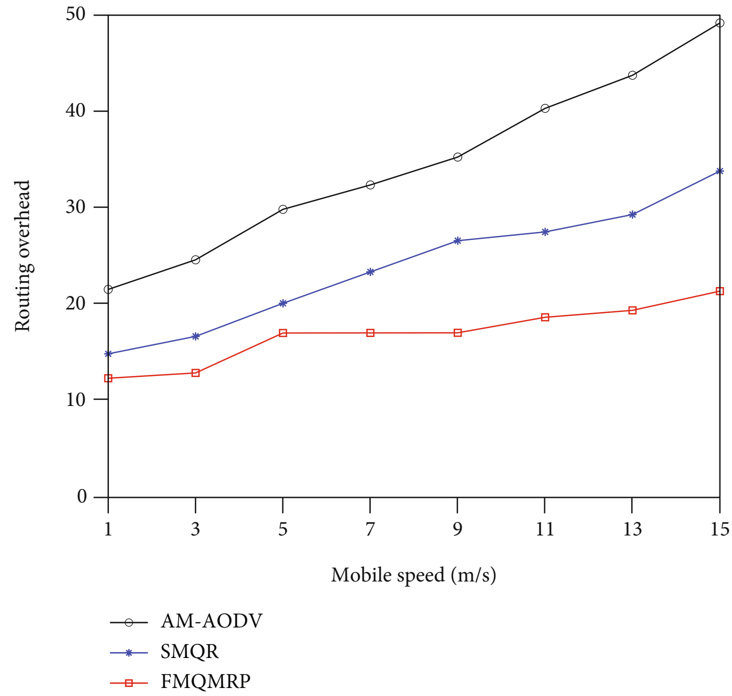
$$CH_{j\_BW} = \left(1 - \frac{\text{DIFS} + B}{T_{\text{total}}}\right)\left(\frac{T_{\text{total}} - T_{\text{busy}} - T_{\text{sense}}}{T_{\text{total}}}\right), \quad (41)$$

where B is the time consumed during the back-off procedure, T_{total} is the total sampling period of the channel, T_{busy} is the duration in the busy state, T_{sense} is the duration in the sense state, and DIFS is the DCF frame interval.

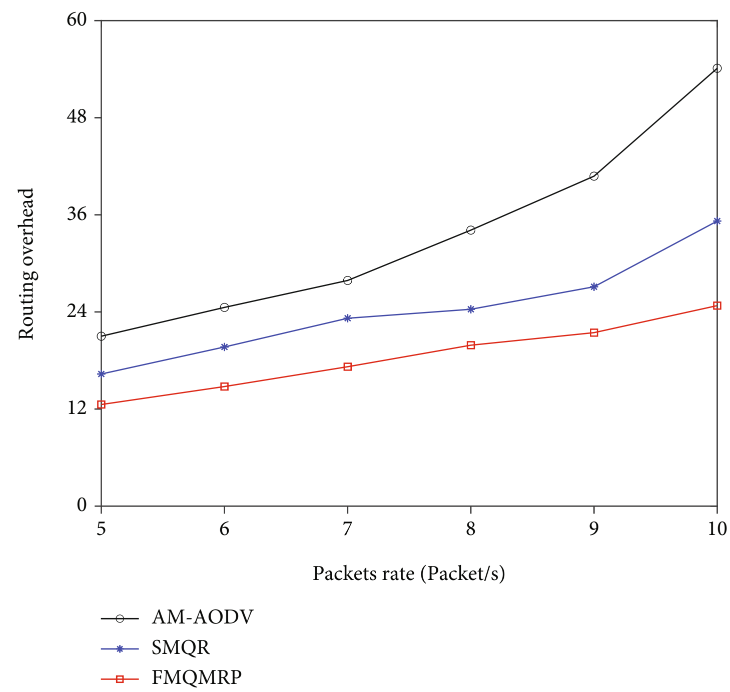
5.3. Reliability. In a MANET network, there is some instability due to node movement. Here, we only consider the stability of a link based on previous findings [31].

$$S_{ij} = \frac{P_{w_{ij}} \times K \times \left(1/BER_{ij}\right)}{d_{ij}}, \quad (42)$$

where S_{ij} is the stability factor and $P_{w_{ij}}$, d_{ij}, and BER_{ij} are the signal strength, distance, and bit error rate, respectively, between node i and node j.

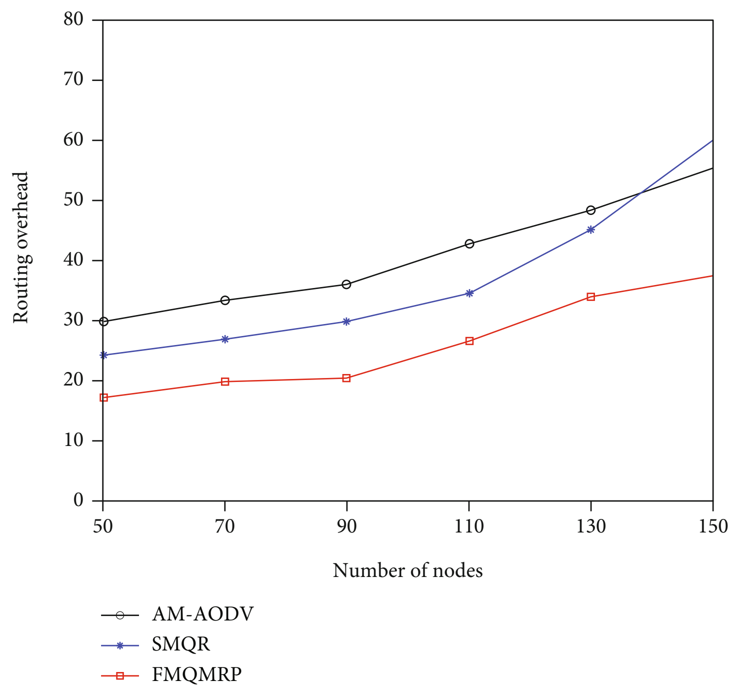


(a)



(b)

Figure 6: Continued.



(c)

Figure 6: Routing overhead: (a) varying the mobile speed, (b) varying packet deliver rate, and (c) varying the number of sensor nodes.

5.4. Lifetime. The lifetime of a path equals the residual energy of the node with the least residual energy along path r_i as a reference.

By changing the node distribution density, data distribution rate, and node movement speed, the following parameters are chosen as indicators to evaluate the efficiency of the protocol. After selecting the indicators, we perform an experimental analysis, and the simulation parameters are defined, as listed in Table 5.

5.5. Data Transfer Rate. Figure 4 shows the changes in the data transfer rate under the different values of the mobile speed, packet rate, and number of nodes.

It is evident that the FMQMRP protocol is superior to the AM-AODV and SMQR protocols. At the different moving speeds, the FMQMRP protocol considers the link stability, and it is better than the AM-AODV protocol in determining the influence of the mobile environment on the network based only on the physical RSSI value. The SMQR protocol sets the power layer threshold of the nodes to evaluate network stability. This subjective decision process makes it difficult for the SMQR protocol to reflect the actual network situation.

5.6. Network Average Delay. The delay, bandwidth, and stability, which contribute to network delay performance, are considered in the simulation experiments.

In Figure 5(a), the changes in node movement speed cause network link instability, and data may not be transmitted to the destination node in a reasonable time. The SMQR and FMQMRP protocols consider the link stability, delay, and bandwidth, and when the node speed changes, the degree of influence is much lower than that for the AM-AODV protocol.

Figure 5(b) shows that increasing the contract rate will increase the network transmission load and affect real-time data transmission to a certain extent. If the network is overloaded, network congestion will occur, which will eventually result in a significant increase in the delay. As the number of nodes increases, more nodes can share the network transmission task, and when the number of nodes increases, the average network delay decreases. In addition, increasing the number of nodes provides more available routing nodes in a given region, which results in more choices to meet the parameter requirements, and the packet delay is alleviated.

Figure 5(c) reveals that the FMQMRP protocol reduces the average delay when the number of nodes increases, and it is much less affected by environmental changes than in the AM-AODV and SMQR protocols. Notably, in the FMQMRP protocol, the acquisition of routing nodes satisfying the QoS attribute requirements is more stable and comprehensive than that in the other protocols, and a decision made under multiple parameter constraints considering multiple path schemes is more accurate than other decisions.

5.7. Routing Overhead. Figure 6 shows the data transmission efficiency of multipath routing with multiparameter constraints from the perspective of routing overhead. It is clear that the FMQMRP protocol is superior to the AM-AODV and SMQR protocols. The analysis shows that the FMQMRP protocol uses cross-layer technology to provide reliable data information for route finding. Additionally, compared to single-path routing technology, multipath routing expands the range of multiparameter optimization solutions. In a mobile environment, the information from the relevant layers is extracted to provide choices for network routing searches.

Figure 6(a) shows that the FMQMRP protocol is less affected by changes in the movement speed than are other protocols, and the AM-AODV protocol simply selects the RSSI value of the physical layer as a criterion, which is too simple. Movement may not lead to changes in the RSSI value. The SMQR receiving power threshold is better than that of the AM-AODV protocol when the speed is low, but the effect becomes less ideal when the moving speed is higher than a certain threshold.

As shown in Figure 6(b), when increasing the transmission rate of source node data, the network transmission load is excessive, and this process will require extensive broadband resources. The SMQR and FMQMRP protocols both consider bandwidth constraints, and they can suitably handle resource allocation with an increasing data transmission rate, thus reducing the impacts of cache overflow and network congestion on data transmission.

The FMQMRP protocol is slightly better than the SMQR protocol because the former relaxes constraints at the beginning of the multipath routing query process. To locate available resources and available paths, the multiattribute reduction algorithm based on IFSs and information entropy is applied to optimize the multiconstraint and multipath scheme. Figure 6(c) shows that in the case of an increasing number of nodes, the FMQMRP protocol does not blindly send RREQ messages. The routing table is updated by comparing the prior and subsequent routing nodes under the constraint conditions. The AM-AODV and SMQR protocols, similar to the FMQMRP protocol, are multipath routing mechanisms based on AOMDV routing; the variation trend of the routing control load is not notably different when the number of nodes increases.

In comparison to SMQR and AM-AODV protocols, the proposed routing scheme decreases routing overhead by 21% and 25% and average network delay by 17% and 21% and increases the data delivery rate by 3% and 7%. The FMQMRP protocol offers a solution for cross-layer routing and multipath routing under multiparameter constraints, and it is suitable for the minimum requirements of all attribute constraints.

6. Conclusions

One important issue concluded from our proposed routing algorithm is that the FMQMRP can be applied to obtain a comprehensive routing scheme that meets different business needs. This scheme provides enough information on the links between sensor nodes for the partitioned multipath routing method to determine the optimal routing scheme. The TOPSIS decision approach based on the entropy weights of IFSs effectively solves the multipath optimization problem for mobile self-organizing networks under multiparameter constraints. This method has low computational complexity and low network control overhead, making it suitable for multiservice-sensitive network applications with specific QoS requirements in complex environments. The business requirements cannot always be satisfied because of the constrained network resources. We may be able to further enhance the quality of service by dividing QoS priorities. In order to better accommodate the evolving needs of wireless communication services in various environments, we will also investigate the QoS priority requirements in heterogeneous networks in the future.

Data Availability

The data that support the research findings are available on request. The data are not publicly available due to the privacy of research participants.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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