HRV: Hybrid Routing in Vehicular Networks

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ABSTRACT

To improve the quality of wireless communication and extend the application of emerging networking paradigms in Vehicular Ad Hoc Networks (VANETs), we design a hybrid routing scheme for VANETs, called HRV. It presents a holistic solution for inter-vehicle, vehicle-to-roadside, and inter-roadside communications in hybrid urban networks. The combination of roadside unit (RSU) resources and ad hoc networks involves a network coding based multicast routing for dense VANETs, using maximum distance separation (MDS) code and local topology information from the forwarding set to achieve robust communication and max-flow min-cut data transmission; an application of opportunistic routing, using a carry and forward scheme, to solve the forwarding disconnection problem in sparse VANETs; and a routing switch mechanism to guarantee quality of service (QoS) in HRV under various vehicular network connectivity and roadside deployment configurations. The performance of our hybrid routing schemes is evaluated using reliable VANET experiments.

Keywords: Vehicular networks; Hybrid routing; Multicast routing; Opportunistic routing; Network coding
INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) are emerging new technologies integrating the capabilities of new generation wireless networks to achieve mobile data communications in Intelligent Transportation Systems (ITS) (1). VANETs include a variety of applications such as co-operative traffic monitoring, control of traffic flows, prevention of collisions, nearby information services, and real-time detour route computation. VANETs can also be used to provide comfort applications, including weather information, automatic parking, map location, mobile e-commerce, infotainment applications, and interactive communications such as Internet access, music downloads, and content delivery.

We address the routing design problem in urban hybrid networks. Specifically, we develop a holistic hybrid routing solution for inter-vehicle, vehicle-to-roadside and inter-roadside communications. The communication nodes involved in hybrid VANETs include vehicles and roadside units (RSUs). Public and personal WiFi routers, mesh routers, wireless sensors, base stations and all other kinds of wireless access points can serve as RSUs, and provide infrastructural support in hybrid VANETs. Considering issues with obstruction of satellite signals from buildings and the limited bandwidth of cellular networks in urban environments, these RSUs can provide better signals, spare spectrum and higher bandwidth for ad hoc data delivery and Internet access services for users in urban hybrid VANETs. Therefore, hybrid routing design by combining vehicular networks and RSU resources can present a cost-effective and performance-adaptive networking paradigm for the development of Cognitive Cars (2), Cloud Computing (3) and Cyber-physical Transportation Systems (4).

One key issue to address in vehicular networks are that these are distinguished from other kinds of Mobile Ad Hoc Networks (MANETs) due to high mobility, rapidly changing topology and various communication environments (5, 6, 7). Existing routing protocols, i.e. GSR (8), do not perform well as a result of their route instability in what are typically disconnected vehicular networks. And broadcast routing significantly increases overhead and communication redundancy when the traffic is heavy, leading to high transmission delay and data congestion. Network coding (9) offers unique advantages for multicast routing in VANETs. With network coding, intermediate nodes may send out packets that are linear combinations of previously received information. It can potentially increase the throughput and the robustness of the wireless network. An algorithm for constructing linear network codes that achieve the Max-flow Min-cut bound was devised in (10). CarTorrent (11) uses random network coding to mix and encode the packet contents at intermediate nodes in VANETs. However, linear network coding needs to know the global topology, and random network coding needs to balance the size of the finite field and decoding success rate. Their coding schemes can not be directly used in highly mobile and frequently disconnected VANETs.

We develop an efficient multicast protocol using Location-based Services (LBS) (12) and a more reasonable network coding scheme for the application of VANETs, called HRV (Hybrid Routing in VANETs). The location information can be obtained from GPS devices or existing wireless localization schemes (13). The vehicles in HRV first use location information to select a set of forwarding nodes to construct a multi-path for the multicast purpose. Then the vehicle uses local topology information, combined with the results of Maximum Distance Separable (MDS) code (9) to determine different transmission rates. At the same time, the vehicle calculates the minimum finite field for the intermediate nodes to encode information. The minimum finite field ensures that the global coding matrix satisfies certain linear independent features, so that the destination...
node can successfully decode the information. HRV can reduce the amount of communication redundancy and ensure the decoding efficiency.

To the best of our knowledge, our paper is the first to address the holistic routing design problem in hybrid VANETs. The features and contributions of HRV are:

- A hybrid routing design method is proposed to improve the data communication quality with vehicles as the users and RSUs as the backbone nodes.
- An MDS code based network coding in multicast routing, called HRV, that provides better robustness and lower redundancy in vehicular communication by minimum finite field. It uses MDS rules and local topology information from the forwarding set to construct a coding matrix and achieve max-flow min-cut transmission.
- Three separate routing modes are proposed to ensure the Quality of Service (QoS) under various network connectivity and roadside situations. These are vehicle-to-roadside and inter-roadside routing when the RSU is available, multicast routing using network coding when the network connectivity is good, and opportunistic routing using carry and forward when the network connectivity is poor.

The rest of this paper is organized as follows. We introduce the main ideas behind the routing switch mechanism in HRV, followed by a discussion of multicast routing and opportunistic routing under various network connectivities. Then we evaluate HRV performance using simulations and a short conclusion section.

ROUTING SWITCH IN HYBRID VANETS

Three types of communication are considered in hybrid VANETs, namely inter-vehicle, vehicle-to-roadside and inter-roadside, as shown in Figure 1. The routing switch mechanism is designed to choose the best routing strategy among the three modes at any given time/place.

Vehicle-to-Roadside Routing

RSUs in hybrid VANETs typically have a longer transmission range, higher bandwidth and better processing capability than the wireless devices in vehicles. In addition, RSUs are fixed and more stable than moving vehicles. Thus, RSU based infrastructure communication could provide better data service than ad hoc communication. The number and location of RSUs, and related location-based service (LBS) from RSUs are important to effective vehicle-to-roadside communication. However, the retrieval of RSUs (14) is a separate issue and will not addressed in this paper.

When a vehicle needs to communicate with an RSU, a request to a local RSU within communication range is sent. Under normal circumstances, the RSU will provide appropriate services. If the vehicle requests Internet service, the RSU will go through a gateway for data service. If the vehicle requests forwarding data to a destination vehicle, the local RSU will collect the data and forward it to the RSU nearest to the destination vehicle, and then further forward the message from that RSU to the destination vehicle. However, when the density of local vehicle users is high, their data requests will cause congestion on the local RSU. In our scheme, the RSU will periodically broadcast BUSY or FREE messages to local vehicles by regularly checking its own cache. Once the RSU is busy processing other data, vehicle users will bypass it and search for another available RSU. In this way, the RSU which is busy will avoid falling into a very congested state.
Inter-Vehicle Routing

When there is no RSU support, a vehicle uses the ad hoc mode to forward the data to the next vehicle. According to the degree of network connectivity, we design different routing schemes for inter-vehicle routing.

- **Multicast Routing in Dense VANETs:** When the network connectivity is high, a vehicle can find many neighbor vehicles to forward the data. Multicast routing is a more efficient way to improve network throughput and decrease network delay by transmitting data to multiple destinations using fewer network resources. In our scheme, a vehicle initially uses location information to select a set of forwarding vehicles for multicasting. And then vehicles use local topology information, combined with network coding to achieve max-flow min-cut multicast transmission by MDS code. The theory and related application of this method will be addressed in following Network Coding section.

- **Opportunistic Routing in Sparse VANETs:** When the network connectivity is poor, a connection hole can easily occur in mobile VANETs. Opportunistic routing takes advantage of the vehicle’s mobility to solve the connectionless problem in sparse networks for data delivery. The data is forwarded to the next proper vehicle using a carry and forward scheme (15), We address the application of opportunistic routing for sparse VANETs in Multicast using Network Coding section.

Inter-Roadside Routing

Once a vehicle retrieves the RSU information and forwards its data to an available local RSU, the RSU needs to find other available RSU to form a multi-hop route to deliver the data to the
destination. If there is an end to end inter-roadside route to the destination, the RSU forwards the
data to an RSU that the destination vehicle associates with the route. Otherwise, the RSU forwards
the data to an RSU that is closest to the destination vehicle. The RSU receives the data and
delivers it to the local vehicle. The local vehicle then forwards the data to the destination vehicle
using inter-vehicle routing as introduced above. The existing work on access scheduling (16) and
routing (17) in static wireless networks can be effectively extended to support the inter-roadside
communication.

HYBRID ROUTING IN VANETS
The design of hybrid routing in VANETs, namely HRV, provides specific solutions to different
VANET scenarios. The combination and seamless switching of the multicast routing using network
coding in dense vehicular networks, the opportunistic routing using carry and forward scheme in
sparse vehicular networks, and the static inter-roadside routing present a holistic routing mecha-
nism in hybrid VANETs.

Network Coding
A network is represented by a directed graph \( G = (V, E, C) \). \( V \) is the set of nodes or vertices, \( E \)
is the set of directed links (or edges), and \( C \) gives the capacity of each link of \( E \). Network coding
is a technique where instead of simply relaying the packets of information they receive, the nodes
of a network will take several packets and combine them together for transmission.

In the multi-hop network as shown in Figure 2(a), there is one source \( S \) (at the top), sending
out two information symbols \( b_1 \) and \( b_2 \). There are two destination nodes \( R_1 \) and \( R_2 \) (at the bottom),
which want to know both \( b_1 \) and \( b_2 \). Each edge can carry only a single symbol. Then the central line
would be able to carry \( b_1 \) or \( b_2 \), but not both by general routing. Suppose we send \( b_1 \) through the
center, then the left destination \( R_1 \) would receive \( b_1 \) twice and not know \( b_2 \) at all. Sending \( b_2 \) poses
a similar problem for the right destination \( R_2 \). We say that routing is insufficient because no routing
scheme can transmit both \( b_1 \) and \( b_2 \) simultaneously to both destinations. Using a simple code, as
shown, we do get both \( b_1 \) and \( b_2 \) simultaneously to both destinations. Using a simple code, as
shown, we do get both \( b_1 \) and \( b_2 \) to both destinations simultaneously by sending the encoded \( b_1 \) and
\( b_2 \) using the formula \( b_1 + b_2 \) through the center. The left destination receives symbol \( b_1 \) and symbol
\( b_1 + b_2 \), and can find \( b_2 \) by subtracting the two symbols.

In a linear network coding problem, a group of nodes are involved in moving the data from
\( S \) source nodes to \( K \) sink nodes. Each node generates a new packet, which is a linear combination
of the earlier received packets on the link and coefficients in the finite field.

A finite field or Galois field is a field that contains a finite number of elements. A finite
field is usually expressed by \( GF(q) \), where the letters \( GF \) stand for Galois field, and \( q \) stands for
the number of elements in the finite field. There exists a prime number \( p \) and a positive integer \( i \)
to satisfy \( q = p^i \). Choosing different non-zero elements from the finite field to fill in the coding
matrix could make the column vectors in the matrix linearly independent.

In linear network coding for multicast, a generated message \( Y_k \) is related to the received
messages \( X_i \) by the relation:

\[
Y_k = \sum_{i=1}^{n} a_{ki} \cdot X_i
\]  

(1)

Each node forwards the computed symbol \( Y_k \) along with all the coefficients \( a_{ki} \) used in the
\( k \)th level. \( a_{ki} \) are the coefficients from the finite field. Since the operations are computed in the
In random network coding, the information is linearly combined with randomly chosen coefficients from a finite field. Because the choice of code and operation of each node is completely independent and decentralized, the random coding scheme has the advantage that code construction can be done independent of the network topology, making it potentially very useful when the network topology is unknown. To recover symbols at the receivers, we require an invertible matrix in the coefficients of all nodes. If a finite field much larger than sufficient is used, receiver nodes can decode with independent linear combinations of the randomly chosen codes. However, a large finite field will cause high computation complexity and communication redundancy. If a finite field is small, then the receiver may not be able to decode and recover symbols successfully.
**Multicast Routing in HRV**

We propose a network coding scheme in multicast routing, namely HRV, for data forwarding in VANETs. HRV forms the forwarding set to select candidate vehicles to disseminate data. Network coding is used in the forwarding set to achieve better capacity and robustness in VANETs.

Instead of using global topology for the linear network coding, we get local topology information from forwarding sets to construct the coding matrix from the source, and forward the coding schemes to the descendant vehicles. A network generalization of a maximum distance separation (MDS) code is used in multicast network coding to achieve the Max-flow Min-cut bound. Meanwhile, it can minimize the finite field to achieve lower complexity of network coding algorithm.

**Forwarding Set**

We model the effective ranges of radio communications in three categories, namely the transmission range $R_{tx}$, the carrier sensing range $R_{cs}$ and interference range $R_i$. The carrier sensing range $R_{cs}$ is an adjustable parameter in the physical layer modules, and is usually set to 2 to 2.78 times $R_{tx}$ [18]. Therefore, the two-hop distance in VANETs is a good approximation of the wireless sensing range.

First, we construct a two-hop neighbor table to select forwarding vehicles. A vehicle periodically broadcasts HELLO messages. After receiving the HELLO message, each one-hop neighbor vehicle will reply to it. In this way, a two-hop neighbor information table can be derived using the TTL (the number of HELLO messages transmitted) information. We set the TTL value and record the source ID and its location initially. Once a message has been received by one neighbor vehicle, the neighbor will also add its ID and location into the message, and then forward it. After sending a message, the vehicle will decrease the value of TTL by 1. When the TTL equals 0, the vehicle that received the message will no longer forward the HELLO message, but record the source vehicle’s ID, the forwarder’s ID and each vehicle’s location. As a result, a two-hop neighbor vehicle information table is formed.

As shown in Figure 3(a), vehicle B’s one-hop neighbor is A and C. Vehicle A’s one-hop neighbor is D, E and F. So the two-hop table of B will include all the vehicle information.

![Two-hop Neighbor Table](image)

**FIGURE 3** Forwarding Set in HRV.

A forwarding set is formed based on the two-hop neighbor information table. Using a greedy method, the nearest vehicle from the destination will be chosen from the table to forward...
the data, and its forwarding table can be used to select other qualified forwarding vehicles. Suppose
we select vehicle $I$ (The nearest vehicle from the destination) and vehicle $J$. If vehicle $I$’s one-hop
neighbor vehicle $K$ is also the neighbor of vehicle $J$, vehicle $K$ will be added to the forwarding
set of vehicle $J$. All of vehicle $I$’s one-hop neighbor vehicles follow the above process.

(19) proved that the routing reliability will be improved using the forwarding set. When a
node failed, another node takes place of it. However, the "hidden terminal" problem may happen
during the routing as shown in Figure 3(b). After transmitting data to a forwarding set, a receiver
in the forwarding set also selects its own forwarding set. There may be some common members
between the two forwarding sets. When two vehicles send data to one vehicle belong to both
forwarding sets, collisions will occur on the vehicle and then scramble the data so that the hidden
terminal problem occurs. We solve this problem by carrying the vehicle ID in the packet. After
obtaining the vehicle ID information of other forwarding sets from new incoming packets, the
receiver checks every member vehicle’s ID from its own forwarding set. Duplicated vehicles will
be removed from its forwarding set.

Maximum Distance Separable (MDS) Code
Consider the $k$-redundant multicast network in Figure 2(b). In this network, there are three layers
of nodes. The top layer consists of the source node $S$, the middle layer consists of $n$ nodes each
connecting to node $S$, and the bottom layer consists of $[n, r]^T$ nodes each connecting to a distinct
subset of $r$ nodes on the middle layer. We call this network an $[n, r]^T$ combination network, where
$1 \leq r \leq n$.

Assume that the multicast data rate is $k$ at the source node. A message consists of $k$ information
symbols $[x_1x_2\cdots x_k]$ taken from a finite field $GF(q)$ is generated at the source node $S$, and it
is sent to receivers. For each link, there is a $k$-dimensional global coding vector $[a_1a_2\cdots a_k]^T$
from the finite field to make the symbol $y$ transmitted in the link to be: $y = a_1x_1 + a_2x_2 + \cdots + a_kx_k$.
By the Max-flow Min-cut theorem, a necessary condition for any non-source node $T$ to be able to
decode the source message is:

$$\maxflow(T) \geq k.$$  \hspace{1cm} (2)

Theorem 1. In a $k$-redundant multicast network, if the global coding vectors for any $k$ links from
the $n$ output links at the source node are linearly independent, then the global coding vectors of
the $k$ input links at every receiver are linearly independent. The receiver can correctly decode the
$k$ information symbols from the source to achieve a multicast rate $k$ in the multicast network.

Proof. For a receiver $R_i$ ($1 \leq i \leq |V_R|$) in the $k$-redundant multicast network, there are $k$ output
links at the source and $k$ input links at the receiver to form $k$ discrete paths. We assume the global
coding vectors for these $k$ input links are $[a_1a_2\cdots a_k]^T, [a_{11}a_{22}\cdots a_{kk}]^T, \ldots, [a_{k1}a_{k2}\cdots a_{kk}]^T$.
Then the $k$ information symbols $y^i_1, y^i_2, \ldots, y^i_k$ received from the $k$ input links at receiver $R_i$ is:

$$[y^i_1y^i_2\cdots y^i_k] = [x_1x_2\cdots x_k] \begin{bmatrix} 1 & 1 & \cdots & 1 & 0 \\ a_1 & a_2 & \cdots & a_q & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_1^{k-1} & a_2^{k-1} & \cdots & a_q^{k-1} & 1 \end{bmatrix}$$

To get $[x_1x_2\cdots x_k]$ from the $k$ symbols $y^i_1, y^i_2, \ldots, y^i_k$, the matrix
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\[
\begin{bmatrix}
1 & 1 & \cdots & 1 & 0 \\
a_1 & a_2 & \cdots & a_q & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
a_1^{k-1} & a_2^{k-1} & \cdots & a_q^{k-1} & 1
\end{bmatrix}
\]

has to be invertible, then these global coding vectors

\[
[a_{11} \ldots a_{1k}]^T, [a_{21} \ldots a_{2k}]^T, \cdots, [a_{k1}a_{k2} \cdots a_{kk}]^T
\]

have to be linearly independent.

Consider a classical \((n, k)\) linear block code with minimum distance \(d\) and use it as a linear network code on the above \([n, r]^T\) network. By accessing a subset of \(n - d + 1\) of the nodes in the middle layer, each node \(R\) on the bottom layer can decode the source message. Since \(\text{max flow}(T) = n - d + 1\), by the Max-flow Min-cut theorem indicated in Eq. (2), we have:

\[
d \leq n - k + 1.
\]

which is precisely the Singleton bound for classical linear block code (20). A classical block code that achieves tightness of the Singleton bound is Maximum Distance Separable (MDS) code. There are several useful characterizations of MDS codes as follows:

**Property 1.** A \((n, k)\) linear code is a MDS code if, and only if, the minimum distance is \(n - k + 1\).

**Property 2.** A \((n, k, d)\) linear code is a MDS code if, and only if, any \(k\) columns of a generator matrix are linearly independent.

By Property 1 we know that the MDS code meets the Singleton bound, and by Property 2 we know that MDS code meets the requirement in Theorem 1. Therefore, MDS code can be used as the multicast network coding scheme in V\(A\)NETs.

Let \(q\) be a prime power, \(GF(q)\) be a finite field of \(q\) elements, \(k\) be a positive integer, and \(m(k, q)\) denote the largest number \(n\) for which an \((n, k, n - k + 1)\) maximum distance separable (MDS) code exists over \(GF(q)\). The value of \(q\) in \(GF(q)\) is related to the size of the network. On one hand, we have to choose different elements from the finite field for each node on the middle layer; on the other hand, we have to avoid choosing \(q\) with a large value because this will cause high computation complexity and communication redundancy. Therefore, the selection of the minimum finite field to provide the coefficients for \(k\)-dimensional linear multicast on the \([n, k]^T\) network is a primary issue in multicast network coding in V\(A\)NETs.

**Theorem 2.** Given \(k\) and \(q\), and let \(m(k, q)\) denote the largest number \(n\) for which an \((n, k)\) MDS code exists over \(GF(q)\), then we have:

\[
\begin{align*}
& \bullet \ m(k, q) = q + 1, \text{ for } 2 \leq k \leq q. \\
& \bullet \ m(k, q) = k + 1, \text{ for } q < k. \\
& \bullet \ m(3, q) = m(q - 1, q) = q + 2, \text{ if } q = 2^i \text{ and } i \in \mathbb{Z}^+
\end{align*}
\]

**Proof.** Detailed proofs has been given by MacWilliams and Sloanc in (21), and by Vermani in (22).
**Proposition 1.** Given that source has $n$ output links and send out $k$ information symbols per unit time, if the $k$-redundant multicast network wants to achieve a data rate $k$ for multicast transmission, we have following $q$ value for the minimum infinite field $GF(q)$:

- When $n - k = 1$, we have $q = 2$.
- When $n$ is a even number, and $k = 3$ or $k = n - 3$, we have $q = n - 2$.
- Otherwise, we have $q$ is the minimum prime number or minimum prime power that is equal or greater than $n - 1$.

**Proof.** From Theorem 2, we can easily prove it. We skip the detailed proof here due to space limitations.

---

**Multicast using Network Coding**

$HRV$ constructs a global coding matrix from the source vehicle based on local topology information and distributes the coding rule to descendent vehicles. Meanwhile, $HRV$ applies MDS code to minimize the finite field for the global coding matrix, so that it can reduce the computation complexity and communication redundancy while guaranteeing successful decoding results.

$HRV$ has to establish multiple paths from source vehicle to destination vehicle for multicast purposes, therefore the number of vehicles in the forwarding set of any sender has to be more than 2. We use $1000m$ as the scale to count the number of vehicles, and apply a uniform distribution formula $N = a \times (1000/2R_c)$, where $a$ is the customized traffic density parameter and $R_c$ is the communication radius, to estimate the minimum number of vehicles in the range as the threshold to use $HRV$ in the networks.

If the number of vehicles in the range is more than the threshold, $HRV$ can achieve effective multicast using network coding so that we could improve the data transmission rate. If the number of vehicles in the range is less than the threshold, network disconnection could occur during communication, and therefore $HRV$ is not suitable for this scenario, and we have to use other data forwarding schemes like carry-and-forward in the opportunistic routing.

Suppose source vehicle $S$ wants to send the data to destination vehicle $R$. vehicle $S$ first collects the location and ID information of the vehicles in two-hop range by broadcasting HELLO messages, and then establishes the two-hop neighbor table. If the number of neighbor vehicles in the two-hop table is more than the computed threshold, then VANETs take the $HRV$ schemes for multicast.

During $HRV$ procedures, every vehicle determines its forwarding set using the two-hop table, and chooses the sending rate $k$ and $q$ value for the minimum finite field based on the number of vehicles in the forwarding set. Multiple coding coefficients will be assigned to vehicles on lower level, and each vehicle follows the coding rule using these coding coefficients. The assignment of multiple coding coefficients can help destination vehicle to successfully decodes information when some vehicles on the middle layer lose function. If a vehicle receives multiple data from some upper level vehicles, the vehicle decides its sending rate $k$ based on the number of the vehicles in its forwarding set, and the amount of received data $m$, by the rule $k = \min(n, m)$. Then, the vehicle can compute the minimum finite field by MDS code, construct the coding matrix, and distribute the coding rule. If $k = 1$, the vehicle will distribute 1 as the coding rule.
As shown in Figure 2(c), there are 3 nodes in the first forwarding set, so the sending rate \( k \) for source node \( S \) is 3. For node 1, 2, and 3 in the first forwarding set, they will distribute coding rule 1 to next level nodes because \( k = 1 \) for the three nodes. As for node 6 in the second forwarding set, it has two data from node 2 and 3, and it has two nodes \( a \) and \( b \) in its forwarding set, so the sending rate for node 6 is 2. It derives the minimum finite field and distributes coding rules \( b_1, b_2 \) and \( b_3, b_4 \) to node \( a \) and \( b \) respectively. In this way, if node \( a \) is dead, node \( b \) can still encode the data by \( b_3, b_4 \), and then send the encoded information to destination node \( R \). Node \( R \) can successfully decode the information as well.

**Opportunistic Routing in HRV**

When the number of vehicles in the communication range is less than the multicast threshold and there is no RSU support, network disconnection can easily occur in VANETs. In this case, the carry-and-forward and opportunistic routing schemes are used to find the proper next vehicle to transmit the data.

The opportunistic routing protocol takes advantage of the vehicle’s mobility to solve the connectionless problems in sparse or highly mobile networks for data delivery. The data is forwarded to the destination using a carry and forward scheme, as shown in Figure 4(a). Source \( S \) wants to send the data to the destination \( R \). It selects node 3 as the next hop. However, after receiving the data, if node 3 cannot find a neighbor which is closer to the destination than itself to forward the data (disconnection), or the number of nodes in node 3’s communication range is less than the multicast threshold (easily disconnected), node 3 will store the data and carry it for a while during its movement. When node 3 meets node 4 in its transmission range and node 4 is closer to the destination and the number of nodes in node 4’s communication range is more than the multicast threshold, node 3 immediately forwards the data to node 4.

The location, velocity, direction of movement of vehicles and other traffic information on the road can be obtained and analyzed by GPS with a geographic information system and inter-vehicle message exchange. By the opportunistic scheme, a next-hop vehicle is selected if the location of its future neighbor vehicle is closer to the destination.

Figure 4(b) shows how opportunistic routing works in the routing switch mechanism. Vehicle \( S \) sends the data to vehicle \( R \), however, none of the neighbors of \( S \) can communicate with \( R \). It is worse that the local RSU is in congestion. At this time, we can only use opportunistic routing. The forwarding vehicle can obtain its moving direction and path with the help of GPS to predict its future neighboring vehicles location on the road. In the case, opportunistic routing find that vehicle \( A \) will move to location around vehicle \( A' \), so \( A \) can serve as the next hop of \( S \). \( A \) stores the packet and forward it until it move into communication area of vehicle \( A' \).

**Load Balancing in HRV**

Because RSUs have better data storage and processing capability than vehicles, the uplink and downlink communications are asymmetrical in Vehicle-to-Roadside mode. Meanwhile, RSUs and vehicles are different on their number and distribution. Thus, load balancing of RSUs is also addressed in HRV.

To better assist the load balancing, there are some operations on the RSU side to handle the access of vehicle users. RSU regularly checks its own cache and determines whether it is under congestion or not. When the cached data reaches a certain threshold, RSU comes into congestion.
The RSU will periodically broadcast BUSY messages to local vehicular users. Once receiving the BUSY message, vehicles will bypass the RSU and search next available RSU to access. Similarly, when the cache is below a certain threshold, FREE messages will be periodically sent to local vehicles by the RSU to indicate the available access. As shown in Figure 4(c), RSUs periodically broadcast BUSY/FREE to local vehicle users.

**EVALUATIONS**

The performance of HRV and its routing switch mechanism have been implemented and tested in the hybrid VANETs structure using reliable VANET experiments from NCTUns v5.0 (23).

The reason why we chose NCTUns v5.0 is that it provides comprehensive and realistic simulations of IEEE 802.11 standards and other networking protocols, including IEEE 802.11p, which is an approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments (WAVE) (24). The essential network management functions complies with the standards to the fullest extend, such as WiFi channel estimation, probing, association, disassociation, re-association procedures, which were mostly unavailable in other simulations, such as NS2 (25). In addition, NCTUns v5.0 directly integrates with existing command line programs, such as FTP, HTTP applications, so that the simulator evaluates real application performance in its simulated environment.
We implemented our hybrid routing protocols in NCTUns v5.0, and evaluated them on transmission delay and delivery ratio in different scenarios, including network coding based multicast, opportunistic routing, and RSU support. In NCTUns v5.0, we can import a road map into the GUI program, choose general road segment, crossroad and road merger to construct a road network, deploy different kinds of ITS cars with max speed and max acceleration profiles, and generate various hybrid networks.

The simulation adopted a user-defined Manhattan-grid of $600m \times 600m$ and the random mobility model as illustrated in Figure 5(a). Some common parameters are given in the table in Figure 5(b).

![Simulation Setting](image)

### (a) Simulation Setting

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Size</td>
<td>600m x 600m</td>
</tr>
<tr>
<td>Road Structure</td>
<td>Two Lanes</td>
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<tr>
<td>MAC</td>
<td>802.11 DCF</td>
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<td>Communication Range</td>
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<tr>
<td>Packet Type</td>
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<tr>
<td>Packet Size</td>
<td>1400bytes</td>
</tr>
<tr>
<td>Moving Speed</td>
<td>10m/s</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>150s</td>
</tr>
</tbody>
</table>

### (b) Common Parameters

**FIGURE 5  HRV Simulation using NCTUns v5.0.**

**HRV Using Multicast**

Our HRV multicast routing utilizes MDS code based network coding for inter-vehicle data delivery. We implement it in NCTUns v5.0 and compare it with GSR (8) and CarTorrent (11) on transmission delay and delivery ratio in the same settings.
As shown in Figure 6(a), HRV performs better than GSR and CarTorrent on end to end transmission delay. GSR is a geographic routing protocol. When there are data to transmit, GSR tries to find the best neighbor vehicle as the next hop by maintaining neighbor vehicle updates. GSR achieves low delay when the vehicle density is low. However, when the vehicle density increases, there are more collisions and transmission failures due to the competition on the links, leading to inefficient link usage and increasing end to end transmission delay. CarTorrent applies random network coding during transmission. It has to maintain a finite field with a certain size to guarantee successful decoding. A large sized finite field will increase communication redundancy when the vehicle density is high, leading to unstable performance on delay. HRV establishes multiple paths for multicast based on forwarding set, and applies MDS in the linear network coding using local topology information to minimize the finite field during communication. Besides, the application of opportunistic routing when the network connectivity is low it also provides
additional support to avoid data retransmission.

Figure 6(b) compares the performance of delivery ratio among HRV, GSR and CarTorrent. It illustrates the average successful probability of data delivery from the source vehicle to the destination vehicle. When the number of vehicles increases, the delivery ratio of GSR decreases fast because of the increased competition on the links leading to the packet loss. CarTorrent performs better than GSR because it takes random network coding to ensure the reception of packets and increase the throughput using multicast. However, when the vehicle density is high, the large size of finite field generated in CarTorrent will increase communication redundancy, and then the increased network loading will cause packet loss. HRV uses MDS to minimize the finite field, therefore provides a robust way to avoid the redundancy. Based on the forwarding set and linear network coding for multicast, HRV expresses high performance on packet delivery ratio. When network connectivity is poor, HRV switches into opportunistic routing mode, so that it can take carry and forward scheme to guarantee successful data delivery.

HRV Using RSUs
The HRV protocol also utilizes the benefits of hybrid VANETs, in which RSUs serve as backbone nodes. Typically, RSUs in VANETs have better signal quality, longer transmission range, higher bandwidth and better processing capability than normal wireless devices in vehicles. Besides, RSUs are fixed and more stable than moving vehicles. Therefore, RSU based infrastructure communication could provide better data service than ad hoc communication. We compared the performance of HRV with and without RSU support in hybrid VANET environments to verify our hybrid communication modes. Five RSUs were deployed on five road intersections (up, down, left, right, middle) in Figure 5(a). The communication range of each RSU is set to be 300 m.

The comparison of end to end transmission delay in Figure 6(c) shows that HRV with RSU support (HRV_{RSU}) can decrease data transmission delay significantly compared to a network without RSU support (HRV_{noRSU}). When there is RSU support available, vehicles always choose to use the RSU node to deliver the data because of the advantage of RSU over vehicular wireless devices. HRV_{RSU} supports the data delivery by vehicle-to-roadside and inter-roadside communications, and it also provides multicast and opportunistic routing features as HRV_{noRSU} when the RSU is under congestion or the RSU route can not reach the destination vehicle.

The deployment of RSU nodes in Figure 5(a) is not fully connected. Therefore, if the vehicle density is too low, there will be some extra delay caused by carry and forward to establish vehicle-to-roadside connection. If the vehicle density is moderate, multicast routing can improve the vehicle-to-roadside performance and inter-roadside can provide stable link connection to maintain low delivery delay. However, if the vehicle density is too high, a high volume of data transmission will bring lead to congestion in the RSUs resulting in delivery delay. Especially for the RSU located in the middle of an intersection, it can quickly get congested because other RSUs need to forward data to it to maintain multi-hop inter-roadside communication. This problem is caused by the distribution of RSUs and the limit of communication range.

HRV_{RSU} also can provide better successful data delivery ratio than HRV_{noRSU} as shown in Figure 6(d). The static route and higher bandwidth maintained among RSUs can provide more stable communication quality than inter-vehicle communication. The congestion detection and route detection on RSUs can effectively switch HRV to multicast and opportunistic routing by utilizing the mobility of vehicles to achieve continuous data delivery.
CONCLUSION

Because of their highly dynamic properties, it is a challenge to design efficient routing protocols for vehicular networks. In this paper we consider the features of hybrid VANETs with vehicle and RSU supports and propose a holistic hybrid routing design to guarantee communication quality in VANETs. The network coding based multicast routing in dense VANETs, the opportunistic routing using carry and forward scheme in sparse VANETs, and corresponding routing switch strategies present a promising solution for reliable data dissemination and delivery services in hybrid VANETs. Our simulations also verify the performance of hybrid routing and its possible application in dynamic vehicular networks.

REFERENCES


