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Towards Delay Tolerant Networking for Connectivity Aware Routing Protocol for VANET-WSN Communications

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Abstract: Vehicular Ad Hoc Networks (VANETs) are increasingly playing a fundamental role in improving driving safety. However, VANETs in a sparse environment may add risk to driving safety. The probability of a low density of vehicles in a rural area at midnight is very high. Consequently, the packet will be lost due to the lack of other vehicles, and the arrival of the following vehicles in the accident area is unavoidable. To overcome this problem, VANET is integrated with Wireless Sensor Network (WSN). The most challenging features of VANETs are their high mobility. This high mobility causes sensor nodes to consume most of their energy during communication with other nodes, leading to frequent network disconnectivity. With the evolution of VANET and WSN, the Store/Carry-Forward (SCF) paradigm has emerged as an exciting research area in the Delay Tolerant Networks (DTNs) to solve network disconnectivity. This paper proposes the Energy-Mobility-Connectivity aware routing protocol (EMCR) for a hybrid network of VANET-WSN. A comprehensive performance analysis that considers realistic propagation models and real city scenario traffic is performed in NS3. The simulation results show that the SCF mechanism is essential in the EMCR protocol to maximize the delivery ratio and minimize energy consumption and overhead.

Keywords: delay tolerant network; vehicular ad hoc network; wireless sensor network; store-carry-forward; VANET; WSN; DTN; SCF

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1. Introduction

Vehicular Ad Hoc Networks (VANETs) and Wireless Sensor Networks (WSN) are experiencing growing interest as they are expected to play a pivotal role in making smarter, safer, and more efficient transportation networks. Recent advancements in automotive, sensing, transportation, wireless communication, and networking technologies have paved the way for the evolution of vehicular ad hoc networks (VANETs) into the Internet of Vehicles (IoV). VANETs are the most crucial component of Intelligent Transport Systems (ITS) [1]. Most modern vehicles are equipped with several devices, such as onboard Units (OBU), sensors, navigation systems, and geographic positioning systems (GPS) for vehicle-to-vehicle, vehicle-to-Infrastructure, vehicle-to-pedestrian, and vehicle-to-wireless sensor network communications. The resulting technology, as specified in Ref. [2], is referred to as cellular-V2X (C-V2X), which is an umbrella term that includes both the long-term evolution (LTE) enhancements and the fifth generation (5G) new radio (NR) latest advancements to support V2X communications using cellular technologies. Typically, vehicles have sufficient resources, such as storage, computing power, batteries, and high-speed wireless communication interfaces, with good reliability and manageability. The main goal of VANETs is to improve driving safety by monitoring road conditions opportunistically. However, VANETs in a sparse environment may add risk to driving safety [3]. Suppose at midnight in some rural area; a vehicle has a critical data packet (i.e., detection of an accident), which should immediately be forwarded to the following vehicles. In this situation, the probability of a low density of vehicles is very high. Thus, the packet will be lost due to the lack of other vehicles, and the arrival of the following vehicles in the accident area is unavoidable. Therefore, VANET is integrated with a WSN, an essential technology for the future Internet of Things (IoT). WSNs usually operate with batteries that cannot be rechargeable.

In the hybrid network of VANET-WSN, the prime concern of routing is to discover and maintain up-to-date information about neighboring nodes, which can be acquired through the transmission of beacon messages. However, high mobility causes sensor nodes to consume most of their energy during communication with other nodes. This battery drainage leads to frequent network disconnectivity. Therefore, the high mobility and battery drainage result in a network partitioning, making it difficult for the packets to be delivered from the source to the destination [4]. In such dynamic environments, a delay tolerant network (DTN) [5,6] uses the Store/Carry-Forward (SCF) mechanism for routing packets from source to destination. The SCF networking allows wireless communication nodes to act as intelligent relay nodes that can store or carry messages waiting for a better opportunity for transmission and then forward the packets to other nodes. The SCF mechanism is vital to solve the network disconnection problem and improve the efficiency of VANET and WSN.

The main contribution of this paper can be summarized as follows:

- We propose an effective data forwarding mechanism called the Energy-Mobility-Connectivity aware routing protocol (EMCR). The EMCR protocol considers the significant factors in the hybrid network of VANET-WSN to balance the energy consumption of WSN and the highly dynamic mobility of VANET and address network partitioning by adopting the SCF mechanism. SCF is essential for limited radio communication environments to solve network disconnectivity and maximize delivery at the destination. The EMCR protocol makes the hybrid network of VANET-WSN useful in a wide range of applications, from critical safety services to infotainment applications.

2. Related Work

Many routing algorithms have been proposed for VANETs and WSNs, including geographic routing protocols. Geographic routing protocols address several limitations of topology-based routing protocols by using the nodes' geographic position information, the destination position, and the next neighbor's location obtained from the GPS to find the route [7]. The use of beacon messages sent periodically allows for a scalable network adapted to a dynamic environment such as VANET. There are three categories of geographic routing protocols:

- Delay tolerant networks (DTN): In the dynamic topology, the routing protocols suffer from communication disconnections, latency, and high error rates. The DTN protocols overcome these problems and maintain network connectivity by using a packet forwarding strategy based on storing messages in the cache until a node is suitable for transmitting the packet;
- Non-Delay Tolerant Network (Non-DTN): This category of non-DTN routing protocols aims to overcome the problems encountered with the greedy approach. The greedy approach sends the packet to the nearest node toward the destination. However, it is possible that the forwarding node itself is closest to the destination. Many types of non-DTN protocols have been developed to handle this failure;
- Hybrid routing protocols: The hybrid routing protocols benefit from both position-based routing (DTN and non-DTN) and merge the two routing strategies to resolve network disconnect issues.

In VANETs, the frequent changes in topology induce serious problems in scaling up traditional routing protocols. Most of the existing routing protocols are unable to handle frequent network disconnections. However, a few protocols such as Vehicle-Assisted Data Delivery protocol (VADD) [8], the Cross-Layer Weighted, Position-based routing (CLWPR) protocol in Refs. [9**?**], and the optimized CLWPR (O-CLWPR) [11] are aimed at improving routing in disconnected vehicular networks in urban scenarios where they benefit from DTN by using a carry-and-forward approach until a relay is found. Thus, it takes a long time to deliver packets in low-density networks. The disconnection phenomenon in VANETs is known as "local-maximum" problems that occur when a packet reaches a node that is closer to its destination than any other node within range. For example, node x in Figure 1 is closer to the destination node D than its neighbors y and w, so node x will not choose to forward to y or w using greedy forwarding. Node x is in a local-maximum in its proximity to destination node D. Therefore, the packet delivery is improved by allowing the current node to carry the packet for a while until it encounters some neighbors.

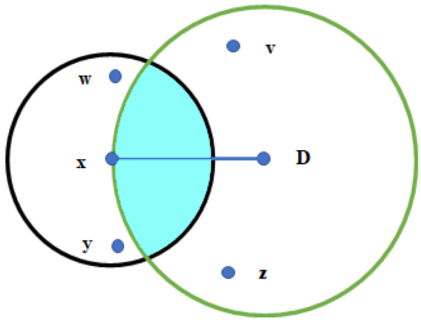


Figure 1. Local-maximum problem when a packet reaches node x that is closer to its destination node D than any other node (w,y,v,z) within the range.

Geographic routing has recently gained a lot of popularity because it is incredibly effective and simply needs to know the positions of sensor nodes. However, a fundamental issue with geographic routing in WSNs is the "local-minimum" phenomenon, which prevents greedy forwarding. This phenomenon is linked to a region known as a hole that is lacking of active sensors and, as a result, either prevents the packet from being transmitted to a destination node or results in a lengthy detour path [12]. Figure 2 indicates that the WSNs suffer from "local-minimum" problems when a packet is forwarded to a node with no direct neighbors closer to the destination than itself. Since there is no direct neighbor closer to the destination than the node A itself, node A receives all destination's traffic packets. This depletes the node A's energy more quickly than other nodes. Uneven energy consumption of sensor nodes can also lead to new routing holes in the WSN [13].

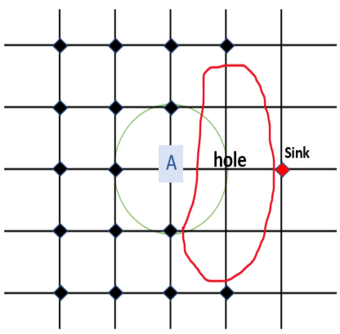


Figure 2. Local-minimum problem when a packet reaches node A and there is no direct neighbor closer to the sink than node A itself

Most existing protocols, such as Refs. [14–17], allow the holes to be detected prior to routing initialization. Others tend to avoid the holes and solve the local-minimum problem by walking along only one side of the routing hole to recover the route. These protocols cannot guarantee that all packets are delivered in an energy-efficient manner once encountering the routing holes. Among them, the proposed scheme in Ref. [18] considers the transmission range of the destination node and the received signal strength (RSSI) to enable the construction of routing paths by self-electing the next hop at each step while performing data aggregation. In Ref. [19], the main idea is to exploit the Q-learning technique to estimate the distance from a node to the hole. The routing decision is then determined based on the residual energy of the nodes, their estimated distance to the holes, and their distance to the destination. The proposed geographic routing protocol, named BSMH in Ref. [20], is a load-Balanced and constant Stretch protocol for bypassing Multiple Holes in WSNs. BSMH considers three essential network lifetime impact factors: routing path length, control overhead, and load balancing. The limitation of the protocol is that it still suffers from extra costs caused by the first two phases (i.e., hole determination and hole information dissemination).

On the other hand, the authors in Ref. [21] proposed an energy-aware dual-path geographic routing (EDGR) protocol for better route recovery from routing holes. EDGR adaptively utilizes the location information and residual energy to make routing decisions and dynamically exploits two node-disjoint anchor lists passing through two sides of the routing holes to shift the routing path for load balance. However, EDGR cannot guarantee the improvements in the network performance in terms of packet delivery ratio, delivery delay, and network lifetime. In Ref. [22], the authors proposed an energy-efficient routing protocol for Opportunistic Networks using Markov Chain (called ELPFR-MC) in which the next best hop selection of a message relies on the node's residual energy and location-based delivery probability for message forwarding. However, the ELPFR-MC protocol was not investigated using real-trace mobility models.

Furthermore, the frequent network disconnection problem is the most critical issue in designing a hybrid network of VANET-WSN. The proposed EMHR [23] is a hybrid network of VANET-WSN that suffers from network disconnection caused by the mobility of vehicles and battery drainage of sensors. In Section 6.2.2, EMHR performance has been comparatively evaluated with CLWPR. By conducting extensive simulation experiments, EMHR demonstrates a higher Packet Delivery Ratio and Throughput and lower end-to-end delay in the hybrid network of VANET-WSN. However, CLWPR demonstrates an improvement in energy consumption using the carry-and-forward mechanism. This is the reason we have selected EMHR as the basis of our work and extended it to the SCF mechanism, as explained in Section 4. Therefore, we propose a novel routing protocol, called the Energy-Mobility-Connectivity aware routing protocol (EMCR), to disseminate messages in the hybrid network of VANET-WSN, aiming to manage network partition problems. The proposed scheme adopts a novel store/carry–forward (SCF) mechanism to overcome network partition problems. The SCF scheme is expected to distribute warning messages with low overhead and a high delivery ratio. In addition, the study in Ref. [24] claims that VANET-WSN can be improved in the future by integrating the 5G New Radio (NR) air interface, which adds expanded functions on top of the 5G NR air interface to facilitate connected and automated driving.

3. The Proposed EMCR Protocol

This paper proposes the Energy-Mobility-Connectivity aware routing protocol (EMCR) to overcome the disconnection problem in a hybrid network of VANET-WSN. The EMCR system model is presented in Figure 3. EMCR uses geographical positions for routing. The nodes periodically broadcast beacons (i.e., Hello messages) with their node's ID, current position, speed, heading, and energy level. The location service maps the node's ID to its current position. EMCR is based on opportunistic forwarding. Therefore, there is no route discovery before the data dissemination. The HELLO module is part of the routing protocol that is responsible for generating HELLO messages. These messages aim to discover direct neighbors and learn their energy level and mobility (velocity and heading).

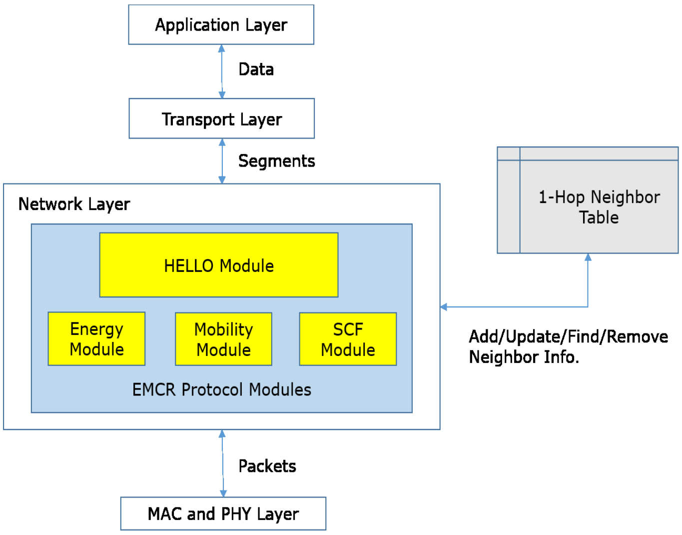


Figure 3. EMCR system model.

The two primary repositories in EMCR are the neighbor set and the position association set. The neighbor set is used to construct and maintain the one-hop neighbor's table. Each time a HELLO message is received, we check this repository and either create a new neighbor or update the neighbor information. Each entry will be automatically deleted after a period of ($2.5 \times helloInterval$) time. This time allows a node to remove neighbors that are not in the vicinity and hold the information if a HELLO is lost. The Position Association Set (PAS) keeps track of the position information of any destination that the specific node has data to deliver. It is a local copy of the location service. If an entry in this set is also a neighbor, it is updated with HELLO messages. Otherwise, a location service will provide this information to maintain the repository.

In the EMCR protocol, the mobility module is based on the fact that some nodes are stationary roadside wireless sensors. The sensor nodes are not equipped with Digital Maps; instead, they use Euclidean distance in their calculation. Other nodes are vehicles. Vehicles can find the road they are traveling on since they are equipped with Digital Maps of the road topology. The position and velocity information are used to predict the position of neighbor (and destination) nodes. Employing position prediction will indeed result in less overhead. The position prediction calculation is

$$
\begin{aligned}
D_x &= d_x + v_x \times \Delta t \\
D_y &= d_y + v_y \times \Delta t,
\end{aligned}
\tag{1}
$$

where D_x and D_y are the future positions based on the current node position (i.e., d_x and d_y), velocity (i.e., v_x and v_y), and Δt (i.e., the elapsed time between the present time and the time of the last received beacon).

The energy module is an essential component of the protocol for routing decisions. The EMCR protocol routes a packet by computing each neighboring sensor node's residual energy ratio (RER). Sensors that consume less energy will be selected as a forwarder node. All this information is jointly combined in a weighting function that calculates a weight for each neighboring node, based on which forwarding selection is performed.

4. Store/Carry-Forward (SCF) Module

Delay tolerant networks (DTNs) are networks with inconsistent connectivity and nonconsecutive end-to-end paths between nodes. DTNs employ the Store/Carry-Forward (SCF) mechanism to manage frequent connectivity disruption [25]. For instance, if a node has data but has no connection to transmit it, the message will be stored in a buffer in the sensor or carried by a vehicle as proposed in Ref. [26] until it finds a forwarding node based on some utility values.

The fundamental question is how to relay packets from the source to the destination fast and reliable through multiple hops. In this research, the Energy-Mobility-Connectivity aware routing protocol (EMCR) utilizes information stored in the neighbor's table to forward the packet toward the destination, typically consisting of two modes—greedy mode and DTN mode. In the greedy mode, packets are forwarded to a neighbor (sensor or vehicle) closest to the destination with the minimum weight. In the presence of a local-maximum problem, when the forwarding node (sensor or vehicle) is the closest to the destination with the minimum weight, the forwarding in the EMCR will change to DTN mode. When a node cannot find any desired neighbor, the sensor will store the packet, and the vehicle will carry the packet for a while until it can forward the packet to some desirable neighbors. Therefore, the DTN mode uses the SCF mechanism to solve the disconnection problem and improve the efficiency of VANET-WSN.

When a node has a packet to route in the network layer, the source and destination information is extracted from the packet's IP header. Once the Location Service has determined the packet's destination, the Position Association Set (PAS) is updated (LS). The packet can then choose the next hop. If the destination's position is known, it can proceed; otherwise, it must wait for a response from the Location Service. Since the PAS is updated, the routing table must be recalculated, and the entry with the minimum weight is extracted. If that entry is the current node, then we are in a local-maximum case and the SCF mechanism is employed. The SCF mechanism creates a virtual route towards the current node, and this route is achieved with the help of a DeferredRouteOutput Tag added to the packet that creates a "route" for local delivery. Otherwise, a route for the selected entry is created. This process is shown in Algorithm 1.

Algorithm 1 A packet to be routed in the network

```
Check destination;
if Position is known then
    Calculate weight
else
    Request information from Location Service.
    Calculate weight.
end if
if Local-Maximum then
    Add DefferredRouteOutput Tag.
    Return Route.
else
    Create Route for the selected node.
    Return Route.
end if
```

As described in Algorithm 2, when a packet is received, it is first checked to see if it has the DeferredRouteOutput Tag, which denotes that the SCF mechanism is employed. Then, the packet is stored in the buffer. The buffer has a limited size, which is the number of packets it stores, and limited cache time. Any packet will be dequeued each time the routing table is updated and the route has changed to check if the forwarding node is not the current node or the current node is the destination. If the local-maximum problem is solved, all packets for that destination will be dequeued. On the other hand, if there is no tag in the packet and it is destined for local delivery, the LocalDelivery Callback is called, and the packet is passed to higher layers. If the packet is not for local delivery, then it has to be forwarded, and the UnicastForward Callback is called.

Algorithm 2 A received packet

if *packet has DeferredRouteOutput Tag* **then**
  Create Query Entry and store the packet.
  Return.
  if *Local Delivary* **then**
    LocalDeliveryCallback.
    Return.
  else
    Request information from Location Service.
    Lookup Routing Table for minimum weight.
    if *Local-Maximum* **then**
      Add DeferredRouteOutput.
      Create Route for Local Delivery.
      UnicastForwardCallback.
      Return.
    else
      Create Route for selected node.
      UnicastForwardCallback.
      Return.
    end if
  end if
end if

5. Forwarding Metric

The mobility in the EMCR protocol considers the calculation of the curve-metric distance between the forwarder node and its neighbors with respect to their distance from the destination. In addition, the transmission range of sensors and vehicles is considered an essential factor in the forwarding decision, with the knowledge that the transmission range of vehicles (i.e., 500 m) is different from the transmission range of sensors (i.e., 150 m). The transmission range factor plays a role in improving the forwarding decision when this factor is used to normalize the distance between the forwarder and neighbor node in the weight function.

A forwarding node i computes the weight of neighbor node j with respect to routing to destination node k. If node j is in the transmission range of sensor node i, then the distance will be normalized by the transmission range of the sensor. Otherwise, if node j is in the transmission range of vehicle node i, the distance will be normalized by the transmission range of the vehicle. The neighbor closer to the destination is the most suitable forwarder node. Therefore, the weight is inversely proportional to the distance between the forwarder and the neighbor. Hence $Weight_{i,j}^{(k)} \propto (Dist_{i,k} - Dist_{j,k})^{-1}$. The equation for the normalized distance is

$$NDist_{i,j}^{(k)} = \frac{Dist_{j,k} - Dist_{i,k}}{R_i} \tag{2}$$

where $NDist_{i,j}^{(k)}$ is the normalized curve-metric distance between forwarder i and neighbor j from destination node k. $Dist_{j,k}$ is the curve-metric distance of neighbor j from destination $nodek$, and $Dist_{i,k}$ is the curve-metric distance of forwarder i from destination node k. R_i is the transmission range of forwarder node i.

$Angle_{j,k}$ is the normalized weight for the angle parameter. $Angle_{j,k}$ gives more weight to the nodes that are moving toward the destination compared to those that are moving away.

$$Angle_{j,k} = \begin{cases} -0.5 & \text{if VN are moving closer} \\ +0.5 & \text{if VN are moving away.} \end{cases} \tag{3}$$

$Road_{j,k}$ is the normalized weight for the road parameter in order to give more weight to nodes that are along the same road compared to those that are on a different road,

$$Road_{j,k} = \begin{cases} 0.0 & \text{if VN are on same road} \\ +0.5 & \text{if VN are on different road} \end{cases} \quad (4)$$

The residual energy ratio metric is an essential component of the protocol for WSN. The algorithm routes a packet from one sensor to another by computing the residual energy ratio for each neighboring node.

$$RER = \frac{E_{rem}}{E_{init}}, \quad (5)$$

where RER is the residual energy ratio that is calculated using the remaining energy, E_{rem}, and the initial energy, E_{init}, which is the capacity stored in the energy source.

The node with the minimum weight value will be selected as a forwarder node. The weight calculation for vehicle nodes with mobility consideration is

$$\begin{aligned} Weight_{i,j}^{(k)}(VN) = (\alpha_1 \times NDist_{i,j}^{(k)}) + (\alpha_2 \times Angle_{j,k}) \\ +(\alpha_3 \times Road_{j,k}). \end{aligned} \quad (6)$$

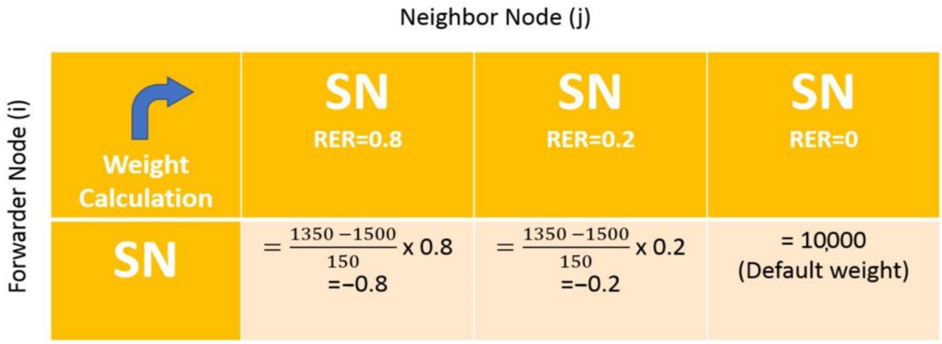
In order to get the minimum weight for sensor nodes, since the weight is inversely proportional to the distance between the forwarder and neighbor node, then the weight has to be directly proportional to the residual energy ratio as $Weight_{i,j}^{(k)} \propto RER_j$. The weight calculation for sensor nodes with residual energy consideration is

$$Weight_{i,j}^{(k)}(SN) = (\alpha_4 \times NDist_{i,j}^{(k)}) \times (\alpha_5 \times RER_j), \quad (7)$$

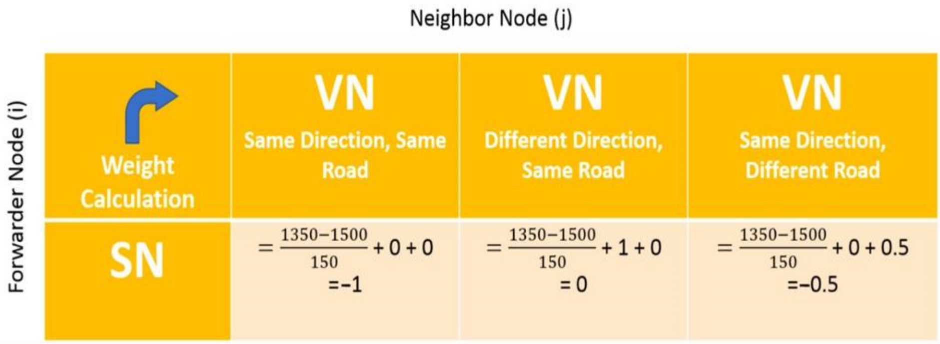
where α_i is the weighting factor for each parameter that indicates the relative importance of the parameter in making forwarding decisions. The weighting factors in Equations (6) and (7) are set to $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 1$, to have equal importance to all factors. The results of our performance analysis are provided in the following section.

Analysis of Weight Calculations

This section provides Algorithm 3 that shows how the forwarding decisions are made based on the weight calculations. According to Algorithm 3, the default weight value is equal to 10,000. When the forwarder node (i) is a sensor, the transmission range of 150 m will be used in the distance normalization. The weight calculations for neighbor nodes are influenced by several independent parameters, such as residual energy (RER), Direction (Angle), and (Road). In Example 1 shown in Figure 4, we assume that the distance from the forwarder node (i) to the destination node (k) is 1500 m, and the distance from the neighbor node (j) to the destination node (k) is 1350 m. Algorithm 3 determines the weight calculation when the neighbor nodes are sensors. The weight calculation for a sensor with a high RER, such as 0.8, is $(1350 - 1500)/150 \times 0.8 = -0.8$, whereas the weight calculation for a sensor with a low RER, such as 0.2, is $(1350 - 1500)/150 \times 0.2 = -0.2$. Therefore, the sensor with the highest RER will have the minimum weight calculation. Moreover, Algorithm 3 determines the weight calculation when the neighbor nodes are vehicles. In Example 2, shown in Figure 4, the weight calculation for a vehicle that is moving in the same direction and on the same road to the destination is $(1350 - 1500)/150 + 0 + 0 = -1$. Whereas the weight calculation for a vehicle on the same road but moving away from the destination is $(1350 - 1500)/150 + 1 + 0 = 0$. In addition, the weight calculation for a vehicle that is moving in the same direction but on different roads is $(1350 - 1500)/150 + 0 + 0.5 = -0.5$. Therefore, the vehicle that is in the same direction and on the same road to the destination will have the minimum weight calculation.



(**a**)



(**b**)

Figure 4. Examples for a forwarder sensor and the weight calculation for its neighbors. (**a**) Example 1. (**b**) Example 2.

Algorithm 3 Weight calculation for the neighbor nodes (Sensors/Vehicles)

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initialization:
weight = 10,000
if neighbor node (j) is Sensor **then**
  if $RER > 0$ **then**
    weight = $((Dist(j) - Dist(i))/TxRange(i)) \times RER(j)$.
  end if
end if
if neighbor node (j) is Vehicle **then**
  if $x - axisforneighbornode(j) \neq x - axisfordestinationnode(k)$ **then**
  $Road(j) += 0.5$.
    if $y - axisforneighbornode(j) \neq y - axisfordestinationnode(k)$ **then**
  $Road(j) += 0.5$.
  if neighbor node (j) approaching destination node (k) on x-axis **then**
    $Angle(j) -= 0.5$.
    $Angle(j) += 0.5$.
  end if
  if neighbor node (j) approaching destination node (k) on y-axis **then**
    $Angle(j) -= 0.5$.
    $Angle(j) += 0.5$.
  end if
  weight = $((Dist(j) - Dist(i))/TxRange(i)) + Angle(j) + Road(j)$.
end if
return weight.

On the other hand, if the forwarder node is a vehicle, the transmission range of 500 m will be used in the distance normalization. When the neighbor nodes are sensors, the sensor with the highest RER will have the minimum weight calculation. In Example 3 shown in Figure 5, the weight calculation for neighbor sensors when the RER is 0.8 or 0.2 will be $(1350 - 1500)/500 \times 0.8 = -0.24$ and $(1350 - 1500)/500 \times 0.2 = -0.06$, respectively. Whereas for the weight calculation when the neighbor nodes are vehicles, the vehicle in the same direction and on the same road to the destination will have the minimum weight calculation. In Example 4 shown in Figure 5, the weight calculation for a vehicle that is moving in the same direction and on the same road is $(1350 - 1500)/500 + 0 + 0 = -0.3$. The weight calculation for a vehicle on the same road but that is moving away from the destination is $(1350 - 1500)/500 + 1 + 0 = 0.7$. Finally, the weight calculation for a vehicle moving in the same direction but on a different road to the destination is $(1350 - 1500)/500 + 0 + 0.5 = -0.2$. As a result, the neighbor with minimum weight calculation will be preferred and selected as a forwarder node.

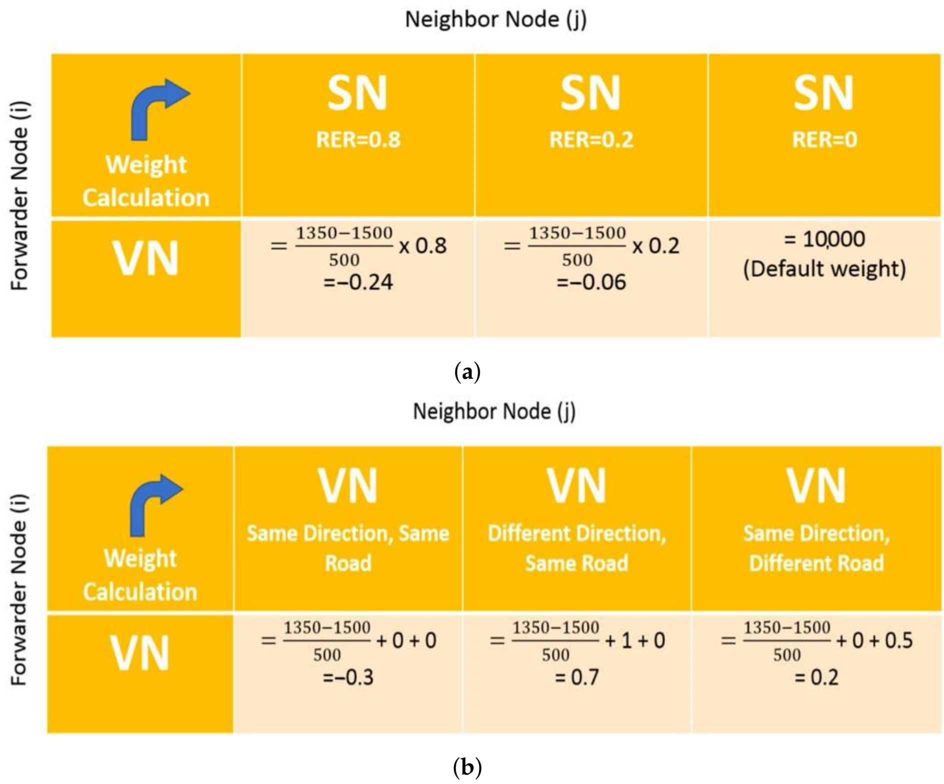

Figure 5. Examplesfor a forwarder vehicle and the weight calculation for its neighbors. (**a**) Example 3. (**b**) Example 4.

The forwarding decisions based on the weight calculations are summarized in Figures 4 and 5.

6. Analysis and Results

6.1. Simulation Setup and Results

This section describes the simulation tool and the parameters chosen to simulate the routing protocols. All parameters used for the simulation are listed in Table 1. We conducted extensive simulations with different mobility traces and random runs to evaluate our proposed protocol. The mobility traces are generated using Simulation of Urban MObility (SUMO) tools for different vehicle speed limits in miles per hour (average speed from 15 Mph to 75 Mph) for the urban area. In NS3, we generate a static wireless sensor node topology in a Manhattan Grid with blocks of 500 m. NS3 is a discrete-event network simulator in which the simulation core and models are implemented in C++. Any routing protocol implementation in NS3 should provide two methods declared in ns3::Ipv4Routing Protocol base class, RouteOutput and RouteInput. The first will deliver a valid route toward the destination for a specific packet to the transport protocol. The latter is called the Ipv4L3Protocol, which is used when a packet is received from a NetDevice, and appropriate action is taken to forward it either to the upper layers (local delivery) or to other nodes (forwarding). The architecture of NS3 internet stack and routing for IPv4 is described in the NS3 manual [27].

Table 1. Simulation settings in urban scenarios

Parameter	Value
Network area	2000 m × 2000 m
Mobility model	Manhattan
Mobility generator	SUMO
Traffic rate	CBR, 512 bytes
Simulation time	100 s
Wireless Sensors Network	
Number of wireless sensors	185
Transmission range	150 m
MAC specification	IEEE 802.11b
Physical rate	DSSS, 1 Mbps
Propagation model	Nakagami
Initial energy	Random [0, 1000] Joule
Vehicles	
Number of vehicles	15 up to 100
Transmission range	500 m
MAC specification	IEEE 802.11p
Physical rate	OFDM, 6 Mbps, 10 MHz
Propagation model	Nakagami

6.2. EMCR Evaluation

In this section, the experiments assess the impact of average vehicle speeds, vehicle density, and cache time on the performance of the EMCR protocol. We set up 10 random communication connections that generate Constant Bit Rate (CBR) traffic between nodes, which generate packets with 512 bytes every 2 s. The maximum buffer size for the SCF mechanism is set to 50 packets. Furthermore, UDP packets of 1500 bytes are used to generate the background traffic at a rate of one packet per second. We evaluate the performance of EMCR over the EMHR and CLWPR protocols. EMCR is a hybrid routing protocol that is aware of hybrid network energy, mobility, and connectivity using the SCF mechanism to hold the packets for a specific time until a better route is found. EMHR [23] is a hybrid routing protocol that is only aware of hybrid network energy and mobility. The EMHR is a hybrid geographic routing protocol that considers energy balancing for sensors to reduce energy consumption and mobility information for vehicles to reduce the end-to-end delay. Moreover, EMHR aims to increase the packet delivery ratio (PDR) and throughput while routing packets in the hybrid network of VANET-WSN. CLWPR [9] is a delay tolerant network for VANETs that is aware of network mobility and connectivity using a carry-and-forward mechanism. In the CLWPR, only vehicles employ a carry-and-forward mechanism by carrying the packets for 2 s.

6.2.1. EMCR over Different Cache Times

We exploit our proposed EMCR protocol to investigate the impact of the SCF mechanism on the network performance in terms of packet delivery ratio (PDR), total throughput, normalized routing overhead (NRO), end-to-end delay, and energy consumption. We vary the cache time to hold the packets for 2 s, 5 s, or 10 s. Additionally, we vary the average vehicle speeds, from 15 to 75 Mph in the hybrid network of VANET-WSN.

PDR is shown in Figure 6 and the throughput is shown in Figure 7. They are decreased by increasing the average vehicle speeds, but increasing the cache time increases the PDR and throughput. NRO is shown in Figure 8. Based on the definition of this metric, an increase in the PDR causes a decrease in the routing overhead. Therefore, NRO is increased with the increasing average vehicle speeds, but is decreased with the increased cache time.

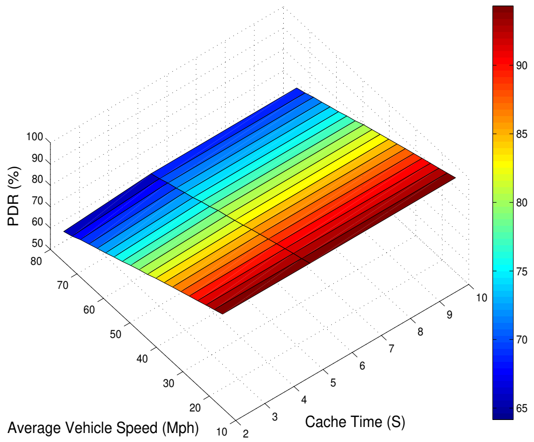

Figure 6. Packet delivery ratio vs. 2 s, 5 s, 10 s Cache Time and Average Vehicle Speed (Mph).

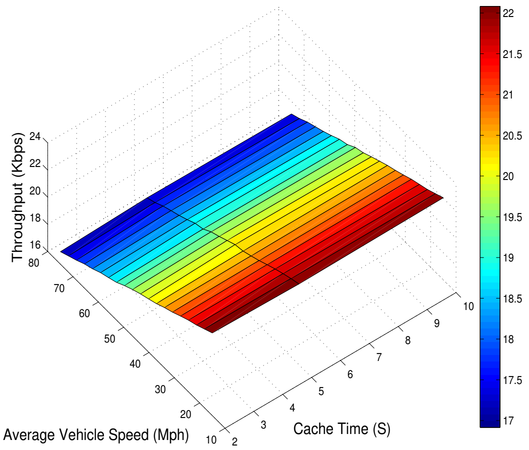

Figure 7. Throughput vs. 2 s, 5 s, 10 s Cache Time and Average Vehicle Speed (Mph).

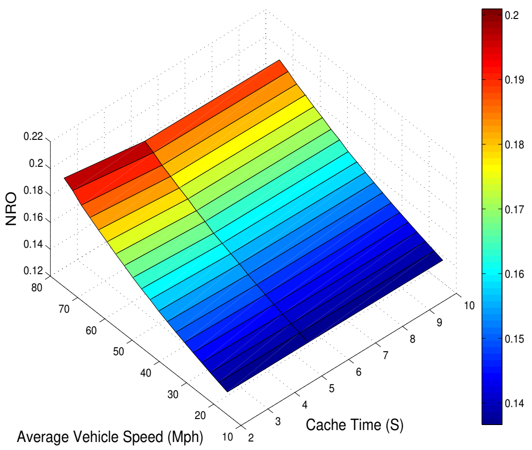

Figure 8. Normalized routing overhead vs. 2 s, 5 s, 10 s Cache Time and Average Vehicle Speed (Mph).

Figure 9 shows the average end-to-end delay, including the total amount of average buffering delay (Store/Carry-Forward delay), and the average transmission delay (forwarding delay) of all successfully delivered packets. Therefore, the average end-to-end delay is increased by the increased average vehicle speeds and increased cache time. As expected, an increase in the average vehicle speeds leads to an increase in the number of dropped packets, as seen in Figure 10, but the number of dropped packets is reduced with the increased cache time, especially for higher average vehicle speeds. Moreover, the energy consumption in Figure 11 increases with the increasing cache time since increasing the number of packets stored in the buffer consumes more energy. Therefore, the EMCR protocol improves the performance in terms of PDR, throughput, NRO, and number of dropped packets, but with some increased delay and energy consumption when the average vehicle speeds are increasing.

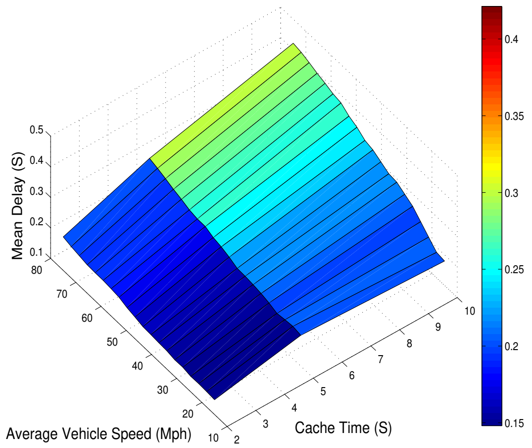

Figure 9. Average end-to-end delay vs. 2 s, 5 s, 10 s Cache Time and Average Vehicle Speed (Mph).

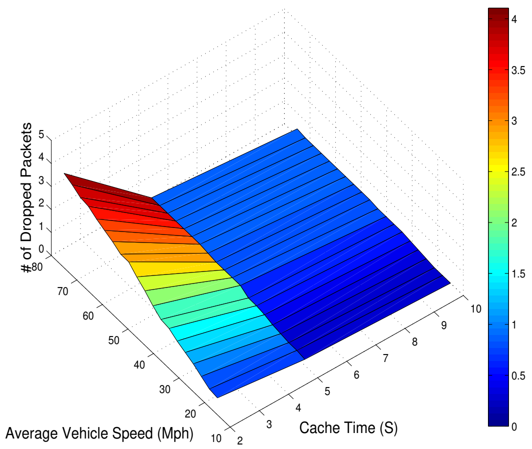

Figure 10. Number of dropped packets vs. 2 s, 5 s, 10 s Cache Time and Average Vehicle Speed (Mph).

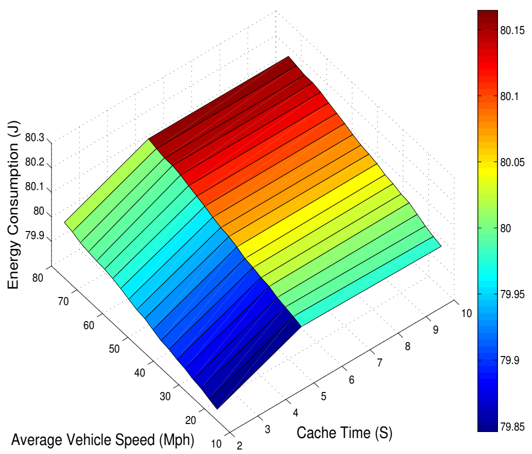

Figure 11. Energy consumption vs. 2 s, 5 s, 10 s Cache Time and Average Vehicle Speed (Mph).

6.2.2. EMCR over EHMR and CLWPR

In order to compare the performance of EMCR with EMHR and CLWPR, we simulate all protocols for a range of vehicle densities, EMCR with no cache, and EMCR with three different cache times. Vehicles in the network have average speeds that range from 15 to 75 Mph. This section shows the performance comparison between EMCR with no cache, EMCR with different cache times, EMHR, and CLWPR. In Figure 12, the x-axis represents the number of vehicles, which varies from 15 to 100 vehicles, and the y-axis represents the packet delivery ratio (PDR). We observe that EMCR with no cache (0 s cache time) has better PDR than the EMHR and CLWPR. Increasing the cache time leads to an increased PDR. For example, EMCR with 5 s cache time has a higher PDR than EMCR with 2 s cache time but slightly less than EMCR with 10 s cache time. Overall, EMCR significantly increases the PDR compared to EMHR.

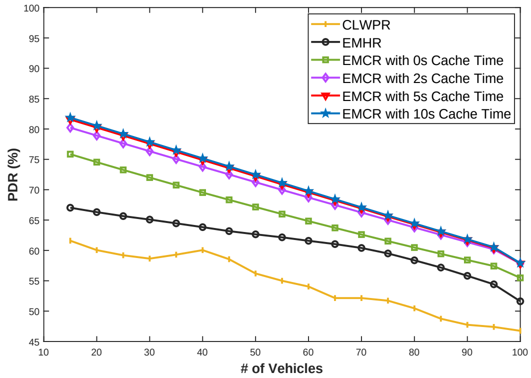

Figure 12. Packet delivery ratio vs. Number of Vehicles.

Figure 13 shows that EMCR with 5 s and 10 s cache time has almost the same throughput performance and is slightly better than EMCR with 2 s cache time but better than EMCR with no cache with an increased number of vehicles. The throughput of EMCR with no cache has the same performance in terms of throughput as the EMHR and better throughput than CLWPR when the network is congested with the number of vehicles. However, the overall throughput performance obtained from EMCR is better than the throughput obtained from EMHR or CLWPR.

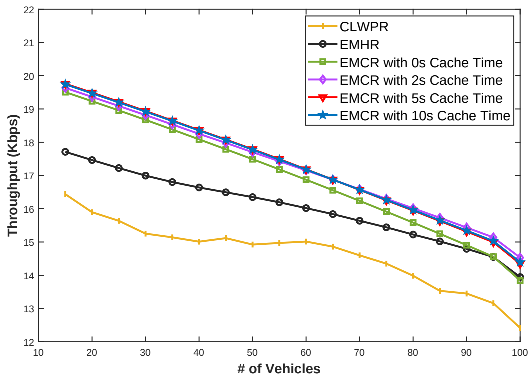

Figure 13. Throughput vs. Number of Vehicles.

Figure 14 shows the NRO of the network. Based on the definition of this metric, an increase in the PDR causes a decrease in the routing overhead. Therefore, the overhead of EMCR decreases by increasing the cache time. Figure 14 shows that the CLWPR protocol has the highest overhead, whereas the EMCR protocol has less overhead than EMHR even as the number of vehicles increases.

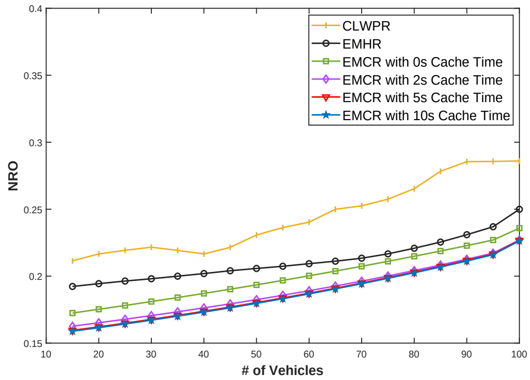

Figure 14. Normalized routing overhead vs. Number of Vehicles.

Figure 15 shows the average end-to-end delay. The average end-to-end delay in the EMCR protocol is reduced while increasing the number of vehicles, but the SCF mechanism causes some delay in the network. Increasing the cache time leads to a higher delay. As a result, the EMCR protocol has a higher delay than the EMHR protocol. However, increasing the cache time helps in decreasing the number of dropped packets, as depicted in Figure 16. Therefore, the EMCR protocol has better performance than EMHR in terms of the number of dropped packets. Moreover, the EMCR with 2 s cache time has a lower delay than the EMCR with 5 s and 10 s cache time. Furthermore, EMCR with 2 s has a lower delay than CLWPR because the CLWPR protocol cannot guarantee to deliver all packets in the hybrid network of VANET-WSN as it has the lowest PDR in Figure 12. Moreover, the number of dropped packets in CLWPR is high, and it is increasing as the number of vehicles increases in Figure 16.

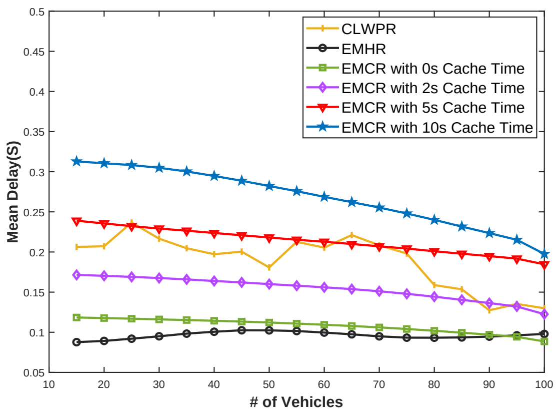

Figure 15. Average end-to-end delay vs. Number of Vehicles.

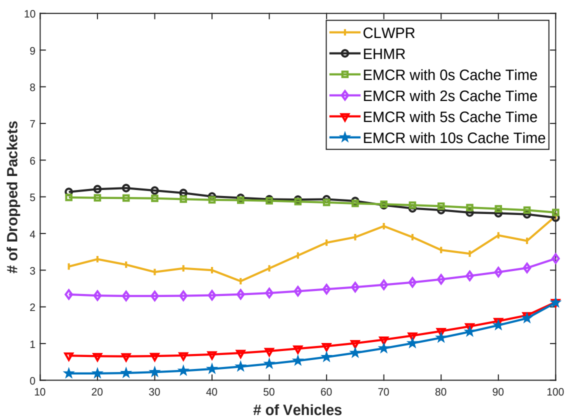

Figure 16. Number of dropped packets vs. Number of Vehicles.

In terms of energy consumption, Figure 17 shows the energy consumption of the networks. Using EMCR with 2 s cache time has less energy consumption than 0 s, 5 s, and 10 s cache time. The reason is that when there is no cache, the SCF mechanism is not employed, and the packets cannot be stored in the presence of network disconnectivity, which increases the number of dropped packets. Moreover, increasing the cache time with 5 s and 10 s cache time means increasing the number of packets stored in the buffer until it overflows and starts to drop the packets, which consumes more energy. The EMCR protocol in all cache time cases consumes less energy than the EMHR and CLWPR protocols. Therefore, the EMCR has better performance than the EMHR and CLWPR protocols when the network is congested as the number of vehicles increases in terms of PDR, throughput, the number of dropped packets, energy consumption, and end-to-end delay. The delay of EMCR with 2 s cache time is 5.8% higher, the EMCR with 5 s cache time is 11.8% is higher, and the EMCR with 10 s cache time is 17.2% higher than EMHR over a range of vehicle density.

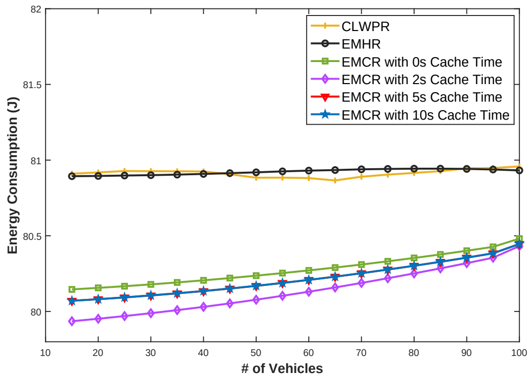

Figure 17. Energy consumption vs. Number of Vehicles.

7. Conclusions

This paper presents a hybrid routing protocol, EMCR. EMCR is aware of the network's energy, mobility, and connectivity issues using the SCF mechanism for storing or carrying packets when there is no contact with other nodes, until meeting at least one node that can forward those packets. The simulation results show that the EMCR protocol outperformed the EMHR and CLWPR and improved the efficiency of the hybrid network of VANET-WSN by increasing the packet delivery ratio and total throughput, and decreasing the energy consumption, routing overhead, and the number of dropped packets. On the other hand, the EMCR protocol outperforms the CLWPR in terms of end-to-end delay.

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