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Improved ant colony-based multi-constrained QoS energy-saving routing and throughput optimization in wireless Ad-hoc networks

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Abstract

In order to establish a route supporting multi-constrained quality of service (QoS), increase network throughput and reduce network energy consumption, an improved ant colony-based multi-constrained QoS energy-saving routing algorithm (IAMQER) is proposed. The ant colony algorithm, as one of the available heuristic algorithms, is used to find the optimal route from source node to destination node. The proposed IAMQER algorithm, which is based on the analysis of local node information such as node queue length, node forwarding number of data packets and node residual energy, balances the relationship between the network throughput and the energy consumption, thus improving the performance of network in multi-constrained QoS routing. Simulation results show that this IAMQER algorithm can find the QoS route that reduce average energy consumption and improves network packet delivery ratio under the end-to-end delay and packet loss ratio constraints.

Keywords wireless Ad-hoc networks, multi-constrained QoS routing, ant colony algorithm, energy-saving, throughput optimization

1 Introduction

Wireless Ad-hoc networks are self-organizing networks without static topology and centralized administration. Hence each node in the wireless Ad-hoc networks not only can be a possible source node or destination node of packets, but also can act as a router for other packets relay. Traditional routing protocols cannot be applied to wireless Ad-hoc network directly, because wireless Ad-hoc networks has many unique characteristics and unavoidable constrains such as dynamic topology, bandwidth-limited unidirectional wireless channel, variable-capacity links, and energy-limited operations compared with both wired and cellular networks.

Moreover, with the fast development of high-speed transmission technique and multimedia applications, QoS guarantee in wireless Ad-hoc networks has been taken into account seriously. QoS is usually defined as a set of service requirements which are expected to be guaranteed while transporting packets from source node to destination node [1]. QoS metrics usually includes bandwidth, end-to-end delay, jitter, packet loss ratio, energy consumption and so on. The QoS metrics can be divided into three categories: addictive, concave and multiplicative. Among these QoS metrics, bandwidth and energy consumption are concave metrics, while end-to-end delay and jitter are additive metrics [2]. The essential task of QoS routing is to find a feasible path from source node to destination node, which should satisfy QoS constraints [3]. However, because of the limited bandwidth and dynamic topology, supporting QoS is a multi-constrained QoS routing problem. Considering the multi-constrained QoS routing is a NP-complete problem, it is advised to utilize heuristic algorithms to establish a multi-constrained QoS route and optimize the network performance indicators. Recently, there are many heuristic algorithms such as genetic algorithm, simulated annealing algorithm, artificial neural network and so on. Ant colony algorithm (ACA), which was proposed by Dorigo et al. [4], inspired by the

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foraging behavior of ant colonies is one of bionic algorithms. The advantages of ant colony algorithm are distributing computation, positive feedback, and constructive greed heuristic.

Aiming at establishing route, saving energy and optimizing the throughput of wireless Ad-hoc networks under the multi-constrained QoS condition, this paper proposes an IAMQER. Firstly, this paper defines some parameters and establishes system model and mathematical model, in which the objective function is the maximum value of path evaluation function, which are related to the network average energy consumption, the total length of route, the end-to-end delay and the packet loss ratio of route. Besides, two constrains are end-to-end delay and packet loss ratio. Secondly, this paper applies IAMQER algorithm to find the optimal route. The algorithm takes node forwarding capability, node queue length and node residual energy into account for avoiding network congestion and balancing the each node energy consumption. In order to save network average energy consumption, the algorithm adjusts nodes transmit power dynamically according to the different distance between two nodes. Finally, this paper takes performance testing of the algorithm and obtains some parameters such as packet delivery ratio, packet loss ratio, average end-to-end delay, network average energy consumption and node residual energy.

This paper is organized as follows: Sect. 2 reviews background information and the works related to our design. Sect. 3 presents system model and parameter definition. Sect. 4 proposes the IAMQER to optimize network routing mechanism performance. Sect. 5 provides some simulation results and analysis. In Sect. 6, this paper summarizes the conclusions.

2 Background and related works

2.1 ACA

The basic idea of the ACA is originated from the food searching behavior of real ants. Given a graph $G=(V,E)$, two nodes $i,j\in V$ are neighbors if there is a link $(i,j)\in E$. K presents the ants set in algorithm. When ants depart from the nest to search for food, they walk along the way. When an ant reaches an intersection, it will decide which branch road leading to food according to the probabilistic transition rule, as shown in Eq. (1). The probabilistic choice is biased by pheromone trails previously deposited on the graph by other ants. At the beginning of the search process, a constant amount of pheromone (e.g., $\tau_{i,j}=1,\forall(i,j)\in E$) is assigned to all the edges. Once an ant $k\in K$ locates at a node i, it uses the pheromone trails $\tau_{i,j}$ to compute the probability of choosing next node j.

$$p_{i,j}^k=\begin{cases}\dfrac{\tau_{i,j}^{\alpha}}{\sum\limits_{z\in N_i^k}\tau_{i,z}^{\alpha}}; & j\in N_i^k\\ 0; & j\notin N_i^k\end{cases} \tag{1}$$

where N_i^k is the neighborhood set of node i. α is the parameter that control the relative importance of the pheromone trail. Ants move from one node to another node using this decision policy repeatedly until they reach the destination node. Due to differences among the ant's paths, the time step at which ants reach the destination node is different.

During the ants' way finding process, ants deposit pheromone on the way, which marks that ants have walked through the route. If the ant k traverses the link (i,j), it deposits an amount $\Delta\tau_{i,j}^k$ of pheromone on link and changes the pheromone value. Additionally, artificial pheromone evaporation also plays the important function of bounding the maximum value achievable by pheromone trails. The pheromone evaporation is interleaved with the pheromone deposit of the ants. Hence, pheromone trails of all the edges are updated by the following equation:

$$\tau_{i,j}=(1-\rho)\tau_{i,j}+\sum_{k\in K}\Delta\tau_{i,j}^k;\quad \forall(i,j)\in E \tag{2}$$

where $\rho\in(0,1]$ is an evaporated factor.

Finally, more and more ants are attracted by the pheromone trails and in turn reinforce the pheromone even more. According to these disciplines described above, this behavior of ants can be used to find out a route that satisfies multi-constrained QoS in Ad-hoc networks [5].

In this paper, the ants represent a set of routes from all source nodes to destination nodes and each node maintains a probabilistic routing table that is also called pheromone tables. According to the probabilistic routing table, ants choose the next hop node with higher probability, which is those links have higher pheromone values. And each ant searches the optimal route rapidly by applying the local updating rule and the global updating rule. Finally, all the ants converge to the global optimal solution, which is the global optimal route.

2.2 Related works

QoS requirement, such as those for multimedia applications with bandwidth and energy constraint, has been intensively studied recently as an issue for mobile Ad-hoc networks (MANETs). Node mobility and wireless radio properties make it more difficult to provide QoS in MANETs than in wired networks. The QoS guarantee is a new challenge for MANETs. Traditional routing algorithms for MANETs, such as Ad-hoc on-demand distance vector routing (AODV) and dynamic source routing protocol (DSR), cannot meet this requirement.

QoS routing for MANETs can be approximately classified into two main paradigms: hop-by-hop and source QoS routings.

In the hop-by-hop QoS routing, each node monitors its own local state information and exchanges them to the other nodes in the networks. This information will be used in route selection process as QoS routing metrics, which is distributed in each intermediate node along the path. In Ref. [6], Ge et al. used the heuristic algorithms in the optimized link state routing (OLSR) protocol to find the maximum bandwidth path from source to destination by modifying multipoint relays (MPRs) and route selection process. The QoS optimized link state routing protocol (QOLSR) [7–8] was proposed to allow each node to select the maximum bandwidth link. However, if there are several links with the same bandwidth, the minimum delay link will be considered. Hence, such an algorithm is called shortest-widest path algorithm. In Ref. [9], the QoS supported routing protocol based on OLSR and the class based queue (CBQ) in MANETs was proposed. In order to minimize the end-to-end delay for QoS flows, this paper applies CBQ to the OLSR. In CBQ, it inserts the packet to the appropriate class queue and decides which class queue is allowed to transmit the packets. QoS routing is also implemented to select the shortest path satisfying the bandwidth requirement for QoS flow.

In source QoS routing, the source node initiates the request packet of the link to the destination in order to collect the local state information stored in each node to constitute the global state information of the network, and then check the constrained path whether it has enough resource to support the required applications or not. Consequently, the path will be selected which satisfies the QoS requirements. In Ref. [10], it proposed an Ad-hoc QoS on-demand routing (AQOR), which provides end-to-end QoS support based on bandwidth and end-to-end delay. Thus, the best path is available in terms of smallest end-to-end delay with bandwidth guarantee. The adaptive dispersity QoS routing (ADQR) protocol [11], based on SPAFAR [12], finds multiple disjoint paths with longer-lived connections based on signal strength. Route maintenance has been implemented in order to recover the new route when the old route is broken.

Most of these QoS routing algorithms described above consider only one or two QoS metrics to find feasible paths from source to destination. They consider one QoS parameter at a time and if there is a tie, another QoS metric will be triggered. However, they neglect the other important QoS parameters such as jitter, packet loss ratio, reliability and etc. Hence, they may not be appropriate and flexible enough to support all kinds of applications, since they require different QoS constraints. However, the problem to find the feasible path based on multiple QoS metrics is considered to be NP-complete. Therefore, many heuristic algorithms have been proposed to solve multi-constrained path (MCP) and multi-constrained optimal path (MCOP) problems in traditional network with static topology. Specially, an ant colony optimization (ACO) as the one of the heuristic algorithms has been widely used in the multi-constrained QoS routing for MANETs.

In the past few years, there have been numerous ant colony-based QoS routing algorithms in wireless Ad-hoc networks. Emergent Ad-hoc routing algorithm (EARA) enhanced with QoS (EARA-QoS) [13] uses metrics from different layers to make routing decisions. But the algorithm only considers the delay constrain. A QoS enabled ant colony based multipath routing (QAMR) [14] considers bandwidth, delay and hop count as the QoS parameters along with the stability of node, number of hops and path preference probability factors for selecting path. But the algorithm does not take the congestion and throughput into account at higher traffic load. An energy-efficient genetic algorithm mechanism to resolve QoS multicast routing problem [15], which depends only on bounded end-to-end delay and minimum energy cost of the multicast tree. Furthermore, there have been else numerous routing protocols to provide QoS for MANET, for example the ADOR [16], the multi-path dynamic source routing protocol (MP-DSR) [17], the ticket-based probing algorithm (TBP) [18] and so on. ADQR is a bandwidth constrained multiple-path on-demand routing protocol for

Ad-hoc networks to support end-to-end QoS. The route discovery algorithm is to find multiple disjoint paths with longer-lived connections, when each path also specifies associated network resource information. MP-DSR is a distributed multi-path dynamic source routing protocol to improve QoS support with respect to end-to-end reliability. In a sort of ideal model, TBP advances a ticket-based QoS routing protocol which study two sorts of routing problems: delay-constrained least-cost routing and bandwidth-constrained least-cost routing. But all these protocols do not consider the congestion and residual energy of nodes to QoS routing. Other approaches make use of geographical location information for routing [19–20]. These previous works primarily applied traditional approaches to routing in wired networks to the more volatile network environment experienced in MANETs. While many optimizations to these above algorithms exist, they still suffer from lack of efficiency and scalability with respect to the multi-constrained QoS.

3 System model and parameter definition

3.1 Network topology and traffic model

In order to describe real Ad-hoc networks topology correctly, this paper assumes that network model is as follows: N nodes locate in a $L\text{ m}\times L\text{ m}$ region randomly. Each node has the same maximum transmit range $R_{\max}$. The neighbor node j of node i is defined as a node that is within the transmission range of node i. M pairs of source nodes and destination nodes are randomly chosen from node set V, which form the source node set S and the destination node set D. The radio propagation model is a free space model. As shown in Fig. 1.

The Ad-hoc network is considered as a connected and undirected graph. Let $G(V,E)$ be used to represent the Ad-hoc networks, where V denotes the finite set of network nodes and E denotes the finite set of bi-directional link. N_i is a set of neighbor node of node i but not including node i and each node has different transmit range with different transmit power. If node j is within the transmit range of node i, there is a bi-direction link $e_{i,j}$ between node i and node j, $e_{i,j}\in E$. Besides, the route $p_{s,d}$ from source node $s\in S$ to destination node $d\in D$ is constituted of the no loop sequence of relay node, $p_{s,d}=\{s,...,i,j,...d\}$. In the IAMQER presented in this paper, K is defined as the ants set. The ant $k\in K$ selects the next hop node j from the current node i at each time step starting from source node $s\in S$ until reaching the destination node $d\in D$. Hence, each ant k will obtain the route $p_{s,d}^k$ from every source node $s\in S$ to every destination node $d\in D$ constituting the route set $P^k=\{p_{s,d}^k\,|\,\forall s\in S,\forall d\in D\}$.

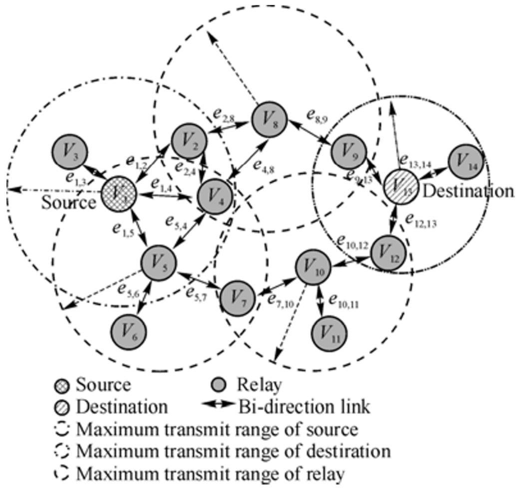

Fig. 1 The model of mobile Ad-hoc networks

In addition, the traffic model is described as follows: at every time step, there are B_s packets generated from every source node s and let $R=\sum_{s\in S}B_s$ presents the total packets generated in the networks at each time step. Source nodes, destination nodes and all other relay nodes can deliver as much as C data packets towards their neighbor nodes at every time step. Once a packet arrives at its destination, it will be removed from the network. The queue length of each node is assumed to be limited and follows the first in first out (FIFO) principle. Furthermore, an important discipline is that a link between a pair of nodes cannot be visited more than twice to avoid loops. Without this rule the throughput of the network may be very low because that a large number of data packets are delivered along the same links unnecessarily many times, thus increase the delay. In the traffic model, this paper defines all nodes as both hosts and routers for generating and delivering data packets.

3.2 Parameter definition

In this paper, there are several parameters defined as follows:

Table 1 Simulation performance metrics

Performance metrics name	Definition
Packet delivery ratio $D_{p_{s,d}}$	The ratio of the number of data packets received by destination nodes to the number of data packets originated at source nodes.
Packet loss ratio $L_{p_{s,d}}$	The ratio of the number of data packets discarded by nodes to the number of data packets originated at source.
Power levels	The continuous grades of node transmit power according to the different transmission distance between nodes and they are proportional relationship.
Route average energy consumption $E_{p_{s,d}}$	The average energy consumption by all nodes, which is used to transmit data packets between all source and destination.
Network average energy consumption E_{net}	The average energy of all nodes consumed in network at the time when the communication terminates.
Node performance factor F_i	A metric to describe congestion status of a node *i*. It is proportional to node queue length, the number of forwarded data packets and the residual energy of node.
Path evaluation function $V_{p_{s,d}}$	A metric to present the performance of route from source node to destination node. It is related to the end-to-end delay, the packet loss ratio of route, the energy consumption in the route and the total length of route.
Average end-to-end delay	The average delay between the time step at which data packets are originated at the source nodes and the time step at which these data packets reach destinations.
Balanced ratio function	The ratio of the number of data packets received by destination nodes to the average end-to-end delay of network.
Node number with residual energy above 50%	The number of node with the residual energy above 50% of initial energy.

3.3 Ad-hoc networks QoS routing model

In this paper, there are two QoS associated with each route $p_{s,d}$ from source node $s \in S$ to destination node $d \in D$ including average end-to-end delay and packet loss ratio to be measured.

The delay $D_{p_{s,d}}$ of a route $p_{s,d}$ is defined as Eq. (3):

$$D_{p_{s,d}} = \frac{\sum_{b=1}^{B_s} \Delta t_{p_{s,d}}^{b}}{B_s} \tag{3}$$

where B_s is the total number of packets generated by source node *s*, $\Delta t_{p_{s,d}}^{b}$ is the time of a packet *b* transmitted from source node *s* to destination node *d* along the route $p_{s,d}$.

The packet loss ratio $L_{p_{s,d}}$ of a route $p_{s,d}$ is defined as Eq. (4):

$$L_{p_{s,d}} = 1 - \frac{P_{p_{s,d}}^{\text{re}}}{P_{p_{s,d}}^{\text{st}}} \tag{4}$$

where $P_{p_{s,d}}^{\text{re}}$ is the number of packet reception transmitted along the route $p_{s,d}$, $P_{p_{s,d}}^{\text{st}}$ is the total number of packet generated by source node *s* and transmitted along the route $p_{s,d}$ to destination node *d*.

Besides, in order to measure the performance of route set P^k presented by ant $k \in K$, which includes all the path $p_{s,d}^k$ from source node $s \in S$ to destination node $d \in D$, this paper defines a path evaluation function V_{P^k} as Eq. 5):

$$\left.\begin{aligned}
&V_{P^k} = \frac{\gamma f_{D_{P^k}} + \eta f_{L_{P^k}}}{C_{P^k}}; \quad k \in K \\
&C_{P^k} = \mu \sum_{s\in S}\sum_{d\in D} E_{p_{s,d}^k} + \nu \sum_{s\in S}\sum_{d\in D} l_{p_{s,d}^k}; \quad p_{s,d}^k \subset P^k, k \in K \\
&f_{D_{P^k}} = \sum_{s\in S}\sum_{d\in D}\left[\varphi_{\text{Dl}}\left(D_{p_{s,d}^k} - D_{\text{T}}\right)\right]; \quad p_{s,d}^k \subset P^k, k \in K \\
&f_{L_{P^k}} = \sum_{s\in S}\sum_{d\in D}\left[\varphi_{\text{Lr}}\left(L_{p_{s,d}^k} - L_{\text{T}}\right)\right]; \quad p_{s,d}^k \subset P^k, k \in K \\
&\varphi_{\text{Dl}}(Z) = \begin{cases} 1; & Z \leqslant 0 \\ v_{\text{Dl}}\left(p_{s,d}^k\right); & \text{otherwise} \end{cases} \\
&\varphi_{\text{Lr}}(Z) = \begin{cases} 1; & Z \leqslant 0 \\ v_{\text{Lr}}\left(p_{s,d}^k\right); & \text{otherwise} \end{cases} \\
&v_{\text{Dl}}\left(p_{s,d}^k\right) = \mathrm{e}^{-\left(D_{p_{s,d}^k} - D_{\text{T}}\right)} \\
&v_{\text{Lr}}\left(p_{s,d}^k\right) = \mathrm{e}^{-\left(L_{p_{s,d}^k} - L_{\text{T}}\right)}
\end{aligned}\right\} \tag{5}$$

where γ, η, μ, ν are positive weights of $f_{D_{P^k}}$, $f_{L_{P^k}}, E_{p_{s,d}^k}, l_{p_{s,d}^k}$ respectively, which indicate the relative important of end-to-end delay, packet loss ratio, average energy consumption and average path length in the path evaluation function. The C_{P^k} is the cost metric parameter, which is proportional to the average energy consumption and average path length. The $\varphi_{\text{Dl}}(Z)$ and $\varphi_{\text{Lr}}(Z)$ are metric function. $\varphi_{\text{Dl}}(Z)$ is the metric function of end-to-end delay. If the value of delay can satisfy the delay constrain D_{T}, then the value of $\varphi_{\text{Dl}}(Z)$ is 1, otherwise the value is $v_{\text{Dl}}\left(0 < v_{\text{Dl}} < 1\right)$ and the greater the difference between the end-to-end delay of path $D_{p_{s,d}^k}$ and the delay constrain value D_{T}, the value of v_{Dl} is smaller. Similarly,

$\varphi_{\mathrm{Lr}}(Z)$ is the metric function of packet loss ratio. If the value of packet loss ratio can satisfy the packet loss ratio constrain L_{T}, then the value of $\varphi_{\mathrm{Lr}}(Z)$ is 1, else the value is $v_{\mathrm{Lr}}(0 < v_{\mathrm{Lr}} < 1)$ and the greater the difference between the packet loss ratio of path $L_{p_{s,d}^k}$ and the packet loss ratio constrain value L_{T}, the value of v_{Lr} is smaller.

According to the Eq. (5), the value of path evaluation function V_{P^k} is proportional to the cost metric parameter C_{P^k} and is inversely proportional to the metric function of end-to-end delay $f_{D_{P^k}}$ and the metric function of packet loss ratio $f_{L_{P^k}}$. Moreover, the cost metric parameter C_{P^k} is proportional to the route average energy consumption $E_{p_{s,d}^k}$ and the route length $l_{p_{s,d}^k}$. Hence, it can derive that the more route average energy consumption is and the longer route length is, the value of cost metric function is greater and the value of path evaluation function is smaller. It presents that the route performance in the energy consumption and route length are worse. Similarly, according to the expression of the metric function of end-to-end delay $\varphi_{\mathrm{Dl}}(Z)$ and the metric function of packet loss ratio $\varphi_{\mathrm{Lr}}(Z)$, it can also derive that if much more route meets the delay or packet loss rate constraint conditions, the value of the metric function $f_{D_{P^k}}$ is greater. Otherwise, if much more route cannot satisfy the end-to-end delay or packet loss ratio constraint, furthermore, the greater the difference between the end-to-end delay of path $D_{p_{s,d}^k}$ and the delay constrain value D_{T} or the greater the difference between the packet loss ratio of path $L_{p_{s,d}^k}$ and the packet loss ratio constrain value L_{T} are, the value of the metric function $f_{D_{P^k}}$ is smaller. In addition, as mentioned earlier, each ant k will obtain the route $p_{s,d}^k$ from every source node $s \in S$ to every destination node $d \in D$ constituting the route set $P^k = \{p_{s,d}^k \,|\, \forall s \in S, \forall d \in D\}$ and each ant in ants set K presents a route respectively. Therefore, comparing the value of path evaluation function V_{P^k} among route set P^k, the maximum is the best route, the value is $V_{P^{k^*}}^{\mathrm{best}}$. And the minimum is the worst route, the value is $V_{P^k}^{\mathrm{worst}}$. And, this paper defines $P_{\mathrm{best}}^{k^*}$ as the global best route set, which has the maximum value of the path evaluation function.

In this paper, node i performance factor F_i which is defined as Eq. (6):

$$F_i(t) = a_1 Q_i^{\mathrm{unit}}(t) + a_2 T_i^{\mathrm{unit}}(t) + a_3\left(1 - \frac{E_i^{\mathrm{r}}(t)}{E_0}\right) \tag{6}$$

where a_1, a_2, a_3 are positive weights, $Q_i^{\mathrm{unit}}(t)$ is the node unit queue length at current time step, $T_i^{\mathrm{unit}}(t)$ is the node unit forwarding packet number at current time step, E_0 is the initial energy of node; $E_i^{\mathrm{r}}(t)$ is the residual energy of node i at current time step. In order to reflect the influence made by the historical node local information on the present node load factor, these two parameters $Q_i^{\mathrm{unit}}(t)$ and $T_i^{\mathrm{unit}}(t)$ are updated as Eq. (7) and Eq. (8) at every time step:

$$Q_i^{\mathrm{unit}}(t) = \frac{\varepsilon Q_i(t) + (1-\varepsilon) Q_i(t-1)}{Q_i^{\max}} \tag{7}$$

$$T_i^{\mathrm{unit}}(t) = \frac{\varphi T_i(t) + (1-\varphi) T_i(t-1)}{T_i^{\max}} \tag{8}$$

where $Q_i(t)$ is the node queue length at current time step, $Q_i(t-1)$ is the node queue length at last time step and $Q_i^{\max}$ is the max forwarding packet number of history. $T_i(t)$ is the forwarding packet number at current time step, $T_i(t-1)$ is the forwarding packet number at last time step and $T_i^{\max}$ is the max forwarding packet number of history. ε and φ are constants, they can be chosen between 0 and 1. The bigger the values are, the current status of node have the bigger proportion in these two parameters $Q_i^{\mathrm{unit}}(t)$ and $T_i^{\mathrm{unit}}(t)$. In the simulation, two parameters ε and φ are set to 0.7.

Hence, according to the Eq. (5), the bigger the values of end-to-end delay, packet loss ratio, average energy consumption and length of path are, the value of path evaluation function is smaller. Hence, the performance of this path is worse. In addition, according to the Eq. (6), the bigger the values of the node unit queue length and the node unit forwarding packet number are, the smaller the residual energy of node i is and the value of node performance factor is bigger. Hence, the performance of this node is worse, which indicates that this node is too busy to have a greater probability of death.

Therefore, this paper applies the IAMQER algorithm to find out a route set p_{best}^k established by the ant k, which has the maximum value of path evaluation parameter V_{P^k}

aiming for increasing network throughput, reducing network energy consumption and improving QoS routing.

3.4 Problem formulation

As described above, this paper presents a multi-constrained QoS energy-saving routing and throughput optimization algorithm based on the improved ACA, which is used to solve mathematical model of optimization problems, which is defined as Eq. (9):

$$\left.\begin{aligned} &P_{\text{best}}^{k^*} = \arg\max_{P^k} \left\{ V_{P^k} \,\middle|\, \forall k \in K \right\} \\ &\text{s.t.} \\ &\quad D_{p_{s,d}^k} \leqslant D_{\text{T}};\quad \forall k \in K,\ \forall s \in S,\ \forall d \in D \\ &\quad L_{p_{s,d}^k} \leqslant L_{\text{T}};\quad \forall k \in K,\ \forall s \in S,\ \forall d \in D \end{aligned}\right\} \tag{9}$$

where V_{P^k} is the path evaluation function and defined as Eq. (5), p^k is the route set established by ant $k \in K$, $p_{s,d}^k$ is the route from source node $s \in S$ to every destination node $d \in D$ established by the ant k, which constitutes the route set $P^k = \{p_{s,d}^k \,|\forall s \in S, \forall d \in D\}$. $P_{\text{best}}^{k^*}$ is the global best route set. $D_{p_{s,d}^k}$ and $L_{p_{s,d}^k}$ are the end-to-end delay and the packet loss ratio of route $p_{s,d}^k$ respectively. D_{T} and L_{T} are the delay constrain value and the packet loss ratio constrain.

4 IAMQER algorithm

4.1 Rules of IAMQER algorithm

1) The state transition rule

In the IAMQER algorithm, the ant $k \in K$ selects the node j which has the maximum transfer probability as the next hop from the current node i at each time step. The transfer probability $p_{i,j}^k$ is calculated as below:

$$p_{i,j}^k(t) = \begin{cases} \max\left\{ \left[\tau_{i,j}(t)\right]^{\alpha} \left[\eta_{i,j}(t)\right]^{\beta} \right\}; & q \leqslant q_0, n \in N_i \\ \dfrac{\left[\tau_{i,j}(t)\right]^{\alpha} \left[\eta_{i,j}(t)\right]^{\beta}}{\sum\limits_{z \in N_i} \left[\tau_{i,z}(t)\right]^{\alpha} \left[\eta_{i,z}(t)\right]^{\beta}}; & q > q_0, n \in N_i \end{cases} \tag{10}$$

$$q_0 = E + \frac{F N_{\text{count}}}{N_{\text{max}}} \tag{11}$$

where $\tau_{i,j}(t)$ is the pheromone intensity of the link connecting node i and node j; $\eta_{i,j}(t)$ is a heuristic function that is defined as the visibility of link between node i and node j. N_i is the set of neighbor node of node i but not including node i; α and β are parameters that control the relative importance of trail versus visibility. q is a random number uniformly distributed in $[0,1]$, q_0 is a dynamic parameters that increases gradually with increasing in the number of iterations according to Eq. (11). q_0 determines the relative importance of exploitation versus exploration. At the beginning, the smaller the value of q_0 is, the algorithm is more likely to search possible solutions and avoids falling into the local optimal solution prematurely. However, at the end, the bigger the value of q_0 is, the algorithm is more likely to converge to a global optimal solution. In the Eq. (11), E and F are constant parameter and the value of them are 0.2 and 0.7 usually. N_{count} is the number of iterations and N_{max} is the maximum number of iterations.

In this algorithm of the paper, heuristic function $\eta_{i,j}(t)$ is defined as below:

$$\eta_{i,j}(t) = \frac{1}{\left(\omega F_j + \theta d_{i,j}\right)^{\lambda}} \tag{12}$$

where F_j is the performance factor of node j, $d_{i,j}$ is the distance between node i and node j, ω and θ is proportional constants, λ is a loss constant between 2 and 5 that depends on the wireless medium.

2) The local updating rule

After an ant moved from node i to the node j, the pheromone intensity on the selected link $\tau_{i,j}(t)$ is updated locally according to Eq. (13). Local pheromone update mechanism can expand the search range of feasible solutions and in this way, ants can make better use of their pheromone trail information. Without local updating, all ants will only search in a narrow neighborhood of the optimal previous route.

$$\tau_{i,j}(t+1) = (1-\rho)\tau_{i,j}(t) + \rho\tau_0 \tag{13}$$

where $\rho(0 < \rho < 1)$ is the local pheromone decay parameter. τ_0 is the initial value of the pheromone.

3) The global updating rule

Once all ants have finished searching for a set of routes from source node to destination node one time, the global updating of the pheromone takes place. Firstly, the path evaluation function V_{P^k}, which contains values of all paths between source node $s \in S$ and destination node $d \in D$ belonging to the route set p^k, is calculated. Then the pheromone intensity of link $\tau_{i,j}(t)$ is updated globally according to Eqs. (14) and (15).

$$\tau_{i,j}(t+1)=(1-\gamma)\tau_{i,j}(t)+\gamma\Delta\tau_{i,j}(t) \tag{14}$$

$$\Delta\tau_{i,j}(t)=\begin{cases}\dfrac{a_4}{V^{\text{best}}_{P^{k^*}_{\text{best}}}}; & (i,j)\in P^{k^*}_{\text{best}}\\ 0; & \text{others}\end{cases} \tag{15}$$

where $\gamma(0<\gamma<1)$ is the global pheromone decay parameter; a_4 is constant for rewarding the pheromone. $P^{k^*}_{\text{best}}$ presents the global best route set including all paths $p^k_{s,d}$ from all source nodes to destination nodes. $\Delta\tau_{i,j}$ is the increment of the pheromone intensity of link (i,j), which is proportional to the maximum value of path evaluation function $V^{\text{best}}_{P^{k^*}_{\text{best}}}$ if link (i,j) belongs to global best route $P^{k^*}_{\text{best}}$.

According to Eqs. (14) and (15), the pheromone trails of the best route offer incentives, intends to provide a greater amount of pheromone to the best path, so it can guide other ants to move toward the best solution. It is a positive feedback process, which can accelerate the convergence speed greatly.

4.2 The steps of IAMQER algorithm

The steps of IAMQER algorithm are elaborated as follows:

Step 1 Initialization: set the total number of network nodes，the total number of ants, the maximum value of a node queue length, the maximum number of iterations N_{max} and reset the number of iterations N_{count}. Initialize the pheromone intensity of each link with τ_0, the node initial energy with E_0 and the node initial power level between node i and node j with. Besides, generate source node set S and destination node set D randomly. Ant $k\in K$ is generated at source nodes $s\in S$ and establishes route set P^k including route $p^k_{s,d}$ between every source and destination nodes via path traversal of all source and destination pairs, which is $P^k=\{p^k_{s,d}\,|\forall s\in S,\forall d\in D\}$.

Step 2 Establish the network topology diagram according to the characteristics of the real Ad-hoc networks. As the results, get the network adjacency matrix $\boldsymbol{A}$ and the node neighbor set N_i. Calculate the node degree with the network adjacency matrix.

Step 3 Each ant k chooses the next hop node according to the transfer probability $p^k_{i,j}$ defined in the state transition rule and adjust the node power level dynamically in accordance with the distance between node i and node j. At the same time, each ant k finds the next hop beginning from source node s until reach the destination node d and obtains the route $p^k_{s,d}$.

Step 4 When an ant choose its next hop node successfully, the pheromone density on the link will be modified based on the local updating rule. Repeat Step 3 and Step 4 until the ant k establishes the route set $P^k=\{p^k_{s,d}\,|\forall s\in S,\forall d\in D\}$.

Step 5 When each ant obtains a route set P^k between pairs of source nodes and destination nodes successfully, calculate the path evaluation function V_{P^k} of every route set P^k, including the metric function of end-to-end delay $f_{D_{P^k}}$ and the metric function of packet loss ratio $f_{L_{P^k}}$ of route set P^k, the energy consumption $E_{p^k_{s,d}}$ and the total length $l_{p^k_{s,d}}$ of path $p^k_{s,d}$. Meanwhile, calculate a node performance factor F_i with the node unit queue length Q^{unit}_i, the node unit forwarding packet number T^{unit}_i and the residual energy E^{r}_i of node i. Then find the maximum value of path evaluation function $V^{\text{best}}_{P^{k^*}_{\text{best}}}$ and the global best route set $P^{k^*}_{\text{best}}$.

Step 6 According to the global pheromone density updating rule, update the pheromone density of the link belonging to the global best route set $P^{k^*}_{\text{best}}$.

Step 7 If the termination condition $(N_{\text{count}}>N_{\text{max}})$ is met, finish the process; otherwise N_{count} plus one and return to Step 3.

5 Simulation results and analysis

In this section, we evaluate the performance of IAMQER algorithm through simulation and compare it with the shortest route based on Dijkstra algorithm and a purely on demand MANET routing protocol AODV is enhanced to provide QoS, called NQoS AODV [21], which considers the end-to-end delay, bandwidth and the node-pair connectivity QoS index. We consider the Ad-hoc networks of 100 nodes randomly located in a $1\,000\text{ m}\times 1\,000\text{ m}$ region; each node has the maximum transmit range of 250 m. The initial unit energy of every node is 1. The unit energy consumption of sending the data packet at each time step is proportional to the distance. The maximum node queue length is set to 20 and choose 5 pairs of source nodes and destination nodes randomly from 100 nodes.

In the simulation, we assume that the total number of ants is 10, the maximum number of iterations is 15 and the initial pheromone density is 10. In this algorithm, assume $\alpha = 0.5$, $\beta = 0.5$, $\rho = 0.7$ and $\gamma = 0.7$. The node capacity C, that is the number of data packets a node can forward to other nodes each time step, is assumed to be a constant. In this paper, we set C to be 10 and the total time steps T are assumed to be 250.

The simulation results, which illustrate the comparisons between our scheme and the shortest route, are shown as follows:

1) Packet delivery number analysis

Fig. 2 indicates the packet delivery number of three routing algorithms for the case the number of data packets generated in the network at each time step is varied from 1 to 25 respectively.

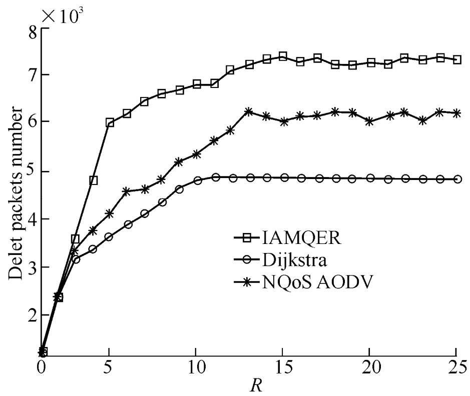

Fig. 2 Packet delivery number comparison under different packet generation rates

As shown in Fig. 2, at the beginning, the packets delivery number of three route algorithms increases with the networks packet generation rate R increasing. But, the overall trend of packets delivery number of the IAMQER is bigger than the Dijkstra and NQoS AODV. The key contribution to this improvement is that IAMQER considers the node queue length, that is, the IAMQER can avoid more data packets is deleted due to the data packets number exceeds the max node queue length. Thus, the IAMQER can improve the number of data packets received by destination successfully. However, when the packet generation rate increases to a certain value, the packets delivery number is unchanged, that is, network is the maximum transmission capacity state.

2) Packet delivery ratio and packet loss ratio analysis

Figs. 3 and 4 indicate the packet delivery ratio and packet loss ratio of three routing algorithms for the case when the number of data packets generated in the network at each time step R is varied from 1 to 25 respectively. For all the approaches, there is a decrease in packet delivery ratio and increase in packet loss ratio when the R increases. The results indicate that there is an improvement in packet delivery ratio and packet loss ratio using IAMQER compared with the other two routing algorithms.

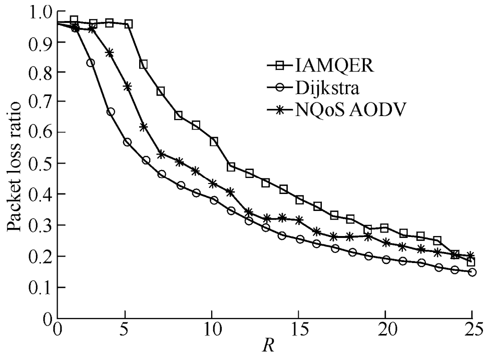

Fig. 3 Packet delivery ratio comparison under different packet generation rates

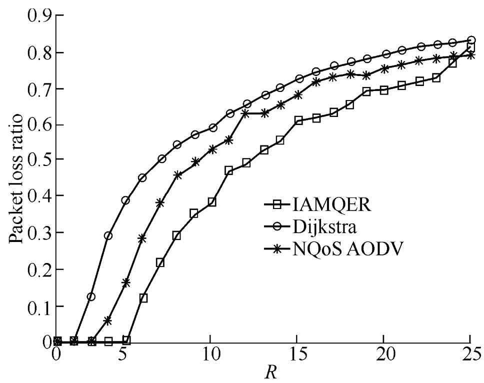

Fig. 4 Packet loss ratio comparison under different packet generation rates

As shown in Fig. 3, packet delivery ratio of the IAMQER is higher than the Dijkstra and NQoS AODV. The key contribution to this significant improvement in packet delivery ratio is the fact that IAMQER considers the node forwarding packet capacity and the node queue length, that is, the node performance factor has been introduced, whereas the shortest route and NQoS AODV have not. Due to these factors, IAMQER algorithm can reduce the local congestion. Similarly, this scheme also brings improvement in packet loss ratio. As shown in Fig. 4, the packet loss ratio of the IAMQER is lesser than the shortest route and NQoS AODV. Besides of the node performance factor, this paper defines the path evaluation function V_{p^k}, which considers the packet loss ratio to measure the performance of route set p^k, so that selecting a route with minimal packet loss ratio to forward data packets by means of the positive feedback of ant colony algorithm, which can reduce network packet loss ratio.

3) Average end-to-end delay and balanced ratio function analysis

Fig. 5 displays the average end-to-end delay of three route algorithms and Fig. 6 displays the balanced ratio function of these routing algorithms with varying number of data packets generated rate in the network at each time step.

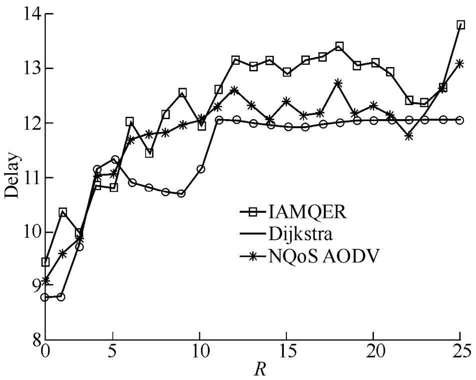

Fig. 5 Average end-to-end delay comparison under different packet generation rates

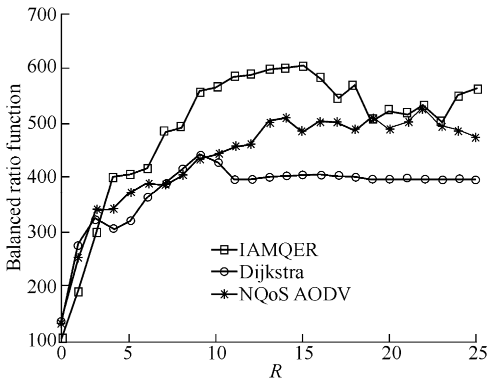

Fig. 6 Balanced ratio function comparison under different packet generation rates

From the results, although the average end-to-end delay in the IAMQER algorithm is bigger than the Dijkstra and NQoS AODV, as increase in the number data packets generated in the network, there is an obvious increase in the balanced ratio function of the three route algorithms and the function value of the IAMQER is bigger than the Dijkstra and NQoS AODV as shown in Fig. 6, that is, the packet delivery number is more bigger under the unit end-to-end delay of the IAMQER and the IAMQER has improvement in the packets delivery capacity. This is due to the fact that IAMQER focuses on finding a route that can balance the packets delivery number and average end-to-end delay by means of the path evaluation function V_{p^k} considering the packets delivery ratio and the average route length to measure the performance of route set p^k and the positive feedback of ant colony algorithm, but the shortest route and NQoS AODV only consider the route length and delay, which leads the number of data packets in some nodes to be beyond the node forwarding packet capacity, so that decreases the packets delivery number and leads to the poor efficiency of packets received successfully. On the one hand, selecting a route with minimal delay to forward data can reduce network delay like the Dijkstra and NQoS AODV algorithm. On the other hand, IAMQER algorithm introduces the node load factor and the path congestion factor including the node forwarding packet capacity and the node queue length, which can decrease the local congestion and avoid node load imbalance that lead to delay increase. These imply that IAMQER can be balanced between packets delivery number and average end-to-end delay.

4) Average energy consumption and node number with residual energy above 50% analysis

Figs. 7 and 8 show the average energy consumption of three routing algorithms at different number of data packets generated in the network at each time step and the number of node with residual energy above 50% of initial energy in the network respectively.

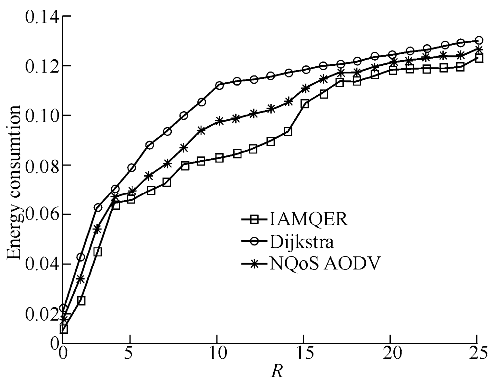

Fig. 7 Network average energy consumption comparison under different packet generation rates

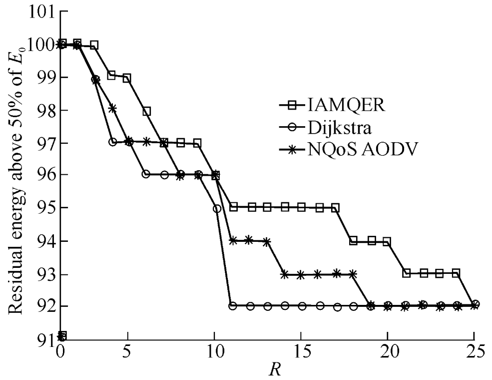

Fig. 8 Nodes with more than half residual energy under different packet generation rates

As increase of the network packets generation rate, three route algorithms show significant rise in network average energy consumption. The results in Fig. 7 indicate that the network average energy consumption of IAMQER is lesser than that of the shortest route and NQoS AODV in the same circumstances.

In addition, the results in Fig. 8 indicate that the number of node with residual energy above 50% of initial energy of IAMQER is more than that of the other two route algorithms at the same packet generation rate. This is because IAMQER takes node residual energy into account when finding routes and considers the node forwarding packet capacity and the node queue length to avoid death of hot nodes untimely, thus balancing the energy consumption of each node. Besides, the shortest route and NQoS AODV do not take measures to network energy consumption, and just uses the default maximum power to transmit data, which will consume more energy. Some nodes of burdening heavy flow excessively consumed their energy, thus the corresponding residual energy is less due to uneven energy consumption. However, IAMQER consume less energy because of using the effective power adjust scheme. According to the different distance between two nodes, nodes adjust the power to transmit data packets dynamically on the basis of power level. By this way, IAMQER can gain 9.23%~26.03% energy savings than the Dijkstra and NQoS AODV, thus prolonging the hot nodes lifetime. These results show that IAMQER can save the network energy consumption and prolong route life.

6 Conclusions

This paper presents an improved IAMQER, which can establish a route supporting multi-constrained QoS, increase network throughput and reduce network energy consumption by means of ant colony algorithm. Performance evaluation using Matlab simulator comparison with the shortest route algorithm and NQoS AODV shows that the importance of considering the node forwarding packet capacity, the node queue length and the node residual energy in route establishing process and the transmit power adjusting scheme in data packets forward. In addition, this paper defines a path evaluation function to evaluate the performance of routes and uses iteration and positive feedback of ant colony algorithm to establish a route, which can better make use of local information. Simulation results show that IAMQER algorithm proposed by this paper can not only reduce network energy consumption, thus prolonging the hot node lifetime, but also improve packet delivery ratio significantly in two constraints of average end-to-end delay and packet loss ratio, thus increasing network throughput.

For future work, we will focus on the implementation to improve the algorithm. Our further investigations include experiments with high network load and more complete network topology. Besides, other factors can improve routing performance to satisfy more network requirement will also be considered in our routing algorithm.

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References

1. Chen L, Heinzelman W B. A survey of routing protocols that support QoS in mobile Ad-hoc networks. IEEE Network, 2007, 21(6): 30–38
2. Karimi M, Deng P. Challenges for quality of service (QoS) in mobile Ad-hoc networks (MANETs). Proceedings of the IEEE 10th Annual Wireless and Microwave Technology Conference (WAMICON'09), Apr 20–21, 2009, Clearwater, FL, USA. Piscataway, NJ, USA: IEEE, 2009: 5p
3. Zhang B, Mouftah H T. QoS routing for wireless Ad-hoc networks: problems, algorithms, and protocols. IEEE Communications Magazine, 2005, 43(10): 110–117
4. Dorigo M, Gambardella L M. Ant colony system: a cooperative learning approach to the traveling salesman problem. IEEE Transactions on Evolutionary Computation, 1997, 1(1): 53–66
5. Dorigo M, Birattari M, Stutzle T. Ant colony optimization. IEEE Computational Intelligence Magazine, 2006, 1(4): 28–39
6. Ge Y, Kunz T, Lamont L, et al. Quality of service routing in Ad-hoc networks using OLSR. Proceedings of the 36th Annual Hawaii International Conference on System Sciences (HICSS'03), Jan 6–9, 2003, Big Island, HI, USA. Los Alamitos, CA, USA: IEEE Computer Society, 2003: 9p

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acoustic sensor networks. IEEE Transactions on Wireless Communications, 2010, 9(9): 2924–2934
3. Huang C J, Wang Y W, Liao H H. A power-efficient routing protocol for underwater wireless sensor networks. Applied Soft Computing, 2011, 11(2): 2348–2355
4. Zhou Z, Pengt Z, Cui J H, et al. Handling triple hidden terminal problems for multi-channel MAC in long-delay underwater sensor networks. Proceedings of the 29th Annual Joint Conference of the IEEE Computer and Communications (INFOCOM'10), Mar 14–19, 2010, San Diego, CA, USA. Piscataway, NJ, USA: IEEE, 2010: 5p
5. Zhou Z, Cui J H. Energy efficient multi-path communication for time-critical applications in underwater sensor networks. Proceedings of the 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC'08), May 26–30, 2008, Hong Kong, China. New York, NY, USA: ACM, 2008: 221–230
6. Guo Z, Colombo G, Wang B, et al. Adaptive routing in underwater delay/disruption tolerant sensor networks. Proceedings of the 5th Annual Conference on Wireless on Demand Network Systems and Services (WONS'08), Jan 23–25, 2008, Garmisch-Partenkirchen, Germany. Piscataway, NJ, USA: IEEE, 2008: 31–39
7. Du X J. An integrated method of attack detection on MAC layer in MANET. Journal of Harbin Engineering University, 2012, 33(10): 1271–1277 (in Chinese)
8. Intanagonwiwat C, Govindan R, Estrin D. Directed diffusion: a scalable and robust communication paradigm for sensor networks. Proceedings of the 6th Annual International Conference on Mobile Computing and Networking (MOBICOM'00), Aug 6–11, 2000, Boston, MA, USA. New York, NY, USA: ACM, 2000: 56–67
9. Xie P, Cui J H, Lao L. VBF: vector-based forwarding protocol for underwater sensor networks. Proceedings of the 5th International IFIP-TC6 Conference on Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications Systems (NETWORKING'06), May 15–19, 2006, Coimbra, Portugal. Berlin, Germany: Springer-Verlag, 2006: 1216–1221
10. Yan H, Shi Z.J, Cui J H. DBR: depth-based routing for underwater sensor networks. Proceedings of the 7th International IFIP-TC6 Networking Conference on Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet (NETWORKING'08), May 5–9, 2008, Singapore. Berlin, Germany: Springer-Verlag, 2008: 72–86
11. Du X J, Lan S L Liu F, et al. Micro-ANP network protocol architecture and simulation implementation. Telkomnika, 2013, 11(4): 1757–1768
12. Du X J, Huang K J, Liu F, et al. Micro-ANP: a novel network protocol architecture for underwater sensor network. Applied Mechanics and Materials, 2012, 303/304/305/306: 223–230
13. Niculescu D, Nath B. DV based positioning in ad hoc networks. Journal of Telecommunication Systems, 2003, 22(1/2/3/4): 267–280
14. Bahr A. Cooperative localization for autonomous underwater vehicles. Ph.D. Dissertation. Cambridge/Woods Hole, MA, USA: MIT/WHOI 2009

(Editor: ZHANG Ying)

From p. 53

7. Badis H, Agha K A. QOLSR multi-path routing for mobile Ad-hoc networks based on multiple metrics: bandwidth and delay. Proceedings of the 59th Vehicular Technology Conference (VTC-Spring'04): Vol 4, May 17–19, 2004, Milan, Italy. Piscataway, NJ, USA: IEEE, 2004: 2181–2184
8. Badis H, Mauaretto A, Agha K A, et al. Optimal path selection in a link state QoS routing protocol. Proceedings of the 59th Vehicular Technology Conference (VTC-Spring'04): Vol 4, May 17–19, 2004, Milan, Italy. Piscataway, NJ, USA: IEEE, 2004: 2570–2574
9. Boukhalfa L, Minet P, Midonnet S. QoS support in a MANET based on OLSR and CBQ. Proceedings of the 6th International Conference on Networking (ICN'07), Apr 22–28, Martinique, France. Piscataway, NJ, USA: IEEE, 2007: 20
10. Xue Q, Ganz A. Ad-hoc on-demand routing (AQOR) in mobile Ad-hoc networks. Journal of Parallel and Distributed Computing, 2003, 63(2): 154–165
11. Hwang Y, Varshney P. An adaptive QoS routing protocol with dispersity for ad-hoc networks. Proceedings of the 36th Annual Hawaii International Conference on System Sciences (HICSS'03), Jan 6–9, 2003, Big Island, HI, USA. Los Alamitos, CA, USA: IEEE Computer Society, 2003: 10p
12. Hwang Y, Lee H, Varshney P K. An adaptive routing protocol for ad-hoc networks using multiple disjoint path. Proceedings of the 53rd Vehicular Technology Conference (VTC-Spring'01): Vol 3, Mar 6–9, 2001, Rhodes, Greece. Piscataway, NJ, USA: IEEE, 2001: 2249–2253
13. Liu Z, Kwiatkowska M Z, Constantinou C. A biologically inspired QoS routing algorithm for mobile Ad-hoc networks. Proceedings of the 19th International Conference on Advanced Information Networking and Applications (AINA'05): Vol 1, Mar 28-30, 2005, Taipei, China. Piscataway, NJ, USA: IEEE, 2005: 426–431
14. Krishna P V, Saritha V, Vedha G, et al. Quality-of-service-enabled ant colony-based multipath routing for mobile Ad-hoc networks. IET Communications, 2012, 6(1): 76–83
15. Lu T, Zhu J. Genetic algorithm for energy-efficient QoS multicast routing. IEEE Communications Letters, 2013, 17(1): 31–34
16. Hwang Y, Varchney P. An adaptive QoS routing protocol with dispersity for ad-hoc networks. Proceedings of the 36th Annual Hawaii International Conference on System Sciences (HICSS'03), Jan 6–9, 2003, Big Island, HI, USA. Los Alamitos, CA, USA: IEEE Computer Society, 2003: 10p
17. Leung R, Liu J L, Poon E, et al. MP-DSR: A QoS-aware muli-path dynamic source routing protocol for wireless ad-hoc networks. Proceedings of the 26th Annual IEEE Conference on Local Computer Networks (LCN'01), Nov 14–16, 2001, Tampa, FL, USA. Piscataway, NJ, USA: IEEE, 2001: 132–141
18. Chen S G, Klara N. Distributed quality-of-service routing in Ad-hoc networks. IEEE Journal on Selected Areas in Communications, 1999, 17(8): 1488–1505
19. Ahn H, Seo Y, Kim J, et al. Multi-metric geo-routing protocol for tactical Ad-hoc networks. Proceedings of the 2013 International Conference on Information Networking (ICOIN'13), Jan 28–30, 2013, Bangkok, Thailand. Piscataway, NJ, USA: IEEE, 2013: 89–94
20. Cadger F, Curran K, Santos J, et al. A survey of geographical routing in wireless Ad-hoc networks. IEEE Communications Surveys & Tutorials, 2013, 15(2): 621–653
21. Akhter A, Sanguankotchakorn T. Modified AODV for multi-constrained QoS routing and performance optimization in MANET. Proceedings of the 7th International Conference on Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON'10), May 19–21, 2010, Chaing Mai, Thailand. Piscataway, NJ, USA: IEEE, 2010: 234–238

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