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A Bio-Inspired Gateway Selection Scheme for Hybrid Mobile Ad Hoc Networks

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ABSTRACT The gateway selection is an essential issue in hybrid mobile ad hoc networks (MANETs). Current independent and random selections without supporting routing negotiation protocol may cause links or gateways overloaded when they are selected by multiple nodes simultaneously. Therefore, the network performance may not be in a proper way. Furthermore, the ad hoc nature of MANETs makes the topology change dynamically, so that the gateway selection becomes even more difficult. This paper presents a mathematical model for gateway capability and a novel approach, called bio-inspired gateway selection, where the gateways are selected according to the network status and associated with a cooperative mechanism for optimization. The novelty includes the use of attractor selection model, the self-adaptability and the autonomy of the biological system. The performance of the proposed approach is evaluated by simulation with different scenarios and compared with the conventional approaches being currently used in hybrid MANETs. The illustrated numerical results present the performance of the proposed approach in terms of packet delivery ratio, average delivery latency, normalized routing overhead, and gateway load balance under different network conditions. Furthermore, the numerical results are also able to demonstrate the significant performance gain compared with the conventional gateway selection approaches.

INDEX TERMS Hybrid mobile ad hoc network, gateway selection, attractive selection model, dynamic topology, cooperative mechanism.

I. INTRODUCTION

Mobile ad hoc networks (MANETs) have attracted increasing attention in recent years due to the capacity in support of multi-hop communications, infrastructure-independent network topology, self-management and easy-deployment [1]. In terms of applications, MANETs have been widely used in the civil and military area to provide ad hoc based communication capacity in support of emergency evacuation in the natural disaster or mission-based operations in battlefield. MANET is originally designed as a stand-alone network, in which mobile nodes communicate with each other inside the network only. However, a new development trend, called hybrid MANETs [2]–[4], recently receives more attention, which is the integration of a number of MANETs with different technologies as well as the connections to infrastructure-based networks, such as the Internet and Cellular network.

Hybrid MANETs aim to assimilate MANETs with infrastructure-based networks to extend network coverage and service [5]. To cope with the technique difference between heterogeneous networks, some nodes called gateway are equipped with multiple interfaces to act as a bridge between MANETs and infrastructure-based networks, as shown in Figure 1. Communications between different networks must be processed and forwarded by the gateway. Therefore, mobile node should first discover and select suitable gateway periodically as access point before communicating with the node located in other networks. Gateway discovery and selection scheme is the key factor

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in the integration of MANETs with infrastructure-based networks [6].

After discovering available gateways in a proactive way or other methods [7], each mobile node should select one and build a route to it. In recent literature, most approaches select gateway based on some QoS parameters [8]–[13], such as route length [8]–[10], route robustness [11], transmission latency [12] and residual load capacity [13]. However, mobile nodes always select gateway independently rather than cooperatively, without considering the impact of selection on each other. Under such circumstances, if a number of mobile nodes select the same gateway simultaneously or there are some common node(s) along the routes to the gateway, then a data transmission bottleneck occurs. Consequently, network performance is degraded. Furthermore, the selected gateway and corresponding route will be used by mobile node until the next round of gateway discovery. Since the topology of MANET changes dynamically, the selected gateway may become no longer optimal. These issues influence the communication performance, however, they are previously rarely considered.

Concerning the issues mentioned above, we first design a mathematical model to study the gateway capability for request service and then discuss the factors that should be considered in the gateway selection. Based on this, this paper proposes a bio-inspired gateway selection scheme for hybrid MANETs, in which attractor selection model is incorporated into the gateway discovery and selection process to optimize the network performance. The attractor selection model, which is derived from biological intelligence, is able to effectively search a stable solution for an optimization problem, especially in a dynamic environment. Thus, it is utilized to inspire the gateway selection for hybrid MANETs, which have dynamic topology. The *activity* in the model is defined as the goodness of the selected gateway and corresponding route measured by combining four performance-related metrics. Each available gateway is treated as an *attractor*, which is a potential selection option. Every source node drives the attractor selection model to evolve and thus could indirectly interact with each other during the evolutionary process. This enables mobile node to adaptively select the optimal gateway in a potential cooperative manner. To the best of our knowledge, this paper first utilizes the attractor selection model for optimization of the gateway selection problem.

The rest of the paper is organized as follows. We first give an overview of some related works in Section II. Section III presents the problem analysis. In Section IV, we introduce the attractor selection model and propose a novel bio-inspired gateway selection approach for hybrid MANETs. Then we illustrate the performance of our method and discuss the simulation results in Section V. Finally, Section VI concludes this paper.

II. RELATED WORKS

With increasing attention on hybrid MANETs, a number of gateway discovery and selection approaches have been proposed with different selection criterion for various application scenarios. An early principle is to select the nearest gateway by taking into account of the shortest hop length from mobile node to possible access point [8], [9], since mobile node is able to obtain the route length to each gateway from the received gateway advertisement (GWADV) packets in the gateway discovery process. Hence, the gateway with the shortest route is selected to relay the traffic flows between MANETs and infrastructure-based networks. Unfortunately, this gateway selection approach based on the shortest route may lead to gateway congestion, especially under heavy traffic load conditions.

Rather than route length, the link stability is also an important parameter to be considered in gateway discovery and selection schemes. In [11], the statistical characterization of link duration in MANETs is considered in the gateway discovery. The GWADV packets are exclusively forwarded in the areas, where the links are expected to remain stable. Consequently, mobile nodes are only informed by the gateway with stable routes. RTMGWS protocol proposed in [14] selects gateway based on the robustness of links and routes, which is derived from the characteristics of vehicle movements and other routing parameters. Furthermore, a link-connectivity prediction based location-aided routing protocol for hybrid MANETs is proposed [15], where the route expiration time is the key factor in selecting the gateway. The route expiration time is estimated by calculating the link expiration time between each pair of neighboring nodes. However, the speed, moving direction and coordinate of mobile node are required when the link expiration time is calculated. Note that additional GPS information is always necessary to obtain the required information. Unlike the mechanism proposed in [15], reference [16] evaluated link stability based on the information obtained from the received signal strength, which can be obtained without additional devices. It is clear that the gateway discovery by taking into account of link stability is able to improve the network performance. However, the weakness in [15] and [16] is that the traffic concentration on some particular nodes cannot be avoided. To obtain stable links, mobility prediction is taken into consideration in [17], where artificial neural network (ANN) is utilized to predict node mobility. However, the computation cost of ANN is too high for resource-constrained MANETs in terms of computation and energy consumption.

Furthermore, there are several gateway discovery and selection approaches considering multiple QoS-related parameters in order to improve overall network performance. Bozorgchenani etc. [18] proposed a gateway selection approach for wireless mesh networks taking into account of traffic load and route reliability, so that the gateway with low traffic load and high route reliability is selected as access point. In contrast, a gateway selection scheme considering multiple QoS parameters, including route availability period, route latency and available route load capacity is presented in [12]. In this scheme, the gateway is selected according to the parameter calculated by combining the above three

QoS parameters with predefined weights. Recently, a novel approach focusing on gateway load balancing has been proposed to select the lightly loaded gateway, which combines four QoS parameter metrics, including presenting connectivity degree, interface queuing length, routing table entries and hop count, respectively [19].

Fuzzy logic systems are adopted in literature to cope with the uncertainty due to node mobility in ad hoc network [20], [21]. Reference [20] applied a type-2 fuzzy logic approach to optimize the integration of MANETs and infrastructure-based networks by considering four parameters, including link lifetime, route length, the ratio of active links per traffic sources and the ratio of error routing packets per requested routes. The two outputs of the type-2 fuzzy logic system, indicating the route status, are used to guide the propagation of GWADV packets and the gateway selection. On the other hand, reference [21] presented a novel approach, named steady load balancing gateway election, based on a fuzzy logic system to achieve a multi-objective optimization in the network performance. The fuzzy system infers a new routing metric, named *cost*, considering three network performance variables, including GWADV packet arrival variance, control packet ratio and gateway load. The gateway with the lowest *cost*is preferred. However, the fuzzy system needs to be optimized by using a genetic algorithm so as to achieve a good effect.

In summary, the gateway discovery and selection approaches presented in [8], [9], [11], [12], and [14]–[21] focus on the discovery efficiency by reducing control overhead and selecting a potential gateway to satisfy special QoS demands. It is noticed that the gateway discovery and selection for each individual mobile node is an independent activity without any cooperating protocol between mobile nodes. However, when such a large number of independent and random gateway selection occur, a gateway may be selected by multiple mobile nodes simultaneously. This certainly generates interference, which has a negative impact on network performance [22]. Furthermore, another weakness is that these approaches may not obtain optimal solutions since they are lack of the ability to cope with the MANET topology, which keeps changing dynamically.

Attractor selection model, which was used to model the adaptive behaviors of *Escherichia coli cell* (*E.coli cell*) in dynamically changing environments [23], has been considered to have some attributes that are suitable to address challenges in dynamic scenarios. Applications of the model in the communication and networking scenarios have revealed its power in achieving optimal solutions. In [24]–[26], the attractor selection model is used to enhance routing messages in dynamic VANETs by defining the goodness of the current multi-hop route as the activity in the attractor selection model. Inspired by the model, each node adaptively selects the optimal next hop when routing message. An adaptive resource allocation mechanism was proposed in [27], where each node runs the attractor selection model so as to autonomously and adaptively allocate wireless network resources to each of networked applications running on it. Hu *et al.* [28] proposed an attractor selection model inspired offloading ratio selection (AORS) algorithm, which can adaptively select an optimum offloading ratio for current network environment. Tian *et al.* [29] applied attractor selection model to cope with the issue that how to enable mobile nodes to make hand-off between networks in heterogeneous wireless networks. Each mobile node is induced by the attractor selection model to make decision in a fully distributed and adaptive manner in time-varying network conditions. These applications reveal some features of the attractor selection model such as adaptation and potential collaboration between possible solutions. These features are believed to contribute to improving or eliminating the issues in gateway selection problem caused by dynamic topology and lack of collaboration. Thus, by integrating the attractor selection model, we design a bio-inspired gateway selection scheme for hybrid MANETs.

III. PROBLEM ANALYSIS

As shown in Figure 1, the gateway is a critical node in hybrid MANETs, through which mobile nodes are able to interconnect with infrastructure-based networks. This section presents a theoretical model to analyze gateway's service ability, which provides a theoretical basis for resolving the gateway selection problem.

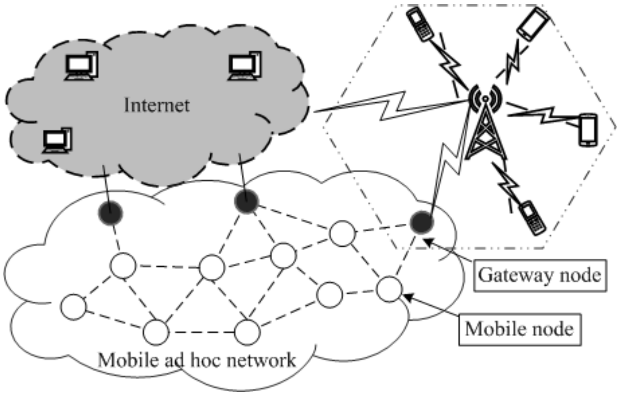


FIGURE 1. The architecture of hybrid mobile ad hoc network.

Considering that a hybrid MANET consists of total M mobile nodes sharing G gateways. In the following analysis, a gateway g ($g \in \{G\}$) is modeled as a priority leaky bucket system with maximum data transmission rate of Cg Mbps. We consider the multiple network QoS classes based on the priority leaky bucket model operating on a first-in-first-out (FIFO) non-preemptive basis while data packets from a mobile node are being served.

Considering that the population of mobile nodes in the network is M, in which each mobile node may generate an independent packet flow with specified arbitrary parameter γ_k, where k is the QoS class index indicating two types of traffic, including delay-and-loss sensitive traffic and normal traffic. Note that γ_k presents the QoS behavior of mobile node, which can be characterized by daily operation statistics.

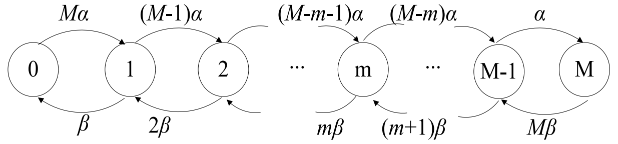


FIGURE 2. Markov modulated process.

Therefore, communication activities are modeled as a Markov modulated process [30], as shown in Figure 2, where state m, ($m \in [0, M]$), represents that m mobile nodes are in the communication process, denoted as "active" state. Other nodes are in "off" state without any communication request. The transition rate of a node from "active" to "off" state is represented as α and the transition rate from "off" to "active" state is represented by β. Thus, the transition rate from the state m to the state $(m-1)$ is $m\beta$ and the transition rate from the state m to the state $(m+1)$ is $(M-m)\alpha$. Considering that m mobile nodes are in "active" state, the number of mobile nodes in QoS class k can be given by $m\gamma_k P(m)$, where $P(m)$ is the probability that m mobile nodes are in "active" state.

$$P(m) = \binom{M}{m} P_{ON}^{m}(1-P_{ON})^{M-m}, \quad \text{where } P_{ON} = \frac{\alpha}{\alpha+\beta} \tag{1}$$

Based on the above description, we analysis the gateway capability for new communication request. The fluid flow technique [31] is used in the following performance analysis with multiple QoS categorizations. The population of mobile nodes is assumed to be large enough, i.e. ($M \gg 1$). The transmission time of data packet is assumed as equal time slots and each time slot is equivalent to one data packet per slot, so that the service time of all mobile nodes is assumed to be uniformly distributed. This assumption is reasonable, given that when the population of mobile nodes is large, the amount of data to a mobile node comparing to the total of data transmission capacity provided by a gateway is negligible. Therefore, the variation of the data in one time unit is also negligible. In the context of mobile communication system, the time slot is assumed to be equal to packet transmission time. The maximum data rate that can be distributed in support of multiple QoS classes through a priority leaky bucket model is denoted as E_P. The QoS control in the priority leaky bucket is implemented by a set of thresholds, denoted as

$$T_k|_{k=1,2} = \begin{cases} T_1 = \xi_1 E_P \\ T_2 = \xi_2 E_P \end{cases} \tag{2}$$

where ξ_j is a threshold parameter and $0 < \xi_2 < \xi_1 \leq 1$. Therefore, the QoS class is implemented as

$$\begin{cases} T_1 \geq E(t) > T_2 & \text{Only service class 1,} \\ T_2 \geq E(t) > 0 & \text{Service class 1 and 2,} \end{cases} \tag{3}$$

where $E(t)$ is the data rate generated by new services. Considering that the number of mobile nodes in the "active" state equals to m ($m \in [0, M]$) at time t, three elementary events can take place during the next interval $\Delta t(\Delta t \ll 1)$, i.e., a mobile node changes its state from "off" to "active" with a probability $(M-m)\alpha\Delta t$. Likewise, a mobile node changes its state from "active" to "off" with a probability $m\beta\Delta t$ and a mobile node does not change its state with a probability $1-[(M-m)\alpha + m\beta]$. Now we define $F_m^k(t, x)$, $m \in [0, M]$, $t \geq 0$, $x \geq 0$ as the probability that at time t, m mobile nodes are in the "active" state and the actual bit rate produced by these mobile nodes does not exceed x, where k is the QoS class index. By taking into account the three elementary events that can take place during the next interval Δt, ($\Delta t << 1$), we have

$$\begin{aligned} &F_m^k(t+\Delta t, x) \\ &\quad = (M-(m-1))\,\alpha\Delta t F_{m-1}^k(t+\Delta t, x) \\ &\qquad + (m+1)\,\beta\Delta t F_{m+1}^k(t+\Delta t, x) \\ &\qquad + [1-((M-m)\,\alpha + m\beta)\,\Delta t]\, F_m^k\left(t, x-(m\lambda^k - C)\right)\Delta t \\ &\qquad + o\left(\Delta t^2\right) \end{aligned} \tag{4}$$

where C is the number of mobile nodes, which completed their services during $(t, t+\Delta t)$ and λ^k is the summation of new service requests with QoS class higher than or equal to k. Looking at the right side of (4), the first term is the transition probability from the state $(m+1)$ to the state m during $(t, t+\Delta t)$, the second term is the transition probability from the state $(m+1)$ to the state m during $(t, t+\Delta t)$, the third term is the probability of remaining in the state m during $(t, t+\Delta t)$ with no change and the last term $o(\Delta t^2)$ is the probability of the compound events such as the changing of state more than one time during $(t, t+\Delta t)$. We note that $o(\Delta t^2)$ represents all higher order terms, which goes to zero much rapidly than Δt when Δt approaches zero. Hence, the effects of $o(\Delta t^2)$ is negligible when Δt is small enough. In (4), we also assume that both $F_{-1}^k(t, x)$ and $F_{M+1}^k(t, x)$ are set to be equal to zero. Now we expand $F_m^k(t+\Delta t, x)$ and $F_m^k(t, x-\Delta x)$ for $\Delta x = (\lambda^k - C)\Delta t$ in their respective Taylor series with assumption that the appropriate continuity conditions are satisfied. Since only time–independent, equilibrium probabilities are being considered, we let $\Delta t \to 0$ to compute the partial derivation of (4) for $m \in [0, M]$, that is

$$\begin{aligned} &\left(m\lambda^k - C\right)\frac{dF_m^k(x)}{dx} \\ &\quad = (M-(m-1))\,\alpha F_{m-1}^k(x) \\ &\qquad + (m+1)\,\beta F_{m+1}^k(x) - ((M_H - m_h)\,\alpha + m\beta)\, F_m^k(\mathrm{x}) \end{aligned} \tag{5}$$

where $F_m^k(x)$ denotes the equilibrium probability that mobile nodes are in the "active" state under the condition that the total data bit rate does not exceed x. Define $\mathbf{F}^k(\mathbf{x}) = \left[F_0^k(x),\, F_1^k(x),\, \ldots,\, F_M^k(x)\right]^T$, then (5) can be expressed in the following matrix notation as:

$$\mathbf{D}^k \frac{d}{dx}\mathbf{F}^k(\mathbf{x}) = \mathbf{H}\mathbf{F}^k(\mathbf{x}), \quad x \geq 0 \tag{6}$$

$$\mathbf{H} = \begin{bmatrix} -M\alpha & \beta & 0 & 0 & \dots & 0 & 0 \\ M\alpha & -\{(M-1)\alpha+\beta\} & 2\beta & 0 & \dots & 0 & 0 \\ 0 & (M-1)\alpha & -\{(M-2)\alpha+2\beta\} & 3\beta & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & 2\alpha-\{\alpha+(M-1)\beta\} & M\beta \\ 0 & 0 & 0 & 0 & \dots & \alpha & -M\beta \end{bmatrix} \tag{7}$$

where $\mathbf{D}^k = diag\left\{0-C, \lambda^k - C, 2\lambda^k - C, \dots, M\lambda^k - C\right\}$ and $\mathbf{H}$ is the $(M+1) \times (M+1)$ tri–diagonal matrix (7), as shown at the top of this page.

Assuming that $m\lambda^k - C$ is not equal to zero for any m $(0 \leq m \leq M)$, the general solution of (6) can be given by

$$\mathbf{F}^k(\mathbf{x}) = \sum_{m=0}^{M} a_m^k \mathbf{V}_m^k e^{z_m^k x} \tag{8}$$

where $\mathbf{F}^k(\mathbf{x}) = [F_0^k(x), F_1^k(x), \dots, F_M^k(x)]$. The elements in $\mathbf{z}^k(\mathbf{x}) = \left[z_0^k, z_1^k, \dots, z_M^k\right]$ are the eigen-values of the matrix $\left(\mathbf{D}^k\right)^{-1}\mathbf{H}$ and $\mathbf{V}_m^k$ is the eigenvector of the same matrix. When solving this, the coefficients $\left\{a_m^k\right\}$ can be obtained from the boundary conditions by defining $S_D^k = \left\{m | m\lambda^k < C\right\}$ and $S_U^k = \left\{m | m\lambda^k > C\right\}$. Therefore, the boundary conditions of the specified priority leaky bucket can be obtained as:

$$\begin{aligned} F_m^1(T_1) &= P(m) \quad \text{if } m \in S_D^1, \text{ for } k = 1 \\ F_m^2(T_2) &= F_m^1(T_2) \quad \text{if } m \in S_U^1 \cup S_D^2, \text{ for } k = 2 \\ F_m^2(0) &= 0 \quad \text{if } m \in S_U^2, \end{aligned}$$

where $P(m)$ is the probability that m mobile nodes are in the "active" state.

The throughput H_1 of a gateway with QoS class 1 can be calculated as:

[*Request Arrival of QoS class 1*] – [*Reject Rate of QoS class 1 Due to Actual bit rate Rate Overflow with Boundary* T_1], that is:

$$H_1 = \sum_{m=0}^{M} \gamma_1 m P(m) + C\left[1 - \sum_{m=0}^{M} F_m^1(T_1)\right] \tag{9}$$

Likewise, the throughput H_2 of a gateway with QoS class 2 can be calculated as:

[Request Arrival of QoS class 2] – [Reject Rate of QoS class 2 Due to Actual bit rate Overflow with Boundary T_2*]*,that is,

$$H_2 = \sum_{m=0}^{M} \gamma_2 m P(m) - \sum_{m=S_U^1 \cap S_D^2} \left[\left(F_m^1(T_1) - F_m^2(T_2)\right) \times \left(m \sum_{j=1}^{2} \gamma_j - C\right)\right] \tag{10}$$

Hence, the blocking probability of service request due to actual bit rate overflow based on the corresponding threshold can be given by

$$P_{B_k} = 1 - \frac{H_k}{\sum_{m}^{M} \gamma_k m P(m)} \quad \text{for } k = 1, 2 \tag{11}$$

In addition to the service ability of the gateway, the quality of the route to the gateway also affects gateway selection decision. In fact, some service requests or data packets may be lost during transmission, due to the characteristics of ad hoc networks, such as multi-hop wireless communication and dynamic topology. In the traditional gateway discovery schemes, gateway discovery and selection for each individual node is independent. The lack of collaboration between nodes may lead to congestion due to the bottleneck in the routes, caused by common nodes in multiple routes. In addition, for a route in a network with dynamic topology, its performance is affected by many factors, such as route length, node capacity, link robustness and wireless interference between nodes. Consequently, the selected gateway may become no longer optimal due to the failure or instability of corresponding route to the gateway. A robust route could reduce the probability of packet loss. Thus, selecting robust route without congestion nodes is also an important task in the gateway selection. Taking these issues into consideration, we propose a novel bio-inspired scheme integrating attractor selection model to optimize the gateway selection.

IV. GATEWAY SELECTION SCHEME

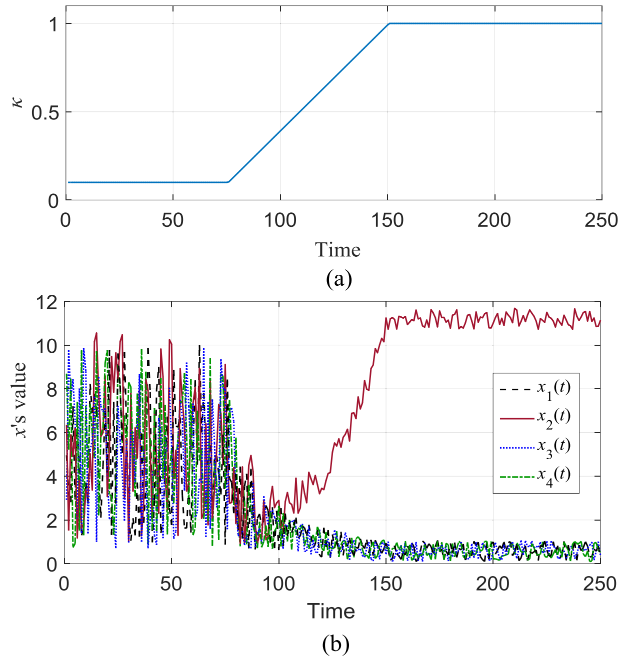
A. PRELIMINARIES OF ATTRACTOR SELECTION MODEL

The attractor selection model is a biologically inspired model that describes the adaptive response of *Escherichia coli-cells* (*E.coli cell*) in dynamically changing environments. The basic mathematical expression of the model is proposed and verified in [23]. The model reveals that the cell could adaptively search an optimal state to achieve a higher activity in dynamic environments. Considering the similarity in the dynamics of biological system and communication network, the attractor selection model is believed to be suitable to address some challenges in communication network scenarios. Some existing researches [24], [25], [27], [28] has already shown the effectiveness of the model in improving solutions.

The extended attractor selection model with high-dimensions is used to cope with the complex problem as the following temporal differential equations:

$$\begin{cases} \dfrac{dx_i}{dt} = \dfrac{f(\kappa)}{1+(x^*-x_j)^2} - d(\kappa)x_i + \eta_i \\ x^* = \max\{x_i | 1 \leq i \leq N\} \end{cases} \tag{12}$$

where x_i is the state variable of an entity in dynamic systems. When $x_i \gg x_j (1 \leq j \leq N)$, x_i is called an *attractor*, which is a potential stable state of the system. The N-dimension attractor selection model has N possible attractors. In the application, each attractor always corresponds to a potential solution. The symbol η_i represents the system noise on the entity, randomly generated from a Guassian distribution with μ and σ denoting the mean value and deviation, respectively. The symbol κ, named *activity*, indicates the current condition of a cell. The function $f(\kappa)$ and $d(\kappa)$ represent the incentive and inhibitory effects of activity to the state variable. To well reflect the degree of the impact effect, $f(\kappa)$ and $d(\kappa)$ are always formulated as the monotonously increasing functions of parameter κ [24], [25], [27], [28]. In this paper, we set $f(\kappa) = a_1\kappa^r + a_2\kappa$ and $d(\kappa) = \kappa$ where a_1 and a_2 are two positive polynomial coefficients and r is a positive integer indicating the degree of the polynomial. The attractor selection model evolves continuously driven by activity κ, which is deemed as system feedback information. Whenever the value of κ is changed, the model updates all state variable x_i. In case of a high activity κ, the model has a single high value of x_i and the system will fall into this attractor and be in a stable state. In the problem domain, the solution corresponds to this attractor will be selected as an optimal solution.



(a)

(b)

FIGURE 3. A simulationexample with four attractors.

Figure 3 gives a simulation illustration with four possible attractors. Figure 3 (a) shows the change of activity κ and Figure 3 (b) shows the evolution of state variables as κ changes. It can be noticed that when the value of κ is small, close to 0, all the four state variables are fluctuating in Figure 3 (b). In such case, the system is in an unstable state, and is prone to randomly switch from a state to other states under the influence of system noise. By contrast, when activity κ increases, state x_2 gradually rises to the highest value while the other states decrease to a lower level. The gap between them becomes large and the system falls into the attractor x_2. Then, the solution corresponding to attractor x_2 will be selected as an optimal solution. This solution could keep the system in a stable status with high activity. The numerical simulation reveals that the activity driver the system to evolve to search a stable state, and also confirms that the higher-level stable state of the system is always accompanied by a high-level activity. This inspires us that once we can map the goodness of a decision-making problem to the activity parameter and the possible solution to the state variable, we can use the attractor selection model to improve the selection decision.

B. GATEWAY SELECTION INSPIRED BY THE ATTRACTOR SELECTION MODEL

To utilize the attractor selection model to inspire the gateway selection, the notations x_i and κ used in the model are needed to be specified new meaning.

As a potential access point to be selected, each gateway is marked with a state variable x_i, which is also the selection probability of the corresponding gateway. To achieve this, each node maintains a routing table to store a set of routing entities indicating the routes to different gateways, which are built or updated during the gateway discovery process. These routing entities are marked by a state vector $\mathbf{X}$, which is defined as

$$\mathbf{X} = [x_1, x_2, \cdots, x_N] \tag{13}$$

where N is the number of available gateways for mobile node s. The state vector is updated on regular interval according to the attractor selection model. Mobile node prefers to choose the gateway with maximum state variable. TABLE 1 is an illustration of routing table.

TABLE 1. Illustration of routing table with three available gateways.

Destination address	Next hop	State value
Fixed node	Default Gateway	0.7
Default Gateway	Gateway *g*2	0.7
Gateway *g*1	*N*1	0.1
Gateway *g*2	*N*2	0.7
Gateway *g*3	*N*3	0.2

$$\mathbf{X} = [0.1,\ 0.7,\ 0.2]$$

Furthermore, the activity κ is specified to indicate the goodness of gateway selection. Thus, the κ with large value indicates that the selection can bring a high-performance network communication. In contrast, a poor selection of gateway always leads to a small κ value. From this point of view, κ should consist of comprehensive information in terms of metrics related to the performance of the gateway and the route to it. Taking into account the dynamic nature of MANETs, the value of κ is calculated frequently so as to feedback the network performance and further guide the gateway selection. Since all gateways are shared by all nodes, each gateway selection decision will have a certain effect on the value of κ. Therefore, nodes could behave in a potential cooperative manner through indirect interaction among gateway selection process by periodically updating their κ and x_i. Thus, with κ as feedback information, the attractor selection model could induce each node to adaptively select optimal gateway in dynamic environments.

C. ACTIVITY DERIVATION

In this subsection, we calculate activity κ by considering several metrics related to the performance of the gateway and the corresponding route to it, so as to indicate the goodness of gateway selection.

During gateway discovery process, a mobile node may receive multiple GWADV packets sent by a gateway. Therefore, there may be more than one route between the node and the gateway. The one with the shortest route length is selected

$$r_{sg} = \begin{cases} \min\{r^i_{sg}\} 1 \leq i \leq n, & \text{if there are } n \text{ routes from } s \text{ to } g \\ 0, & \text{others} \end{cases} \tag{14}$$

where r^i_{sg} represents the ith route between node s and gateway g, and r_{sg} is the one with shortest route length. Equation (14) equaling to 0 represents that there is no available route. The route with longer route length is more likely to be impacted by dynamic network topology since it involves more intermediate mobile nodes. To some extent, route length could reflect the delivery efficiency and reliability of a route. Generally, a shorter route is more preferable in transmitting data packets. We formula a metric φ_1 to indicate the impact of route length on the gateway selection:

$$\varphi_1 = \frac{\min\{h_j | \forall r_{sg} \in R(s)\}}{h_{cur}} \tag{15}$$

where h_{cur} represents the length of route being currently used to the selected gateway in terms of hop count, and h_j is the length of route to the jth available gateway. $R(s)$ is the route set of node s to all gateways.

The route robustness is another issue related to the network performance, since link failure triggers a new round of gateway discovery, which brings extra routing overhead. Given a route $r_{sg} = (l_0, l_1 \ldots, l_{h-1})$, where l_i represents a link, its robustness, denoted as $S(r_{sg})$, is obtained by

$$S(r_{sg}) = \min\{s(l_i) | \forall l_i \in r_{sg}\} \tag{16}$$

where $s(l_i)$ represents the robustness of a link on the route. Equation (16) indicates that the robustness of the connection to the gateway is determined by the worst link. According to the recent literature [16], it is a simple and efficient method to evaluate the route robustness based upon the information extracted from received signal strength. In this paper, we adopt this method. The robustness of a link is mainly affected by the distance between the two end nodes of a link. Longer distance means a link is more likely to fail. According to the propagation model of wireless signals, the distance d and the received signal p_r has the relations $d \propto 1/p^n_r$, where n ranges from 2 to 4 in different propagation models, for example n is equal to 2 in the free space propagation model [32]. Based on this feature, we define $s(l_i)$ as the following equation:

$$s(l_i) = K\sqrt{p_r/p_t} \tag{17}$$

where K is a constant coefficient, p_r and p_t denote the received signal strength and the transmitted signal strength of nodes, respectively. Based on the route robustness, a metric φ_2 is defined to present the impact of robustness on the gateway selection, that is

$$\varphi_2 = \frac{S(r_{sg})}{\max\{S(r_{sg_i}) | r_{sg_i} \in R(s)\}} \tag{18}$$

Traffic load is an important parameter that should be taken into consideration in the gateway selection. In general, heavy existing traffic load limits the capacity for accepting new service requests. Heavy loaded routes also suffer from transmission delay and data packet loss. Furthermore, the traffic load is determined by the number of nodes that are using the route. Therefore, the remain route capacity of r_{sg} is expressed by

$$c(r_{sg}) = \min\{c_n | \forall n \in r_{sg}\} \tag{19}$$

where c_n is the available capacity of node n, that is

$$c_n = \mu - \sigma_n = \mu - \sum_{i=1}^{Z} \tau_i \rho_i \tag{20}$$

where μ is the maximum capacity of a node, σ_n is the current traffic load on node n, Z represents the number of the traffic transmitted by node n, τ_i and ρ_i are the traffic rate and packet size of the ith traffic, respectively. Therefore, a metric φ_3 is defined to present the effect of route traffic load on the gateway selection, that is

$$\varphi_3 = \frac{c(r_{sg})}{\max\{c(r_{sg_i}) | \forall r_{sg_i} \in R(s)\}} \tag{21}$$

The fourth important issue to be taken into account is the gateway load balance, which is represented by the distribution of traffic load among the gateways. The available capacity θ_g of the gateway g is defined according to the gateway blocking probability as

$$\theta_g = 1 - P_{B_k} \tag{22}$$

Then the metric φ_4 to measure the ratio of available capacity on gateway g to the maximum available capacity of all the gateways is defined as

$$\varphi_4 = \frac{\theta_g}{\max\{\theta_{g_i} | \forall g_i \in G\}} \tag{23}$$

Note that (23) also indicates the percentage of the traffic load carried by the gateway g.

It can be noticed that the metric $\varphi_i (i = 1, 2, 3, 4)$ are cost functions that have been normalized in a range [0, 1], so that these metrics $\varphi_i (i = 1, 2, 3, 4)$ can be combined using a predefined weight w_i ranging from 0 to 1, that is

$$q = \sum_{i=1}^{4} w_i \varphi_i, \quad \text{where} \sum_{i=1}^{4} w_i = 1 \tag{24}$$

In (24), q can be deployed to present the comprehensive performance of the selected gateway. However, since q is the combination of performance metrics $\varphi_i (i = 1, 2, 3, 4)$, the trade-off between these metrics is also important. To quantify the difference between those metrics, a weighted based standard deviation, denoted as δ, is expressed using the following equation:

$$\delta = \sqrt{\sum_{i=1}^{4} w_i (\varphi_i - q)^2} \tag{25}$$

Based on (24) and (25), we define ψ to effectively indicate the performance of the currently selected gateway, that is

$$\psi = q - b\delta \tag{26}$$

where b is a positive constant coefficient.

Now, we can derive the activity κ based on ψ by adopting a sigmoid function and two relevant positive coefficients d_1 and d_2, which are used to control the sensitivity of κ, that is

$$\kappa = \frac{1}{1 + \exp(-d_1 \times \psi + d_2)} \tag{27}$$

D. PROPOSED GATEWAY DISCOVERY AND SELECTION ALGORITHM

We present the procedure of the bio-inspired gateway discovery and selection algorithm incorporating the attractor selection model.

Mobile node discovers available gateways mainly in a proactive way. All gateways broadcast their GWADV packets independently with a synchronized time interval t_1. The GWADV packets are flooded across the network via intermediate mobile nodes. If duplicated GWADV packets from a gateway arrive at a node through different routes, only the first one is accepted and the others are discarded. Upon the GWADV packets from different gateways are received by a mobile node, it is able to build up routes connecting to these gateways. If there is no default gateway in the routing table, the first connected gateway is temporarily specified as the access point to infrastructure-based networks. Clearly, such temporary connection link to the gateway is obviously short in terms of hop count or with small end-to-end delay. Note that connections to all available gateways are presented by the state vector $\mathbf{X}$, which can be used by node to decide which gateway to select. Therefore, the state vector makes node be able to select the optimal gateway in ad hoc networking environment. The gateway discovery procedure is presented in Algorithm 1.

Algorithm 1 Gateway Discovery in a Proactive Way

```
All gateways periodically broadcast GWADV packets;
When node $u$ receives a GWADV packet $p$ sent by gateway $g$:
if($u$ first receives GWADV packet sent by $g$) then
    if($u$ has a route to $g$) then
        update the route to $g$ according to $p$ in $u$'s routing table;
    else
        build route to $g$ according to $p$ in $u$'s routing table;
        initiate the state value $x$ of this route to 0;
    end if
    rebroadcast $p$ to neighbors;
else
    drop $p$;
end if
```

After the gateway discovery is done, source node needs to periodically unicast detection packets at a fixed time interval t_2 to every available gateway, so as to obtain performance feedback parameter κ. This operation is done between two consecutive gateway discovery processes, so that t_2 is required to be smaller than t_1. The detection packet aims to find out the route status from the source node to the corresponding gateway by collecting the statistics reflecting the performance of the connection link. When a gateway receives a detection packet, it unicasts an acknowledgement packet with performance parameters, including h, $S(r)$, $c(r)$ and θ_g, which are the route length in terms of hop count, route robustness, route available capacity and gateway available capacity, respectively. Along the route from the gateway back to the source node, each intermediate node processes the acknowledgement packet by calculating the route robustness $S(r)$ and the route available capacity $c(r)$, as well as updating all parameters contained in the acknowledgement packet before forwarding it to the next hop. When the acknowledgement packet arrives at the mobile node, the parameter κ that indicates the goodness of gateway selection is calculated and updated. Then, the attractor selection model is driven to evolve and update the state values corresponding to all available gateways. Since κ is able to represent the goodness of gateway selection based on the statistics related to the network performance, the source node is able to adjust the gateway selection decision according to the state vector accordingly. For a node, the gateway with maximum state value in the routing table will be selected as a new access point. The details are given in Algorithm 2.

E. ALGORITHM ANALYSIS

The proposed scheme is analyzed in two aspects, including overhead and computation cost. The overhead produced by gateway discovery in conventional scheme is analyzed

Algorithm 2 Gateway Selection Algorithm

```
Each source node unicasts detection packets to all available gateways periodically.
As a response, each gateway calculates $\theta_g$ and return an ack packet ($h = 0$, $S(r) = K\sqrt{p_r/p_t}$, $c(r) = \mu$, $\theta_g$).
When node $u$ receives ack packet $p$ from node $v$:
h ← h + 1;
Calculate $s(l_{uv})$, $c_u$ by (17) and (20), respectively;
Calculate $S(r)$, $c(r)$ by (16) and (19), respectively;
Update parameters $h$, $S(r)$ and $c(r)$ in $p$;
if ($u$ is a source node) then
    if (receive ack packets from all available gateways or waiting time is expired) then
        Calculate $\varphi_1$, $\varphi_2$, $\varphi_3$, $\varphi_4$ by (15), (18), (21) and (23), respectively;
        Calculate $q$, $\delta$, $\psi$ and $\kappa$ by (24), (25), (26) and (27), respectively;
        Implement the attractor selection model described in (12);
        Update state value $x_i$ of each route entry to gateway;
        Select the gateway with max $x_{j(1\leq j\leq N)}$;
        Send register message to new gateway;
    end if
else
    Forward $p$ to next hop;
end if
```

in [33]. Compared with conventional scheme, the proposed scheme needs to unicast detection packet periodically to every available gateway and then it is confirmed by an acknowledgement packet. The number of control overhead caused with this cycle is $2 \times m \times n \times h$, where m, n and h are the number of source nodes, the number of gateways and the average route length from source node to the gateway, respectively. However, the size of unicast packet and acknowledgement packet are usually much smaller than the size of data packets. Thus, such control overheads only consume a limited communication cost and their interference can be negligible. On the other hand, the algorithm proposed in this paper has no loop structure. Hence, the computational complexity is O(1). The main computation cost is due to the calculation of parameter κ and the evolution of attractor selection model. As detailed in the previous section, the calculation of κ requires only basic arithmetic operations. The evolution of the attractor selection model can also be simplified by the basic arithmetic operations [24], [34]. Overall, there is no heavy computing load added to mobile nodes.

V. PERFORMANCE EVALUATION

The simulations with specific networking scenarios are used to evaluate the performance of the proposed scheme. Furthermore, the performance is also compared with other conventional schemes with the same networking scenarios correspondingly.

A. SIMULATION SETUP

To analyze the performance of the proposed gateway selection scheme by comparing it with other schemes, the NS2.33 is adopted and extended to support global connectivity [35]. The performance is evaluated using one square kilometer as the basic coverage unit with 4 gateways located at the central position on the out boundary of the overall networking coverage area to provide access service. The density of mobile nodes is assumed to be homogeneous ranging from 40 to 120 mobile nodes per square kilometer with a negative exponential distribution, which is similar to the simulation settings being used in [11], [12], and [19]–[21]. The transmission range of mobile node is equal to 250m and the mobile mobility is implemented using the Random Way Point (RWP) mobility model [36] with 10 seconds pause time. The radio channel capacity for each mobile node and gateway is 2Mbps, using IEEE 802.11bDCF MAC layer. The free space propagation model, with default parameter settings in NS2.33, is used to predict the received signal strength of each packet. Each mobile node has the potential to produce data traffic according to a given probability. For easy implementation in the simulations, we randomly select some mobile nodes as source nodes every 100 seconds. Each source node randomly decides to generate constant bit rate (CBR) or variable bit rate (VBR) packets with the size of 512 bytes to simulate traffic from applications with different QoS requests, such as loss–and-delay sensitive applications. The packet interval (τ) of CBR is set to 0.2 and the rate of VBR is set to 20kb/s. To fulfill different QoS based requests, the threshold parameter ξ_1 and ξ_2 in (2) are set to 1 and 0.9, respectively. The coefficients a_1 and a_2 are set to 8 and 10, and the parameter r is set to 3. The weights for combing the four performance metrics in (24) are all set to 0.25, based on the consideration that all metrics are equally important in the evaluation of the network performance. The simulation parameters are detailed in TABLE 2.

The performance of the proposed scheme is compared with conventional schemes, including the multiple QoS parameters based gateway discovery and selection schemes proposed in [12] and [21], denoted as MQPP and SLBGE, respectively. For the illustrative purpose, the optimized effect on gateway selection in hybrid ad hoc networking environment using the attractor selection model is evaluated by the following performance metrics:

Packet Delivery Ratio (PDR) is defined as the ratio that the amount of data packets successfully delivered over the number of data packets generated by source nodes.

Average Delivery Latency (ADL) is defined as the average time of data packets from the source to the gateway.

Normalized Routing Overhead (NRO) is defined as the ratio that the number of correctly received packets over the total number of control packets in the network.

TABLE 2. Simulation parameters.

Parameter	Value
Simulation area	1000m*1000m
Transmission range (R)	250m
Simulation time	1000s plus 100s warm up period
Mobility model	Random way point (RWP)
Pause time	10s
Propagation model	Free space propagation model
Number of mobile nodes	40-120
Number of gateway nodes	4
Source nodes	4-12
Channel	2Mbms
Traffic type	CBR,VBR
CBR interval(τ)	0.2
Protocol	AODV+
t_1, t_2	5s, 1s
a_1, a_2, r, μ, σ, K, b, d_1, d_2	8, 10, 3, 0, 1, 1, 0.8, 16, 8
w_1, w_2, w_3, w_4, ξ_1, ξ_2	0.25, 0.25, 0.25, 0.25, 1, 0.9

Balanced Load Index (BLI) [21] is a metric to indicate the degree of load balance between gateways, that is

$$BLI = \sum_{i=1}^{N_{GW}} \left| \frac{GW_i}{GW\_Total} - \frac{1}{N_{GW}} \right| \tag{28}$$

where N_{GW} is the number of gateways in the simulation, GW_i and GW_Totoal are the load supported for the ith gateway and the total load of all gateways, respectively. The value of BLI will be small if all gateways have similar traffic load.

The simulation time is 1000 seconds and a network warming up time of 100s is added in the front of each simulation run. Each scenario is simulated 50 times independently. The numerical results are based on the average of the results obtained from these 50 independent simulation runs.

B. NUMERICAL RESULTS AND ANALYSIS

1) EFFECTS OF THE MOBILE VELOCITY

Firstly, the evaluation focuses on the effect of the node velocity on the performance of the gateway discovery and selection scheme, where the maximum moving speed is selected in a range of 2m/s - 12m/s for a comparison purpose, while the number of mobile nodes and the number of source nodes are set up to 60 and 6, respectively.

Figure 4 shows the evidence that the proposed scheme is able to improve the PDR compared with the other two schemes. For example, when the moving speed is 8 m/s, the PDR of the proposed scheme is 93.3%. In contrast, the PDR of SLBGE and MQPP are 88.3% and 87.7%, respectively. In such case, the PDR of the proposed scheme is almost 112% and 106% comparing that with SLBGE and MQPP, respectively. From the PDR point of view, the attractor selection model in the gateway selection is able to self-organize the dynamic network topology compared with the other two schemes. Likewise, Figure 5 is able to demonstrate that the proposed scheme is able to select more suitable across

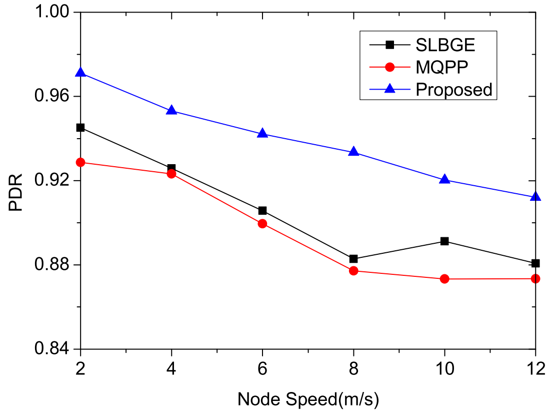


FIGURE 4. PDR vs. node speed.

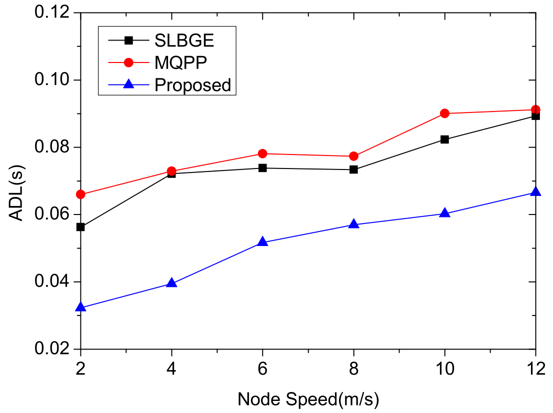


FIGURE 5. ADL vs. node speed.

network routes connecting to the gateway and also able to transmit data packets with lower packet loss rate and delay respectively.

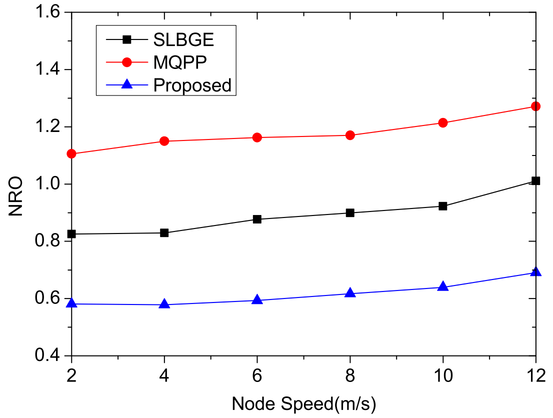


FIGURE 6. NRO vs. node speed.

The proposed scheme will bring some control overhead caused by periodical detection packets. However, as shown in Figure 6, the NRO value of the proposed scheme is still lower than that of the other two schemes. The main reason is that the proposed scheme could achieve a higher PDR value compared with the other two schemes. On the other hand, the attractor selection model could reduce some overhead associated with re-gateway discovery by optimizing the gateway selection.

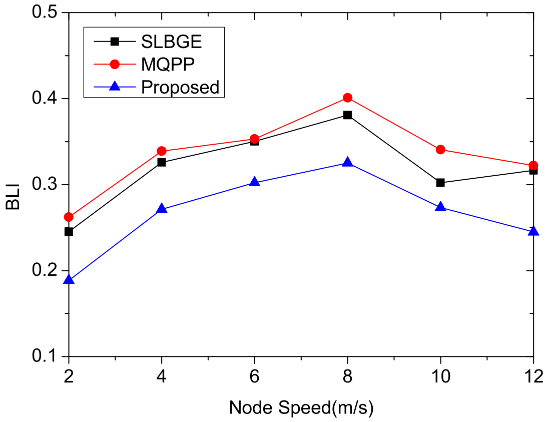


FIGURE 7. BLI vs. node speed.

As shown in Figure 7, the proposed scheme is able to achieve a lower BLI value than the other schemes do. This indicates that the attractor selection model based selection approach is able to achieve a high degree of gateway load balance. The reason is that both of MQPP and SLBGE select gateway only one time in each gateway discovery process. In contrast, the proposed scheme is able to adjust the decision of gateway selection for more than one time based on the status value in each gateway discovery process.

2) EFFECTS OF THE NODE DENSITY

The node density is also an important measurement to demonstrate its effect on the performance of gateway discovery and selection. The following numerical results shown in Figure 8 – Figure 11 illustrate the effect of node density on the performance in terms of PDR, ADL, NRO and BLI for SLBGE, MQPP and the proposed scheme, where the number of mobile nodes is from 40 to 120 per square kilometer while the number of source nodes and maximum speed are fixed at 6 and 6m/s, respectively.

As shown in Figure 8 and Figure 9, the value of PDR increases and the value of ADL decreases for all the three schemes because of a low probability to search the optimal routes to the gateways in the low-density network. Its impact on the network performance is the increase of the delay for data packet transmission and even data packet loss. In contrast, when the node density is high (>70 per square kilometer), the PDR and ADL are slightly influenced by it. However, a comparison of these three schemes shows that the proposed scheme has higher PDR value and lower ADL value than the other two schemes have. The reason is that the essential features of the attractor selection model adopted in the gateway selection scheme are able to provide possibility for the optimal route to the gateway.

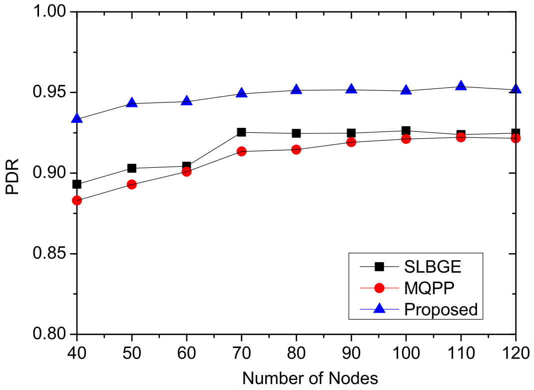


FIGURE 8. PDR vs. number of nodes.

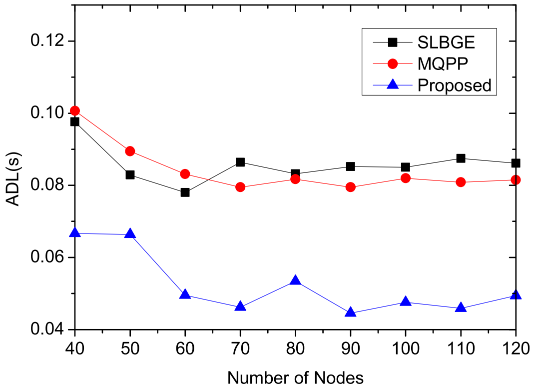


FIGURE 9. ADL vs. number of nodes.

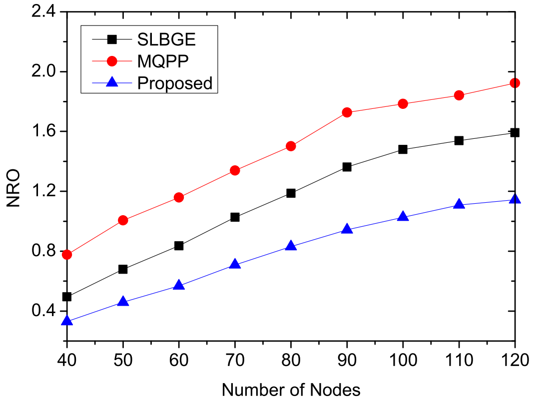


FIGURE 10. NRO vs. number of nodes.

Figure 10 shows that the NRO of the three schemes is obviously sensitive to the node density. It is known that if the GWADV packets are received and forwarded by more inter-nodes, then the control overhead increases. However, a comparison of these three schemes in terms of NRO shows that the proposed scheme generally achieves a good network benefit between control overhead and packet delivery ratio. Therefore, it can be noticed in Figure 10 that the NRO value of the proposed scheme is lower than that of the other two schemes. In contrast, Figure 11 shows that the BLI value of the proposed scheme is smaller than that of the other

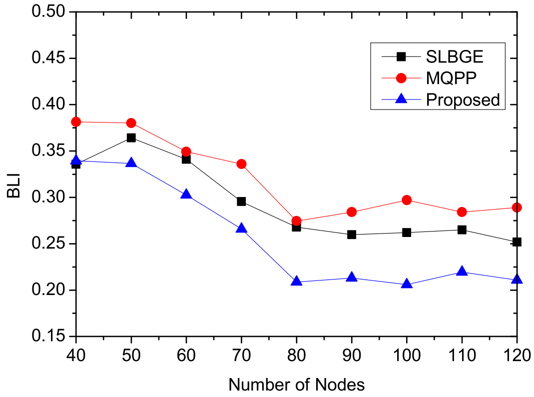


FIGURE 11. **BLI vs. number of nodes.**

two schemes. The reason is that the proposed scheme is able to frequently probe the optimal gateway inspired by the state value updated by the attractor selection model, which is driven by the activity κ. In contrast, the other two schemes are only able to select the gateway once in each gateway discovery process. Hence, the proposed scheme is able to achieve a better load balance.

3) EFFECTS OF THE TRAFFIC LOAD

In general, more source nodes bring more traffic load in the network and thus lead to more network delay and even congestion. The following numerical results shown in Figure 12 – Figure 15 illustrate the effects of the number of source nodes on the network performance in terms of PDR, ADL, NRO and BLI for SLBGE, MQPP and the proposed scheme, where the number of source nodes is from 4 to 12 per square kilometer while the number of mobile nodes and maximum speed are fixed at 60 and 6m/s, respectively.

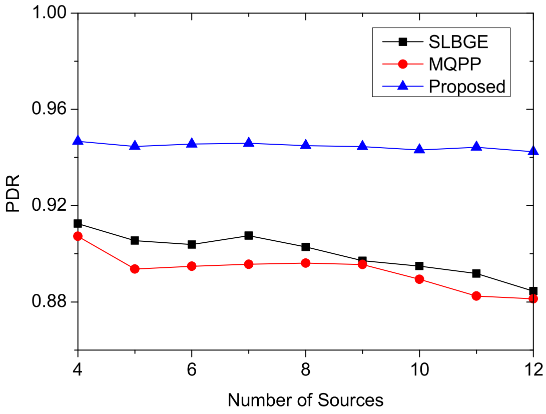


FIGURE 12. **PDR vs. number of sources.**

As shown in Figure 12, the PDR values of all the three schemes are reduced when the network traffic load increases, however, the PDR value of the proposed scheme is higher than that of the other two schemes. The main reason is that the attractor selection model based selection approach is flexible enough with more options of selecting the route to gateway than that of the other two schemes. Thus, the proposed scheme can avoid the routes with congested nodes when selecting gateways. This can also be evidenced by the numerical results shown in Figure 13 since the proposed scheme suffers from a lower ADL than that of the other two schemes. As expected, Figure 14 shows that the NRO values of the three schemes are significantly reduced as the number of sources increases. The main reason is that more data packets are sent by the source nodes and arrive at the destinations.

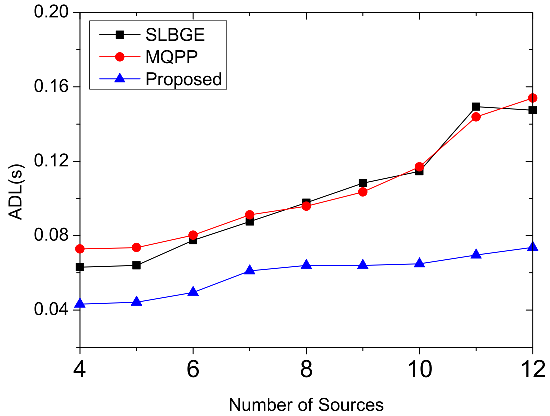


FIGURE 13. **ADL vs. number of sources.**

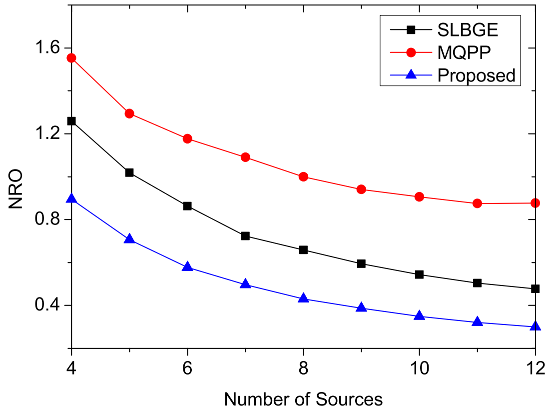


FIGURE 14. **NRO vs. number of sources.**

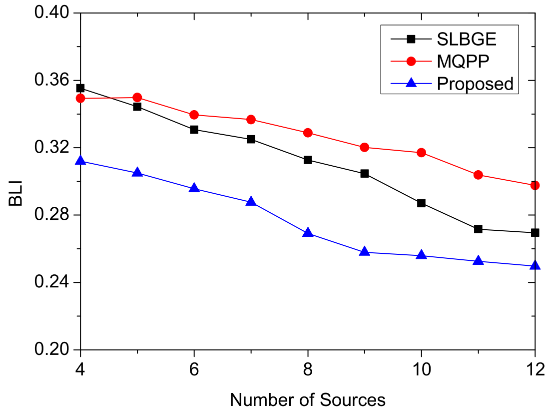


FIGURE 15. **BLI vs. number of sources.**

However, the number of control packets doesn't increase obviously. Therefore, the NRO shows a downward trend. In contrast, the proposed scheme has a lower value of NRO than that of the other two schemes compared with the other two schemes.

In Figure 15, it can be observed that the BLI values of the three schemes decrease as the traffic load increases. However, compared with MQPP and SLBGE, the BLI value of the proposed scheme is lower, which indicates that the proposed scheme is able to achieve a higher level of load balance.

VI. CONCLUSION

This paper discusses the gateway capacity for traffic by designing a mathematical model and presents a bio-inspired gateway selection scheme for hybrid MANETs, which is able to make source nodes dynamically select suitable gateways in a potential cooperative manner, especially in ad hoc network environment, by deploying the attractor selection model. To well reflect the goodness of gateway selection, four performance-related metrics are defined to calculate the activity parameter. The activity parameter drives model to evolve, and thus makes source nodes adaptively select suitable gateways according to the state vector. The proposed scheme is evaluated by numerical simulations. The obtained results show that the proposed scheme is able to improve the network performance in terms of packet delivery ratio, average delivery latency, normalized routing overhead and gateway load balance compared with the conventional schemes.

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