A Border Node Based Routing Protocol for Partially Connected Vehicular Ad Hoc Networks[1]

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***Abstract*—Research on vehicular ad hoc networks (VANETs) has focused primarily on efficient routing protocol design under conditions where there are relatively large numbers of closely spaced vehicles, typical of major highways and urban areas. These routing protocols are designed principally for fully connected networks and are not suitable for packet delivery in a sparse, partially connected VANET. In rural areas, vehicle densities are low and roadway communication infrastructure is scarce, leading to long periods where vehicle-to-vehicle or vehicle-to-roadside communications is infrequent, interrupted, or simply not possible. These attributes characterize a sparse VANET, and are characteristic of delay tolerant networks (DTNs). In this paper, we examine the challenges of VANETs in sparse network conditions, review alternatives including epidemic routing and propose a Border node Based Routing (BBR) protocol for partially connected VANETs. Unlike many VANET protocols that assume location awareness or mobility patterns to aid in routing decisions, BBR is designed to function in domains where location and mobility information is not available, as is typical in rugged terrain conditions. The BBR protocol can tolerate network partition due to low node density and high node mobility. The performance of this protocol is evaluated in OPNET™ with a Random Waypoint mobility model and a Geographic and Traffic Information (GTI) based mobility model that captures typical highway conditions. The simulation results are compared with those obtained using the Dynamic Source Routing (DSR) protocol and with an epidemic routing protocol. The simulation results show that BBR performs well for partially connected VANETs where other protocols fail and provides the advantage of not relying on a location service required by other protocols proposed for VANETs.**

***Index Terms*—VANETs, ad hoc routing, sparse networks, delay tolerant networks**

I. Introduction

Vehicle communication networks are designed to provide drivers with real-time information through vehicle to vehicle or vehicle to infrastructure communications. Vehicle communication methods often rely upon the creation of autonomous, self-organizing wireless communication networks, or vehicle ad hoc networks (VANETs) designed to connect vehicles with fixed infrastructure and with each other. Research projects such as COMCAR [1] and DRIVE [2] have examined how vehicles in a network communicate with each other or with the external networks, such as the Internet, through the use of such communication infrastructure as wireless cellular networks. Other projects, including FleetNet [3] and NoW (Network on Wheels) [4] have explored ad hoc network techniques.

Recent improvements in mobile ad hoc network (MANET) technology and ever-increasing safety requirements as well as consumer interest in Internet access have made VANETs an important research topic. Vehicle to vehicle and vehicle to roadside communications have become important components of vehicle infrastructure integration. Most of the VANET research has focused on urban and suburban roadway conditions, where the numbers of vehicles are large, the inter-vehicle spacing is small, terrain is not a significant factor and fixed communication infrastructure is available. In rural and sparse areas, the conditions and constraints are significantly different. Node densities are low, inter-vehicle spacing can be large, terrain effects may be significant and there is very little or no fixed communication infrastructure available. The coverage provided by wireless carriers is predominantly in urban areas and along major highways, not in rural areas and minor roadways.

VANETs have particularly important applications in sparse and rural areas because of the lack of fixed communication infrastructure. VANETs in sparse areas can be characterized as partially connected MANETs with low node density and high node mobility. Routing algorithms appropriate for these circumstances have been less explored and the design of such a routing protocol is challenging.

In this paper, we propose a Border node Based Routing (BBR) protocol for partially connected VANETs. This protocol is motivated by properties of

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epidemic routing, which are demonstrated by simulations. We define and use a “border node” as a means of reducing flooding effects typical in epidemic routing and ensuring efficient use of intermittently available communication bandwidth. Using the popular Random Waypoint mobility model, we evaluate the performance of the epidemic and the BBR protocols on a mobile ad hoc network with a variety of network connectivity conditions. To further evaluate the BBR protocol performance on a VANET under sparse network conditions, we apply a Geographic and Traffic Information based mobility model (GTI mobility model) [5] designed to model the movement of mobile nodes under typical highway constraints. As a comparison, the performance of the DSR and epidemic routing protocols are evaluated under the same conditions.

The remainder of the paper is organized as follows: Section II discusses related research work on routing protocol design for partially connected ad hoc networks. Preliminary work using an idealized epidemic routing protocol is reported in Section III. The proposed BBR protocol is described in Section IV. In Section V we present results of BBR protocol simulation and its comparison with DSR. The conclusions are drawn in the final section.

II. RELATED WORK

The general approach for information delivery in partially connected MANETs is to relay messages hop by hop, not necessarily continuously, but at discrete time intervals as links become available. Data may be stored in intermediate nodes for some time before it can be forwarded. With this message relay approach, data delivery may incur a long delay. In a fully-connected MANET if a route is found, packet delivery will be accomplished in a relatively short time, determined by a combination of the propagation, processing and transmission delays.

The design of efficient routing protocols for VANETs is challenging due to the high node mobility and the movement constraints of mobile modes. VANETs, as one category of Inter-Vehicle Communication (IVC) networks, are characterized by rapid topology changes and frequent fragmentation [6]. Conventional topology-based routing schemes are not suitable for VANETs. Reactive routing schemes will fail to discover a complete path due to frequent network partition and proactive routing protocols will be overwhelmed by the rapid topology changes and even fail to converge during the routing information exchange stage [7].

Position-based routing schemes generally require additional node physical position information during the routing decision process. A location service is needed as well to provide the position information of nodes. Generally, location service is provided based on position information derived using GPS or other positioning systems. Broadcast protocols that make use of GPS information to improve the broadcast performance in IVC networks were proposed in [8].

Considerable work has been done using position – based routing for VANETs in the FleetNet and Network on Wheels projects. These efforts have included the development and evaluation of roadway mobility models and position-based routing techniques and comparisons with topology-based protocols including DSR and AODV [9]. The results generally show excellent performance for position-based routing (e.g., high packet delivery ratio and low latency) relative to other protocols, but have been applied primarily to high node density conditions. Some work has been reported that addresses non-ideal wireless propagation, but does not include specific terrain effects [9]. Recent work to address terrain effects and assure quality of service for routing in remote areas for roadside to vehicle communications was recently reported in [10], where stationary nodes (access points) play a key role in route maintenance. This approach uses a predication algorithm to estimate the lifetimes of wireless links among moving nodes.

A multicast protocol for inter vehicle geocast by defining a restricted broadcast group using GPS information was studied in [11]. Other inter-vehicle communication schemes using GPS information include [12]-[14]. In [12], a zone-of-relevance is defined based on the distance from a receiving node to a source node. In [13], by using GPS information, a spatially aware packet routing is proposed to predict the topology holes that might be exist due to the spatial constraints of node movement. Intelligent opportunistic forwarding decisions using velocity information obtained through a GPS system are explored in [14].

A direction-oriented routing scheme for inter vehicle multi-hop wireless networks is proposed in [15], where the direction information of each node is exploited for routing decision. Relative speed-based routing for VANETs is proposed in [16], in which the relative speed and the cumulative change of the distance of a node to its neighboring nodes are used as the metrics to estimate whether a route is stable or not. Similarly, in [17], optimal hop selection in VANETs on highway was analyzed to maximize the expected route lifetime. These schemes and approaches are focused on the fully connected VANETs and not appropriate for sparse, partially connected networks.

An ad hoc network that uses the generalized message relay approach is also called a Delay Tolerant Mobile Network (DTMN) [18]. Data delivery in partially connected ad hoc networks is generally based on the store-and-forward message relay approach [19]-[22]. A message ferrying approach was presented in [20], where a set of special mobile nodes called message ferries move around the deployment area according to known routes while other nodes transmit data to distant nodes out of range by using the ferries as relays. A similar method is proposed in [21], where some nodes called “data mules” are used to collect data in a sparse sensor network. The sensor nodes are generally static, but the data mules are mobile. Another approach using message relay was proposed in [22], in which mobile hosts actively modify their trajectories to minimize the transmission delay when they transmit messages. All approaches mentioned above are mobility-assisted and proactive in nature since nodes modify their trajectories proactively to assist communication. However, it is not always the case that non-randomness in the movement of nodes can be exploited to help data delivery. Sometimes no mobile nodes can serve as "message ferries", and there is generally no repetition in the individual node's trajectory.

Several authors have explored the feasibility of forms of opportunistic routing. Data forwarding by nearby nodes is discussed in [23] where nodes that are closer to the destination are selected as the next hop. However, this technique requires some method of determining whether the intermediate node is located in a path that leads to the destination. A probabilistic approach for routing in sparse networks is proposed in [24], where multiple copies of a message are transmitted. This method is promising, but assumes limited battery power and sleep periods, as would be the case in a sensor network application rather than a VANET.

Epidemic routing was introduced as an alternative approach for partially connected ad hoc networks [25]. In that routing algorithm, random pair-wise exchanges of messages occur among proximate mobile nodes. The movement inherent in the nodes themselves is exploited to help deliver the data when a network is partially connected. The epidemic algorithm is flooding-based, and it trades system bandwidth and node buffer space for the eventual delivery of a message. In [26], the authors examine a recovery process that deletes unnecessary packets from the network.

To control flooding or save system bandwidth and node buffer space, different flooding control schemes have been proposed [27]-[29]. However, these control schemes all assume that nodes have some prior knowledge or history information about other nodes. Probabilistic metric "delivery predictability" is explored in [27] to select the better next step candidates. The "delivery predictability" function is based on the history of encounters, assuming nodes know how many times they encounter other nodes. Similarly, a forwarding decision based on the "utility function" is proposed in [28], in which more information about other nodes, including the nodes recently noticed and the most frequently noticed, the power level, the rediscover interval etc., are used to calculate the utility function. An opportunistic exchange algorithm using a spatio-temporal relevance function to manage node buffer space was proposed in [29].

These flooding control schemes based on prior knowledge or history information about other nodes are not readily applicable for partially connected VANETs. The low node density, combined with the difficulty of obtaining the information used in the routing determinations limits the effectiveness of these schemes. Furthermore, the assumption that nodes will have GPS-based location information is an additional constraint and there may not be repetition in node trajectories as needed in some of the approaches. Terrain effects in mountainous areas make GPS-based location awareness problematic.

We propose a Border node Based Routing (BBR) protocol for partially connected VANETs that considers the characteristics of partially connected VANETs while at the same time takes into account the limitations of existing routing approaches for partially connected ad hoc networks. The BBR protocol is mainly based on broadcast and applies the store-and-forward approach used in epidemic routing. Instead of simply flooding the network, a flooding control scheme is explored by using one-hop neighbor information only. The BBR protocol is specifically designed to accommodate for the effects of node mobility on data delivery.

III. EPIDEMIC ROUTING IN SPARSE NETWORKS

VANETS in sparse and rural areas can be characterized as partially connected with low node density and high mobility. With the motivation to design a routing protocol that is appropriate under these conditions, we carried out a simulation study to evaluate the performance of an ideal routing protocol, which is briefly described in the following paragraph. The ideal routing protocol is similar to an epidemic routing protocol, which was originally proposed in [25] for partially connected ad hoc networks. There are two reasons to choose the ideal routing protocol. First, using an ideal routing protocol we can better investigate the connectivity characteristics of the underlying mobile ad hoc network. Second, it provides some insights into the design of a practical routing protocol that might be more effective for a partially connected ad hoc network.

A. The ideal routing protocol

For purposes of simplification, the ideal routing protocol uses ideal message exchange rules:

1) Message hand offs occur when moving nodes are within radio range, and

2) Information exchange is instantaneous when two nodes are within radio range.

And we also make the following assumptions:

1) No message processing time in each individual node.

2) Nodes keep the message when they move on.

3) The number of nodes in the network during the simulation period is constant.

4) The simulation ends once the message reaches the destination.

5) Nodes move in accordance with predefined trajectories associated with the available roadways

B. Simulation Environment

We apply this routing protocol to a rural example based on the roadways of Yellowstone National Park (YNP) (see Fig. 1) and use the geographic and traffic information-based (GTI) mobility model described in [5]. The simulation scenario is designed as follows: A source node or *Event node*, which represents a node that has an accident or has some local incident information, is located at the cross point of West Thumb of YNP. This node generates data traffic and sends this data to the destination node or *End node,* representing the Information Center, located at the West Entrance of YNP. The ideal routing protocol is used in the information delivery. The explored questions are: Can the event information be transmitted from the *Event node* to the *End node* through the mobile ad hoc network? If the message can be successfully delivered, the *Transit time* (T_{trans}) that it takes to transmit a message from the *Event node* to the *End node* will be calculated, and what are the

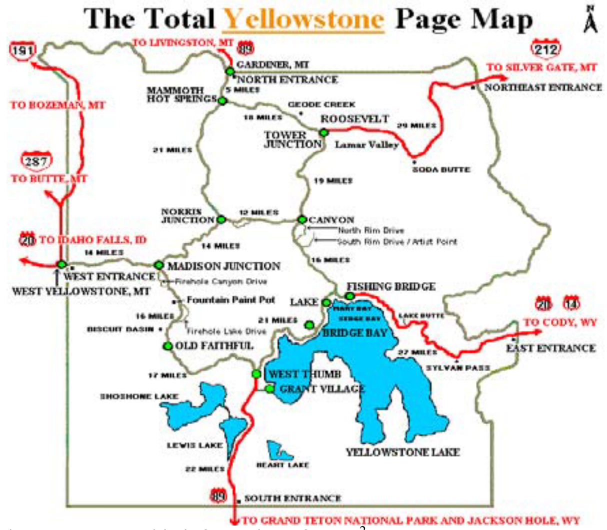


Figure 1. Geographic information of YNP.[2]

upper bounds on delivery time? Based on the geographic and traffic data obtained from the park administration office, a scenario with an average traffic load (the total number of mobile nodes inside YNP is 1400) has been studied; Table 1 summarizes the general simulation parameters.

C. Simulation Results

The GTI mobility model introduces randomness to the initial node distribution, node speed and direction chosen, and trajectories generated with each use of the model are different even with the same initial configuration parameters. With the parameters indicated in Table 1, trajectories for all mobiles nodes are generated for 15 trials and the transit times are calculated. Table 2 summarizes the simulation results.

TABLE 1: SIMULATION PARAMETERS

Parameters	Value
Total simulation time	2 hours
Total number of nodes	1400
Approximate total physical road length after linearization	194.36 miles
Average distance between neighboring vehicles	223.4 meters
Transmission range	100~500 meters
Movement speed	12.1~14.7 m/s

[2] From the data source: http://www.yellowstone-natl-park.com/map.htm.

TABLE 2: SIMULATION RESULTS

Radio range (R) (m)	Transit time (T_{trans})		
	Avg (s)	Max (s)	Standard deviation (s)
100	5463.0	7077.3	1103.7
200	4968.2	6692.0	847.3
300	0	0	0
>=400	0	0	0

The simulation results show that during average traffic load hours, when the radio range is less than 200 meters, the mobile ad hoc network is partially connected. When the radio range is 200 meters or less, which is less than the average distance between neighboring vehicles, the delivery of the message is mainly dependent upon the movement of the mobile nodes themselves, instead of forwarding by the intermediate nodes hop by hop. The average transit time of about 5000 seconds is close to the time for a vehicle to move from the position of the *Event node* to the position of the *End node*. The results also show that when the radio range is greater than 300 meters, the network is connected and the delivery time drops to zero, as transmission and propagation times have been ignored in this example.

While such epidemic similar routing protocols are effective in achieving packet delivery under sparse conditions, there are several drawbacks. First, nodes must store messages requiring buffer space. Message exchange overhead can become significant as the network size increases. Several techniques have been developed to mitigate these effects, including coin-based, counter-based and blind message deletion schemes [30]. Methods that limit flooding and that use information about neighbors (e.g., lists or position) tend to be more efficient, as described below.

IV. BORDER NODE BASED ROUTING (BBR) PROTOCOL

The BBR protocol is designed for sending messages from any node to any other node (unicast) or from one node to all other nodes (broadcast). The general design goals are to optimize the broadcast behavior for low node density and high mobility networks and to deliver messages with high reliability while minimizing delivery delay.

The BBR protocol has two basic functional units: a neighbor discovery algorithm, and a border node selection algorithm. The neighbor discovery process is responsible for collection of current one-hop neighbor information. The border node selection process is responsible for selection of the right candidate/candidates for packet forwarding based on the one-hop neighbor information collected in the neighbor discovery process.

In the following section, the general assumptions that the BBR protocol is based on are first briefly discussed. The neighbor discovery algorithm and border node selection algorithm are then described in detail.

A. Assumptions

The protocol design is based on the following assumptions. First, no node location information is available. Second, the only communication paths available are via the ad hoc network itself. There is no other communication infrastructure. Third, node power is not a limiting factor for the design. Fourth, communications are message oriented. Real time communication traffic is not supported. The protocol requires no assumptions regarding network topology, and can be applied to scenarios where the nodes are unconstrained as well as where the nodes are constrained to move on roadways, as explained and demonstrated below.

B. Neighbor Discovery Algorithm

Neighbor discovery is the process whereby a node discovers its current one-hop neighbors. For a particular mobile node, any other node that is within its radio transmission range is called a neighbor. All the neighbors of a particular mobile node constitute a neighbor set. Since all nodes might be moving, the neighbors for a particular mobile node are always changing. The neighbor set is dynamic and needs to be updated frequently.

Generally, neighbor discovery is realized by using periodic Hello messages for neighbor node detection. Each node informs other nodes of its existence by sending out periodic Hello messages. A node updates its neighbor node set after receiving Hello messages from other nodes.

The BBR neighbor discovery algorithm is similar to the neighbor discovery protocol (NDP) proposed in the Zone Routing Protocol (ZRP) [31]. The NDP in the ZRP is MAC-level based and a periodic Hello beacon is sent out by the node MAC layer to advertise its existence. The BBR neighbor discovery algorithm is a network layer-level based NDP. The Hello message is sent out by network layer. The advantage of using a network layer based NDP is that all routing functions are accomplished in the network layer, without consideration of the specific MAC layer technology used.

C. Border Node Definition and Distributed Border Node Selection Algorithm

In the BBR protocol, border nodes are selected per broadcast event. A border node is defined as a node which has the responsibility of saving received broadcast packet/packets and forwarding the packet/packets when appropriate. For a group of nodes that receive the same broadcast message, only those nodes selected to be border nodes will keep the received data and rebroadcast it later when those nodes meet new neighbors. The selected border node must use *broadcast*, rather than *unicast*, as it has no knowledge of the trajectories of the nodes that are within its transmission range, or of their routing tables. The BBR protocol uses a distributed border node selection algorithm. The decision whether a node is a border node or not for a particular broadcast event is made independently by an individual node based on its one-hop neighbor information and the received broadcast information.

1) Heuristic for the Selection of Border Nodes.

Based on intuition, for a specific broadcast, an ideal candidate to forward a packet would be node/nodes that is/are located at the edge of the radio transmission range of the source node. The minimum common neighbor concept is used to select the border node based only on one-hop neighbor information. Position-based routing methods apply similar approach, but use explicit location information to compute the distance between neighbor nodes and the destination, and select the neighbor closest to the destination to forward the packet. Alternative non-position-based border selection approaches are discussed below. The following terms are first introduced.

Covered: A node j is covered by a node k when node j is within the direct radio transmission range of node k and can receive packets from node k when node k sends out packets. When node j receives a broadcast packet from node k, node j is said to be covered by the broadcast of node k.

Neighbor set: A one-hop neighbor set of node i, noted as N_i, consists of those nodes that are covered by node i.

Common neighbor set: An arbitrary node i has a one-hop neighbor set N_i. Another node s has a one-hop neighbor set N_s. A third node j is called a common neighbor of node i and node s, if and only if $j \in N_i$ and $j \in N_s$. The common neighbor set of node i and s, noted as N_{is} consists of all common neighbors of node i and node s.

Border node selection based on minimum common neighbors uses the intuitive notion that nodes at the edge of radio transmission range should have fewer common neighbor nodes with the broadcast source node, as compared to those nodes that are closer to the source node. As indicated in Fig. 2, a circle delineates the direct radio transmission range of the node located at the center of the circle. R is the radio transmission range. For example, suppose node s is a broadcast source. Nodes at the edge of the radio transmission range, such as node b and h, as compared to nodes closer to the broadcast source node, such as node a, have fewer common neighbors with node s. Selection of nodes such as b or h or both as the border nodes for further rebroadcast is appropriate in that this selection results in maximum range and rapid information dissemination while saving bandwidth by minimizing unnecessary rebroadcasts.

An alternative selection rule would be to choose the node(s) that have the most number of uncommon neighbors. This rule would also tend to designate as border nodes those nodes that are furthest from the broadcast source. We have compared these two selection rules and find them to be effectively equivalent. As a third alternative, we have also tested a random selection approach. Simulations have demonstrated that random selection yields inferior results, measured in terms of average message delay time.

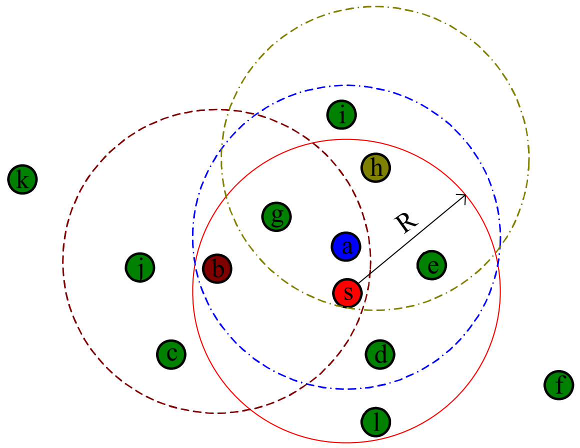


Figure 2. A typical broadcast and node distribution.

2) Border Node Selection Scheme and Rules.

With the BBR algorithm, every node has three tables/buffers: a Neighbor Table, a Border Node Selection Table and a Forward Table. The Neighbor Table is used to save the current one hop neighbor information. The Border Node Selection Table is used for border node selection. The Forward Table is used to buffer data packets that need future forwarding. When a node has a packet to forward and there is no available neighbor, it keeps the packet in the Forward Table and broadcasts it later when there are neighbors in range. A source node that generates a data packet is by default chosen as a border node. A node that broadcasts or rebroadcasts a data packet will use a packet format as indicated in Table 3, which has a list of its current neighbors attached. The "Comm. neigh. #" field is set to be the number of the common neighbors between the current node and the previous node that broadcasted the data packet. If a node is a source node, then the "Comm. neigh. #" field is set to zero. Each packet has its unique packet ID, generated by the originating node. The packet ID remains unchanged as the packet moves from source to destination.

TABLE 3. BROADCAST DATA PACKET FORMAT

Source node ID	Dest. node ID	Comm. neigh. #	Reserved	Packet ID	Packet content	Neigh. list

When a node receives a data packet, it first searches its Forward Table to see whether there is already a packet entry with the same packet ID. If there is, then the data packet is ignored. This approach conserves energy and bandwidth. Otherwise, the node checks the attached neighbor list of the received data packet and carries out the following procedures based on the following cases.

Case 1: Single neighbor on the neighbor list of the broadcast packet. The node is the only node on the neighbor list. Then no border node selection will be carried out and it is a border node by default. The node will check its current one hop neighbor list. If this node has no additional neighbor nodes within range, then it will store the data packet in its Forward Table. It will carry this data packet and rebroadcast for a total of p times at different time points in the future when there are new neighbors within its transmission range. The rebroadcast parameter p is configurable and indicates the willingness of intermediate nodes to forward a data packet. If this node has additional neighbor nodes within range, then it will rebroadcast immediately and rebroadcast $p-1$ times in the future when new neighbors coming into range.

Case 2: Multiple neighbors on the neighbor list of the received broadcast packet. There are multiple neighbors on the neighbor list. Those nodes receiving the data packet for the first time will initiate two timers, an access delay timer T_{ad} and a maximum delay timer $T_{\max}$. The timer T_{ad} is used to decide when a node needs to rebroadcast if it has to do so. The timer $T_{\max}$ is used to decide when a node should initiate the border node selection process. The value of timer $T_{\max}$ is set to $T_{\max} = a \times (n \times \Delta t)$, where n is the total number of neighbors on the neighbor list of the received packet. The parameter Δt is the estimated transmission delay for sending one packet, which can be approximated, by (packet length / data transmission speed). The parameter a ($a \geq 1$) is used to increase the value of the timer to make sure that a node receives all the rebroadcast packets that might be coming from the neighbors of the previous forwarding node. The value of T_{ad} is set to $T_{ad} = (i-1) * \Delta t$, where i is the position of the node on the neighbor list of the received packet. The value of T_{ad} is node dependent, while the value of $T_{\max}$ is the same for the group of nodes receiving the same broadcast data packet. During $T_{\max}$, each node in the group decides to rebroadcast or not when its T_{ad} timer expires. The decision is made depending on whether all its current one hop neighbors are covered or not, namely, whether they have received the broadcast packet information or not. If a node needs to rebroadcast when its T_{ad} timer expires, the rebroadcast packet will have a format as shown in Table 4, which looks almost the same as that of the data packet format indicated in Table 3. However, the values for fields "Node ID", "Comm. neigh. #" and "Neigh. list" are all different from that of the received broadcast packet. During the whole T_{max} interval, each node will listen continuously. Rebroadcast packets from its neighbors will also be recorded and saved temporarily for the use of the border node selection procedure. When T_{max} expires, a node checks whether it is the node with the least common neighbor number with the previous broadcast source based on all packets received and recorded in its Border Node Selection Table. If it is, it will select itself as a border node. Otherwise it is not a border node. As a node can only receive packets from the source node and from its common neighbors with the source node, the least common neighbor comparison is carried out between itself and its common neighbors with the source node.

TABLE 4. REBROADCAST PACKET FORMAT

Node ID	Dest. node ID	Comm. neigh. #	Reserved	Packet ID	Packet content	Neigh. list

To illustrate the border node selection process described in Case 2, an example network is shown in Fig. 3 with the details of the border node selection process shown in Table 5.

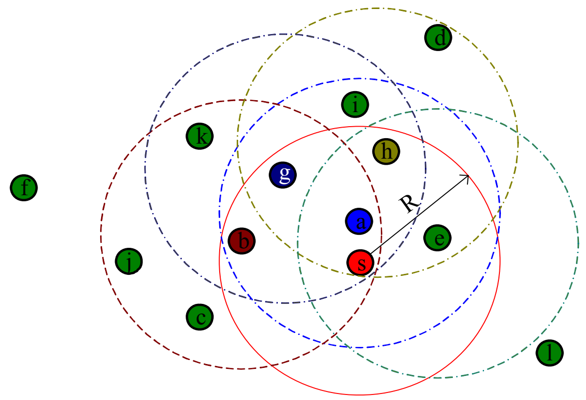


Figure 3. A typical network with a broadcast source node s.

For vehicular ad hoc networks, assuming mobile nodes move on a highway grid, it is expected that the nodes will be distributed along a narrow but long area, as indicated in the Figure 4. The width of a highway section is noted as W. Generally with modern wireless radio technology, W is much less than 2 times of the radio transmission range (R) of an individual node, namely, W<<2R. For example, the typical radio range based on 802.11b technology is about several hundred meters while the width of a highway road is generally less than 100 meters. Assuming a uniform node distribution, the neighbor nodes at the left and right transmission edge of the source node s, such as node b and node i, compared with node a, c and e, node b and i will have fewer common neighbor nodes with node s. With such a node distribution pattern, one observation is that neighbor nodes at the far left and far right ends of node s coverage area will have fewer common neighbors with node s, compared to those nodes that are closer to node s. In a real application, it is desirable that the message can be propagated along both road directions. Ideally nodes at far left and far right ends of node s coverage area will be selected as border nodes. This is effectively achieved in a linearly topology by choosing border nodes based upon the heuristic of least common nodes with the previous broadcasting node.

TABLE 5. BORDER NODE SELECTION PROCESS ILLUSTRATION

Node	Neigh. Set	*Comm. neigh. with node s*	Comm. neigh. #	Node action when T_{ad} expires	Border node decision when T_{max} expires
s	{h, e, g, b, a}				
h	{s, a, g, e, i, d}	{a , g, e}	3	Rebroadcast	yes
e	{s, a, h}	{a, h}	2	Keep silent	yes
g	{s, a, b, h, i, k}	{a, b, h}	3	Rebroadcast	no
b	{s, a, g, j, c, k}	{a, g}	2	Rebroadcast	yes
a	{s, b, g, e, h, i}	{b, g, e, h}	4	Keep silent	no

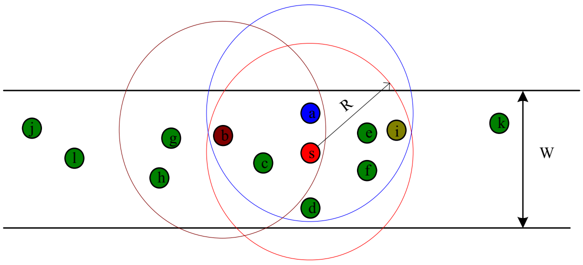


Figure 4. Typical node distribution on a highway section.

V. Simulations and Results

The BBR protocol was implemented in OPNET[TM] Modeler using C/C++. The BBR process model was integrated with the existing mobile MANET station node model. The simulation has two parts: The first part of our simulation is to study the general performance of the BBR protocol on a mobile ad hoc network using the Random Waypoint mobility model. The second part of the simulation is to study the BBR protocol performance on a VANET in a sparse area based on the GTI Mobility Model. To make comparisons, the performance of the DSR routing protocol is also evaluated under the same network configurations. DSR is chosen as the basis for comparison because it has better and more consistent performance at all mobility rates than other standard routing protocols that do not use explicit location information [32], such as AODV, TORA and DSDV.

For all simulations, the results are averaged over 15 runs with different random number seeds. The results are illustrated in the figures by the mean and error bars indicating the standard deviation. Metrics measured to evaluate the protocol performance are defined as follows:

Packet delivery ratio: The ratio between the number of non-repeat packets delivered to the destination and the number of packets sent by the source.

Delay: The average end-to-end transmission delay calculated by taking into account only the packets non-repeatedly received.

A. General Simulation Scenario

This scenario is designed to evaluate some general behaviors of BBR under different network connectivity characteristics and mobility.

Table 6 summarizes the basic parameter values used in the simulations. The nodes are initially uniformly placed within the simulation area. For the initial stationary distribution, the average distance among neighboring nodes which is noted as L_{av}, can be approximated by assuming these nodes are completely uniformly distributed in the simulation area. For this simulation area configuration, $L_{av} \cong \frac{(1+\sqrt{2})}{2} \cdot \sqrt{\frac{(1000 \times 1000)}{50}} = 171.4$ meters.

A parameter α is defined as the ratio between the radio transmission range R and L_{av}, namely $\alpha = \frac{R}{L_{av}}$. This parameter characterizes the degree of network connectivity. For $\alpha < 1$, the nodes are on average separated by more than the radio range, and the network is disconnected. For $\alpha > 1$, the average node separation is less than the radio range, and the network becomes gradually connected.

The Random Waypoint mobility model [33] with pause time equal to zero is used to model node movement. Shortly after the simulation begins, each node randomly chooses a destination node other than itself and sends out data packets for 20 seconds. The data packet inter-arrival time is uniformly distributed with an average of 2 seconds. The packet size has an exponential distribution with an average of 1024 bits. The parameters used in the simulations were selected to characterize rural area conditions where vehicle density is low and where the limits of current radio technology ranges result in frequent disconnections. The packet size ad transmission rates were selected as typical of messaging applications. The sections below present typical examples of BBR performance and comparisons with other protocols under similar conditions. Additional examples are available in [5] and [34].

Table 6. Simulation Parameters

Network simulator	OPNET[TM] Modeler	
Simulation area	$1000 \times 1000 m^2$	
Number of nodes	50	
Mobility model	Random waypoint	
Node speed	Uniform(0, 20) m/s	
MAC protocol	IEEE 802.11b	
Data rate	2Mbps	
Data traffic	Packet inter- arrival time	Uniform(1,3) s
	Packet size	Exponential Average:1024bits
BBR configurable parameters	HelloInterval	2 s
	MaxHelloLoss	2 times
	MaxRebroadcast	3 attempts
	TranDelaySlot	3 ms

B. Simulation Results for General Scenario

1) BBR performance as a function of radio transmission range. This set of simulations evaluates the routing protocol performance as a function of radio range. The simulation time for each run was 5000 seconds. The radio range was varied from 8 meters to 800 meters. The packet delivery ratio and the average delay per delivered packet as a function of the radio transmission range were shown in Figure 4 and Figure 5 respectively. The vertical dotted line in the figures indicates the point where the radio transmission range equals the average neighbor separation distance L_{av}.

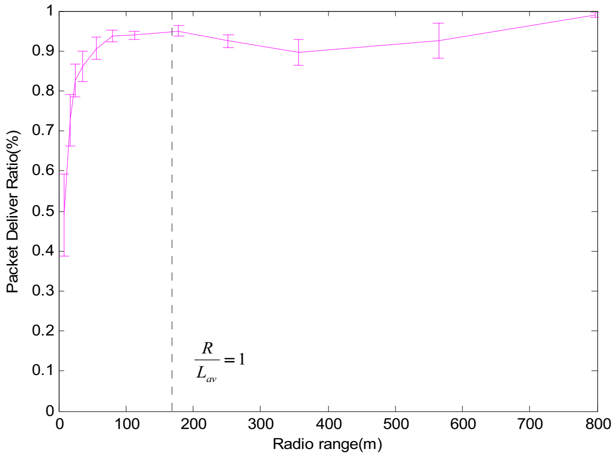


Figure 5. Packet delivery ratio vs. radio transmission range.

Figure 5 shows that as the radio transmission range increases, the packet delivery ratio initially increases rapidly. After the radio transmission range reaches about 80 m, the packet delivery ratio remains constant at about 90% and then gradually reaches 99%. BBR can achieve a relatively high percentage delivery ratio even when the network is partially connected. The increased sizes of the error bars for radio range greater than 300m are due to fewer runs used in the simulations, and the apparent dip in delivery ratio between 300m and 600m is an artifact of the dimensions of the simulation area, as when the radio range becomes comparable to the simulation area, the selection of border nodes in affected by the study area dimensions.

The low delivery ratios at small value of radio range R are mainly due to the value selected for HelloInterval, which is fixed to be 2 seconds for all simulations under different radio ranges. This value is not short enough for small radio range. Define t_R as the time that two nodes are within radio range of each other as they are moving towards each other. Then a small R corresponds to a small t_R. The selection criterion is that HelloInterval should be less than t_R to ensure that nodes can detect each other when they are in radio range. The use of a small HelloInterval yields a higher delivery ratio for short radio ranges, but at the same time increases the overall overhead, as is discussed below.

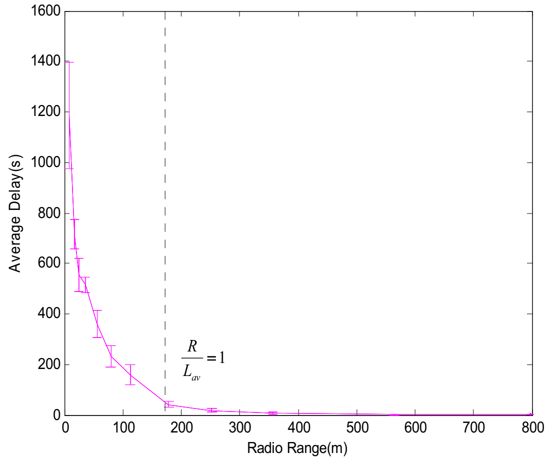


Figure 6. Average delay per delivered packet vs. R.

Figure 6 shows that average delay decreases rapidly when R increases. When R is larger than L_{av}, the delay is very short. The long delivery delay at small radio ranges is expected due to the fact that the network is highly partitioned at those radio ranges. Packet delivery under this condition is mainly dependent upon nodes carrying packets forward instead of using wireless communication among nodes. The network gradually becomes connected as R increases and exceeds L_{av}. In a more connected network, packets are delivered mainly through wireless communication among nodes, which significantly shortens the delay time. With BBR a relatively high and constant packet delivery ratio can be achieved for both fully connected and partially connected conditions. However, a high packet delivery ratio is achieved with a much longer packet delivery delay when the network is partially connected or highly partitioned.

2) Comparisons between the BBR Protocol and the DSR Protocol. Performances of both protocols were evaluated using the same network configurations. To test the effects of node mobility on protocol performance, each routing protocol was simulated with varying node mobility. The three groups of node speeds applied are with low, middle and high node mobility, where the speed of each node in the network is distributed uniformly with ranges (0, 2) m/s, (10, 20) m/s and (25, 35) m/s respectively. A detailed comparison of these two protocols under different node mobility conditions is given in Figure 7 for the delivery ratio and Figure 8 for average packet delivery delay. In Figure 7, the radio transmission range is on a logarithmic x-axis.

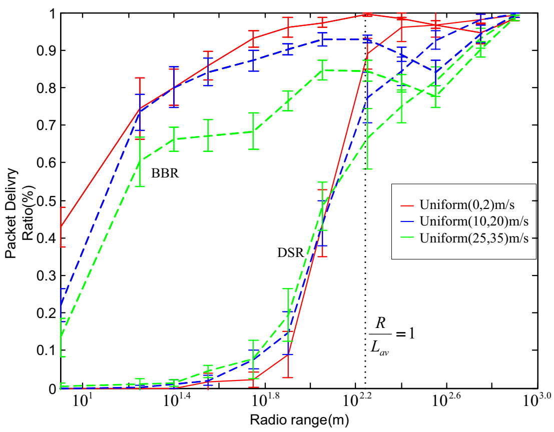


Figure 7. Packet delivery ratio comparison between BBR and DSR protocols.

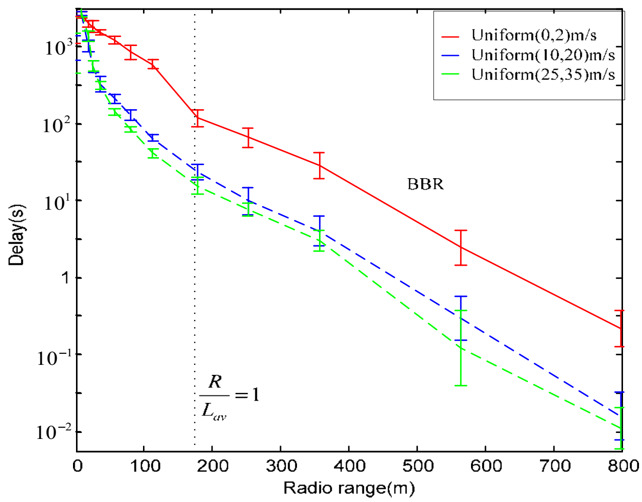
Figure 7 shows that when the radio range is very small and the network is highly partitioned, the packet delivery ratio with DSR is close to 0 percent. The packet delivery ratios with BBR are also low at very small radio ranges but increase much more rapidly than with DSR as the radio range increases. As discussed above, the packet delivery ratio of BBR is sensitive to the HelloInterval selected. For all simulations shown here, the HelloInterval is 2 seconds. If instead, a much smaller HelloInterval is chosen, the packet delivery ratio at small radio range can be substantially improved and other simulations, conducted with varying values of the HelloInterval validate this effect. Hence, the BBR routing protocol can yield much better performance than DSR when a network is highly partitioned. This result is expected since packet delivery using DSR is based on the discovery of connected route from source node to destination node at a specific time, which has very low probability when the network is highly partitioned. While for BBR, packet delivery is based on “carry and forward”. As long as enough neighbors are encountered during the simulation time, the probability that packets get delivered is much higher.

As R increases, the packet delivery ratio for both routing protocols increases. However, the packet delivery ratio of BBR reaches a relatively high value well before the point where the network becomes fully connected. While for DSR, the packet delivery ratio remains low until the network becomes more fully connected. Finally, the packet delivery ratios of both protocols converge to 100% when the network is fully connected.

Figure 7 also shows that for BBR, the packet delivery ratio is higher at low node speed than at high speed for the whole radio transmission range. In other words, in terms of packet delivery ratio, BBR performances better at low node mobility. The reason behind this is that for BBR, packet forwarding sometimes is not packet by packet. Instead, when a forwarding node meets a destination node and there is a sequence of packets destined to that node in its Forward Table, the forwarding node will forward that node the entire sequence at one time. High node mobility increases the possibility of packets getting lost in such situations, which is the main reason that packets can’t be delivered with the BBR protocol. For the DSR protocol, when the radio transmission range is small, node mobility actually helps to slightly improve the packet delivery ratio, as indicated in the figure. At radio ranges less than about 100 meters, the packet delivery ratio with high node mobility is higher than that of low node mobility. However, as the radio range further increases to larger than the L_{av} and thereafter, DSR has better performance at low node mobility in terms of packet delivery ratio. The reason high node mobility improves the packet delivery ratio at small radio ranges for DSR routing can be explained as follows. When R is small and network is highly partitioned, the possibility that a source node will find a connected path to the destination node is very low if the destination node does not happen to be in the neighbor range of the source node. In DSR, packet delivery is always packet by packet. Within these radio ranges, high node mobility increases the possibility that a source node meets a destination directly and results in a higher packet delivery ratio. On the other hand, as the radio range increases and the network becomes fully connected, high node mobility will cause an existing connected route to be easily broken, causing packets to be lost during forwarding, resulting in a lower packet delivery ratio.

It is also noted from the figure that when the radio transmission range increases to the point where almost all nodes are neighbors of each other, both BBR and DSR can deliver a packet using only one hop. Then the effects of node mobility on packet delivery ratio can be neglected. In fact, at this point, each protocol reaches an almost 100% delivery ratio.

Figure 8 shows the simulation results for average packet delay using BBR and DSR protocol. We note that with DSR, for short radio ranges, the packet delivery probability goes to zero and the delay becomes infinite. Hence to make useful comparisons the radio range on the x-axis begins at 80 meters for the DSR case. For both protocols, the average packet delivery delay drops rapidly as the radio transmission range increases and node mobility also helps to decrease the packet delivery delay. The high delivery delay for BBR at low radio ranges is due to the network being highly partitioned. The delivery of packets is mainly dependent upon node movement. This also explains why the average packet delivery delay is shorter when node mobility is higher. The low delivery delay for the BBR at high radio ranges is the result of the network becoming gradually connected, and packet



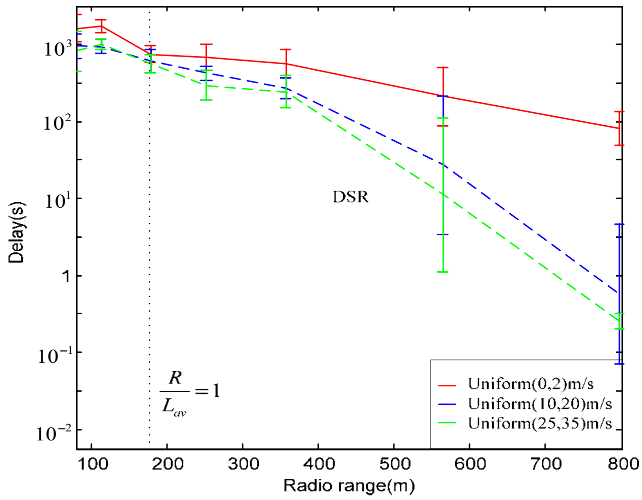


Figure 8. Average packet delivery delay comparison between BBR and DSR protocol.

delivery is dependent upon more on wireless communications among neighboring nodes instead of node movement. For DSR, the high delivery delay is due to the low probability of finding an end to end path when the network is highly partitioned. Packets must be queued in the send buffer for long time intervals before the route discovery procedure is successfully completed.

For both routing protocols, high node mobility helps to reduce packet delivery delay but decreases the packet delivery ratio. For BBR, the packet delivery ratio is relatively constant over radio ranges considered, but the packet delivery delay is much longer when the radio range is small corresponding to a highly partitioned network. For DSR, the packet delivery ratio remains low until the radio range increases sufficiently to make the network connected.

The simulation results also indicate that when a network is fully connected, DSR outperforms BBR slightly in terms of packet delivery ratio, but with a little bit longer packet delivery delay. Due mainly to control overhead related to the neighbor discovery process, BBR has higher control overhead than DSR. The neighbor discovery process is executed regardless of whether there is any data traffic. DSR is a reactive routing protocol. The main control overhead is related to route discovery, which only occurs when there are data packets to be sent.

C. Highway Simulation Scenario

This simulation scenario is designed to evaluate the performance of the BBR protocol in a VANET, where mobile nodes movement is restricted to roads. The GTI Mobility Model [5] is used to model node movement. The simulation area chosen for this scenario is based on the highway system inside Yellowstone National Park. The number of mobile nodes in the network is 150, with the approximate average neighbor distance L_{av} to be 2085 meters. These parameter choices were selected based on examination of park usage data. To make a comparison of packet delivery delay with the actual time for a mobile node to move from one specific location to another, the data traffic is specified as follows. Shortly after the simulation begins, a source node located at the West Thumb point within Yellowstone National Park sends out data packets to a destination node located at the west entrance of the park. Data traffic continues for 40 seconds. The packet inter-arrival time is exponentially distributed with an average of 1 second. The packet size is exponentially distributed with an average packet size of 1024 bits. Table 7 gives a summary of the basic simulation parameters and values.

TABLE 7. SIMULATION PARAMETERS FOR HIGHWAY SCENARIO

Network	OPNET™ Modeler	
Simulation area	Yellowstone Highway System	
Number of nodes	150 (*Lav* =2085 meters)	
Mobility model	GTI mobility model	
Node speed	Uniform(18, 22) m/s	
Simulation time	1.5 hrs	
MAC protocol	IEEE 802.11b	
Data rate	2Mbps	
Data traffic	Packet inter-arrival	Exponential(1) s
	Packet size	Exponential(1024) bits
BBR configurable parameters	HelloInterval	2 s
	MaxHelloLoss	2 times
	MaxRebroadcast	3 attempts
	TranDelaySlot	3 ms

D. Simulation Results for Highway Scenario

Figure 9 shows a comparison of the packet delivery ratios obtained with BBR and DSR. The results indicate that BBR yields a very high delivery rate that is close to 100% for all radio transmission ranges. For DSR, the delivery rate is close to 0 when the ratio $\alpha = \frac{R}{L_{av}}$ is less than 1. Once α is larger than 1, the delivery ratio increases rapidly to a relatively high point over 90%. When the radio range is sufficiently large so that the whole network becomes fully connected, both protocols exhibit a 100% packet delivery ratio. Note that α characterizes the network in terms of its end-to-end connectivity. When α>1, the network is fully connected and DSR performs well. When α<1, the network partitions into disconnected subnets, and DSR cannot find end-to-end paths between disjoint subnets, resulting in low packet delivery ratios. We also note that these results are optimistic in that terrain effects have not been taken into account.

For BBR, the packet delivery ratio is relatively consistent at different radio transmission ranges and has a higher delivery ratio even at low radio ranges. The reason for this behavior is that BBR is based on store-and-forward approach. For sufficiently long simulation time, the possibility that a source node or a forwarding node can meet the destination node is high, resulting in the high delivery ratio even at low radio ranges.

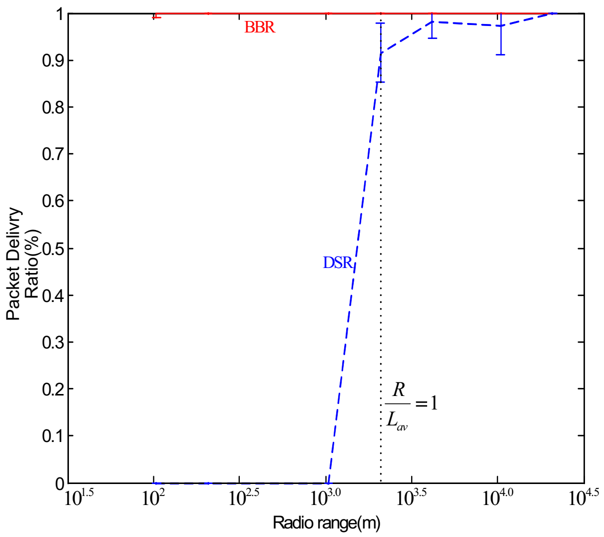


Figure 9. Packet delivery ratio comparison between BBR and DSR protocols.

Figure 10 gives a comparison of the packet delivery delays with BBR and DSR. For DSR, once the network becomes connected, delivery delay is short. With DSR, the packet delivery is always accomplished by wireless communication among nodes composed of a complete path from source node to destination node. As long as a complete route can be found, the packet delivery is accomplished within a minute.

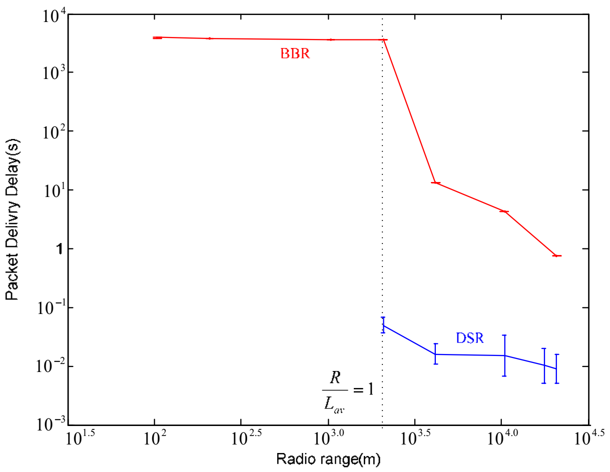


Figure 10. Packet delivery delay comparison between BBR and DSR protocols.

For BBR, when the radio range is small and the network is partially connected, before α reaches 1, the packet delivery delay remains relatively large, (about 3700 seconds for the scenario modeled). This time period is very close to the time interval for a node to move from the source point to the destination point, which is about 3300 seconds with an average node speed of 20 m/s. In Figure 10, when α is larger than 1, the packet delivery delay decreases gradually, as now the delivery of packets depends partly on wireless communication among mobile nodes and partly on node movement. When the network is fully connected, the packet delay is also in the range of minutes and comparable to DSR[3] since the packet delivery at these radio ranges is fully due to wireless communication among mobile nodes.

Additional simulations as discussed in Section III were carried out using an epidemic routing protocol, where every node keeps copies of all packets that it receives and then exchanges these packets with every other node that comes within its transmission range. The parameters used were the same as in Table 7, but the simulation was carried out using a model written in C. The results of these simulations showed that the delay time for epidemic routing with $\alpha<1$ is essentially the same as was obtained with BBR. However, the epidemic routing approach incurs considerably greater overhead, as packet exchange occurs among all nodes instead of only among border nodes. Furthermore, with epidemic routing, large packet buffers are required as packets are never discarded. With BBR, packets are discarded when the number of attempts exceeds the MaxRebroadcast counter, limiting the buffer size requirements.

It should be noted that the overhead incurred with BBR will be larger than with DSR, as BBR uses periodic broadcasts for neighbor discovery. While this is a disadvantage in dense networks, the cost is inconsequential in sparse and partially connected networks. An ideal approach would be to apply an adaptive procedure that uses BBR when the node density is low and reverts to DSR or another conventional protocol, when the network becomes fully connected. We also note that position-based protocols may perform better than DSR under fully connected conditions. However, these protocols require a location service, which may not work effectively in rugged terrain conditions and in sparse networks.

VI. CONCLUSIONS

In this paper, a BBR protocol was proposed for partially connected VANETs. Using OPNET™, the performance of the BBR protocol has been evaluated and compared with the DSR routing protocol with node mobility characterized by the Random Waypoint mobility model and the GTI mobility model. The simulation results indicate that BBR performs well for networks with frequent partitioning and rapid topology changes. With the BBR protocol, high packet delivery ratios can be achieved with long packet delivery delays when the network is highly partitioned. Compared to the DSR

[3] Note that the y-axis in Figure 10 is logarithmic to show a wide range of delay times.

protocol, the BBR protocol yields a better performance when the network is partially connected and comparable performance when the network is fully connected. This new protocol is well suited for vehicle-to-vehicle communications along sparsely used highways, as would be the case in rural and remote areas. The BBR protocol may also have application in rural public safety networks, where responders must rely on ad hoc networks rather than fixed infrastructure and cannot assume connectivity. Further work is needed to address these less constrained conditions, and to consider support for real time applications and quality of service.

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