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A Microbial Inspired Routing Protocol for VANETs

Daxin Tian, *Senior Member, IEEE,* Kunxian Zheng, Jianshan Zhou, Xuting Duan, Yunpeng Wang, Zhengguo Sheng, and Qiang Ni, *Senior Member, IEEE*

***Abstract*—We present a bio-inspired unicast routing protocol for vehicular Ad Hoc Networks which uses the cellular attractor selection mechanism to select next hops. The proposed unicast routing protocol based on attractor selecting (URAS) is an opportunistic routing protocol, which is able to change itself adaptively to the complex and dynamic environment by routing feedback packets. We further employ a multi-attribute decision-making strategy, the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), to reduce the number of redundant candidates for next-hop selection, so as to enhance the performance of attractor selection mechanism. Once the routing path is found, URAS maintains the current path or finds another better path adaptively based on the performance of current path, that is, it can self-evolution until the best routing path is found. Our simulation study compares the proposed solution with the state-of-the-art schemes, and shows the robustness and effectiveness of the proposed routing protocol and the significant performance improvement, in terms of packet delivery, end-to-end delay, and congestion, over the conventional method.**

***Index Terms*—Vehicular ad hoc networks, routing protocol, adaptive mechanism, biologically inspired networking, cellular attractor selection.**

I. Introduction

OVER the past few decades, the Intelligent Transportation System (ITS) has been developing rapidly, owing to the rapid development of wireless network technologies and the increasing traffic demand. The Vehicular Ad Hoc Networks (VANETs) has become an emerging research focusing on the communication among vehicles without the extra support of infrastructure [1], [2]. There are many potential applications in the field of VANETs, such as traffic management, collision avoidance, cooperative driving [3], [4]. As one type of Mobile Ad Hoc Networks (MANETs), VANETs have to face many problems not only inherent in MANETs, such as competition, interference, channel weakness but also high vehicular mobility, quick topology changes, limited geographical position and direction of movement. Due to the mobility nature of vehicles, the duration time of communication link between two vehicles is quite short [5]. For example, when the signal radius is 250m and the average speed is 100 km/h, the probability of two vehicles keeping continuous communication for 15 seconds is only 57% [6]. Due to the restrictions of the urban road and the differences in time, development and function of various regions as well as distribution among traffic flows, traditional MANETs routing protocols will not be suitable in VANETs and thus we need seek new mechanisms.

Currently, there already exist many routing protocols for enabling information dissemination in MANETs, such as Dynamic Source Routing (DSR) [7], Ad-Hoc On-Demand Distance Vector (AODV) [8], Greedy Perimeter Stateless Routing (GPSR) [9]–[11]. The nodes in the DSR protocol need to maintain and update their own routing buffer in real time. When the message stored in the routing buffer is available to construct a routing path, the message is forwarded in a hop-by-hop fashion according to the traffic conditions. When there is no feasible routes, the nodes will discover a new route using flooding-like broadcasting mechanism and update the entries of their routing buffer. AODV needs to establish a routing path in advance, and transfers packages over a complete and consecutive routing path, which requires that all the nodes during the transmission should keep connected. If the current path is broken, the routing discovery process will restart, and the data transmission will be paused until a new routing path is found and determined. It is evident that AODV cannot adapt to the frequent and rapid changes of the network topology in VANETs. GPSR uses the vehicular GPS to get the position of other vehicles, and selects the node within the signal radius that is closest to the destination node as the next-hop node, which is called greedy forwarding strategy. In some situations where no node is closer to the destination node than the current forwarding node, GPSR cannot use the greedy forwarding strategy to send the data packets to the next-hop node. To deal with this problem, the current node uses the boundary forwarding strategy to send the data packets. However, this may result in high routing delay and low reliability [12]. Even though these traditional routing protocols can function well in MANETs, they may have poor performance in meeting with the high routing reliability required by VANETs [13].

In this paper, we present a bio-inspired unicast routing protocol for VANETs which adopts the mechanism of cellular attractor selection to select the most suitable next hop. We use Cellular Attractor Selecting Model (CASM) because CASM can achieve better performance in the fields of self-adaption and robustness when it is compared to the traditional methods [14]. As a new bio-inspired model, CASM has been successfully applied in many fields. For example, the adaptive vehicular epidemic routing method [15], the network selection method for multimode communications in heterogeneous vehicular telematics [16], the adaptive signal control for traffic networks [17] etc. CASM also offers a new choice for future

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D. Tian K. Zheng, J. Zhou, X. Duan and Y. Wang are with Beijing Advanced Innovation Center for Big Data and Brain Computing, School of Transportation Science and Engineering, Beihang University, Beijing 100191, China (e-mail: 231665217@qq.com).

Z. Sheng is with Department of Engineering and Design, the University of Sussex, Richmond 3A09, UK.

Q. Ni is with School of Computing and Communications, Lancaster University, Lancaster LA1 4WA, UK.

mobile network management [18]. CASM has been proved effective for designing a self-adaptive decision-making strategy [19]. Because of the frequent changes in VANETs topology, ineffective routing process will lead to higher latency and lower arrival rates. Traditional routing protocols cannot correct this automatically, while CASM can adapt itself to changes in VANETs and fix the wrong routing process autonomously in real time. CASM determines the next-hop node based on the routing activity information brought by the feedback data from the destination node to the source. If the routing activity is monitored at a lower level, which means the current routing path is not adaptable to the network environment, CASM will search for another path randomly until the current routing activity rises to a sufficiently high level. As shown in some existing works such as [15]–[19], the attractor selection model provides a self-adaptive and robust approach to boost the system performance in fluctuating environments. Our protocol, URAS, uses vehicular GPS to get the position and speed of destination and neighbor node, and uses this information to assist selecting the next-hop nodes. In order to narrow the range of choice and let URAS achieve the best condition, current forwarding node sorts neighboring nodes that are closer to the destination node than current forwarding node by TOPSIS, and selects the next-hop node from the top few nodes. When there is no suitable neighboring node, the data packet will be stored in the current forwarding node buffer and forwarded to next node until a suitable node appears.

The rest of this paper is organized as follows: Section II discusses a number of approaches and protocols which are related to our research. Section III describes in detail the components of UARS, and follows it with Section IV discussing the results of the comparison of simulated models of URAS with other routing protocols: GPSR and pre-URAS. Finally, we conclude in Section V.

II. Related Work

The main ingredient of URAS is a biological mechanism describing an adaptive behavior of a E.coli's gene network in a varying environment, which is discovered by Kashiwagi *et al* [14]. Such a bio-inspired mechanism is termed the adaptive attractor selection, in which different adaptive attractors and the cellular activity indicate different stable cellular states and the cellular adaptation to the external environment, respectively. The dynamics can be described by a group of differential equations, i.e., the cellular attractor selection model (CASM):

$$\begin{cases} \frac{dm_1}{dt} = \frac{S(A)}{1+m_2^2} - D(A) \times m_1 + \eta_1 \\ \frac{dm_2}{dt} = \frac{S(A)}{1+m_1^2} - D(A) \times m_2 + \eta_2 \end{cases} \tag{1}$$

where m_1 and m_2 are two different mRNAs or the protein concentration of two mutual inhibited manipulation genes. A is the cellular activity, and its variation influences the process of mRNAs or protein products' synthesis and degradation. η_1 and η_2 are independent white noise terms. When the activity A of the cells is reduced, the metabolism of the cells becomes unstable and susceptible to environmental disturbances, resulting in a change in the cell state, which inspires the addition of random interference to the model, allows the model to reasonably reflect the cellular state adaptation process. In the model, if the environmental changes make cell activity A lower, the cell state is affected by the random term, switching between the two attractors. When an attractor increases the activity, the cell state tends to stable, in order to adapt to the new environment. The ad hoc network is a distributed network composed of network nodes. Each node is both a source node and a routing node. Each node in the route is faced with a complex network environment. If the data transmission process can simulate the cellular adaptation process to the environment, such as load balancing, network congestion, quality of service and other issues can be further optimized.

In general, vehicular communication terminals and E. coli cells have a strong similarity. There are three points as follows: First of all, both natural and network environment are complex and changeable. Secondly, both terminals and cells need to always maintain a strong adaptability to the environment. The most important thing is that both of them improve performance by selecting from several scenarios, in which the selection of cells is selective for the gene, and the selection of terminals is the choice for the next hop node. In view of the similarity between cells and terminals, and the strong adaptability of cells in the dynamic environment, the idea is obtained that uses the mechanism of cell adaptive gene selection expression to optimize the selection of next node in multi-hop routing.

In the previous work [16], the authors have extended the basic attractor selection model to the high-dimension decision-making space. According to [16], given the probabilities that the current forwarding node i's candidate nodes are selected as next-hop node, a vector $M_i = [m_1, m_2, \ldots, m_n]$, where m_n is the probability of node n in the set of candidate nodes and $m_{\max}$ is the maximum probability in vector M_i, the extended attractor selection model (EASM) is given as follows:

$$\frac{dm_n}{dt} = \frac{s(\alpha)}{1 + (m_{\max} - m_n)^2} - d(\alpha)m_n + \eta_n \tag{2}$$

where α is the activity that indicates the adaptation to the VANETs of current routing path. The formulas of $s(\alpha)$ and $d(\alpha)$ can be expressed as follows:

$$\begin{cases} s(\alpha) = a\alpha^c + b\alpha \\ d(\alpha) = \alpha \end{cases} \tag{3}$$

where a, b, and c are application-related constants.

In [15], the EASM has been applied to design an adaive and robust epidemic-based routing protocol. According to the previous study, when the activity α is at a low-level, implying that current routing path does not adapt to the current network environment, the selection probabilities of candidate nodes fluctuate in the same magnitude. This means that a current forwarding node selects a next-hop node randomly. With the activity α increases, just only one of the candidate nodes' selection probability increases rapidly to a high level, at the same time, others down to a low level. This implies that the behavior of current forwarding node switches from a random state to a stable state, i.e., a stable attractor in the phase space. The system state is characterized by the degree of activity, which means the better the system state is, the higher the activity is. In other words, the "goodness" of current state can be mapped to the activity. If the system state is not good enough, the activity will be low, which results in a poor stability of current attractor. Then the system will switch among several attractors until it finds the best state with high activity. In a dynamic environment, the EASM can seek the most adaptable state by adaption, which induces the system to remain a optimal state and improves the system robustness.

Based on the EASM, the authors have designed a basic unicast routing protocol for VANETs (named pre-URAS hereafter) in [20]. In pre-URAS, the activity α is used to represent the adaptability to VANETs of current routing, and it controls the next hop selection of the forwarder and induces the forwarder to adapt to the changing network environment. The system constructs an effective routing path by repeating the process of selecting next-hop node based on the EASM. Then a new activity α that is calculated by the destination node and propagated backward to the source, during which all activities of nodes along the routing path are updated with the new one. Hence the intermediate nodes along the path can update their next-hop selection depending on the updated activity. If the activity α is low, the routing path constructed is not adaptive to the current vehicular network environment. The forwarding nodes are then driven by the EASM to seek for a more suitable next-hop node, such that an optimal routing path is established again.

It is pointed in [20] that a part of neighboring nodes of a forwarder that are farther away from the destination than this forwarder should be excluded, such that the other neighbors are treated as candidates. However, the filtering mechanism in [20] has not considered some potential problems, such as routing congestion [21], diverse requirements imposed by different applications. In addition, pre-URAS cannot accommodate the sensitivity of the activity α in a dynamical environment. In this paper, we formulate a utility function to capture the time-varying activity α according to real-time routing conditions. Furthermore, with this utility function we propose a new vehicular unicast routing method also based on the biologically inspired attractor selection mechanism, termed URAS, and a decision-making strategy with TOPSIS for adaptive construction of the next-hop candidate set. The bio-inspired routing protocol is then enhanced by combination of the cellular attractor selection mechanism with the multi-attribute decision-making strategy. We also compare the performance of the proposed URAS in this work and that of pre-URAS in a more realistic traffic environment, which confirms a significant performance improvement of our method here.

III. Unicast Routing Protocol Based on Attractor Selection (URAS)

A. Protocol overview

URAS is a bio-inspired unicast routing protocol for VANETs which makes the next-hop selection based on the attractor selection mechanism. The main process of URAS is outlined as follows:

- When a routing to the destination node d is required, but not known at source node s, s triggers a routing request, constructs a next-hop candidate set with TOPSIS and then forwards the message to a forwarder selected from the candidate set by the attractor selection mechanism.
- Any intermediate forwarder also behaves in the similar way that the source makes a next-hop selection decision and forwards the message to the selected next hop, so as to establish a multi-hop routing path to the destination node.
- When d receives the message, it calculates the routing activity α and perform a backward forwarding, i.e., sending α backward along the routing path, in order to update the activity of each node along this path.
- When a current forwarding node cannot find a suitable next hop, it will store the message in its buffer and keep moving until meets a suitable node.

B. Data structures

The data structure (1) and (2) below are the header of forward data structure and backward data structure, respectively; the data structure (3) below is maintained at each node, and is updated every time when a backward data packet arrives at this node.

(1) *Forward data structure*: The following information is carried by a forward data packet A:

- The message ID of the forward data packet, which is the pair: (source node ID, destination node ID).
- The number of nodes, m, which A has visited, including the node A originated from.
- The nodes-visited-stack, π_A, containing information about nodes $V = \{v_1, v_2, \ldots, v_m\}$, such as the ID of nodes, the congestion and so on, and that can be reached by backtracking the A's movement (using the nodes-visited-stack).
- The latency information on a routing from the source node to the current forwarder.

(2) *Backward data structure*: The following information is carried by a backward data packets B:

- The message ID of the backward data packet, which is the pair (destination node ID, source node ID).
- The routing activity α_0 that is calculated by the destination node. This routing activity should decay over time to reflect the time-dependent negative effect on the routing performance. That is, after t seconds, the routing activity α_0 reduces to α_t, which is calculated as following:

$$\alpha_t = \frac{\alpha_0}{2^{\frac{t}{x}}} \tag{4}$$

where x is a constant. The routing activity α is a new concept that is established by imitating the activity A of the cellular attractor selection model. The activity α symbolizes the adaptability of the current path to the current network topology environment and can be used as the basis for the state selection of the attractor selection model. The network topology of the vehicular ad hoc network is constantly changing, and the backward data packet takes some time to completely update the activity α of nodes along the current routing path, which will inevitably lead to the information lag, resulting in node selection optimization be poor. For example, if the current route is highly active, it means that the current path is more suitable for the current network environment, but with the passage of time, this path perhaps no longer adapt to the current environment. If the degree of activity is not attenuated, then the next data package is also likely to be transmitted along this poorly performing path. To solve this problem, we propose to keep the activity α decay in accordance with the formula (4) with time.

- The backtracking-stack, which is obtained from the node's ID sequence of nodes-visited-stack. The backward data packet can be used to update the activity of each node in the inversive routing path.

(3) *Routing decision table at node i, ξ_i*: A routing decision table is a data structure that stores different source-destination pairs' routing activity α_i, which also decays over time as given in the formula (4), and the respective probabilities of candidate nodes that they will be selected as a next hop, $M_i = [m_1, m_2, \ldots, m_n]$ where n is the number of the candidate nodes of i.

C. Protocol description

The framework of our routing protocol, URAS, is mainly composed of two mechanisms, one of which is a multi-attribute decision-making strategy and the other is a CASM-based next-hop selection mechanism.

1) Construction of candidate set: To construct an optimal candidate set for a forwarder, we develop a multi-attribute decision-making strategy based on a Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [22]. Then, this proposed strategy is employed to rank all the neighboring nodes of a forwarder, among which the top five nodes are chosen as potential next hops, i.e., constructing a set of candidate set. Given the neighbor set of a forwarder i, N_i, we further denote its candidate set by C_i, i.e., $C_i \subset N_i$. We consider four attributes associated with each neighboring node, including 1) the projection of the relative speed of node i and its neighboring node j on the communication direction from node j to i, v_{ji}, 2) the projection of the relative speed of node j and the destination node d on the direction from j to d, v_{jd}, 3) the distance between node j and node d, $dist_{jd}$, 4) the congestion degree of data buffer of node j, $cong_j$. Specifically, v_{ji} can be used to reflect the stability of the communication link between j and i, i.e., a larger v_{ji} indicating that node j moves faster towards i, such that more stable link can be maintained by the two nodes. v_{jd} and $dist_{jd}$ can quantify the potential of node j to forward the message to the destination d. A higher v_{jd} or a smaller $dist_{jd}$ implies that the message could be delivered to the destination by node j with a shorter delay. $cong_j$ is used to measure the occupancy of data buffer of node j. A larger $cong_j$ indicates a larger queue consisting of more data packages waiting to be processed, which means that it will take more time to schedule the message transferred from i.

- *Construction of an attribute matrix*: considering n alternatives (neighboring nodes, $\{j : j \in N_i\}$, of i) and 4 types of evaluation attributes $\left\{v_{ji}, v_{jd}, dist_{jd}, cong_j\right\}$, we can yield a matrix consisting of the intersection of each neighboring node and an attribute as given in Table I where $(dist_{jd})_{\max} = \max_{j\in N_i}\{dist_{jd}\}$ and $\left(cong_{jd}\right)_{\max} = \max_{j\in N_i}\left\{cong_j\right\}$:

TABLE I
ATTRIBUTE MATRIX.

$j \in N_i$	Attributes			
	v_{ji}(m/s)	v_{jd}(m/s)	$dist_{jd}$(m)	$cong_j$
1	v_{1i}	v_{1d}	$(dist_{jd})_{\max} - dist_{1d}$	$(cong_j)_{\max} - cong_1$
2	v_{2i}	v_{2d}	$(dist_{jd})_{\max} - dist_{2d}$	$(cong_j)_{\max} - cong_2$
...	...	...	...	...
n	v_{ni}	v_{nd}	$(dist_{jd})_{\max} - dist_{nd}$	$(cong_j)_{\max} - cong_n$

- *Normalization of the attribute matrix*: In order to eliminate the impact of measurement units of indexes, we normalize the measured value of each attribute. Let $x_{j,l}$ be an element of the intersection (j, l) in Table I ($j = 1, 2, \ldots, n; l = 1, \ldots, 4$). We can normalize it by:

$$x'_{j,l} = \frac{x_{j,l}}{\sqrt{\sum_{j=1}^{n} x_{j,l}^2}}. \tag{5}$$

Furthermore, we weigh the effect of different attributes on the routing performance with different factors $\left\{w_l, w_l > 0, \sum_{l=1}^{4} w_l = 1\right\}$. That is, we derive a weighed value, $x''_{j,l}$, associated with $x'_{j,l}$:

$$x''_{j,l} = w_l \cdot x'_{j,l}. \tag{6}$$

- *Derivation of the ideal best and the ideal worst solutions*: Let the best solution be $\boldsymbol{X}^+$ and the worst $\boldsymbol{X}^-$. These two ideal solutions can be established as follows

$$\begin{cases} \boldsymbol{X}^+ = \left\{\max_{j\in N_i}\left\{x''_{j,l}\right\}, l = 1, 2, \ldots, 4\right\}; \\ \boldsymbol{X}^- = \left\{\min_{j\in N_i}\left\{x''_{j,l}\right\}, l = 1, 2, \ldots, 4\right\}. \end{cases} \tag{7}$$

- *Calculation of difference between each alternative and an ideal solution*: We derive the Euclidean distance between each alternative $\boldsymbol{X}_j = \left\{x''_{j,l}, l = 1, 2, \ldots, 4\right\}$ and the best solution $\boldsymbol{X}^+$, and that between $\boldsymbol{X}_j$ and $\boldsymbol{X}^-$ by

$$\begin{cases} Score_j^+ = \sqrt{\sum_{x''_{j,l}\in \boldsymbol{X}_j, x^*_{j,l}\in \boldsymbol{X}^+} \left(x''_{j,l} - x^*_{j,l}\right)^2}; \\ Score_j^- = \sqrt{\sum_{x''_{j,l}\in \boldsymbol{X}_j, x^*_{j,l}\in \boldsymbol{X}^-} \left(x''_{j,l} - x^*_{j,l}\right)^2} \end{cases} \tag{8}$$

for $j = 1, \ldots, n$. According to (8), we can further rank each node j with the score

$$Score_j = \frac{Score_j^-}{Score_j^- + Score_j^+}. \tag{9}$$

Thus, we choose the top five neighboring nodes as candidates to be selected as a next hop, i.e.,

$$C_i = \left\{j_k : Score_{j_k} \geq Score_{j_{k+1}}, k = 1, 2, \ldots, 5\right\} \tag{10}$$

Note that if C_i is an empty set, then let $C_i = N_i$. After construction of C_i, we propose a next-hop decision-making mechanism based the cellular attractor selection for the forwarder i to select an appropriate next hop from C_i. Our bio-inspired mechanism is detailed in the next subsection.

2) Stochastic optimization for a next-hop selection: To introduce the attractor selection mechanism into the next-hop selection decision, a forwarder calculates the probability of its each candidate node that is selected as the next-hop node and updates the probability vector by using the EASM (2) and (3). The forwarder can then select the node with the highest probability when a forwarding is requested. We further point out that due to the node i mobility, C_i will changes all the time. Thus, we update the selection probability m_j for $j \in C_i$ in different situations:

(1) The current forwarder is one of the nodes in the previous routing path, and its candidate node set is unchanged: the probability of a candidate j to be selected from C_i is updated by a discrete form of the EASM:

$$m_j = m_j + \left(\frac{s(\alpha)}{1 + (m_{\max} - m_j)^2} - d(\alpha) m_j + \eta_j \right) \times \Delta t \tag{11}$$

for $j = 1, 2, \ldots, n$ where Δt is an time interval. With the updated m_j, $j \in C_i$, we can choose a candidate, j^*, with the maximum selection probability, as a next hop of the forwarder i:

$$j^* = \underset{j \in C_i}{\operatorname{argmax}} \{m_j\}. \tag{12}$$

(2) The current forwarding node is one of the nodes in the previous routing path, and its candidate node set has changed: Let the updated candidate set be C_i'. The selection probability of a candidate j that remains in i's candidate set, i.e., $j \in C_i'$ and $j \in C_i$, is determined by

$$m_j = \frac{m_j}{\sum_{k \in C_i \bigcap C_i'} m_k} \times \frac{|C_i \bigcap C_i'|}{|C_i'|}, \tag{13}$$

and the selection probability of any new candidate, $j' \in C_i'$ and $j' \notin C_i$, is calculated by:

$$m_{j'} = \frac{1}{|C_i'|}. \tag{14}$$

(3) The current forwarding node is not the node of the previous routing path:

Since current node does not participate in the previous routing, we cannot speculate the influence of the connection between the current forwarding node and candidate node to the current routing. In order to avoid serious error, we assume all the probabilities of candidate nodes that are selected as next-hop node as same, and the formula is same as equation (14).

(4) The destination node in neighboring node set:

The current forwarding node directly forwards the message to the destination node, but does not record the probability of the destination node, that is the destination node is out of the random selection. In order to counteract the influence of the destination node on the probabilities that other neighbor nodes are selected as the next-hop node in next routing, let the probabilities of all other neighbor nodes except the destination node is:

$$m_j = \frac{1}{N_{all} - 1} \tag{15}$$

After the new probability vector is obtained, in addition to select next-hop node from it, URAS uses it to update the previous computed probability vector that stored in the packet decision table of node i.

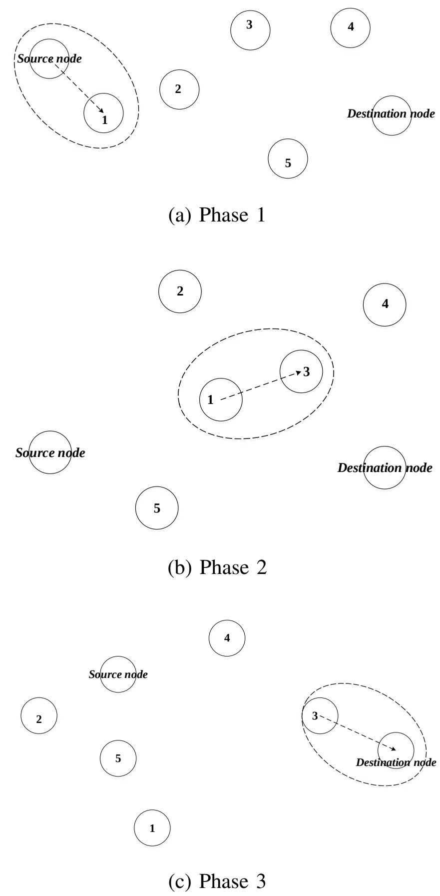


Fig. 1. A 3-phase illustration of an opportunistic forwarding example.

3) Opportunistic message delivery: URAS is not only a bio-inspired routing protocol but also an opportunistic routing protocol that almost does not rely on a complete routing path to forward message, which, is especially adapt to VANETs that is difficult to maintain a complete link for a long time because of the rapid changing of network topology. Traditional routing protocols need to establish a complete routing path of the source node and destination node, such as AODV and DSR, which, is not adapt to VANETs well. As an opportunistic routing protocol, URAS directly forwards the message when the communication requirement is put forward, which without the need to establish and maintain a smooth link all the time. When the current forwarding node does not have neighboring nodes to forward message, the message will be cached on the current forwarding node until meets a suitable node, which, is be called opportunistic message delivery. The specific process is as follows:

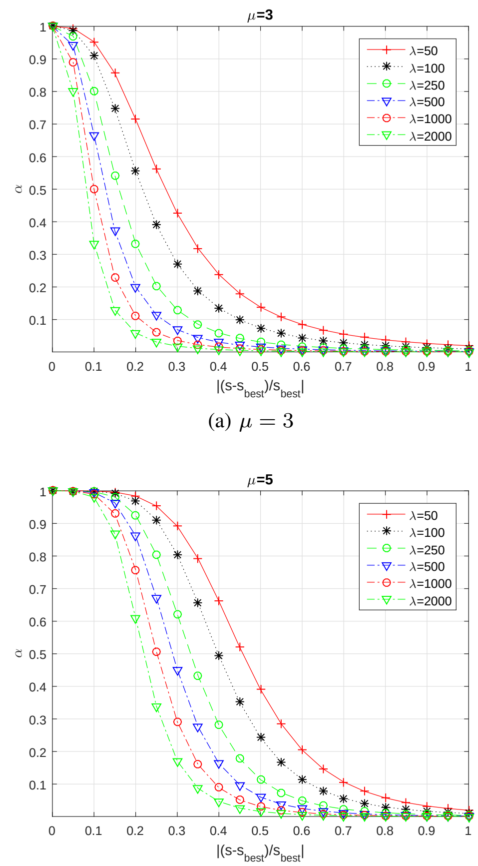
Fig.1 shows the basic process of opportunistic message delivery. First, node 1 is selected as next-hop node and receives message from source node when the routing starts. Then node 1 cannot find a suitable node to forward the message, so it will store the message and keep moving until meets the suitable node 3 which receives the message from node 1 and repeats the action of node 1. Finally, node 3 meets the destination node, and the message is forwarded to the destination node directly. This routing is over.

Unlike traditional routing protocols that treat the mobility of node as a threat or malformed state, URAS treats it as a normal state and uses the mobility of node to help forward message. Opportunistic routing is obviously better than traditional routing both in terms of reliability and delay. Because vehicles have high speed, so the link between two vehicles does not stay for a long time, traditional routing protocols often face the disruption caused by the link break, and then re-start the route discovery process, which would undoubtedly waste a lot of time leading to higher delay and poorer reliability. GPSR is a MANETs opportunistic routing protocol like URAS that we proposed in this paper, and it has been widely studied, with excellent comparative value, so in this paper we also compare the performance of URAS and GPSR.

4) Activity calculation: After the forward data packet arrives at the destination node, URAS calculates the activity α that represents the adaptation to the network environment of current routing by the information is carried in the forward data packet, then stores activity α in the backward data packet, which, updates the activity α of the nodes along the current path. The activity α is calculated as follows:

$$\alpha = \frac{\gamma}{\lambda \left| \frac{s - s_{best}}{s_{best}} \right|^{\mu} + \beta} \tag{16}$$

where s represents the state of the current routing path; s_{best} represents the best state of all previous paths. $\gamma, \lambda, \mu, \beta$ are positive constant. γ, β are used to determine the boundaries of activity α, λ, μ are used to control the change rate of activity α. We assume that $\gamma = \beta = 1$, so $\alpha \in [0, 1]$. It can be find that the activity α is proportional to the state of the routing path that between the source and destination nodes. The worse the current routing path, the smaller the activity α, and vice versa, that is the bigger the deviation of s from s_{best}, the smaller the α. Different parameter of the equation (16) leads to curves with different characteristics, it is necessary to determine the most appropriate parameter. By setting $\mu = 3, 5$ with different λ, simulation results can be obtained as follow:



(a) $\mu = 3$

(b) $\mu = 5$

Fig. 2. Impact of μ on the activity α.

From Fig.2 we can find that both increasing μ and decreasing λ are conducive to improve the range of high activity α, which, increases the existence time of the current path. In equation (16), the formula of s as follows:

$$s = \tau^{e} \psi^{g} \tag{17}$$

where τ is routing delay, ψ is the average congestion of the current routing path, and e, g are the weight of τ, ψ respectively. In order to exclude the influence of the number of nodes to the path congestion, ψ is calculated as follows:

$$\psi = \frac{\sum_{h=1}^{p} cong_h}{p} \tag{18}$$

where $cong_h$ is the congestion of the h-th node in the previous routing path, and total node number of this routing path is p. Here, the concept of congestion is explained. First, each node on the network has a cache of receiving messages, and the transmission processing is based on the principle of first come, first-round. The node may suspend forwarding packets because the next hop node is not suitable, so the concept of congestion is introduced to describe the number of packets of the next hop node before a packet reaching, that is, the degree of congestion. The greater the congestion, the longer the packet waiting in line, the more likely to miss the appropriate forwarding time, so current node should try to consider the small congestion node while choosing the next hop.

D. Routing procedure

Lets take a routing at an intersection as an example to demonstrate the URAS routing process, the schematic diagram is as follows:

In Fig.3, all nodes in the network have same coverage and transmission ability, the source node sends a message to the destination node in this example.

(1) When the source node (current forwarding node) has a data packet to send, first checks the destination node ID of the data packet, if the destination node is one of the node 1, 5, 6, the packet is sent directly to the destination node.

(2) If the destination node of the packet is not the neighboring node of the current node, current forwarding node uses TOPSIS determine node 1, 5 as candidate node.

(3) According to the case 3 in the random optimization, the probability of node 1, 5 is 0.5 respectively, then both the candidate node ID and the probability of being selected as the

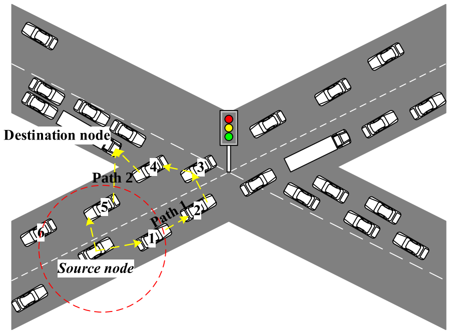


Fig. 3. An exemplary routing scenario.

next-hop node are recorded in the current forwarding nodes packet decision table. The congestion of the current node is stored in the forward data structure.

(4) Because of the probability of 1, 5 is same, so the current forwarding node randomly selects one of the nodes as the next-hop node, we assume that node 1 as the next-hop node.

(5) At the next time step, return to the first step until the packet is sent to the destination node. Finally, the path 1 is established:

$$\text{Source node} \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow \text{Destination node}$$

(6) At the destination node, the activity α is calculated according to equation (16). Then destination node sends a backward data packet to update the activity of nodes 1, 2, 3, 4 along the previous path (path 1). It is worth noting that the activity α both carried in the backward data packet and node are attenuated with the time that since the last update according to Equation (4).

(7) When the time has passed T_{wait} since the source node last sent the data packet, or source node receives backward data packet from destination node within T_{wait}, the source node starts the next routing until all data packets are forwarded.

(8) The second routing gets path 2:

$$\text{Source node} \rightarrow 5 \rightarrow \text{Destination node}$$

We can find that the path 2 is better than path 1, both path 2's number of hop and routing delay are smaller than path 1. The above process will continue, the path that is found at each routing is better than the previous, and ultimately stabilize at the optimal path, of course, this stable path would not last a long time in a rapidly changing network.

IV. Simulation Results

URAS is simulated in Matrix Laboratory (MATLAB), and the performance of URAS is compared with another famous MANETs routing protocol, GPSR, and pre-URAS that we present in our earlier work, with the same VANETs network environment that provided by Simulation of Urban Mobility (SUMO) and load characteristics. This paper chooses GPSR to compare with our proposed routing protocol URAS, because the superior performance of this routing protocol in MANETs is recognized, and it also can be applied to VANETs. Our work here is an extension of our earlier work [20], which only compares the performance of pre-URAS with GPSR in a simple random mobile node environment that just has one pair of source node and destination node. In order to prove that our strengthening of the routing mechanism is effective, we also need to compare URAS that is proposed in this paper with pre-URAS.

A. Simulation and network model

1) URAS parameters: The parameters of equation (3) has been discussed in [16], in order to ensure equation (2) has stable attractor states, we use $a = 8, b = 10, c = 4$.

The value of λ, μ in equation (16) affects the survival probability of the current path by controlling the change rate of activity α, which, shown as Fig.2. Increasing μ or decreasing λ is conducive to expand the range of high activity α, which increases the survival probability of the current routing path, in other words, it improves the tolerance of the routing system to the badness of the current routing path. On the contrary, if the tolerance too low, the routing path would be too unstable. Ideally, when the deviation of the current situation and the best case is small, the changing of activity is small and gentle, once the deviation becomes large, the activity can be rapidly reduced. Through the simulation of Fig.2, we use $\lambda = 100, \mu = 5$.

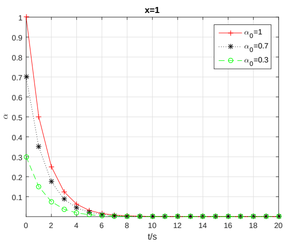
The value of x in equation (4) affects the sensitivity of the system to the change of external network environment. It can be found from Fig.4 that the decay speed of activity α is decreased with the increasing of x, which would reduce the sensitivity to the rapidly changing VANETs, but too rapid decay would make the attractor selection mechanism cannot take advantage of the information of previous routing. In different traffic conditions, the decay speed also should be different, the solution is that let x change according to the local average speed and road complexity. For simplicity, we use x=20.

The parameters e, g of equation (17) represent the weight of latency and average congestion in routing path state s respectively. In order to pursue the overall optimal performance, we use $e = g = 1$.

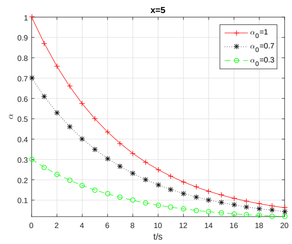
2) Network environment parameters: We study the performances of URAS, GPSR, and pre-URAS with different signal transmission radius in a SUMO traffic scenario that is shown as Fig.5. We use twelve pairs of source nodes and destination nodes forward messages together within the whole simulation period.

The above scenario is a small-scale scenario based on the city of Bologna [23], and its traffic flow is obtained from the statistical data of local real traffic flow. The congestion of each vehicle is equivalent to the number of its data packets that need to be forwarded. Because each vehicle only forwards one packet at each time step, if a data packet arrives at a high congestion vehicle, the longer time it would be forwarded, it may even miss its destination node, which results in packet loss.

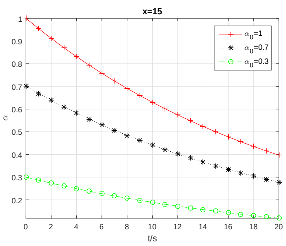
We need to compare the routing delay, overall congestion, and arrival rate of URAS, GPSR and pre-URAS:



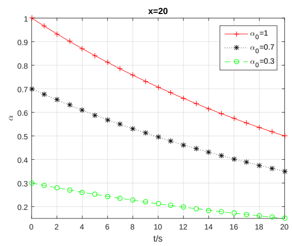
(a) $x = 1$



(b) $x = 5$



(c) $x = 15$



(d) $x = 20$

Fig. 4. Subfigures (a)–(d) show the impact of different x on the activity α.

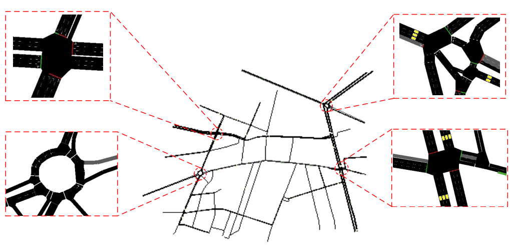


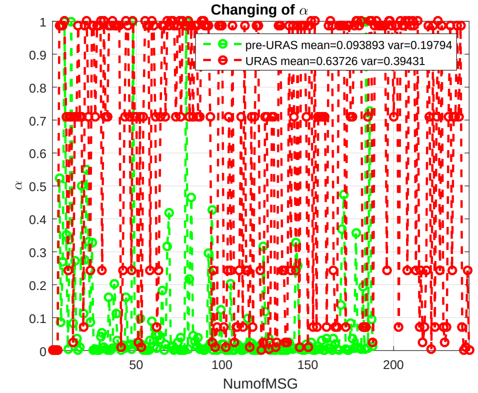
Fig. 5. The traffic scenario of SUMO.

- *Routing delay*: measured as the average time that the data packet is sent to the destination node from the source node and averaged over the number of source-destination pairs.
- *Overall congestion*: measured as the average ψ throughout the simulation period and averaged over the number of source-destination pairs.
- *Arrival rate*: measured as the ratio of the packets arriving at the destination node to the packets sent by the source node within the whole simulation period.

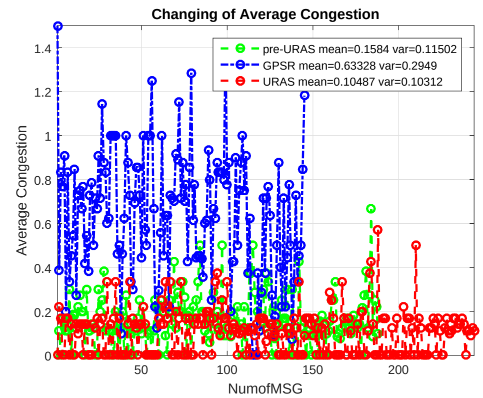
We obtained measured results with 95% confidence intervals, which are plotted and analyzed in the next section.

B. Simulation results

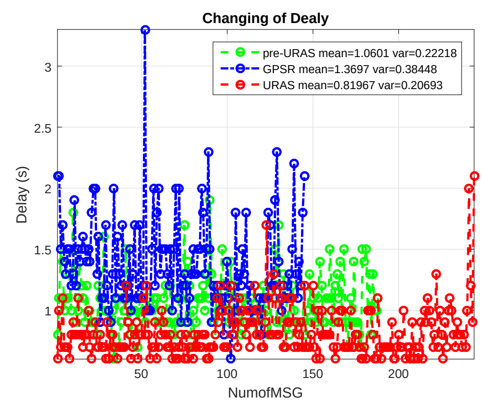
Fig.6 shows some performance projects of each data packet that be forwarded in one of the source-destination pairs of URAS, pre-URAS, and GPSR in the SUMO scenario of an Italian city Acosta with real local traffic flow data and 280 meters of signal transmission radius. Fig.7 shows the approximate position of the source-destination pair selected, about 1400m away. It can be seen from Fig.7 that the route between this source-destination pair is complicated, and the traffic volume is affected by the distribution of the road network. We can find that the performance of URAS is better than pre-URAS and GPSR in the simulation in terms of arrival rate, overall congestion and delay. URAS can improve



(a) Activity change of pre-URAS and URAS.



(b) Congestion change of pre-URAS, GPSR and URAS.



(c) Delay change of pre-URAS, GPSR and URAS.

Fig. 6. Performance change of pre-URAS, GPSR and URAS.

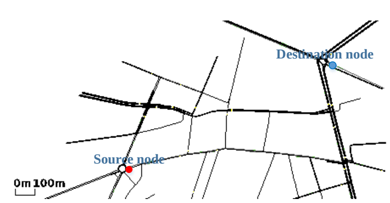
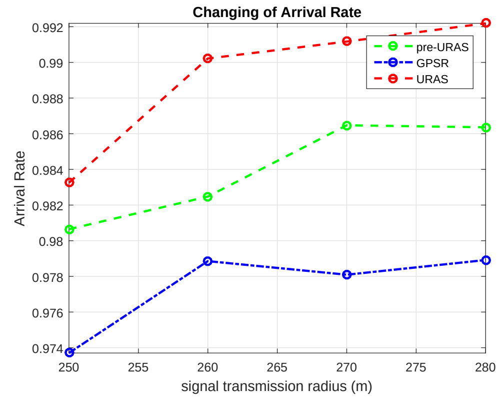


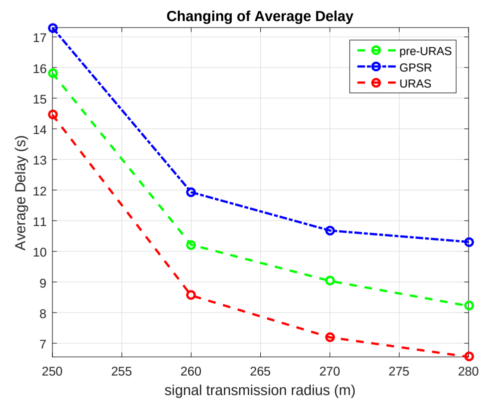
Fig. 7. The position of the source-destination pair.

the performance of next routing according the index such as routing delay by EASM. With the moving of vehicles, the topology of VANETs keeps changing, which leads to the result that the current routing path may not be the optimal path to the current environment. And because the activity α is calculated by the comparison of the state of current routing path and previous optimal path, the above problem may not be found in time. The solution is introducing a random term, so even if the activity α is high, the current forwarding node still has a certain randomness when selects the next-hop node. However, such a searching is random, so there is no way to ensure that the path is better than previous path. Fig.2 shows that in the experimental parameters under the conditions of λ= 100, μ= 5, the description parameters of the current state s and the best of the past s_{best}, the relative deviation of 0.6, the activity is reduced to 0.1, which indicating that the parameters selected during the simulation cause the attractor selection mechanism to be sensitive to changes in the performance of the routing path. Take an example, if τ_1=0.5, ψ_1=0.4, then s_1=0.2, if τ_2=0.6, ψ_2=0.5, then s_2=0.3, so s_{best}=0.2, relative deviation$\left|\frac{s_2-s_{best}}{s_{best}}\right|$=0.5, as shown in Fig.2, the activity α is immediately reduced to 0.25. Therefore, although there is little difference, a greater impact on changes in the degree of activity α, which in order to maintain a considerable sensitivity to complex and changing traffic conditions. And that is why the activity α of both URAS and pre-URAS in Fig.6a are difficult to maintain high value for a long time, and keep fluctuating between high and low values. This paper removes redundant candidate nodes by TOPSIS, so as to reduce the unnecessary randomness. So the high activity of URAS is more common than pre-URAS, thus the average value of URAS activity is higher than pre-URAS ones about 0.16. In the later period of routing simulation, we can find that the activity α of both URAS and pre-URAS at a low level for a long time. That is because the increase of vehicles leads to more complex VANETs topology, URAS needs to continue finding the optimal routing path because of the high randomness, on the other hand, the value of activity α is related to the sensitivity of the equation (16) to the VANETs environment. Although the activity calculation formula of pre-URAS is different from URAS, the reasons that affect its value are same as URAS. The value of activity affects the duration of the current path. We can find that the congestion, delay of each routing path (data packet) of URAS and pre-URAS are constantly changing in Fig.6b and 6c. In addition to the reason that the network topology keeps changing, on the other hand, as mentioned earlier, even if the activity is high, the current path does not necessarily last longer because of the existence of the random term in equation (2). But EASM has an automatic adjustment function, so this changing is not large except data packet loss or other special circumstances.

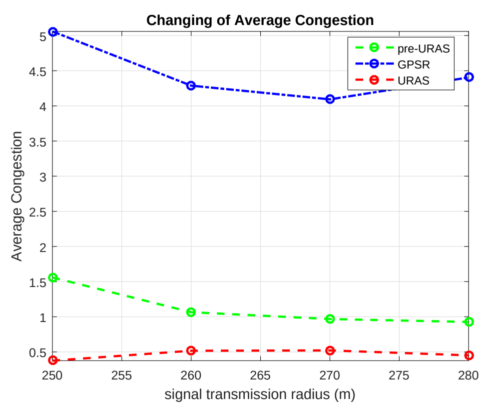
From Fig.6 we can clearly find that the number of data packets arrives at destination node successfully of this source-destination pair, which is reduced in the order of URAS, pre-URAS and GPSR. In this simulation of SUMO with the source-destination pair that is studied, the delivery rates of URAS, pre-URAS and GPSR are 84%, 72%, 58% respectively. In the complex urban road environment with many intersection, it is clearly that GPSR only uses the location information to select the next hop node, which is difficult to adapt to the complex traffic conditions and communication requirements. And when there is no neighboring node closer to the destination node than the current forwarding node, GPSR uses right-hand rule to bypass this void, which increases the delay and error probability [7], and this void is common at intersections. When a routing path is used by several pairs source-destination with similar position together, GPSR selects the next-hop node without considering the congestion of the candidate node, each forwarding node selects the neighboring



(a) Arrival rate of pre-URAS, GPSR and URAS.



(b) Average delay of pre-URAS, GPSR and URAS.



(c) Average congstion of pre-URAS, GPSR and URAS.

Fig. 8. Performance comparison of pre-URAS, GPSR and URAS.

node closest to the destination node as the next-hop node, which would result in a high congestion of the routing path that is 0.633 in Fig.6b, much higher than URAS and pre-URAS, thus causing a backlog of data packets. As above described, void and high congestion are the reasons that the arrival rate of GPSR is lower than URAS and pre-URAS, and the delay of GPSR is higher than URAS and pre-URAS in Fig.6c. The biggest improvement in URAS compared to pre-URAS is a more comprehensive screening of candidate nodes by the conjunction with TOPSIS, thus minimize unnecessary randomness of EASM, which results in the performance of URAS is better than pre-URAS as Fig.6b and 6c.

Fig.8 shows various average performance projects of all source-destination pairs of URAS, pre-URAS, and GPSR in the SUMO scenario of an Italian city Acosta with different signal transmission radius. We find that the performance of URAS is better than pre-URAS and GPSR in the simulation in terms of all performance indexes. These three routing protocols have a common trend, when the signal transmission radius is enlarged, the performance of routing protocols become better. It is obvious that larger signal transmission radius increases the number of candidate vehicles, which increases the probability of the data packet arrivals at the destination node as good as possible. In this case, GPSR still only selects the candidate node that is closest to the destination node as next-hop node, which limits its performance, so its performance is not as good as URAS and pre-URAS. The combination of URAS with TOPSIS reduces the randomness of EASM, so URAS can quickly find the optimal path and improve routing performance in the constantly changing VANETs environment, thus the performance of URAS better than pre-URAS.

V. Conclusion

In this paper we complement our previously proposed URAS (pre-URAS) and provide a more comprehensive study of performance under improved experimental conditions. Compared to GPSR with mechanical routing mechanism and pre-URAS with high randomness, in this paper URAS achieves rapid self-correction and improvement by the self-adaptive characteristic of EASM, and uses TOPSIS to filter candidate nodes, thus improves the speed of the adaptation to the change of external network environment. From the above experimental results, we can find that URAS performs better than GPSR and pre-URAS in the simulation in terms of arrival rate, delay and overall congestion.

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